Cave and Karst Science

The Transactions of the British Cave Research Association

BCRA

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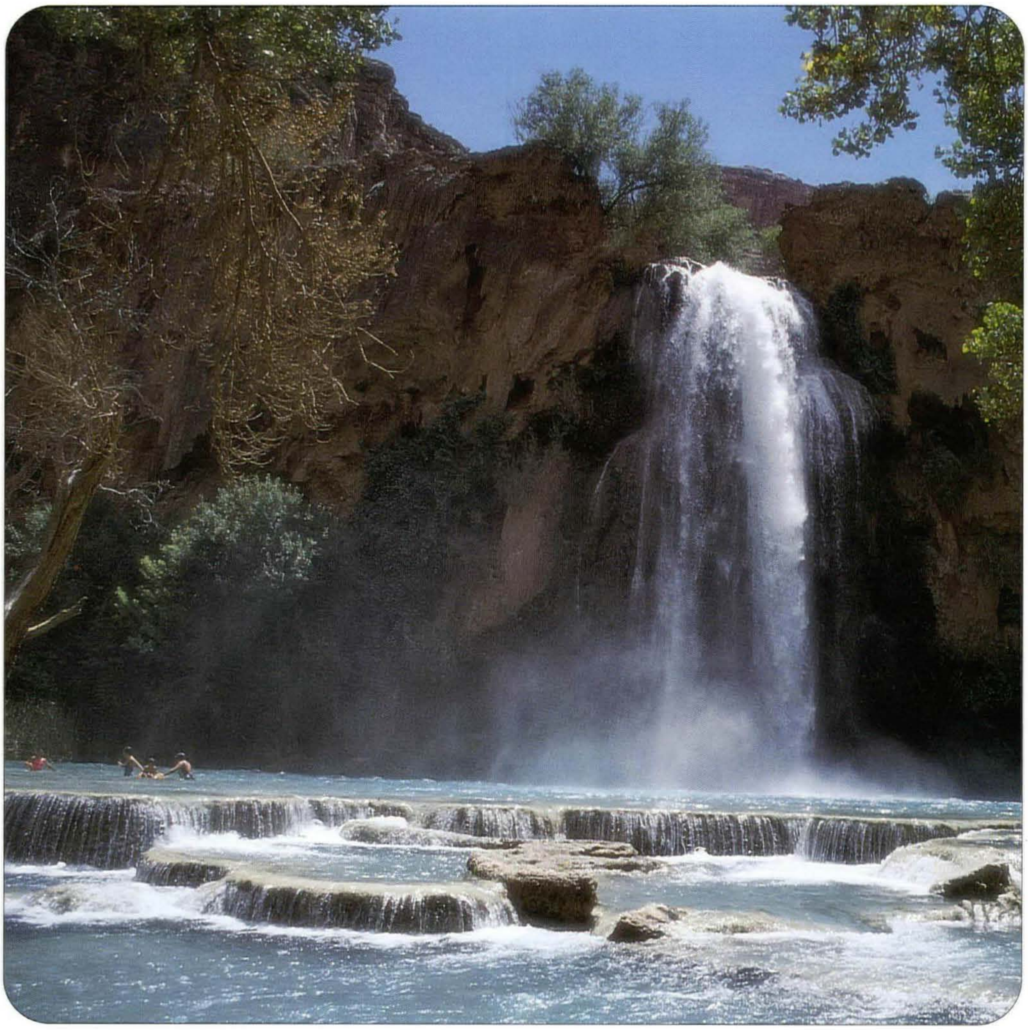

Cave and Karst Science

Authors are encouraged to submit articles for publication in the Transactions of the British Cave Research Association under four broad headings:

1. Mainstream Articles
Scientific papers, normally up to 6,000 words, on any aspect of karst/speleological science, including archaeology, biology, chemistry, conservation, geology, geomorphology, history, hydrology and physics. Papers should be of a high standard and will be subject to peer review by two referees.

2. Development Articles
Shorter papers, normally 500-3,000 words, on aspects of karst/speleological science listed above, or more descriptive material such as caving expedition reports and technical articles. These will be reviewed by the editorial board unless the subject matter is outside their fields of expertise, in which case appropriate expert assessment will be sought.

3. Forum
Personal statements of up to 1,000 words on topical issues; discussion of published papers and book reviews. Statements should put forward an argument and make a case, backed-up by examples used as evidence.

4. Abstracts
Authors (or supervisors) of undergraduate or postgraduate dissertations on cave/karst themes are asked to submit abstracts for publication. Please indicate whether the thesis is available on inter-library loan. Abstracts of papers presented at BCRA and related conferences or symposia will also be published.

Manuscripts may be sent to either of the Editors: Dr. D J Lowe, British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK, and Professor J Gunn, Limestone Research Group, Department of Geographical and Environmental Sciences, The University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, UK. Intending authors are welcome to contact the Editors, who will be pleased to advise on manuscript preparation.

Notes for Contributors

These notes are intended to help the authors to prepare their material in the most advantageous way so as to expedite publication and to reduce both their own and editorial labour. It saves a lot of time if the rules below are followed.

All material should be presented in a format as close as possible to that of *Cave and Karst Science* since 1994. Text should be typed double-spaced on one side of the paper only. Subheadings within an article should follow the system used in *Cave and Karst Science*; a system of primary, secondary and if necessary, tertiary subheadings should be clearly indicated.

Abstract: All material should be accompanied by an abstract stating the essential results of the investigation for use by abstracting, library and other services. The abstract may also be published in *Caves and Caving*.

References to previously published work should be given in the standard format used in *Cave and Karst Science*. In the text the statement referred to should be followed by the relevant author's name and date (and page number, if appropriate) in brackets. Thus: (Smith, 1969, p.42). All such references cited in the text should be given in full, in alphabetical order, at the end. Thus: Smith, D.E., 1969. The speleogenesis of the Cavern Hole. Bulletin Yorkshire Caving Assoc., Vol. 7. p.1-63. Books should be cited by the author, date, title, publisher and where published. Periodical titles should be abbreviated in standard style, or, where doubt exists, should be written out in full.

Acknowledgements: Anyone who has given a grant or helped with the investigation, or with the preparation of the article, should be acknowledged briefly. Contributors in universities and other institutions are reminded that grants towards the cost of publication may be available and they should make the appropriate enquiries as early as possible. Expedition budgets should include an element to help publication, and the editor should be informed at the time of submission.

Figures: Line diagrams and drawings must be in black ink on either clean white paper or card, or on tracing paper or such materials as Kodatrace. Anaemic grey ink and pencil will not reproduce! Illustrations should be designed to make maximum use of page space. Maps must have bar scales only. If photo-reduction is contemplated all lines and letters must be large and thick enough to allow for their reduction. Letters must be done by stencil, Letraset or similar methods, not handwritten. Diagrams should be numbered in sequences as figures, and referred to in the text, where necessary, by inserting (Fig. 1) etc. in brackets. A full list of figure captions should be submitted on a separate sheet.

Photographic plates are welcome. They must be good clear black and white prints, with sharp focus and not too much contrast; prints about 15 x 10 cm (6 x 4 inches) are best; if in doubt, a selection may be submitted. They should be numbered in sequence but not referred to in the text, except where essential and then after discussion with one of the Editors. A full list of plate captions, with photographer credits where relevant, should be submitted on a separate sheet.

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Approximate locations for tables, plates and figures should be marked in pencil in the manuscript margins.

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Speleological expeditions have a moral obligation to produce reports (contractual in the case of recipients of awards from the Ghar Parau Foundation). These should be concise and cover the results of the expedition as soon as possible after the return from overseas, so that later expeditions are informed for their planning. Personal anecdotes should be kept to a minimum, but useful advice such as location of food supplies, medical services, etc. may be included, normally as a series of appendices.

Authors will be provided with 20 reprints of their own contribution, free of charge, for their own private use.

We prefer articles to be submitted on disk if possible, although paper copy is also acceptable. We can read most PC based word processing packages but if in doubt please consult one of the Editors. Apple Mac disks are accepted as a last resort!

If you have any problems regarding your material, please consult either of the Editors in advance of submission.

Cave and Karst Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

Volume 24 Number 3 December 1997

Contents

Cover photo:
Travertine cascades at Havasu Falls, in the Grand Canyon, Arizona
Photo by Tony Waltham (see article by Trevor Ford)

The 30m-high waterfall is one of a series formed where Havasu Creek descends the stepped profile characteristic of the Grand Canyon. This site is a major tributary canyon and lies 800m below the south rim, well to the west of the main tourist area at Tusayan. Travertine is deposited by lime-saturated waters that emerge from springs in the Redwall Limestone. The main fall is draped with travertine, and the low rimstone banks in the foreground impound shallow pools that provide welcome swimming holes.

Editors: Dr. D. J. Lowe — British Geological Survey, Keyworth, Nottingham, NG12 5GG.
Prof. J. Gunn — Limestone Research Group, Department of Geographical & Environmental Sciences, The University of Huddersfield, Queensgate, Huddersfield, HD1 3DH.

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EDITORIAL

David Lowe and John Gunn

When we took over from Trevor Ford as editors of *Cave and Karst Science*, we had two related ambitions for the publication's development. One was to widen the spectrum of subjects that could legitimately be dealt with under the umbrella of the new, and purposely extended, title. The second, which fits hand in glove with the first, was to seek and encourage submission of papers by well-known and less well-known authors from around the world, as well as those within the UK. Arguably, there has been some measure of success in both areas, though we remain aware that some members of the international and UK-based karst research establishment still prefer to publish in higher profile but less subject-orientated journals.

During the past four years *Cave and Karst Science* has attracted a truly multi-national and multi-subject suite of submissions. It is gratifying that, having established and refined our own editorial policies, we now receive a steady stream of enquiries, and draft manuscripts continue to arrive regularly. Rather than struggling to be able to fill the *Transactions* with material that is both interesting and of the desired quality, we are faced with an ever greater need to prioritise and "juggle" the submissions. This volume will be the first for several years to reach the printers in the "cover year" and we aim to have all three parts of Volume 25 with subscribers in 1998. One negative aspect of the volume of material now being received is that some contributors will have to face delays before they can see their work in print. Though such delays are by no means unusual in scientific publishing, the underlying problems do mean that sometimes, for reasons either of balance or the need to optimise on available space, we have to postpone publication of one or more papers in favour of material received more recently. Obviously we would prefer to avoid disappointing any of our contributors, but to date we feel fully justified in the editorial decisions we have had to make, and most authors affected in this way have accepted the delays without demur. Our thanks to all concerned for this tacit support. Recognising the delay between submission and publication, many international journals list the date that a manuscript was first received and the date it was approved following revision based on referees comments. We will be introducing a similar system in Volume 25.

Since starting to work on *Cave and Karst Science* we have tried to widen the circle of experts upon whom we can call to read and review the submitted manuscripts, while continuing to use our own expertise where appropriate. We have been fortunate that few of our requests for refereeing support have been refused, though on rare occasions "turn-round" of the task has been slower than we hoped, for all the usual reasons of work loads and priorities. Our last "thank you" to those that had helped us appeared in the Editorial of Volume 22 Number 3. During the compilation of the issues comprising Volume 23 and the current Volume, we have been helped by Dr Simon Bottrell, Dr Tony Cooper, Ian Drummond, Dr Trevor Ford, Dr Dave Gillieson, Dr Paul Hardwick, Dr Chris Hunt, Associate Professor Stein-Erik Lauritzen, Max Moseley, Graham Mullan, Professor France Šušteršič, Dr Tony Waltham, Dr Fiona Whitaker, Dr John Wilcock and Dr Paul Wood - our grateful thanks to these individuals, some of whom have given freely of their time on more than one occasion, and all of whom have expressed a willingness to help in the future.

Several of those named above, and a number of other karst experts around the world, have expressed an interest in joining a *Cave and Karst Science* "International Editorial Board". The concept of such a panel of experts is common in the world of scientific publishing, even among the relatively few publications that deal with karst-related topics. The availability of an unpaid but committed pool of scientific expertise, from whom the editors can draw advice, provides a significant increase in efficiency when assessing the value of highly specialised scientific, or locally specific, manuscripts, or in identifying potential referees. BCRA Council has agreed to the establishment of an advisory Editorial Board for *Cave and Karst Science,* with members from a variety of disciplines based around the world. The full membership will be listed in Volume 25. In establishing this network we were very much aware of the role now played by electronic mail in enabling rapid and efficient transmission of information and comments, a facility that we have used and developed constantly since taking over in 1994.

Turning from people to scientific topics, we must once again point to a widening of our subject base in this issue, where for the first time we examine some of the environmental aspects relating to land reclamation in the aftermath of limestone quarrying. We acknowledge that this topic is on the very limit of what can be considered "cave and karst science", but on reading the original series of papers from which the current submission was condensed, we were convinced that its contents would be of interest to those concerned about the long-term survival of limestone environments in the face of industrial needs. Many readers will gain at least some reassurance from the findings reported by Katinka Ruthrof, that short- or medium-term resource exploitation need not equate with long-term dereliction and sterilisation, assuming that there is a will (and a budget) to deal with the problem of rehabilitation, and so long as the results of this type of study are acknowledged and applied. It is perhaps also pertinent to point out that Katinka is not "an acknowledged expert". She is currently undertaking studies towards a PhD, and the paper is based upon her undergraduate dissertation! Hopefully this example will provide an incentive to other caving graduates [surely there are some out there!], to submit papers based on their own dissertations.

Continuing the theme of the subject matter covered in recent issues of *Cave and Karst Science*, most established readers will be aware that a general tendency towards publishing a mix of papers from around the world and on a broad range of topics continues. We do not record every phone call and letter, but it is probably true to say that we receive more enquiries about publication from workers outside the UK than from home-based authors. Equally, far more manuscripts sent to us concern aspects of karst science than research that applies directly to caves. Among the cave-related papers that we do receive, however, there is a healthy variety of material, including historical considerations, discussions of cave development, and theoretical and practical aspects of archaeology, biology, chemistry, mineralogy and physics. We would like to see more papers that relate specifically to individual caves, or groups of caves, as well as papers that examine theoretical cave science issues, but, as we move towards Volume 25 of the Transactions we would like to emphasise, yet again, that we will read, consider and report back upon any potential contribution, at whatever "level".

Finally, in closing the Editorial comment on Volume 24, we would like to repeat our thanks of two years ago to Mrs Jean Reeve, who has continued to deal, good-naturedly, with all our Desk Top Publishing requirements. She has worked closely with us, and with our printers, The Sherwood Press, to produce a publication of an increasingly high standard, and has suffered constantly from the inevitable imposition of being asked to cope with more and more demanding tasks against remotely imposed deadlines. We hope that this successful working partnership will continue.

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Organ pipes in carbonate-sulphate rocks at the Kungur Ice Cave, near Perm, Russia

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† We regret to announce the death of Viacheslav Lukin during the Autumn of 1997

Abstract: Vertical dissolution channels or organ pipes, formed in gypsum cave roofs, are described from the Kungur Ice Cave, near Perm, Russia. Many, but not all, of the organ pipes connect between surface depressions and horizontal cavities. Organ pipes are formed within the vadose zone in thickly bedded and massive sulphate rocks, in mantled karst situations where the cover beds include carbonate, carbonate-sulphate or carbonate-clay deposits. The presence of carbonate rocks in the overlying sequence is important for organ pipe development, as most of the pipes are formed by water percolating from overlying aquifers. Pipes do not form where cover beds are absent. In Kungur Cave, 146 organ pipes with cross sections ranging from 0.2 to 10m in diameter have been mapped. The organ pipe locations are guided by jointing in the rock, the nature of the overlying aquifer and the presence of thick gypsum.

INTRODUCTION

Gypsum and gypsum karst features are widespread in the Permian rocks of the Perm area of Russia. The Kungur Ice Cave is developed in Kungurian gypsum next to the River Sylva at Kungur, 80km south-east of Perm (Fig.1). Large vertical channels occur in the vadose zone within the massive gypsum-anhydrite that contains this cave. These channels, investigated by Karakash (1905), have been called "organ pipes". They occur in numerous cave roofs, are up to 10-20m high and from a few tens of millimetres to 10m in width. Pipe cross sections may be sub-circular, ellipsoidal or of more complex form. Downpour of water from the surface and from overlying strata passes through these pipes, and the volume is augmented when the snow melts. Tripartite systems, where organ pipes connect surface depressions and horizontal cavities, were described as the "...common system of karstopolynoms (multinomial)" by Aprodov (1949). Organ pipes are abundant in the Kungur Ice Cave; some of the results of their extensive investigation are reported here.

GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

Organ pipes are formed in the percolation zone of thickly bedded and massive sulphate rocks in mantled karst, with a cover of either carbonate, carbonate-sulphate or carbonate-clay deposits. Morphologically similar features found in carbonate karst caves are characterised by their large dimensions, and commonly have a fill of sinter deposits. In the sulphate karst situation the involvement of carbonate rocks in the overlying sequence is of crucial importance for organ pipe development. For example, in the Western Ukraine a limestone layer (0.5 - 3m thick) and clay strata (5 - 100m or more thick) cover the gypsum, and organ pipes have formed between the top of the gypsum beds and the general level of cave development. In the Pre-Urals karst regions, the gypsum-anhydrite sequences contain intercalations of carbonate (Fig. 2) or are covered by carbonate-sulphate deposits. The organ pipes are confined to this sulphate-carbonate stratum and the overlying carbonate deposits, or the carbonate intercalations, guide their location. Both the strength and

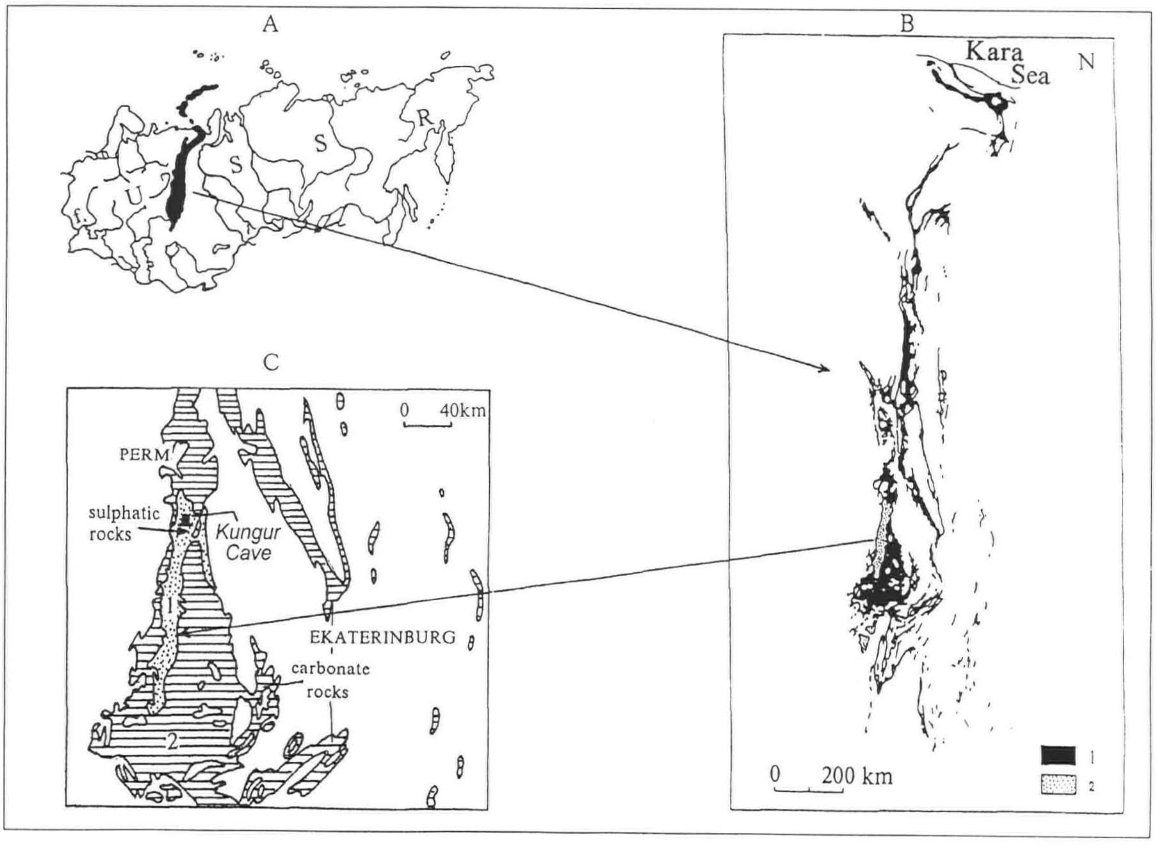

Figure 1.(A) The location of the Ural region within the former USSR; (B) the spread of karst rocks in the Region; (C) the location of the Kungur Ice Cave in the Middle Ural area. [1 - carbonate rocks, 2 - gypsum rocks.]

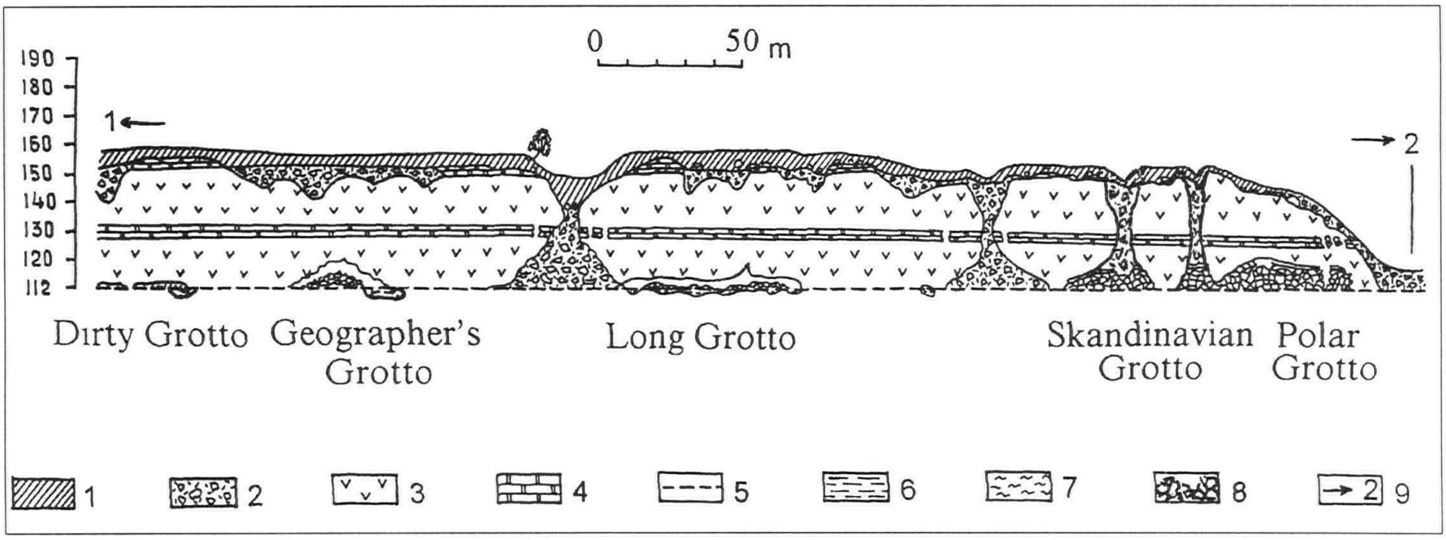

Figure 2. Geological section through the Ledjanaja Gora (Ice Mountain) and Kungur Cave. [1 - loam/soil; 2 - blocks of dolomite/limestone (dissolution breccia); 3 - gypsum/anhydrite; 4 - limestone/dolomite; 5 - surface of the karst aquifer; 6 - underground water; 7 - clay; 8 - breakdown material; 9 - line of section. (see Figure 3A).]

the permeability of the overlying carbonate rocks are of great importance for organ pipe development. Fractured limestones and dolomites are permeable to water but are strong enough to support any unconsolidated material in the overlying deposits.

As organ pipes are formed by water percolating from an overlying aquifer one of the main factors influencing their development is the permeability of the overlying rock. In the Pre-Urals area, for example, the infiltration of water derived from rain and snow-melt causes water to permeate from the surface and collect in karst cavities at the upper limit of the gypsum and anhydrite beds. Where there is a uniform sulphate stratum with vertical tectonic fractures, the features guide organ pipe development, affecting the width and stability of the pipes and imposing the essentially vertical nature of their walls. Where gypsum and anhydrite beds are separated by bands of other rock types (mainly dolomite or limestone), two or three levels of organ pipe development can occur (as for example, above some of the grottoes in the Kungur Ice Cave). In such cases, pipes that form at different levels and during different stages can lie on a single vertical axis or their positions may be stepped sideways where they intersect carbonate beds. This effect explains why organ pipe locations shown on the plan of Kungur Cave's underground galleries (Fig. 3B) do not necessarily coincide with the positions of overlying surface features (Fig. 3A). It also explains why organ pipe centres in bedding-guided caves at different sub-surface levels are not inevitably coincident.

Organ pipes do not form where overlying strata (cover beds) are absent. In such situations tubular forms related to sub-surface karren genesis or the localized absorption of surface water (from rain, snow-melt, river leakage or subsoil infiltration) are formed. Their dimensions are small compared to those of organ pipes, and they are commonly referred to as tubular karren (Kunitsa and Andrejchuk, 1985), sinkholes or wells.

MORPHOLOGY

Organ pipes are essentially vertical sub-circular channels, with heights exceeding their diameter. The height-diameter ratio may vary greatly. Many of the Kungur Cave organ pipes are conical in shape, becoming wider towards their mouths; cylindrical channels are also not uncommon. The pipe walls are sculptured, with numerous karren that occur as grooves and furrows, separated by protrusions and crests of different sizes. Small channel-pipes, formed by localized discharge, are also common in the walls of the larger pipes.

In Kungur Cave the organ pipes widen at the contacts between the sulphate rock and the dolomite. In the Druzhba Narodov (Peoples' Friendship) Grotto, the pipe walls are also crossed by karren at the contact, and the dolomite has collapsed to form a 5m-high chamber with greater lateral measurements than the associated pipe. Similar collapsed cavities occur above other large pipes in places such as the Efirny Grotto (Plate 1). Water infiltration can saturate argillaceous dolomites within the sequence, reducing their strength and promoting the development of such collapse cavities.

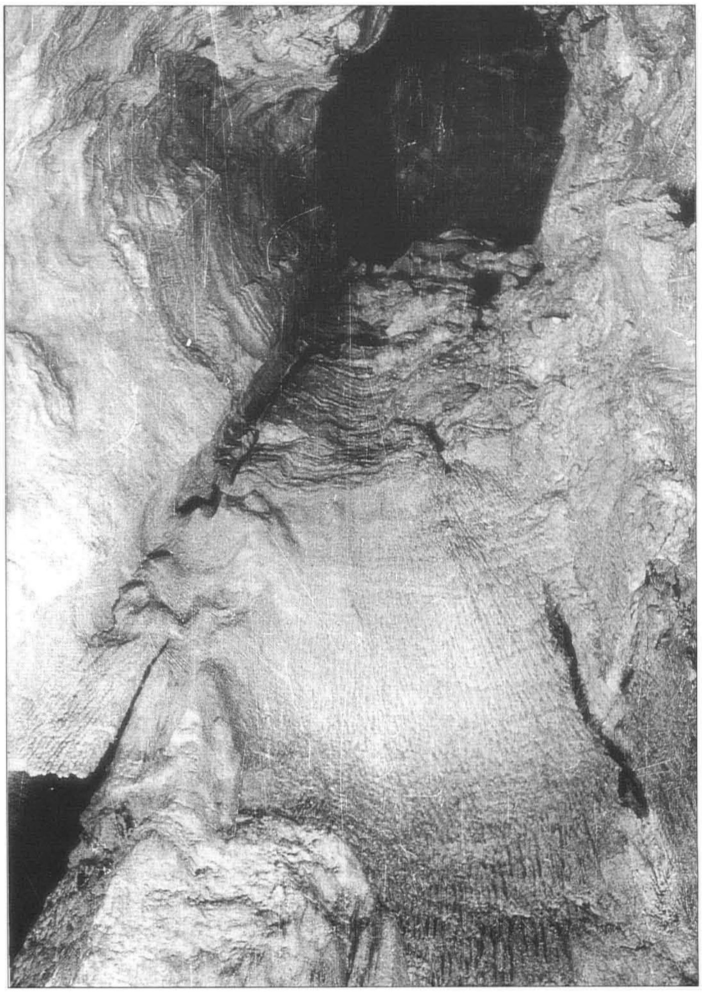

Plate 1. Organ pipe in the Efirny Grotto. The dimensions of the pipe mouth are 2 x 3m and the tube is 20m high. (Photo by Evgenij Dorofeev)

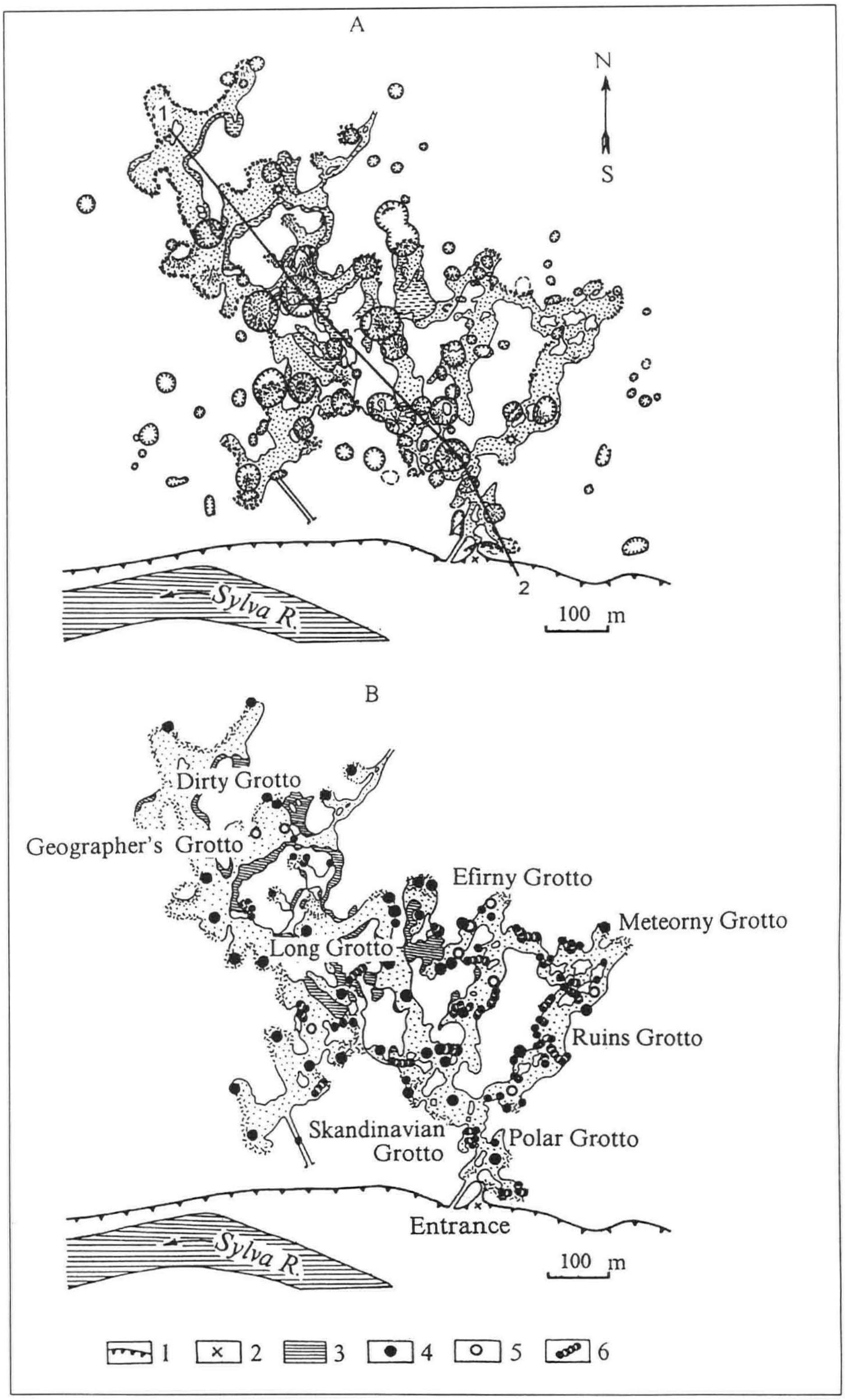

Figure 3. (A) Distribution of dolines on the surface above the Kungur Ice Cave, related to (B) large organ tubes above the galleries of the Kungur Cave. [1 - gypsum escarpment; 2 - Cave entrance; 3 - underground lakes (level of aquifer); 4 - infilled organ tubes; 5 - open (active) tubes; 6 - chain of tubes.]

DISTRIBUTION

Underground forms of organ pipe type occur in gypsum caves within the Pre-Urals, Povolzje (Middle Volga area), Podolia and Bukovina (Western Ukraine) karst regions. In the Pre-Urals, they occur typically in elevated banks where relaxation of the rock towards eroding valley sides has caused fissures to open. In Kungur Cave, 146 organ pipes with cross sections ranging from 0.2 to 10m have been recorded (Fig. 3B). Eighty-five of these are filled with loose material, and there are debris cones on the cave floor beneath the pipe mouths. Four pipes in the ceiling extend up to the overlying carbonate bed. The upper ends of 57 pipes that are open inside contain karst breccia composed of dolomite fragments cemented by calcite.

WATER IN ORGAN PIPES

In most of the caves, water drips constantly down the insides of the pipes. Most of the vadose zone drainage in the sulphate rocks is concentrated within them, with the separating (pipe-free) pillars mainly forming dry areas. Natural expectation is that the pipes would form where water infiltration is most intense. However, in the Ruins, Geologists, Long and Autumn Night sections of the Kungur Ice Cave no organ pipes have been observed in the zones of maximum water input. In these zones, the water has high total dissolved solids (TDS) concentrations, and consequently the water is less aggressive, simply percolating through fractures in the cave roof. It is probable that this drainage is restricted to the sulphate rock

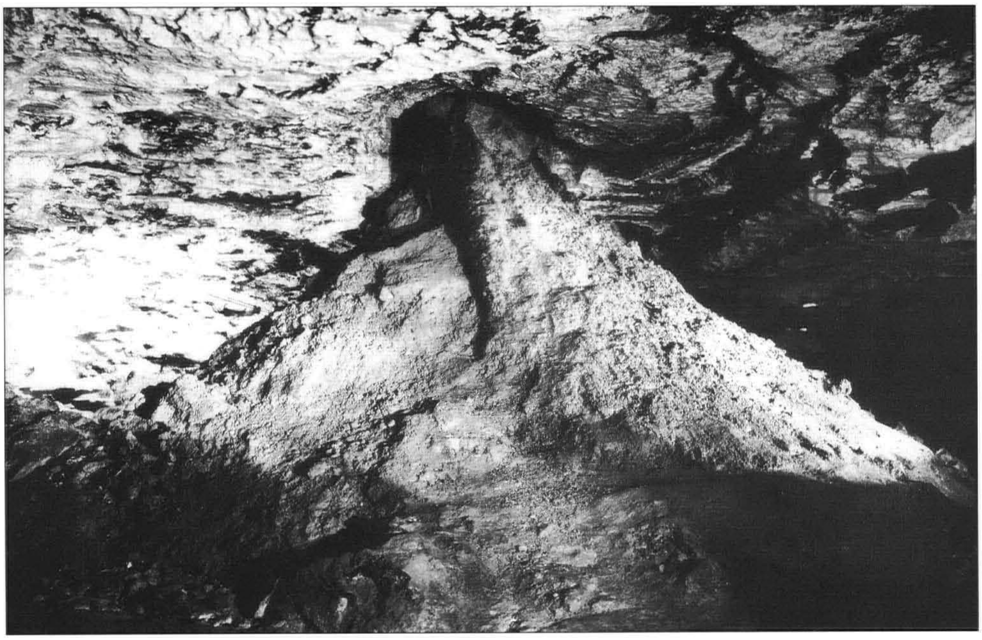

Plate. 2. Talus under an infilled organ pipe mouth. The dimensions of the pipe mouth are 2 x 4m. (Photo by Evgenij Dorofeev)

and does not pass through the overlying carbonate rock, where aggressive water would be present.

The TDS values measured for water dripping from selected pipes are presented in Table 1. In the Morskoje Dno (Sea Bottom) Grotto, of the Kungur Cave, volume and chemical composition values of water from an organ pipe are oscillatory (Fig. 4), but the changes in TDS values are not synchronous with local, strongly marked, seasonal weather rhythms. In other pipes, such as those in the Efirny and Mokraja Kochka (Wet Tussock) grottoes, the infiltration and volume of dripping water increase when snow melts on Ledjanaja Mountain.

DEVELOPMENT AND FILLING OF ORGAN PIPES

Initially organ pipes form at fracture intersections. The pipes are complex with an irregular form and locally they include parallel channels. Gradually the dripping water dissolves and abrades the gypsum and anhydrite, resulting in more uniform vertical channels of sub-circular cross section. Further growth of the pipes, such as has occurred in Kungur Cave, leads first to the collapse of the overlying carbonate beds and then to the collapse of any unconsolidated cover deposits (Fig. 5). Some of the collapsed material forms cone-shaped clay-bound talus heaps beneath pipe mouths (Plate 2). Where the thickness of unconsolidated cover rocks is small, the pipes can open to the land surface, to become karst channels and sinkholes (Plate 3, Fig. 5). Many pipes become completely filled with loose material derived from collapse of the upper layers.

Organ pipes can connect horizontal caves with subsidence basins on the surface. Such interconnection is demonstrated in the Kungur Cave galleries by the presence of 33 large talus cones that correspond to subsidence features on the surface of Ledjanaja Mountain (Dorofeev, 1970). However, because the cavities above them have not yet penetrated the upper layers, some talus cones do not have corresponding surface depressions above them. The appearance of surface-derived loam in the talus cone beneath a pipe indicates a collapse that has propagated to the surface.

Downward movement of groundwater and air takes place through organ pipes. This initiates geochemical processes in any loose material through which the water is percolating, and this causes dolomite calcitization, spherulite growth and sinter formation. Gypsum spherulites up to 50mm in diameter, with a radial-fibrous structure, have formed on the walls of some organ pipes. The temperature of the stagnant warm air is generally between 3 and 5°C, but it is often higher near the ceiling of some organ pipes than in their lower levels. Cold periods during the winter result in the growth of numerous ice stalagmites.

With time the organ pipes evolve, gradually becoming filled with loose material and losing their characteristic appearance and properties. They enlarge more quickly at the top and their wall morphology becomes of more complex, with a more irregular form. Eventually they become identical in appearance to the vadose zone cavities that form at the surface of the karst and are constantly filled with karst deposits.

KARST RELIEF

In the Pre-Urals region most surface collapse features are related to the failure of organ pipes (Lukin, 1975). With rare exceptions the initial diameters of collapses in the Kungur area vary from 0.5 to 5m, with depths

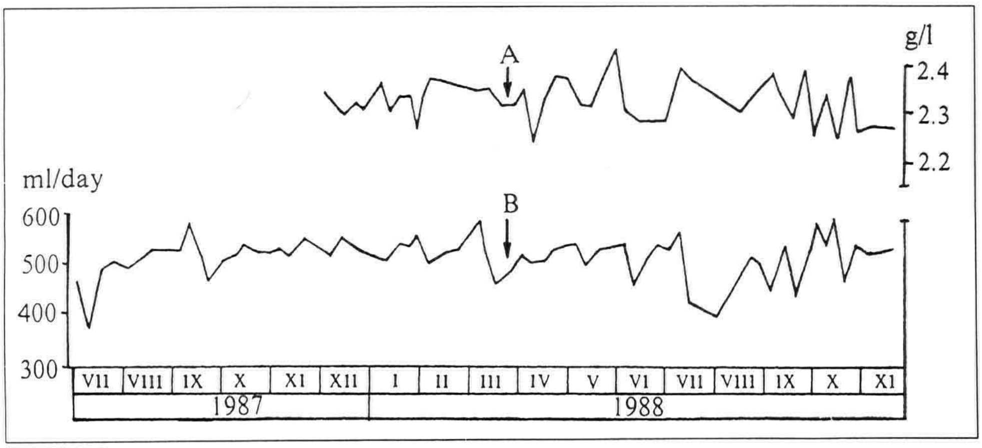

Figure 4. (A) Changes of the total dissolved solids (TDS) concentration and (B) the quantity of water dripping from a pipe in the Morskoje Dno (Sea Bottom) Grotto. [Based on daily measurements.]

	Water sample location (Named grottoes or chambers)	Date of sampling	TDS - concentration, mg/l	Chemical components						
				HCO_3^-	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	$Na^+ + K^+$	CO_2
1	Krestovy [Crossed]	7-2- 1968	6820	85.4	4010	5.7	163	16.5	9.2	0.08
2	Krestovy [Crossed]	28-7-1968	7450	85.4	4610	4.6	148	44.8	1.4	2.80
3	Morskoje Dno [Sea Bottom]	28-7-1968	1882	85.4	1265	5.0	462	52.7	12.0	1.90
4	Efirny	28-7-1968	1951	85.4	1306	5.0	505	36.4	12.4	2.30
5	Mokraja Kochka [Wet Tussock]	28-7-1968	1923	85.4	1281	9.5	531	18.0	4.1	--
6	Gothic	28-7-1968	1670	61.0	1145	5.7	387	67.1	3.9	2.30
7	Gothic	8-4-1985	2061	85.4	1374	3.5	541	36.5	2.3	8.00
8	Coliseum	2-3-1956	1730	65.0	1162	11.4	438	48.0	---	7.00
9	Shapka Monomacha [Monomakh's Cap]	28-7-1968	2068	85.4	1408	8.5	470	86.4	9.0	5.00
10	Geographer's	12-3-1956	2210	97.6	1485	14.2	520	80.5	8.3	6.00

Table 1. Chemical content of water dripping from organ pipes in the Kungur Cave (in mg/l).

of up to 4m. About 83% of the underlying organ pipes in Kungur Cave have similar dimensions.

On the slopes of river valleys in the Pre-Urals, where superficial deposits and the carbonate cover of the gypsum are denuded (downslope or into karst cavities), areas of bare gypsum karst occur, with vast numbers and high densities (5,000 to 8,000 forms per square kilometre) of karst dolines and shallow (3-6m) shafts. They are infilled to different depths (2-10m or more) with loose material and fragments of carbonate rocks, and their appearance is typical of old organ tubes, opened by denudation and transformed into surface karst features (Fig. 6). Such places are very typical for the southern part of the Pre-Urals (the Bashkortostan Republic). Their appearance is very striking against the background of the open steppe landscape. Thus, pre-existing organ pipes are a vital factor in the mechanism of surface karst relief development in the gypsum karst areas of the Pre-Urals.

CONCLUSIONS

Organ pipes are original and distinct sub-surface features of sulphate karst. The geological conditions necessary for their formation are:

- thick and homogenous beds of sulphate rocks;
- a cover of weakly soluble and non karstic rocks;
- a fracture system in the sulphate rock.

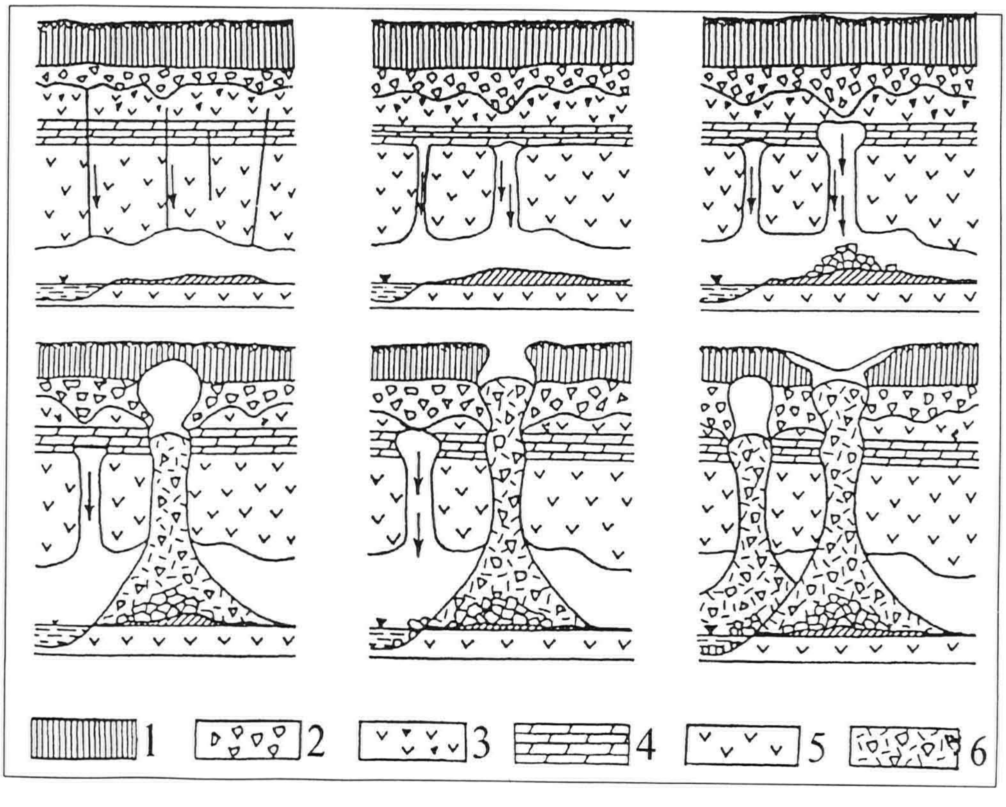

Figure 5. Sequence of sinkhole (doline) development above the organ pipes. [1 - loam/ soil; 2 - karst-collapse deposits; 3 - gypsum; 4 - dolomite; 5 - anhydrite; 6 - breakdown material.]

In some regions and in some cases, the pre-existence of sub-surface organ pipes is one of the major factors influencing the nature and extent of surface karst relief development.

ACKNOWLEDGEMENTS

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Figure 6. Development of karst relief on the slope of river valley (Aurgaza River basin, Bashkortostan Republic).

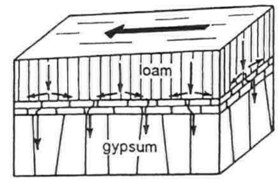
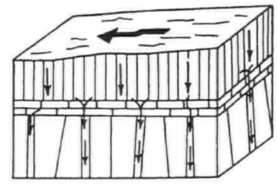
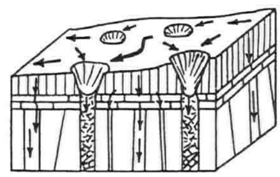
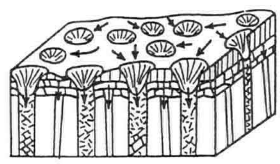
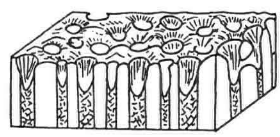
1		Gypsum is covered by layer of carbonate rock. Ground water percolates from loose deposits into gypsum through the permeable limestones dissolving walls of fractures.
2		Percolate water dissolves gypsum and increases vertical fractures transforming them into channels. Thickness of covered deposits decreases owing to surface erosion.
3		Sinkholes form above the channels. They intercept superficial flow and drift of loose material. Water percolation continues through karst forms and fractured limestone. New channels grow in gypsum and old channels increase in size.
4		Precipitations and superficial flow are absorbed *in situ*. The surface is dotted with cone-shape dolines. Wash-out of loose deposits and their drift into sinkholes take place. Limestone cover is deformed, partially destroyed.
5		Loose superficial deposits and limestone cover are eroded, destroyed and replaced into vertical karst channels. The bared surface of gypsum is dotted with many of small shaft-shape holes - preserved parts of karst channels (tubes).

Plate 3. Dolines at the land surface above underground vertical channels. (Photo by Evgenij Dorofeev)

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Tufa and travertine deposits of the Grand Canyon

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Abstract: Although tufa is widespread in the Grand Canyon, it has attracted only passing attention in guide books. There has been limited research on a few occurrences, but no details of specific investigations have been traced. The present account describes the deposits, and suggests which formational mechanisms have been operative. Potential effects of wet climatic phases versus those caused by lava dams are also assessed.

INTRODUCTION

Though the Grand Canyon is not usually regarded as a karstic feature, considerable thicknesses of strata in its walls are limestone or dolomite containing numerous caves, and there are many freshwater deposits of calcium carbonate, generally known as tufa and travertine. Some such deposits in the western Grand Canyon have been claimed as among the most spectacular in the world (Hamblin and Rigby, 1969), but no specific description of the various deposits has been traced. There are summary accounts in several guide books, such as Hamblin and Rigby (1968, 1969) and Elston et al (1989) and brief notes in Feth and Barnes (1979), in Breed and Roat (1976, p.128) and Beus and Morales (1990, p.481-2). None of these made any real attempt to give a full description, provide a classification or discuss the mechanisms of deposition. The present account is intended to try to fill these gaps in knowledge and to point out where further research is needed.

Terminology

The terms tufa and travertine are used almost interchangeably in reports on freshwater calcium carbonate deposition, with tufa more common in European and travertine in American literature. Some polarization in definition has come about in recent years and *tufa* is generally regarded as a freshwater limestone deposited from spring systems at ambient temperatures, whereas the term *travertine* is reserved for deposits formed from thermal waters (Pedley, 1990; Ford and Pedley, 1996). However, the definition of a thermal spring is still unsatisfactory: it is usually taken as being greater than 20°C but hot climatic regimes, such as that in the Grand Canyon, may have average ambient temperatures around that figure. Dilution of undoubted thermal waters by meteoric percolation will also produce springs around the definitive temperature of 20°C. Several "thermal" springs in the Grand Canyon have temperatures recorded at 21°C, and these may well result from the merging of meteoric and deep-seated thermal waters.

A possible means of distinction between meteoric tufa and thermal travertine is in the chemistry of the rising waters. Thermal waters, by virtue of their longer residence time within aquifers, their deep-seated circulation and extended reaction time with rocks are likely to have higher concentrations of sulphur, H_2S and phosphate, whilst meteoric waters have little besides carbonate in solution. Even then, if meteoric waters circulate in strata containing evaporites they may contain relatively high concentrations of sulphur compounds.

Mechanisms of deposition

The distinction between tufa and travertine may be taken a stage further by examining the mechanisms of deposition. Though opinions vary as to the relative importance of purely physico-chemical and bio-mediated causes of precipitation, it is generally accepted that biological processes operate more effectively at ambient temperatures and so yield tufa. High temperature thermal springs (c.90°C plus) usually have no life forms present and precipitation is physico-chemical, but there is a whole range of conditions where both processes may operate at temperatures less than 90°C, with bacteria and algae becoming more important as the temperature falls.

Physico-chemical precipitation is largely a matter of de-gassing, i.e. loss of CO_2. This loss may start from supersaturated waters on resurgence, but is more common downstream, as turbulence increases the potential for de-gassing, for example at waterfalls. Higher temperatures decrease the solubility of calcium bicarbonate and thus increase the rate of de-gassing. In warm climates meteoric springs warm up as they are affected by ambient air temperatures and so carbonate precipitation may not start until some distance downstream from the spring. As CO_2 is lost, so $CaCO_3$ is precipitated, and the rate of deposition is greatest where turbulence is highest, i.e. on the lips of waterfalls. Evaporation also increases the rate of deposition in hot climates.

Bio-mediation can take several forms: as CO_2 is taken up from the bicarbonate in solution by plants during photosynthesis, so $CaCO_3$ may be precipitated directly on to growing plant tissue. The "leaves" of mosses are an obvious focus for such growth. Less obvious is the fact that many algae have a polysaccharide mucus coating and finely-divided carbonate adheres to this sticky material. Cyanobacteria may also have mucus sheaths and so bind finely-divided $CaCO_3$. Some red algae deposit $CaCO_3$ directly within their cell walls. Macrophytic remains that grow within tufa-depositing streams, or which have fallen in, act as nuclei for algal/bacterial growth, as sites for increased turbulence and as mechanical traps. Aquatic insects and their structures, such as caddis-fly tubes, may also act as nuclei for tufa deposition.

Both physico-chemical and bio-mediated mechanisms can operate together, and research is needed on individual deposits to decide which is the dominant process. Such research should be both physico-chemical and microbiological: these will include detailed petrography of growth textures and structures, and will necessitate identification of the micro-organisms present together with an assessment of their effect on the precipitation of carbonate.

A further complication is that as thermal waters cool they become more environmentally friendly to plant life, so that thermal travertines may pass into ambient tufas. Changing hydrologies in the catchments may also affect the character and temperature of resurging waters.

Some writers have distinguished tufa as "soft and crumbly" and travertine as "hard and solid, suitable for constructional use", but as neomorphic recrystallization of soft tufa may lead to a hard lithology, the resultant travertine crosses the definitions given above.

So far as the authors are aware there has been little attempt to study the detailed mechanisms of tufa deposition in the Grand Canyon. Little has been said on the petrography or on the microbiology of any deposit, and only limited comments have been made on the chemistry (Giegengack et al, 1979).

Dating tufa deposits

The age of tufa deposits is another matter for controversy. Many are still growing, but it is the date of commencement of growth that is more significant in unravelling the geomorphological history of an area. Inactive deposits may be of any age; whereas some may clearly be related to the present erosional cycle, it may be critical to know when older deposits started growing. Radiocarbon dating has been tried for some younger deposits, but has yielded distinctly different dates from the tufa and for the wood it encrusted (Giegengack and Ralph, 1973; Giegengack et al, 1979). Organic matter ages depend upon direct contact with atmospheric ^{14}C, but spring waters may have a blend of isotopic ratios from the atmosphere and from water held underground for long periods, where it may have reacted with ancient limestones. Thus the ^{14}C method is unreliable, except where both tufa and organic matter produce the same age. The Uranium-series dating method has been applied to some Grand Canyon deposits but only abstracts have been published (Szabo et al, 1986, 1991). The difficulty with the uranium-series method is in analysing primary growth samples alone, preferably those of microbiological origin, and where no recrystallization has taken place. Many tufas are cavernous and secondary calcite is commonly deposited in the voids later. Such secondary calcite deposits must be excluded in sampling for uranium disequilibrium determinations. Contamination by clastic sediments containing thorium may make the method unworkable.

Environments of deposition

According to Pedley (1990) and Ford and Pedley (1996), tufas are deposited in the following environments:

1. Fluvial:
   a. Braided sheets: in shallow braided channel systems;
   b. Barrages: dams built up across streams with phytoherms ("algal build-ups") at their cores, and with phytoclast accumulations both up- and downstream.

2. Perched springline: lobate slope deposits associated with springs part way up valley sides:
   a. Proximal: with small cascades, micro-terraces and small pools;
   b. Distal: low angle sheets with much phytoclast material.

3. Lacustrine: associated with large bodies of water wherein algal bioherms or bacterioherms build up round the margins. Deposits are flat on top and commonly overhang below water. *Chara* is often common. Adjacent lake floors are covered with fine to coarse phytoclastic sediment.

4. Paludal: deposits on poorly drained slopes associated with abundant macrophytes and bryophyte hummocks. Local small pools with fine phytoclast sediment.

Travertines are deposited with similar lithofacies but tend to be focused on the type of orifice where hot water rises. Some deposits are formed around linear fractures and yield fissure-ridge structures, i.e. elongate domes. Many travertine deposits are in complex terrace sequences, as at Mammoth Hot Springs in Yellowstone National Park, Wyoming. There series of small barrages hold up pools and have overhangs adorned with stalactites. Whilst the waters are hot there is little bio-mediation but variegated colours downstream mark the incoming of various algae and bacteria as the water cools.

In the hot semi-arid climate of the American Southwest it is tempting to correlate inactive tufa deposits with former wetter climatic phases, i.e. pluvial periods, and thence to propose possible correlations with glacial phases farther north. However, without corroborating evidence from other dated geological features this can lead to unwarranted assumptions.

The following description is based on observations made on several raft trips through the Grand Canyon by the first author and interpretation of photographs made with the help of the second author. Significant comments have been taken from the guide books where appropriate (Hamblin and Rigby, 1968, 1969; Elston et al, 1989).

DESCRIPTION OF THE DEPOSITS

There are considerable thicknesses of limestone in the walls of the Grand Canyon. These include the Muav Limestone (Cambrian) and the Redwall Limestone (Mississippian). They are both underlain by, separated by and overlain by thick clastic sedimentary formations, and the surrounding plateau surface is largely composed of the Permian Kaibab Limestone, much of which is dolomitized. Recharge of these limestone aquifers is

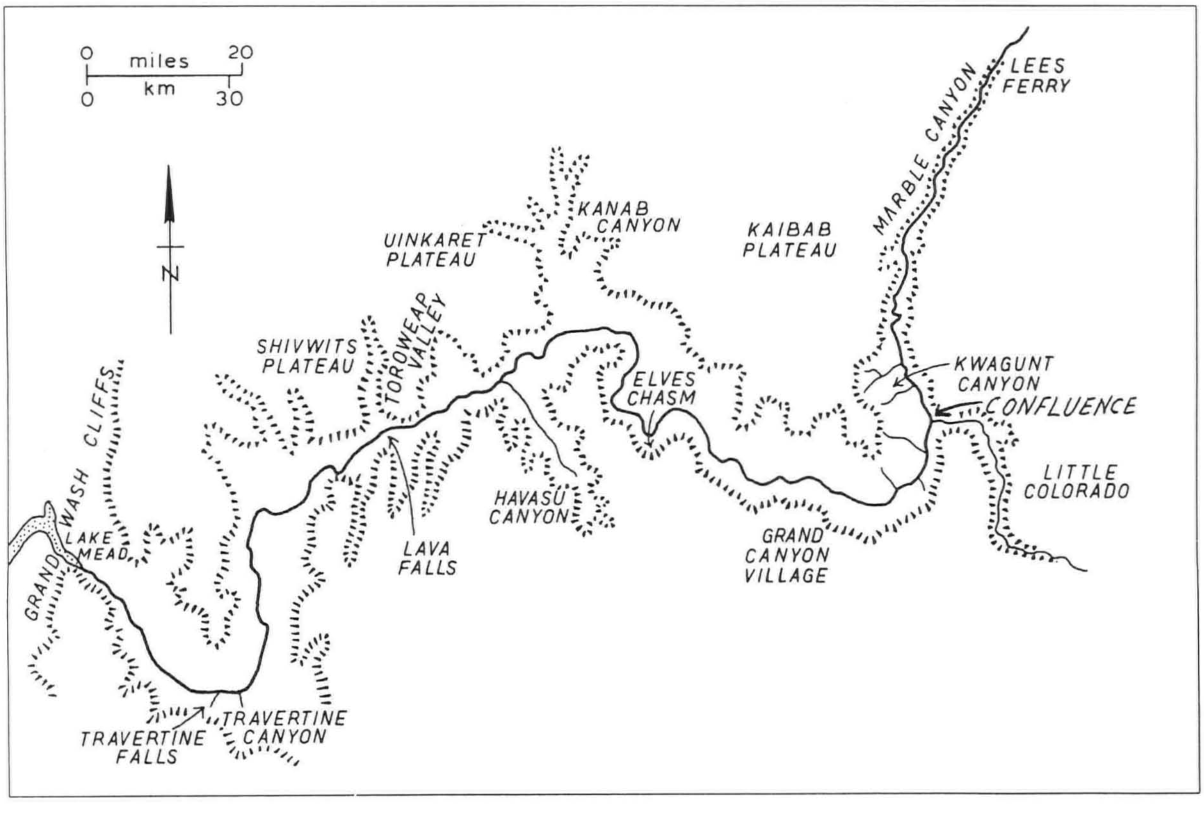


Figure 1. Sketch map of the Grand Canyon, showing principal tufa localities.

largely by infiltration along faults and by slow percolation through the clastic formations. There are extensive cave systems in both the Redwall and Muav limestones, and spectacular springs discharge from their outcrops in the Canyon walls. Incision of the Canyon since Mio-Pliocene times has gradually drained the aquifers, but both climatic changes and lava dams (see below) have affected the hydrological regime during the Pleistocene.

Both ambient temperature tufa and thermal travertine occur in the Grand Canyon (Fig.1). However, the springs feeding the latter are generally little above the defining temperature of 20°C (Feth and Barnes, 1979) and with daytime temperatures commonly being well above that figure, it is probably better to consider all the Grand Canyon deposits together. The following descriptions are arranged according to the conventional distance of river miles down the Colorado from Lees Ferry. Throughout, left bank refers to the southern side of the Canyon, and right bank to the northern. Before entering the Grand Canyon at Lees Ferry, the Glen Canyon Dam has some minor tufa deposits. These form from the drainage water running out of tunnels in the Navajo Sandstone (Early Jurassic) walls. When the water reaches the open air (with higher temperatures) de-gassing of CO_2 causes small barrages and associated pool deposits to form in the artificial channels above the power house. As soon as the water reaches the River Colorado it is so diluted that deposition ceases.

0 to 56 miles (0 to 90km):

Marble Canyon: in spite of many springs from the Redwall Limestone there is little tufa. Seeps in the Royal Arch and Triple Alcoves form minor tufa deposits largely covered by moss.

56 to 61.3 miles (90 to 98.7km):

Opposite Kwagunt Canyon to the Confluence with the Little Colorado (Fig.2): these 5 miles (8km) of the left bank have thick talus lying on the Bright Angel Shale slopes beneath the vertical cliffs of Redwall and Muav limestones cemented by and covered by tufa. Together the sheets of talus and tufa form an armour covering the Bright Angel Shale from a few metres above river level to some 60m higher upslope and in places the armour is up to 16m thick. This spring-line tufa deposition ceased long ago and the talus plus tufa armour has been breached deeply by storm water cascading off the high cliffs. Gullies cut down some 10m into the Bright Angel Shale. The tufa deposits are all on the left bank, as the limestones on the right (west) bank are cut off by the Butte Fault, 3km to the west, and so provide little catchment.

61.3 miles (98.7km):

The Little Colorado: except when there is high rainfall or snow melt on the Navajo Reservation, with consequent high run off, the Little Colorado river rises from a series of springs up to 13 miles (21km) above the Confluence (Fig.2). The main resurgence of drainage from the Navajo Reservation rises from much faulted Redwall and Muav limestones at the mildly thermal Blue Spring (21°C; 2600 L/s)(Cooley, 1976; Feth and Barnes, 1979). Soon after reaching daylight loss of CO_2 results in a blue colouration of the river all the way to the Confluence. Much carbonate precipitates in the river bed with small barrages building up on the many scattered boulders. Further downstream the total thickness of river-bed tufa-plus alluvium deposits is estimated at 16m whilst older deposits cover talus on the Bright Angel Shale slopes up to 50m above the river.

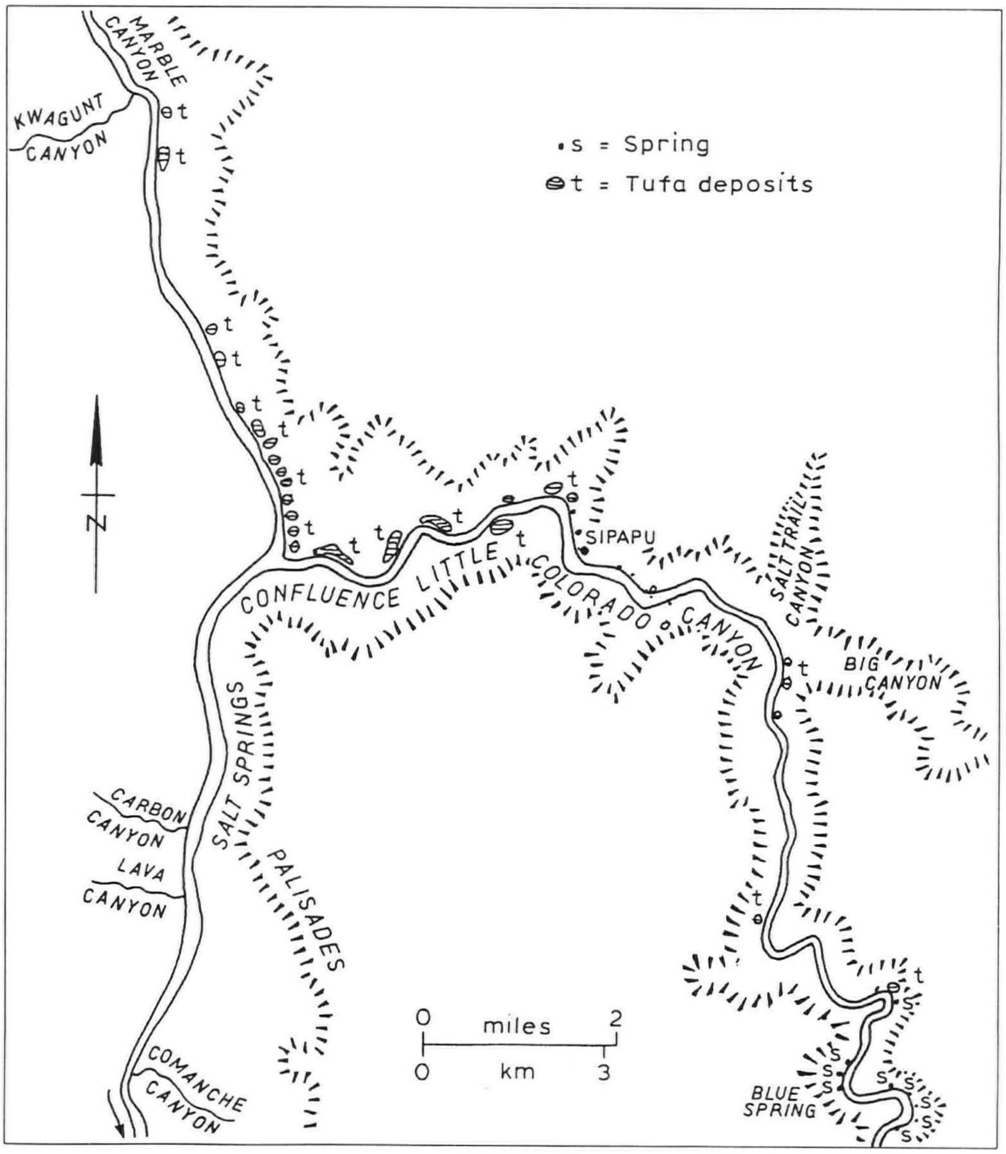


Figure 2. Sketch map of the Little Colorado area, showing tufa localities.

Inclined tufa sheet on colluvium covering Bright Angel Shale in Marble Canyon north of the Confluence.

Much of the tufa incorporates fine silt washed down from the Navajo Reservation in wet weather. The silt appears to be trapped amongst the growing carbonate crystallites. Some 3.5 miles (6km) from the Confluence there is a weakly thermal spring (21°C) that has built a large travertine dome. A sacred site, known to the Hopi Indians as the Sipapu, it is some 10m high and 25m wide at the base, and a trickle of water still rises from an orifice about 3m wide on the top.

63 to 64 miles (101.4 to 103km):

Downstream from the Confluence the Tapeats Sandstone has extensive crusts and grottos of "salt", sometimes mistakenly referred to as "travertine". It is mainly an evaporite deposit of about 75% common salt and 25% sodium sulphate, with minor carbonate.

65.5 to 67 miles (105.4 to 107.8km):

Small areas of tufa-cemented talus occur on both sides of the river at Cardenas Canyon on the right (north) bank and in Comanche Canyon on the left (south) bank.

95 miles (153km):

Above Hermit Creek: some 240m above river level the southern slopes exhibit isolated relics of an ancient perched spring-line tufa sheet extending down to within 50m of the river. Springs rising from the Muav Limestone still deposit a little tufa in the bed of Hermit Creek (Metzger, 1961).

114 to 118 miles (183 to 189km):

Aztec Amphitheatre: large dissected remnants of a former wall of tufa some 3 miles (5km) long mantle the southern slopes up to 1200 ft (365m) above river level (Fig.3). Tufa lies on colluvium at three main levels about 100m apart, which Hamblin (1994) suggested might be correlated with lake levels behind the lava dams, though no direct proof is available. The trickle of water coming from high in the Muav Limestone is sometimes known as Royal Arch Creek (not to be confused with the Royal Arch in Marble Gorge). Pendant masses also hang within shallow alcoves in the Redwall Limestone. These are discoloured by fine mud particles washed down from the overlying Supai Formation. The tufa slope remnants descend to within 50m of the river and there are large fallen blocks wedged in the bottom of Elves Chasm (Reilly, 1961).

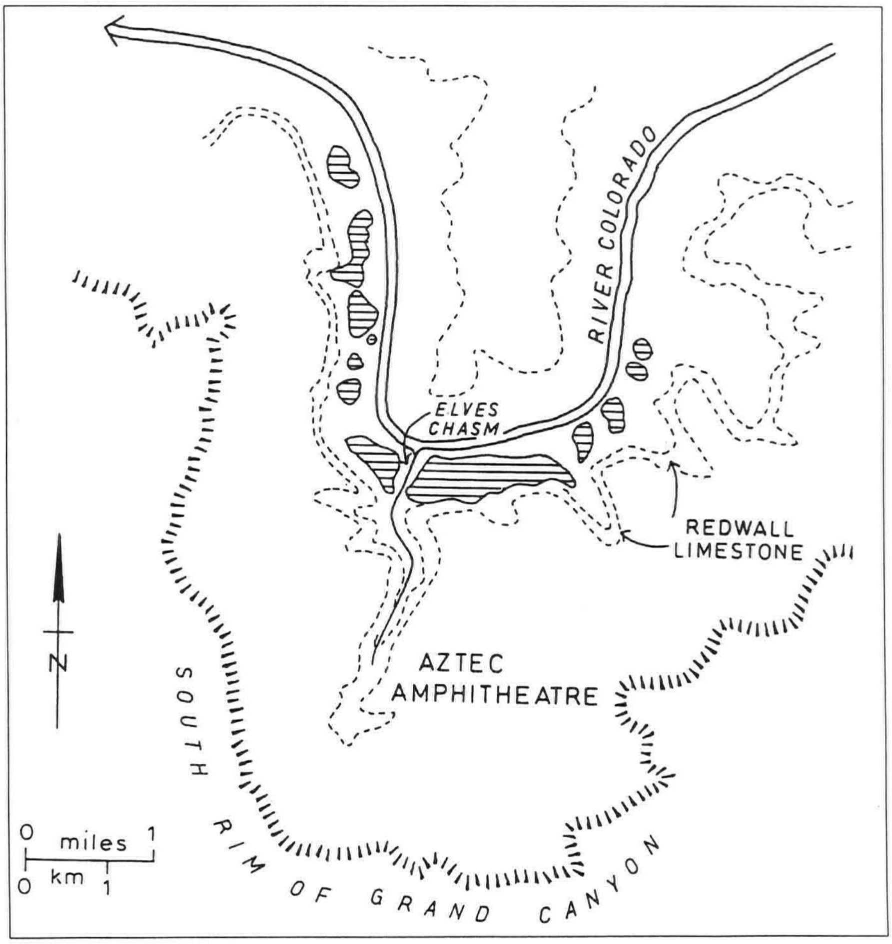
124 miles (199km):

Conquistador Aisle: scattered patches high on the left-hand cliffs may be former continuations of the Aztec Amphitheatre deposits.

127 miles (204km):

Middle Granite Gorge: a fine display of salt stalactites has grown beneath an overhang of Tapeats Sandstone on the left.

Figure 3. Sketch map of the Aztec Amphitheatre and Elves Chasm area, showing the distribution of tufa.



135 to 136 miles (217 to 218.5km):

The Surprise Valley landslip covered tufa-cemented gravels. The landslip is mainly on the right (north) bank but relics lie on the south bank as the river eroded its new channel through one side of the landslip material. The tufa is now some 30m above river level. Relics of an ancient spring-line deposit are high up on the left opposite Deer Creek Falls. No tufa is deposited by Deer Creek Falls themselves but the evaporation of wind-blown spray yields a tufa-like coating on adjacent bushes and boulders. Upstream above Deer Creek Falls there are small barrages in one of the feeder streams near Vaughn Spring (Reilly, 1961).

138.8 miles (223.7km):

Stone Creek has ancient tufa cascades mantling the Tapeats Sandstone to the north: they exhibit a variety of growth forms (Reilly, 1961). Today's small stream rises from springs in the Muav Limestone but does not appear to be depositing tufa any longer.

147.5 miles (237.3km):

A small tube cave in the Redwall Limestone of the right bank, high above the river, yields water that has built out a cantilevered apron of tufa some 15m wide and high (Reilly, 1961). Pendulous growths hang down from rimstone dams and there is profuse plant growth.

151 to 151.5 miles (243 to 243.7km):

Small tufa deposits form from highly vegetated springs on the north near Upset Rapids.

152.3 miles (245.1km):

Tufa in a minor tributary stream on the left (south) side.

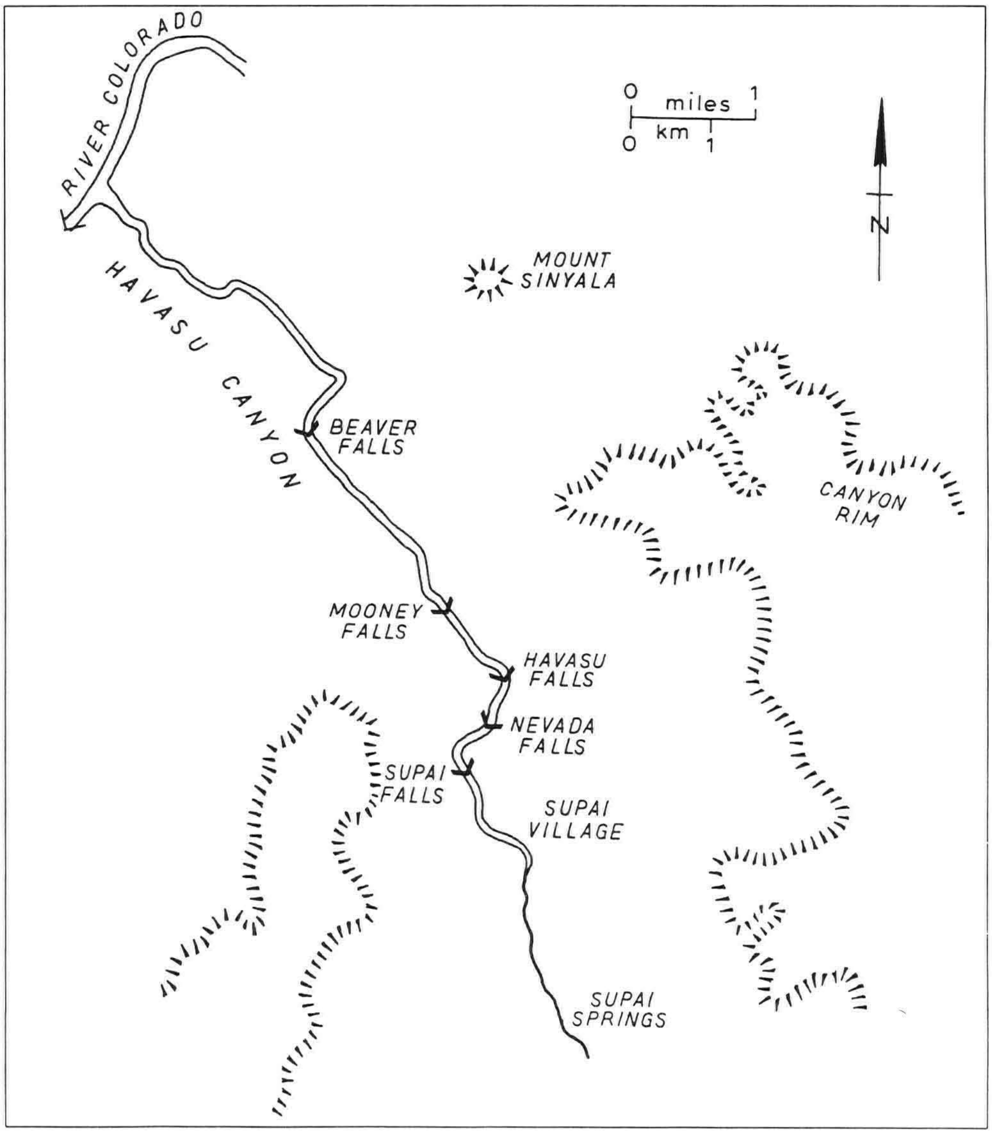
155.4 miles (250.1km):

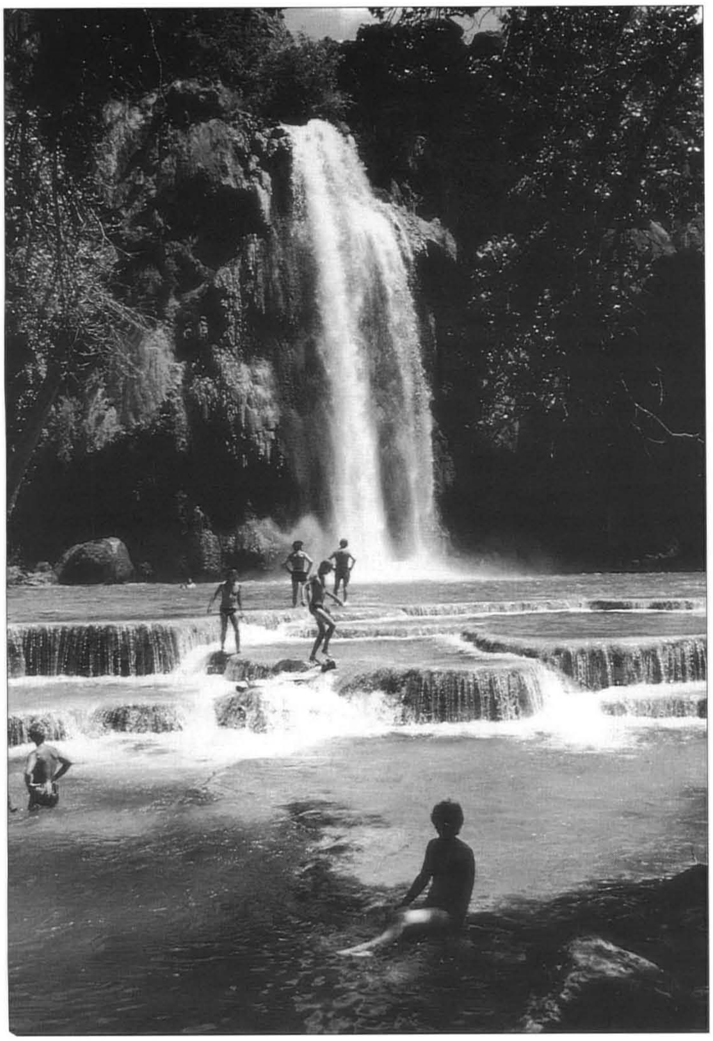
Small but striking tufa cascade on the north (right) bank.

156 miles (251km):

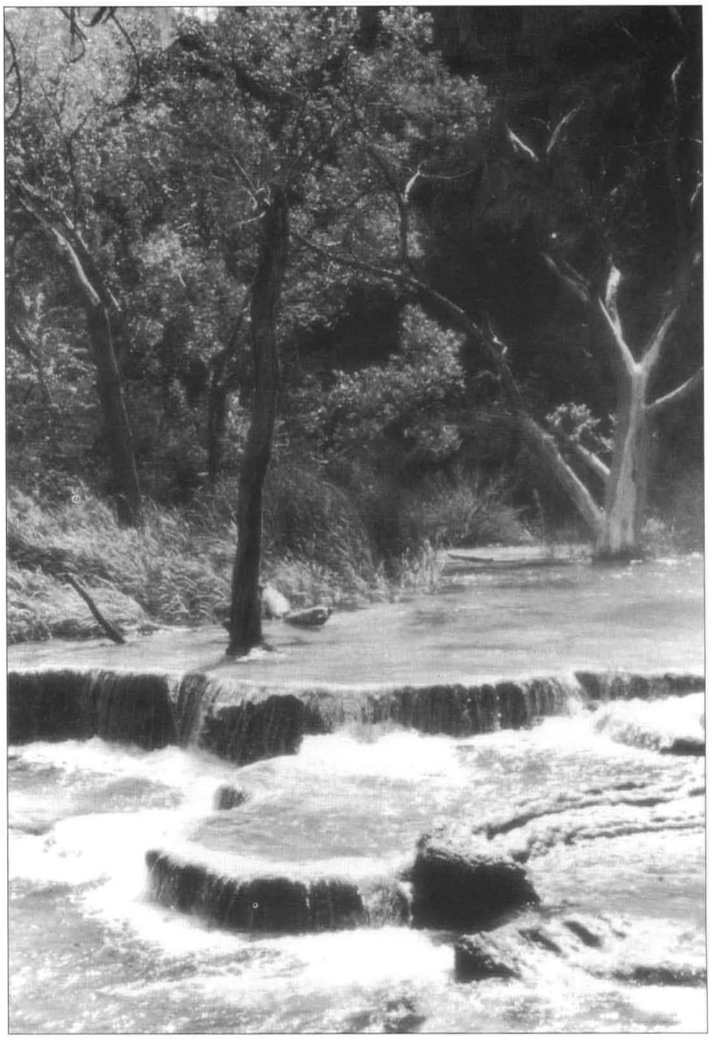
Havasu Canyon: the mildly thermal Supai spring (21°C) (Feth and Barnes, 1979) rises some 10 miles (15km) up this major south bank side canyon (Black, 1955; Giegengack et al, 1979; Hamblin, 1994). The Supai Spring rises from the Lower Pennsylvanian Supai Formation where a fault crosses the canyon (Fig.4); the Redwall Limestone is not far beneath the canyon floor and so both Formations may transmit the water. The Supai spring (1900 L/s) feeds the creek, which deposits tufa along most of its course to the Colorado. There is little deposition until a kilometre or so below the spring, by which point sufficient de-gassing of CO_2 has taken place. Thereafter barrages have built up on obstructions in the channel, particularly encrusting fallen trees, branches, twigs and leaves (Black, 1955) and covering mosses (Beus and Morales, 1990). Barrages are said to build up as much as 60cm in a year. Occasionally this causes problems in fording the river and the barrages are broken down by the Havasupai Indians, though periodic flash floods may also remove them. There are five large waterfalls, each heavily encrusted with tufa. The two largest are the Havasu Falls and Mooney Falls, each some 60m high, and these have thick tufa cascade sheets covering eroded silt fills. The cascades have built out by as much as 5m in places. The top of the silt fills is considered to

Figure 4. Sketch map of Havasu Canyon, showing the principal tufa areas.





Havasu Falls, with tufa cascades covering silt fills (photo by R J Rice).



Small barrages in Havasu Canyon (photo by A C Waltham).

correspond to the highest impounded water level upstream of the Late Cenozoic Toroweap Lava Dam (Hamblin, 1994). The altitude of the waterfalls appears to correspond to successive later and lower dam impoundment levels. Immediately downstream of the waterfalls spray encrusts trees with tufa. Barrages up to 1 metre high hold up numerous pools downstream from the waterfalls. The barrages and associated pools conceal a series of pre-tufa clastic sediments, perhaps as much as 200m thick beneath the canyon floor (Hamblin, 1994). The survival of these silt fills has been attributed to the protection afforded by the tufa sheets. Relics of ancient deposits encrust the walls high above the present creek and appear to be parts of a semi-continuous sheet mantling the canyon floor before the waterfalls were developed, Both current and ancient tufa deposits include calcite and aragonite, as well as being contaminated with silt and clay: dark stains are thought to be due to manganese (Black, 1955).

Attempts to obtain ^{14}C dates for the deposits in Havasu Canyon have produced conflicting results for dates on included wood and on encrusting tufa (Giegengack and Ralph, 1973; Giegengack et al, 1979). The latter authors concluded that ^{14}C date determinations on tufa are unreliable unless corroborated by other means.

168 miles (270km):

Fern Glen Canyon on the north bank has seeps from the Redwall Limestones that deposit a small amount of tufa, largely masked by vegetation. Large fallen blocks some distance up the canyon indicate former more active tufa deposition.

173 to 177 miles (278.4 to 284.8km):

Patches of tufa occur high on each side of the Canyon along the stretch before Toroweap Point and Lava Falls.

179.5 miles (288.8km):

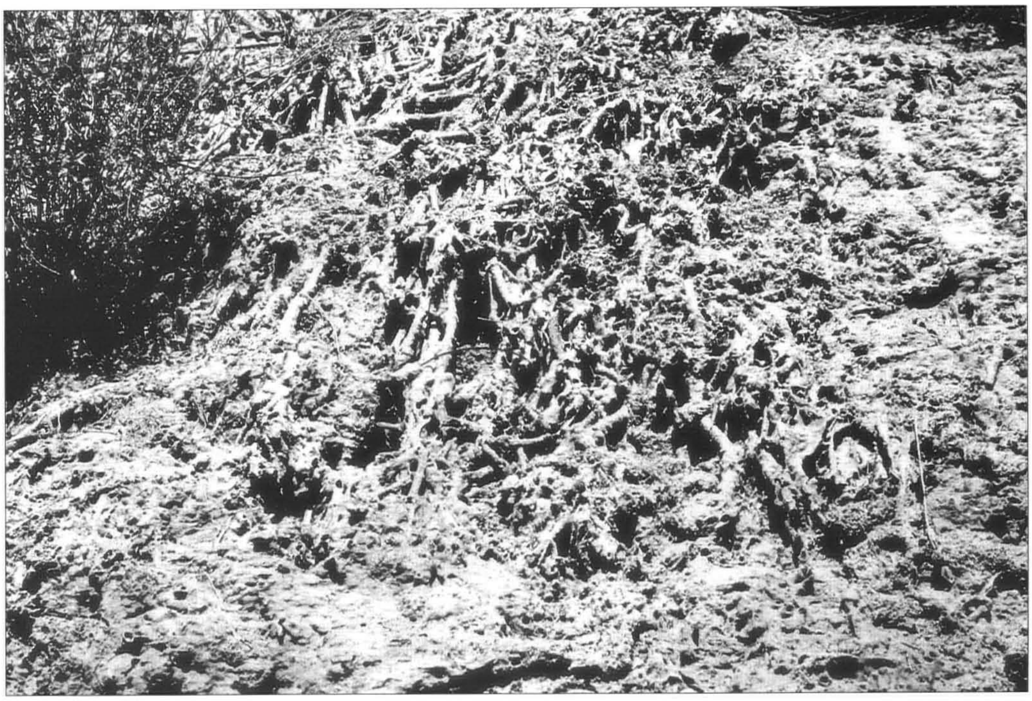
Lava Falls: the warmest thermal springs in the Grand Canyon (80°F, 26.6°C) rise near the Prospect Fault on the left bank. The adjacent marshy ground immediately south of Lava Falls has some of its vegetation impregnated and coated with tufa. Some deposition still occurs. As ambient air temperatures in summer exceed 40°C it might be thought that these springs are not thermal, but the annual average ambient temperature is well below 26°C and a thermal mechanism seems certain. Though there were Pleistocene volcanoes close by, little evidence is forthcoming to suggest a volcanic heat source, and deep circulation through faulted ground may be more significant.

189.8 miles (305.4km):

Patches of tufa occur high on the left, near the Hurricane Fault zone.

213 miles (242.7km):

Great Pumpkin Spring (also known as Charlie Brown's Great Pumpkin) is close to river level where the Muav Limestone forms low cliffs on the south bank. A mildly thermal spring rises through an orifice some 30cm



Tufa encrusting vegetation below Prospect Canyon, near Lava Falls.

wide in the floor of a pool 5 by 3 metres, held up by a tufa barrage at least 2m high that may be partly submerged at high stages of river flow. Covered with patches of lichens, this is very impure tufa owing to fine silt being incorporated when the river overflows the whole structure.

229.2 miles (368.7km):

Travertine Canyon: a large mass of tufa has accumulated in a tributary canyon but the stream is no longer depositing tufa where it crosses the Precambrian gneiss. In fact, re-dissolution appears to be taking place and massive fallen blocks occur in the lower part of the canyon. Hamblin and Rigby (1969) refer to the deposits hereabouts as "some of the most spectacular in the world" but this is rather an exaggeration when the Antalya deposits in Turkey and the Plitvice deposits of Croatia are taken into account.

230.5 miles (370.8km):

Travertine Falls: an obvious large cascade some 20m high is present on the left bank. The base of the sheet overhangs and perhaps indicates that some ancient flood has removed a sandy beach from beneath the tufa.

250 miles (402 km):

A broad tufa dome rises some 50m above the south bank. Though its form suggests a possible thermal source there is little activity today.

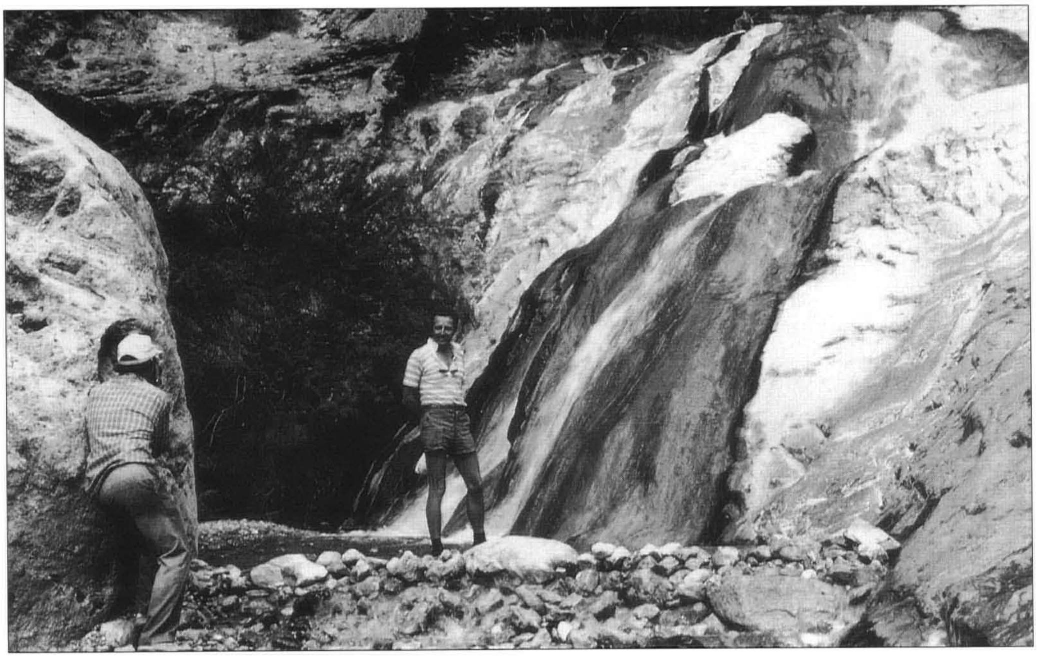
259.2 miles (417.4km):

Quartermaster Canyon: a large spring some miles up the Canyon deposited sufficient tufa to form a dam that trapped alluvial gravels. More tufa deposited on these, followed by further alluviation, filled the Canyon to a depth of about 120m, diverting the present creek so that it now forms a waterfall over Tapeats Sandstone.

266 miles (428km):

Large patches of inactive tufa extend for a kilometre or more, covering slope wash to heights of over 200m on the northern slopes. A gully eroded into the tufa sheet provides a section through a gravel-filled drainage channel (Reilly, 1961).

Great Pumpkin Spring - a weakly thermal spring rises in the floor of the pool.



Travertine Canyon - fallen tufa block and thin crust on Precambrian gneiss.

267 miles (429.6km):

Extensive veneers of tufa lie on top of slope wash up to 200m above the river on the northern cliffs. The tufa is deeply dissected, and so it is presumably old.

274 to 276 miles (441 to 444km):

There is a large patch of inactive tufa on the north bank, only a mile or so from the downstream end of the Grand Canyon at Grand Wash Cliffs.

DISCUSSION

Mechanisms of deposition

It has not yet been possible for the authors to carry out detailed sampling in the Grand Canyon, so the relative importance of physico-chemical and biological mechanisms cannot be assessed. Nor, to the authors' knowledge, has any other detailed work been done. At best it appears that de-gassing is probably the dominant mechanism. Bio-mediation is probably most significant in Havasu Canyon, where considerable amounts of organic waste products, from agricultural and other human activities on the Havasupai Indian Reservation, enter the creek.

Environments

The majority of tufa deposits in the Grand Canyon belong to the perched spring line category, with tufa sheets covering colluvium banked against the Canyon walls. Most springs resurge from the Upper Cambrian Muav Limestone but, as the surface catchment areas are on the Permian limestones of the Kaibab plateau, the underground movement of water must pass through intervening clastic formations to reach the Mississippian Redwall Limestone, and this may be the principal source of dissolved carbonate. Most subterranean flow appears to follow faults, and some springs occur where such faults are intersected at or near the Redwall Limestone by the Canyon or its tributaries. Particularly favourable catchments are the plateau east of Marble Canyon and north of the Little Colorado (Fig.2), and the area south of the Aztec Amphitheatre. In the former area the dip of the strata is gently eastwards, away from the Grand Canyon, but in the absence of any more favourable outlets for percolating meteoric water, at least part of it moves along the strike until it can escape into the Little Colorado Canyon. The underground water has a considerable residence time within the Redwall and Muav limestones during which to dissolve carbonate. Although the dip is southwards away from the Canyon along most of the South Rim, the strata south of Aztec Amphitheatre dip gently northeastwards towards the Canyon, so that there should be subterranean flow in the same direction (Fig.3). The incision of Havasu Canyon has meant that the flow to the Aztec Amphitheatre springs has been truncated and they have long been inactive; the local flow seems to feed the Supai Spring nowadays (Fig.4). The Kaibab Plateau north of the Grand Canyon also yields subterranean flow, but this tends to run through more rapidly, with a short residence time, and to resurge via caves and springs showing little tufa deposition, e.g. Vasey's Paradise and Thunder Springs. The catchments for the Western Grand Canyon tufa sheets are less easy to define.

Apart from the perched springline deposits, barrages with impounded pools are best known downstream of the Supai Springs in Havasu Canyon, and to a lesser extent in the course of the Little Colorado.

Mildly thermal travertine occurs in association with fault-guided springs, as at Prospect Canyon by Lava Falls, at the Sipapu in the Little Colorado and at mile 259 in the Western Grand Canyon.

Age of the tufa deposits

As none of the deposits can be related directly to other dated sediments or events, recourse must be made to radio-isotope dating, in spite of inherent uncertainties. Samples of wood encrusted with tufa in Havasu Canyon have yielded ^{14}C dates back to 3170 years BP, with other samples generally less than 900 years old (Giegengack et al, 1979). These young dates may be acceptable for deposits that are still growing, but they give no indication of when growth started or whether there have been changes related to climatic variations. However, uranium-series dating of deposits in the Kwagunt, Comanche, Cardenas, Elves Chasm and Havasupai areas (Szabo et al, 1986; Szabo and Rosholt, 1991) suggests that ancient deposits there grew from palaeo-springs active about 170, 110, 80 and 10 Ka ago. As those authors do not give details of the sampling sites or of petrographical evidence, it is difficult to judge the significance of these dates, but it is worthy of note that they suggest a possible relationship to wetter (pluvial?) climatic periods. These may in turn relate to contemporary glaciations farther north. Uranium-trend ages obtained by Machette and Rosholt (1989) for cemented terraces are also difficult to relate to events in the Grand Canyon area.

Relationship to lava dams

In the Late Cenozoic (early Pleistocene) intense volcanic activity in the Uinkarets and Shivwits Plateau areas resulted in a series of lava dams being built up in the Grand Canyon beneath Toroweap and Prospect valleys (Hamblin, 1994). Thirteen successive lava dams were built and

Travertine Falls - a barely active cascade tufa mass.

destroyed in a period of about 0.25 Ma, from 1.2 Ma to 0.95 Ma ago and reached a maximum of 600m high. Each resulted in water being impounded for hundreds of kilometres up the Grand Canyon, at times reaching the base of the Redwall Limestone. Overflowing waters soon eroded each dam and released the impounded water over a period probably amounting to no more than a few thousand years. Each dam was in turn at least partly filled by silts that were largely washed out again during each draining episode. The hydrological effect of each dam would have been to raise water-tables in the Muav and lower Redwall Limestones for the duration of each damming episode. Draining these aquifers, as each dam was eroded, would doubtless cause discharge of waters rich in dissolved $CaCO_3$ for a few thousand years. It is tempting to argue that such episodes are represented by some of the tufa in the Grand Canyon, but no way of proving this has yet been found. Hamblin (1994, p.104) suggested that the presence of tufa interbedded with silts was significant, but he gave no details of the sections concerned. It should also be noted that extensive tufa sheets in the western Grand Canyon are far downstream of the lava dams, and the hydrological systems there are unlikely to have been affected by the high impounded water levels upstream of the lava dams. It should also be noted that the lava dam episodes occurred much earlier than the pluvial phases of the later Pleistocene.

CONCLUSIONS

Active tufa deposition in the Grand Canyon is now confined largely to the Little Colorado and Havasu canyons, though it has been much more widespread in the past.

The mechanisms of precipitation are currently in need of full investigation by both petrographical and microbiological techniques.

Many of the inactive deposits appear to be fairly young. They are either graded to near present river level or have the toes of the sheets truncated by recent river erosion. However, the mean rate of down-cutting is uncertain owing to the effects of lava dams and resultant renewal of incision.

The limited attempts at dating by radio-isotopic methods have not been very successful, as they have not been linked either to petrography or to other dating approaches. There is, however, some suggestion of correlation with pluvial climatic phases.

At present there is very little evidence to suggest that tufa deposition was linked with the early Pleistocene lava dams.

There is some evidence of thermal travertine deposition though, with temperatures of warm springs being around 21°C, the water from thermal sources mostly seems to be diluted by meteoric waters.

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Improving the success of limestone quarry revegetation

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Abstract: The study investigated the possibility of improving the success of revegetation of limestone quarries, using a diverse range of local flora, including species from the surrounding Tuart (*Eucalyptus gomphocephala*) forest and Banksia woodland. A field survey of a rehabilitated limestone quarry was carried out adjacent to Cockburn Cement's Russell Road Plant, near Perth, Western Australia. Results showed that only 20% of species planted were surviving. Key growth constraints appeared to be very low levels of available nitrogen, phosphorus and some micro-nutrients. Glasshouse trials indicated that the omission of either nitrogen or phosphorus strongly depressed plant growth. Lime chlorosis symptoms were induced when no iron fertilizer was added, though this treatment had no effect on the dry shoot weight of seedlings. Field trial results showed that the addition of a complete fertilizer in slow release pellet form was the most successful amendment compared with sewerage sludge, micro-nutrients, off-site topsoil and broadcast fertilizer. These results are likely to pertain to other limestone quarries with similar age and soil characteristics elsewhere in Australia and worldwide.

INTRODUCTION

Limestone excavation is a large industry in Western Australia (Fig.1), with approximately 2,100,000 tonnes being mined every year (Wyroll and Glover, 1989). Commonly, open-pit mines are used to extract limestone and, in common with many other limestone areas, there are conflicts between the desire to exploit the stone, which is a valuable mineral resource, and the need to conserve landscapes that are frequently of high amenity value (Gunn and Bailey, 1993). In this context there is a need to minimize the environmental impacts of stone extraction and to reclaim quarries when working is completed. Research into improving the success rate of revegetation of open-pit mines is vitally important, because it will lead to a decrease in the time needed to return a quarried area to a near natural state, reducing water erosion, wind erosion and subsequent dust generation. Of course, any revegetation process comes at a cost. However, any expenditure can be minimized by implementing proven revegetation techniques and is amply repaid by the considerable benefits that flow from successful plant restoration. Particularly in urban areas, where public scrutiny is becoming more intense, extracting companies must make certain that revegetation is effective. Greater community understanding of ecological processes is leading to a demand that mined areas are restored in ways that are conducive to nature conservation, recreation and education.

This paper describes research carried out in Western Australia into the possibility of improving the success of revegetation of limestone quarries by using a diverse range of local flora, including species from the surrounding Tuart (*Eucalyptus gomphocephala*) forest and Banksia woodland. The study site lies on the Spearwood Dune System of the Swan Coastal Plain, the second of three dune systems running parallel to the coast. Rising to about 75m above sea level, the Spearwood Dune System consists of a core of aeolinite (Tamala Limestone) with a hard capping of secondary calcite (Caprock), over which lie varying thicknesses of yellow to brown sand (McArthur, 1991). The Tamala, or coastal, limestone formed during the mid to late Pleistocene (1.75 million years ago) and Holocene (10 thousand years ago) epochs. Like chalk, the relatively young Tamala Limestone is soft and friable, and can weather into fine-grained material that can be mixed quickly and evenly into the overlying soil by soil fauna. It is therefore not surprising that calcium carbonate is found throughout all the soil horizons, keeping the pH above 7 (Eyre, 1968).

Perth and its surrounding area have a Mediterranean climate with hot, virtually dry, summers and cool wet winters. The average annual rainfall is 897mm, most of which falls between May and August (McArthur and Bettenay, 1974). In the porous sandy calcareous soils found at the study site, saturation in winter is reached only in the lowest-lying part, the remainder being leached throughout the wet season (McArthur and Bettenay, 1974). In October, precipitation and evapotranspiration in Perth are equal (Speck, 1952). High temperatures in November bring about a decline in soil water content, which falls below field capacity, and in late summer there is no plant-available water for about half a metre below the surface (McArthur and Bettenay, 1974). The average evaporation rate for January is high, at 8.5mm/day (Bureau of Meteorology, 1996), and this has severe implications for the rehabilitation process. Moreover, this high evaporation rate must be considered when attempting to extrapolate information on quarry revegetation from other parts of the world.

Work by Davis et al (1993), Bailey et al (1991), Gunn et al (1992), Gunn and Bailey (1993) and Bailey and Gunn (1991) investigated limestone quarry reclamation in the UK. Some of their results can be extrapolated for use in the Australian context. Davis et al. (1993) suggest that a major constraint to plant growth in limestone quarries is the very low availability of essential plant nutrients. Gunn et al (1992) suggest that the application

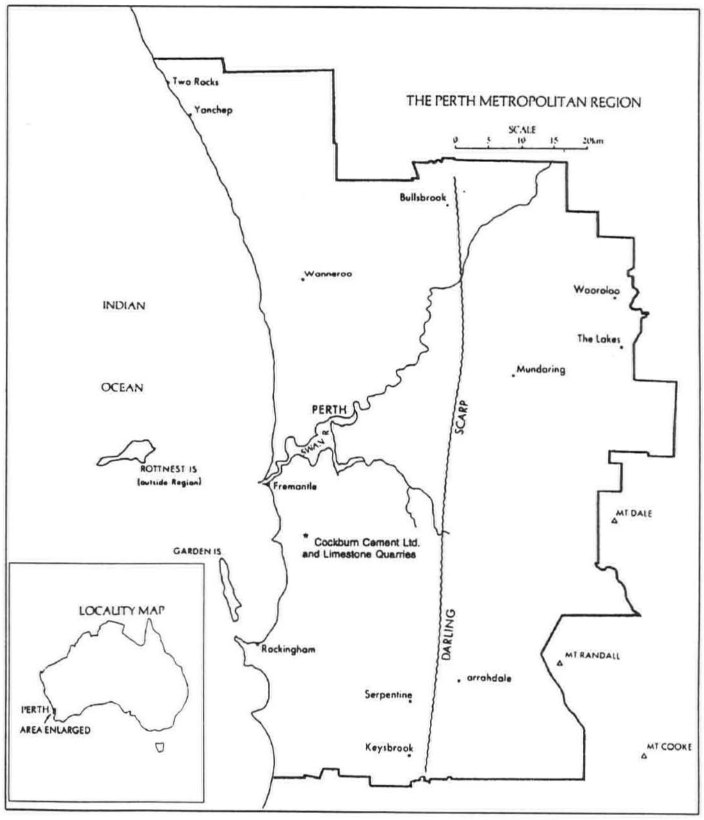

Figure 1. Locality map of Perth, Western Australia. Adapted from Powell (1990)..

of nitrogen, phosphorus and potassium nutrients is of particular importance in the restoration of limestone quarries. Refertilisation is normally required, though only with nitrogen and phosphorus (Gunn et al, 1992). The importance of the addition of organic matter in areas to be rehabilitated is stressed by Bailey et al (1991), Gunn et al (1992) and Bailey and Gunn (1991). Addition of imported, off-site, topsoil to scree or shallow quarry floor material is mentioned by Bailey and Gunn (1991). However, such imported topsoil is unlikely to assist natural limestone flora due to its physical, chemical and biological characteristics being unlike those of infertile, well-drained, limestone soils (Gunn and Bailey, 1993). Furthermore, weed species contained in the imported topsoil, and unwanted seedlings from the surrounding area, quickly out-compete the limestone flora in such a fertile substrate (Bailey and Gunn, 1991).

Species selection is especially important in the limestone quarry rehabilitation process. It is recommended that limestone/chalk adapted flora be used in limestone quarry revegetation (Bailey et al, 1991). In addition, Gunn et al (1992) suggest that abundant leguminous, or nitrogen-fixing, plants are an important requirement in the species selection, to assist in nutrient cycling to other plants. Nitrogen accumulation into a nitrogen cycle (and the central role that nitrogen-fixing plants play in it) has been identified as the most important factor in soil and vegetation development in limestone quarry revegetation. Post revegetation vermin exclusion can have significant implications for the success of revegetation programs. Trials by Davis et al (1985, cited by Bailey et al, 1991) in the UK concluded that slow development of vegetation on the limestone quarry floor had to be attributed to rabbit grazing. Davis et al (1993) found that vegetation cover values increase by up to 52% after excluding rabbits.

Compared with these studies, little research has been completed on limestone quarry restoration in Australia. This study covered the 18 months from January 1995 to July 1996 and investigated possible reasons for plant death in a limestone quarry and ways of increasing the success of plant survival and vigour. The study site is approximately 25km from the city of Perth, at Cockburn Cement's Russell Road plant (Fig.1). Four distinct experiments were undertaken.

Experiment One:

Quarry 7, 2km north-east of the Cockburn Cement plant, was chosen as an example of a typical post-mining quarry, abandoned in 1990, in which annual rehabilitation had been undertaken for the past four years. Plant growth success was determined by assessing vegetation health and vigour. Chemical and physical tests were carried out on the overburden/topsoil mixture present at the study site.

Experiment Two:

A glasshouse trial was set up to test which nutrients are most beneficial for plant growth in two quarry substrates, overburden/topsoil mixture and quarry floor substrate.

Experiment Three:

Designed to show firstly whether nutrient addition increased growth in a range of local plant species, and secondly, whether iron availability is a growth constraint. Iron is well known to be minimally available in an alkaline and/or calcareous environment (Anderson, 1982b; Anderson, 1983; Kinzel, 1983; Kulkarni et al, 1995; Parkpian et al, 1988; Loeppert and Hallmark, 1985; Mortvedt et al, 1991; Islam et al, 1980).

Experiment Four:

The field trial aimed to rate the success of various treatments on six local plant species in a newly ripped, non-planted area of Quarry 7.

MATERIALS AND METHOD

Experiment One: Field Survey

To understand which plant species were surviving in Quarry 7, a field survey was carried out. Thirty 5m by 3m quadrats were set up randomly to identify species number, vigour, height, plant number and density. The survey quadrat size was chosen because seedlings were planted approximately 1m apart in the rip lines (0.5m apart), giving a total of 30-35 plants in each 5m by 3m area. As only 15-20 species were planted each year, it was assumed that these survey quadrats would be the minimum size to be able to cover all species. Following Clarke (1992) a rating of 1 to 5 was given for each tree in each quadrat, depending on its vigour (1 = dead; 2 = severe (>50%) dieback; 3 = 10-50% dieback; 4 = symptoms of stress (yellowing of leaves and/or strong red pigmentation) and 5 = healthy (vigorous and alive with <5% dieback and none of the above symptoms)). Chemical soil analysis was carried out for pH, organic carbon, total nitrogen, bicarbonate-extractable phosphorus, micro-nutrients, soil respiration and microbial biomass.

Experiment Two: Glasshouse Trial

A factorial combination of nine fertilizer treatments (Tables 1 and 2), two species (*Eucalyptus gomphocephala* and *Acacia cyclops*), two substrate types (overburden/topsoil mixture and quarry floor material) and four replicates were used, totalling 144 pots. A subtractive design was chosen for this trial in order to identify the response of a seedling if an element, or group of elements, was not added. Seedlings were watered daily to field capacity. Responses were recorded by dry shoot weight increase after 12 weeks and analysed using SUPERANOVA (Abacus Concepts, 1992).

Experiment Three: Glasshouse Trial

A factorial combination of three chemical fertilizer treatments (all nutrients, all nutrients minus iron and nil nutrients), nine species (Table 3) and four replicates were used, totalling 108 pots. Nutrient concentrations were as for pot trial 1. Dry shoot weight was recorded after eight weeks and analysed using SUPERANOVA (Abacus Concepts, 1992).

Treatments:	
1. All + OM	All nutrients plus sewerage sludge
2. All	All nutrients
3. All - N	All nutrients minus nitrogen
4. All - P	All nutrients minus phosphorus
5. All - Mg, K	All nutrients minus magnesium and potassium
6. All - Fe	All nutrients minus iron
7. All - Zn	All nutrients minus zinc
8. All - Others (Mn, B, Mo, Cu)	All nutrients minus manganese, boron, molybdenum and copper
9. Nil	No nutrients

Table 1. Treatments used in pot trial.

Table 2. Nutrient concentrations used.

Salt	Rate per pot mg/pot	Stock solution g/l	Aliquot ml/pot
K_2SO_4	522	52.20	10.00
NH_4NO_3*	280	28.00	10.00
NaH_2PO_4	544	54.40	10.00
$MgSO_4.7H_2O$	73.8	7.38	10.00
$ZnSO_4.7H_2O$	28.7	2.87	10.00
$MnSO_4.H_2O$	25.4	2.54	10.00
H_3BO_3	2.5	0.25	10.00
$Na_2MoO_4.2H_2O$	1.2	0.12	10.00
$CuSO_4.5H_2O$	3.9	0.39	10.00
Fe EDDHA (seq.)	75	7.50	10.00

*NH_4NO_3 application was re-applied at 4, 6, 8 and 10 weeks.

Experiment Four: Field Trial

This trial was made up of four blocks, each measuring 36m x 10m, each of which contained six plots. Single plots measured 6m x 10m. Plots were split, creating 12 sub-plots per block. Six local plant species were chosen (*Eucalyptus gomphocephala, Acacia saligna, Banksia prionotes, Eucalyptus decipiens, Templetonia retusa* and *Dodonea aptera*). Plants were set at 1m intervals in rows approximately 50cm apart. Five plants of each species were planted in each sub-plot, totalling 1440 plants. Treatments included: sewerage sludge, off-site topsoil, a complete slow-release fertilizer in the form of tree pellets, broadcast fertilizer and micro-nutrients (Zn, Cu, Mn, Fe, B). These were arranged in a split plot design with basal fertilizer in subplots and other treatments allocated randomly to plots within the subplots. Soil colour and texture uniformity was assured across the study site (Munsell Colour Company, 1975).

RESULTS AND DISCUSSION

Experiment One: Field Survey

Species that were not noted in the quadrats assessed were mostly smaller species, with heights less than 1m; nor were these species seem outside the quadrats. The 'unsuccessful' species included *Dodonea aptera, Gompholobium tomentosum, Orthrosanthus laxus, Oxylobium capitatum* and prostrate species like *Hardenbergia comptoniana* and *Kennedia prostrata*. They were perhaps more prone to rabbit grazing, or failed to establish themselves before the winter rains ended, or simply did not survive the hot summer without the shade of an overstorey. Other species that were not seen at all were *Allocasuarina fraseriana, A. humilis, A. lehanniana, Banksia attenuata* and *B. grandis*. This absence could reflect sensitivity to root system disturbance during transplanting, but there is insufficient evidence to confirm this. The relative lack of diversity of surviving species contrasts with the relative success of *Eucalyptus gomphocephala* and *Acacia saligna*, which were recorded as healthy in 18 of the 30 quadrats. The most successful plant species were identified by the vigour and number of plants found in Quarry 7. Table 4 is a list of all species used in Quarry 7 from 1992 to 1995, indicating the successful species. A "successful" rating was given to species that had survived in at least one quadrat. Physical and chemical soil characteristics are shown in Table 5.

pH

The pH value of calcareous soils varies with calcite ($CaCO_3$) content. The common pH limit of calcareous soils with low sodium levels is 8.4, which is the pH determined by $CaCO_3$ in equilibrium with atmospheric CO_2 (Leeper, 1967). At an alkaline pH of 8.0, problems may arise for plant growth with the decreased availability of some nutrients (Munshower, 1994). Iron (Loeppert and Hallmark, 1985; Strom et al, 1994) and zinc deficiencies (Dixon and Weed, 1977; Pessarakli, 1994; Iyengar and Deb, 1971) are common in alkaline soils (Mortvedt et al, 1991), as is a deficiency of phosphate (Dixon and Weed, 1977; Kinzel, 1983).

Organic Carbon (OC)

Organic carbon levels are used to assess the amount of organic matter in soils. Organic matter is valuable for plant growth as it increases soil porosity, infiltration, cation exchange capacity, water holding capacity, and nutrient reserves. It also improves soil structure and lowers bulk density (Munshower, 1994). As expected, organic carbon readings for Quarry 7 were very low, with a total mean of 0.18% organic carbon compared with similar studies (Marks, 1980; Rokich, 1993; McArthur, 1991).

Total Nitrogen

Total nitrogen concentration in soils range from less than 0.02% in subsoils to greater than 2.5% in peats (Rayment and Higginson, 1992). Total nitrogen levels in Quarry 7 were very low, at an average of 350mg/kg, or 0.035%. For Western Australian soils, a concentration of less than 0.15% total nitrogen is regarded as low (Moore, 1995).

Bicarbonate-extractable Phosphorus

The average level of extractable phosphorus for Quarry 7 was 15.82mg/kg. This can be compared with values reported by Davis et al (1993), who analysed extractable phosphorus levels of a limestone quarry floor at 4.9mg/kg. Perhaps the higher levels of extractable phosphorus in the overburden/topsoil mixture reflect the addition of overburden and topsoil. A concentration of 10-30mg/kg is regarded as a medium level of soil phosphorus (Moore, 1995).

Micro-nutrients

Micro-nutrient levels were very low. The critical level of Diethylenetriaminepentaacetic acid (DTPA) extractable soil manganese for plant growth given by Mortvedt et al (1991) is 1-5mg/kg. The

No.	Species Name	Success	Abbreviation
1.	*Banksia attenuata* R. Br.	n/s	*B.a*
2.	*Banksia menziesii* R. Br.	n/s	*B.m*
3.	*Dodonea aptera* Miq.	n/s	*D.a*
4.	*Eucalyptus gomphocephala* DC.	s	*E.g*
5.	*Hakea prostrata* R. Br.	f/s	*H.p*
6.	*Kennedia prostrata* R. Br.	n/s	*K.p*
7.	*Lupinus angustifolius* cu Gungurru		*L.a*
8.	*Orthrosanthus laxus* (Endl.) Benth.	n/s	*O.l*
9.	*Scaevola crassifolia* Labill	f/s	*S.c*

Table 3. Nine species and success rate in previous revegetation at Cockburn Cement.

NB. s = successful, f/s = fairly successful, n/s = not successful in Quarry 7.

PLANT	Rating	PLANT	Rating
Acacia cochlearis	*	*Eucalyptus calophylla*	*
Acacia cyclops	*	*Eucalyptus decipiens*	*
Acacia lasiocarpa	*	*Eucalyptus gomphocephala*	*
Acacia pulchella		*Gompholobium tomentosum*	
Acacia rostellifera		*Grevillea crithmifolia*	*
Acacia saligna	*	*Hakea lissocarpha*	*
Acacia truncata	*	*Hakea prostrata*	*
Acacia xanthina	*	*Hakea trifurcata*	*
Agonis flexuosa	*	*Hardenbergia comptoniana*	
Allocasuarina fraseriana		*Hemiandra pungens*	
Allocasuarina humilis		*Jacksonia sternbergiana*	
Allocasuariana lehanniana		*Kennedia prostrata*	
Anigozanthos manglesii		*Melaleuca acerosa*	*
Atriplex isatadia	*	*Melaleuca huegelii*	*
Banksia attenuata		*Melaleuca lanceolata*	*
Banksia grandis		*Olearia axillaris*	*
Banksia menziesii	*	*Orthrosanthus laxus*	
Callitris preissii	*	*Oxylobium capitatum*	
Calocephalus brownii	*	*Scaevola crassifolia*	*
Calothamnus quadrifidus	*	*Spyridium globulosum*	
Dianella revoluta		*Stipa elegantissima*	*
Dodonaea aptera		*Templetonia retusa*	*

Table 4. Species planted in Quarry 7 from 1992 to 1995 and a rating of plant success

Ratings: * = Plants successful or fairly successful in Quarry 7.

overburden/topsoil mixture manganese levels are 0.8mg/kg, suggesting that manganese may be limiting for plant growth. Mortvedt et al (1991) quote a critical iron level of 2.5-5mg/kg for plant growth, suggesting that lack of iron may be a plant growth constraint in the overburden/topsoil mixture. These concentrations are comparable to those recognised by other studies (Haridasan, 1985; Leggett and Argyle, 1983). Zinc analysis indicated that the soil had low, but not limiting, zinc levels. Mortvedt et al (1991) give critical zinc levels at 0.2-2mg/kg. Mortvedt et al. (1972) claim that increasing calcium levels decrease the extractable boron concentration. Soil boron concentrations between 0.1 and 2.0mg/kg are suggested by Mortvedt et al (1991) to be necessary for adequate plant growth, indicating that boron deficiency may be a plant growth constraint in the overburden/topsoil mixture. Critical levels of copper were noted by Mortvedt et al (1991) as between 0.1 and 2.5mg/kg. Low levels of copper could, therefore, be another plant growth constraint in this substrate.

Soil Respiration and Microbial Biomass

Soil respiration may be defined as the amount of carbon dioxide expired by micro-organisms in the soil. According to Sparling (1995), the respiration rate should be 1-10µg CO_2 as C per g soil per hour, indicating that the results obtained here are very low. As expected, soil respiration was very low in the overburden/topsoil mixture, presumably due to the low numbers of active soil micro-organisms. Soil respiration rate depends on a number of factors, including soil moisture (Orchard and Cook, 1983) and organic matter content (Sparling, 1995), both of which were very low during this study. Soil moisture was very low because samples were taken in early May (9 May 1995), before the start of the winter rains. Microbial Biomass can be defined as the total amount of soil microbes in the soil, whether or not they are active. The overburden/topsoil mixture had a very small microbial biomass. Microbial biomass values obtained here are approximately half of the lowest readings attained by Sparling et al (1993) in an arable site at Kalannie, Western Australia. To increase microbial biomass populations, reclamation practices such as mulching, fertilizing, re-seeding, irrigation and, especially, topsoiling are suggested by Fresquez and Aldon (1986), who noted that within just three months of the reclamation of coal mine spoils and soils the micro-organism population equalled or surpassed those found in undisturbed soil.

Experiment Two: Glasshouse Trial

Eucalyptus gomphocephala

Maximum shoot dry weights in overburden/topsoil mixture were recorded in the All + OM, All, All - Mg, K, All - Fe, All - Zn and All - Other treatments ($p<0.05$). Lowest dry weights were obtained with the All - N, All - P and Nil treatments, indicating the need for nitrogen and phosphorus

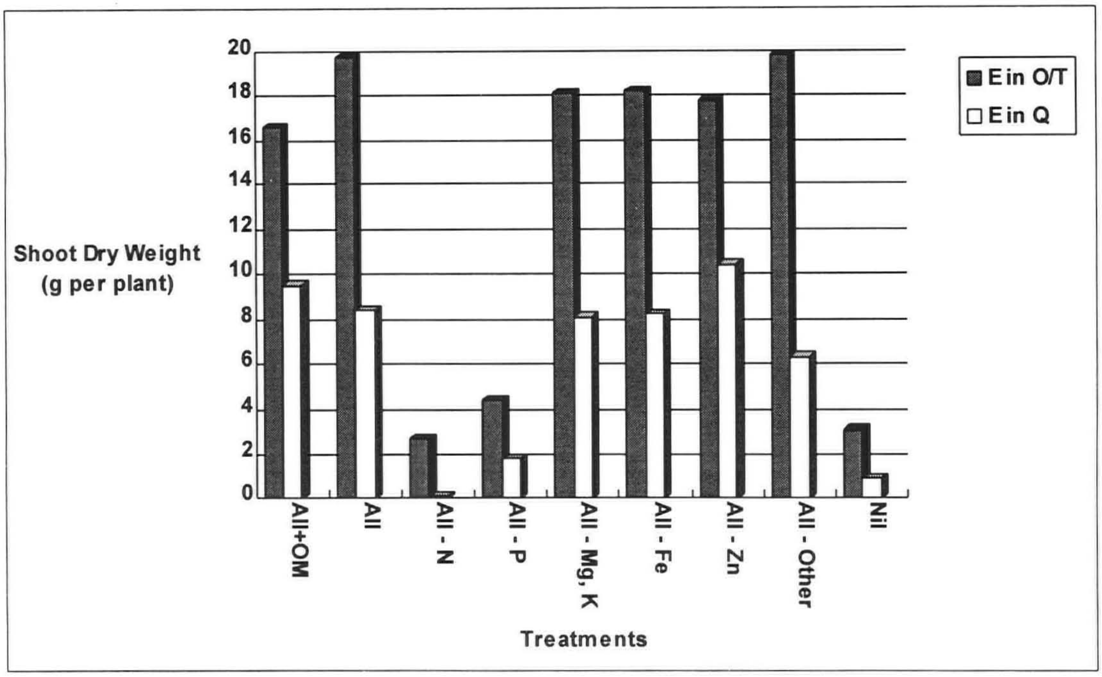

Figure 2. Effect of nutrient omission on dry shoot weight (g per plant) of Eucalyptus gomphocephala after 12 weeks growth in overburden/topsoil mixture (O/T) and quarry floor material (Q). Values are means of four replicates. All+OM = all nutrients plus organic matter, All = all nutrients, All - N = all nutrients minus nitrogen, All - P = all nutrients minus phosphorus, All - Mg, K = all nutrients minus magnesium and potassium, All - Fe = all nutrients minus iron, All - Zn = all nutrients minus zinc, All - Others = all nutrients minus manganese, boron, molybdenum and copper, Nil = no nutrients. LSD (0.05) = 3.4

(Fig.2). Interestingly, the addition of organic matter in the form of sewerage sludge did not increase plant growth significantly ($p<0.05$) relative to those supplied with All nutrients. The sewerage sludge was administered according to the middle range of sewerage sludge application rates described by Wong and Ho (1994), and should therefore have been adequate. A possible explanation is that plants treated with All nutrients had an optimal growth nutrient supply in the All treatment alone; adding sewerage sludge caused a surplus nutrient level. The higher levels of nitrogen due to added sludge were insufficient to cause growth depression. Shoot dry weights of *E. gomphocephala* in the quarry floor material were depressed by approximately 50% compared with those in the overburden/ topsoil mixture, even though both substrate types have similar pH values, and were supplied with the same levels of nutrients. Shoot weights for the Eucalypt in the quarry floor material showed similar patterns to those in the overburden/topsoil, stressing the need for phosphorus and nitrogen by this species, regardless of substrate.

Plant Symptoms

Nitrogen deficiency symptoms were noted in treatments All - N and Nil. Older leaves displayed chlorosis, plants displayed a general paleness, and there was an overall reduction of growth. Following these initial signs of chlorosis, the symptoms spread to the younger leaves and then all leaves turned pale yellow, as was also seen in *E. maculata* during a study by Dell and Robinson (1993). *E. gomphocephala* seedlings minus phosphorus were more vigorous than those without nitrogen. However, those without phosphorus did show a reduction in growth and displayed the phosphorus deficiency symptoms of darker foliage, purple pigmentation of leaves and some necrotic lesions (Dell and Robinson, 1993). *E. gomphocephala* plants without iron fertilizer had symptoms indicative of iron chlorosis, including: interveinal yellowing of younger leaves, followed by necrosis, seen mostly in older leaves (Dell and Robinson, 1993; Salisbury and Ross, 1985). Nutrient deficiency symptoms were more pronounced in plants growing in the quarry floor material than in those in the overburden/ topsoil mixture.

Acacia cyclops

As with *E. gomphocephala, A. cyclops* showed best growth in the All + OM, All, All - Fe, All - Zn and All - Other treatments (Fig.3), and poorest growth in the All - N, All - P and Nil treatments ($p<0.05$). However, the All - Mg, K treatment produced a lower shoot weight than All - Fe, All - Zn and All - Other, whereas in *E. gomphocephala* in the overburden/

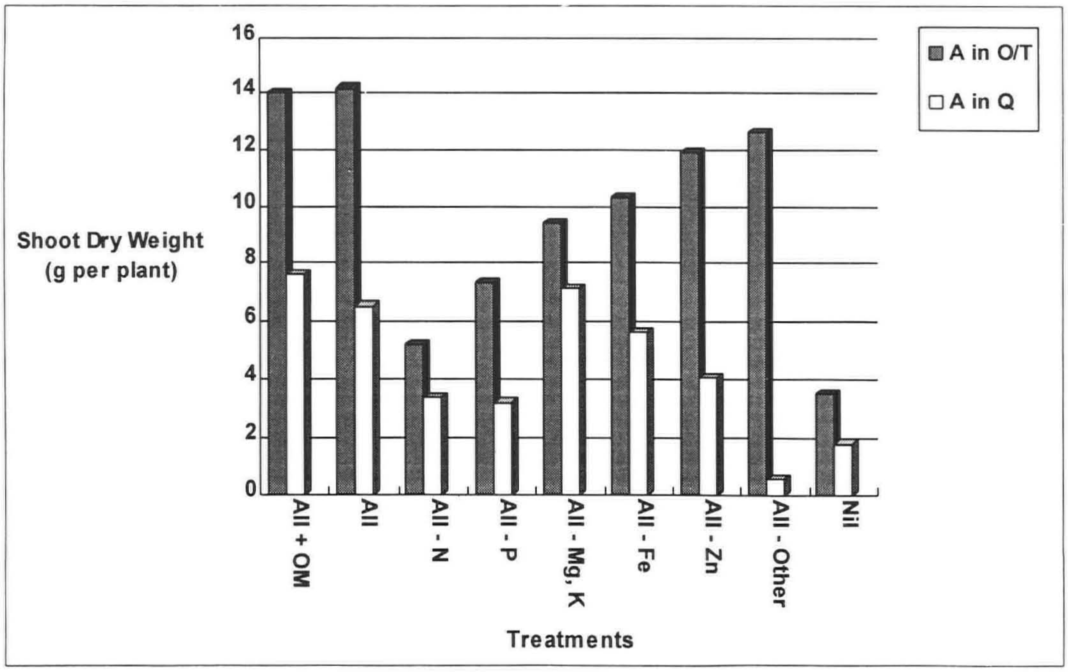

Figure 3. Effect of nutrient omission on dry shoot weight (g per plant) of Acacia cyclops after 12 weeks growth in overburden/topsoil mixture (O/T) and quarry floor material (Q). Values are means of four replicates. See Figure 2 for treatment codes. LSD (0.05) = 2.6

Property	Concentrations in overburden/topsoil Mixture
pH	8.0
Organic Carbon	0.18%
Total Nitrogen	350mg/kg
Bicarb-Extract Phosphorus	15.8mg/kg
Soil Respiration	0.25µg CO_2 as C per g soil per hour
Microbial Biomass	42.8 C (mg/kg)
Micro-nutrients:	
Manganese	0.8mg/kg
Iron	2.6mg/kg
Zinc	0.7mg/kg
Boron	0.1mg/kg
Copper	0.4mg/kg

Table 5. Soil characteristics of overburden/topsoil mixture.

topsoil these four treatments had similar values, suggesting that a deficiency of the nutrients in the All - Mg, K treatment was more limiting for *A. cyclops* than for *E. gomphocephala*. Also, as with *E. gomphocephala*, the *A. cyclops* showed weaker growth in plants grown in quarry floor material compared with those in the overburden/topsoil mixture. By contrast with *E. gomphocephala*, the shoot dry weight of *A. cyclops* was depressed in treatments All - Fe and All - Zn. However, growth of *A. cyclops* was less limited by the lack of nitrogen and phosphorus than was that of *E. gomphocephala*. That the omission of nitrogen was less limiting to *A. cyclops* than to *E. gomphocephala* suggests that nitrogen fixation was active in the Acacia, though still at a rate that limited growth to some extent.

Plant Symptoms

A. cyclops in overburden/topsoil mixtures did not show symptoms of nutrient deficiency as strongly as did the Eucalypt. However, seedlings in the All - N and Nil treatment groups displayed nitrogen deficiency symptoms, with a general paleness of leaves and decreased glossiness compared with healthy Acacias. The Acacia also showed signs of iron deficiency, though, once again, not as strongly as did the Eucalypt.

Experiment Three: Glasshouse Trial

In terms of dry shoot weight, the All and the All - Fe treatments were not significantly different from one another ($p<0.05$), with means of 4.8g and 5.1g, respectively. These two treatments were significantly different from the Nil treatment, which had an average dry shoot weight of 1.3g. Terry and Abadia (1986, p. 300) state that: *"Although iron deficiency does not seem to affect general parameters of leaf growth, such as cell numbers per unit leaf area or number of chloroplasts per cell, it decreases the chloroplast volume and protein content per chloroplast."* This accounts for the shoot weights in the All - Fe treatment being similar to those in the All treatment, even though iron deficiency symptoms were pronounced. Further information regarding iron nutrition can be found in Kinzel, 1983; Anderson, 1982a; Handreck, 1991; Anderson, 1982b; Inskeep and Bloom, 1986; Loeppert and Hallmark, 1985; Anderson, 1983). Overall, the species fell into two groups of dry shoot weight results, the low shoot weight plants and high shoot weight plants. Low weights were recorded for *Lupinus angustifolius, Orthrosanthus laxus, Dodonea aptera* and *Banksia attenuata*. The species with significantly high shoot weights were *Kennedia prostrata, Banksia menziesii, Hakea prostrata, Eucalyptus gomphocephala* and *Scaevola crassifolia* (Fig.4). This, however, can depend not only on the treatment, but also upon how large the plant will be at maturity. As expected, *Lupinus angustifolius* cu Gungurru, the alkaline sensitive plant tested, performed badly, dying in all treatments in the first few weeks of the pot trial. However, classical iron deficiency symptoms were noted in the All - Fe and Nil lupin plants before they died. Entire leaves became yellow, brown spots developed in the middle of leaves and younger leaves died from the tip inwards before older leaves (see Snowball and Robson, 1986 for details on this deficiency in lupins). Poor growth and chlorosis also appeared in *L. angustifolius* in an experiment carried out by White and Robson (1989, p. 63) and was said to have been caused by iron deficiency. Lupins in the All treatment died perhaps due to iron deficiency in such a calcareous substrate. Yet the addition of iron to this substrate did not prevent death of lupins, reflecting perhaps their extreme sensitivity to alkaline soils. The two Banksia species, *B. attenuata* and *B. menziesii* did not grow as well as other local species and did not look as healthy as expected, even in the All treatment. Even though these plants increased in height and leaf number, they tended to look stressed, and younger leaves were burnt. This, perhaps, was caused by the disturbance of removing nursery soil at the beginning of the potting trial. It could also have been caused by the addition of phosphorus in the All treatment. Black (1979; cited by Marshall, 1983) investigated rehabilitation following sand mining in Eneabba, Western Australia, and found that members of the Proteaceae family required no fertilizer for the first six months. After this, Banksia species responded well to applications of nitrogen, but not to phosphorus. This sensitivity to phosphorus addition, which may result in toxicity, is related to the Banksia phosphorus uptake mechanism, which is adapted to very low levels of the nutrient in its native sandy soils (Handreck, 1991; Barrow, 1977).

Plant symptoms

Differences between All and All - Fe treatments were noted in plant vigour and colour. *Eucalyptus gomphocephala, Hakea prostrata, Kennedia prostrata*, and *Orthrosanthus laxus* in the All - Fe treatment showed signs of iron deficiency, with yellow or pale green colouring of the interveinal

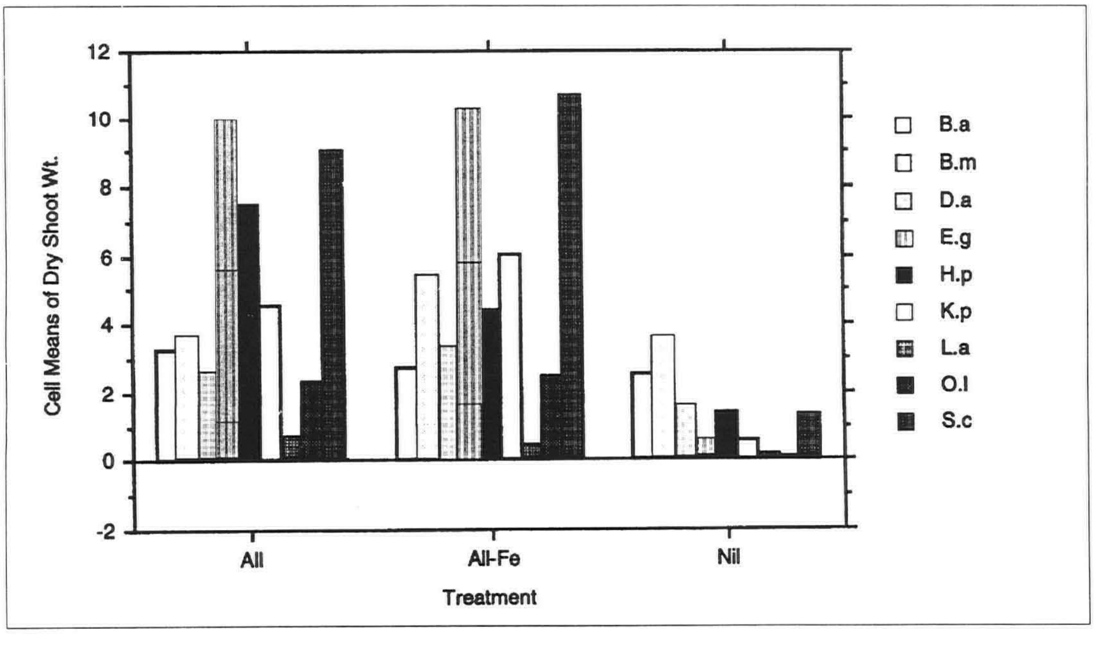

Figure 4. Effects of complete fertilizer (All), omitting iron (All - Fe) and no fertilizer (Nil), on dry shoot weight (g per plant) of nine plant species grown in limestone quarry substrate. Values are means of four replicates. LSD (0.05) = 0.48

Species	Percentage Survival
Acacia saligna	92
Banksia prionotes	20
Dodonea aptera	32
Eucalyptus decipiens	38
Eucalyptus gomphocephala	81
Templetonia retusa	0.004

Table 6. Species survival in April 1995, 11 months after planting. Values are a percentage of 240 plants.

spaces, chlorosis and subsequent necrosis, called iron chlorosis. Iron deficiency symptoms were similar in all species affected. Symptoms were first found in younger leaves and then progressed to the older leaves due to iron being phloem immobile (Dell and Robinson, 1993; Robson and Snowball, 1986; Salisbury and Ross, 1985). By contrast, species that did grow very well in both the All and All - Fe treatments were *Eucalyptus gomphocephala* and *Scaevola crassifolia*. *E. gomphocephala* was expected to do well, as it had performed very well in the previous pot trial. Other plants whose growth improved significantly with the addition of nutrients were: *Hakea prostrata, Kennedia prostrata* and *Orthrosanthus laxus.*

Proteoid Roots

Proteoid roots were observed in both Banksias and in *Hakea prostrata*. These dense, bottle-brush-like, clusters of rootlets of limited growth (Dinkelaker et al, 1994), increase nutrient uptake by increasing root surface area and by producing strong reducing, acidifying and chelating agents for poorly-soluble sources of phosphorus, iron, and manganese (Lamont, 1993; Dinkelaker et al.,1989). This is seen clearly in Banksias, which form a dense mat within 10cm of the surface, thus trapping nutrients as they enter the soil (Lamont, 1982).

Experiment Four: Field Trial

In terms of survival, , *Eucalyptus gomphocephala* and *Acacia saligna* were generally the most successful species in the field trial (Table 6). *A. saligna* also showed excellent field survival in experiments in an alkaline substrate by Bell et al (1993). Two species (*Templetonia retusa* and *Dodonea aptera*) suffered rabbit grazing. *D. aptera* survived at a rate of 32%. However, if the plants were very large when planted, rabbits tended to ignore them. Of the two remaining species, *Banksia prionotes* did not survive well (approximately 80% of the plants died) and *Eucalyptus decipiens* had a survival rate (38%) similar to that of *D. aptera*. Meaningful statistical analysis of field trial results was hampered because many of the fertilized plants were grazed by rabbits. This allowed plants in some of the control plots, which were not grazed to the same degree, to have the same, or better, vigour ratings as those in treated plots. Removing grazed or missing plants from the results and re-analysing remaining values is not feasible because it is impossible to differentiate between plants that have been eaten or damaged by rabbits, and plants that have died due to treatment or another cause and hence are missing. However, by looking at some plants in terms of height, leaf number and vigour, the difference between treatments is easily recognisable. Large numbers of annual weeds, covering up to about 80% of the quadrat, were found in most quadrats. These were not on-site weeds, as they differed from those found elsewhere in Quarry 7. This supports the case for the use of on-site topsoil, which is likely to contain fewer weed seeds. Indeed, importing topsoil is not recommended by Bailey et al (1991), because of high purchase and transport costs, as well as the possibility of competition from weeds in the seed bank and natural invasion into a soil likely to be more fertile. Off-site topsoil was also rejected as a substrate for revegetation by Gunn and Bailey (1993), due to the differences between the physical, chemical and biological characteristics of imported topsoils and soils characteristic of limestone dale sides. Thus, retention of topsoil from the pre-mining quarry, even if quantities are very small, is valuable. As little as 5-10cm of such topsoil has proved beneficial for vegetation (Down and Stock, 1977).

Treatments

Disregarding the use of broadcast basal fertilizer, the treatment showing the best growth ($p<0.05$) was All - OM (sewerage sludge) (Table 7). This was followed by the All - Micro-nutrient plots, and All. The better growth associated with omission of sewerage sludge could reflect reduction of the weed invasion that was evident in plots treated with sewerage sludge. Treatment plots showing the lowest vigour were All - Pellets, with a vigour rating of 3.0. It can thus be suggested that, if rabbits are likely to graze in such quarries, use of pellets can help to increase plant vigour. Species richness in relation to fertilizer treatments and rabbit grazing has been studied by Davis et al (1993). It was shown that high species richness can be produced even without protection from rabbits, providing the fertilizer application is doubled. However, plant mean percentage cover was very much higher with year-round protection from grazing. This suggests that less fertilizer is needed if vermin-proof fencing is kept intact. The use of broadcast basal fertilizer was studied in a split plot design. A Fisher's Protected LSD test at a significance level of 0.05 showed that the difference of vigour in plots containing basal (versus no basal) fertilizer, was not significant. It is therefore not surprising that interaction between basal fertilizer and any of the other treatments was also insignificant. A higher application of broadcast basal fertilizer with nitrogen is likely to prove more beneficial.

Species

Acacia saligna grew very well under most treatments, especially the All, All - OM (sewerage sludge) and All - Micro-nutrients treatments. The lowest vigour rating for this species was noted in the All - Topsoil treatment (Table 8). By contrast, *Banksia prionotes* had the highest vigour ratings in the All - OM and Control plots. High ratings in the control plots indicate that the treated plots were damaged by rabbits or had a surplus of nutrients. The lowest ratings were in the All, All - Topsoil, All - Pellets, and All - Micro-nutrients treatments, with no significant differences ($p<0.05$) between them. The proteoid roots of Banksias enhance nutrient uptake in low nutrient soils by a) increasing the root surface area and b) providing a strong reducing, acidifying and chelating capacity for poorly-soluble sources of phosphorus, iron and manganese (Lamont, 1993). The uptake of phosphorus, for example, can be up to 13 times higher than that by non-proteoid roots (Lamont, 1982). Therefore, if large quantities of phosphorus were applied, as in this field trial, Banksias would take up available phosphorus quickly, as their proteoid roots are adapted to do, thereby killing the plant by phosphorus toxicity. *Dodonea aptera* seedlings

Table 7. Treatments affected by rabbits damage in field trial on the 29th September 1995, four months after planting (0 or 1).

Treatments	Level of Rabbit Damage*	S.E.
Control	0.0	0.0
All-Topsoil	0.0	0.0
All	0.12	0.12
All-OM (sewerage sludge)	0.38	0.18
All-Micronutrients	0.5	0.19
All-Pellets	0.5	0.19

* 0= no damage, 1= all damaged

Table 8. Vigour ratings (1-5, see text) for each species (see Table 3 for key) for each treatment in Experiment 1 in April 1995, 11 months after planting. Values are means of 40 plants.

Species	A.s	B.p	D.a	E.d	E.g	T.r
Treatment						
All-OM	4.4	2.1	2.1	2.4	4.8	1.0
All-Micro	4.6	1.5	1.5	2.2	4.1	1.0
All-Topsoil	3.6	1.4	1.4	2.4	3.5	1.0
All-Pellets	4.0	1.4	1.4	1.6	3.5	1.0
All	4.3	1.3	1.3	1.4	4.3	1.0
Control	3.8	2.1	2.1	2.0	3.5	1.0
LSD (0.05)=	0.4	0.7	0.7	0.7	0.7	0.05

LSD= Species *Treatments

that remained after rabbit grazing showed very high vigour ratings in the All - Micro-nutrients, Control and All - OM plots. Imported weed species in the All - Micro-nutrients and All - OM plots resulted in very low vigour rating among fairly small-sized *D. aptera*. Growth of *Eucalyptus decipiens* was favoured by treatments All - Topsoil, All -, Control and All - OM. The All - Pellets treatment displayed, once again, the lowest vigour rating. Broadcast fertilizer did not improve growth significantly. The second most successful field trial species, *Eucalyptus gomphocephala*, was favoured by treatments All - OM, All and All - Micro-nutrients, as was the other successful species, *Acacia saligna*, discussed above. Treatments that produced poor vigour ratings generally did the same for *A. saligna* and *E. gomphocephala*, namely All - T, All - P and the Control plots. The least successful trial species was *Templetonia retusa*, mostly due to the effects of rabbit grazing. Data for the final vigour rating show this species grew badly in all plots. Of the seedlings planted, only one plant survived in a Control plot. Rabbits had grazed all treatments other than the Control plots, then grazed the remaining *T. retusa* plants.

CONCLUSIONS

This study investigated ways of improving the success of limestone quarry revegetation, using local flora and soil amendments. Field survey showed that only 20% of species planted in the Cockburn Cement quarry were surviving. Suspected reasons for this low survival rate were low levels of available nitrogen and phosphorus. Glasshouse trials indicated that omission of nitrogen or phosphorus depressed plant growth. Field trials showed that the addition of a complete fertilizer in slow release pellet form provided the most successful amendment. Slow release fertilizer would especially suit Proteaceous species, as it reduces a risk of phosphorus toxicity that is prevalent in Proteaceous plants. Slow release fertilizer placed beneath tree roots would also produce a strong growth spurt to help all plants survive the first summer drought without providing nutrients for unwanted weeds (Buchanan, 1989). The results of this study are now being incorporated in long term restoration programs for this and other Cockburn Cement limestone quarries. Other restoration projects in Australia and elsewhere in the world, where similar soil conditions occur, could profit from the results of the specific research undertaken in this study.

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Geochemical and depth controls on microporosity and cavity development in the Maynardville Limestone: Implications for groundwater

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Abstract: Understanding the controls on micro- and macroporosity development and their relationship to the karst system in the Upper Cambrian Maynardville Limestone are important in determining possible contaminant transport pathways within the Oak Ridge Reservation, Tennessee. Adequate groundwater flow modelling in this system is difficult because of the highly heterogeneous nature of the karst system. In the Maynardville Limestone, several important factors control the development of microporosity and cavity formation: 1) lithological controls of secondary microporosity, 2) depth below the ground surface related to the most active zone of groundwater flow, and 3) structural controls (dissolutionally enlarged fractures and faults). Secondary microporosity is lithologically controlled, with higher porosities in the dolomitic upper part of the Maynardville Limestone that are related to dissolution of evaporite minerals and de-dolomitization in supratidal facies. Secondary porosity development in the dolomitic facies, particularly the stromatolitic dolostones, occurs to at least 330m depth below ground surface (bgs). In the lower part of the Maynardville Limestone, karst development and secondary porosity are depth dependent, with karst features rare below 35m depth bgs in the sub-tidal to intratidal limestones. However, karst development is prevalent in the lower Maynardville Limestone at shallower depths (<35m). Large-scale cavities and water producing zones are present along fracture sets parallel and perpendicular to bedding and do not relate directly to any particular facies or lithology, but may be associated with thickly bedded units. Dissolutional enlargement along minor faults has been documented in only one area. Cross borehole injection and monitoring tests and well hydrograph analyses are useful in identifying general trends in the locations and directions in which quick flow is more dominant. Quick flow is common at shallow depths (<35m bgs) in all directions, and this supports the observations of cavities intercepted during drilling, and lithological observations in core, which both indicate significant secondary porosity and cavity development at these shallow depths, with fewer karst features at greater depths. At shallow depths, rapid fluid velocities are expected in directions roughly parallel to the dip of the strata in all lithologies and at various angles to strike. In any hydrological modelling of this aquifer, considerably higher hydraulic conductivities should be assigned to the shallow (<35m) depths when modelling a large scale problem. Models should also account for the higher hydraulic conductivities expected in along strike and dip directions.

INTRODUCTION

The U.S. Department of Energy's Oak Ridge Y-12 facility (Fig. 1), located in the Bear Creek Valley of east Tennessee, contains several hazardous and non-hazardous waste sites and underground storage tank sites within the valley and adjacent ridges that have the potential of contaminating local surface streams and groundwater. Of all the water-producing zones located during drilling in the Maynardville Limestone of the Bear Creek Valley, 36% have been identified as cavities, 32% are fractures, and 32% are identified as slow-flow water-producing intervals (Shevenell and Beauchamp, 1994). Hence, a considerable portion of this aquifer is influenced by large features as a result of secondary porosity development.

An understanding of karst development in this area is essential for proper flow characterization and for potential development of remedial alternatives. Because of the heterogeneous nature of the karst aquifer in the Bear Creek Valley and its profound effects on potential transport of contaminants, several hydrological and geological studies were conducted to help define groundwater pathways in the Bear Creek Valley and to investigate the factors influencing the occurrence and distribution of water-bearing intervals. The geochemical characteristics of the groundwater as they relate to identifying quick flow zones through fractures and conduits have been evaluated by Shevenell (1994). Results from drilling in the Bear Creek Valley, hydrograph analysis, core descriptions, diagenetic interpretations, and evaluation of lithological controls on secondary porosity development have been documented by Goldstrand (1995), Goldstrand et al (1995), Shevenell et al (1992), Shevenell (1996) and Goldstrand and Shevenell (1997). Selected results from all of these studies are combined here to help in the construction of a conceptual model of the aquifer.

The microporosity within the different lithofacies must be incorporated into hydrological models of this aquifer. Although higher fluid velocities are associated with the fractured and karst elements within the aquifer, matrix porosity provides zones where contaminants can be stored and later released, and hence, these areas can be an important secondary source of contaminants into the fracture and karst systems (e.g. Shevenell et al, 1994). Matrix diffusion of possible contaminants from the microporosity into fractures and cavities will differ considerably from one lithofacies to another. There is greater storage capacity in the upper Maynardville Limestone, and therefore, the effects of matrix diffusion of contaminants should be greater than in any of the other part of the Maynardville Limestone due to its higher microporosity (Goldstrand and Shevenell, 1997).

This paper describes the factors that result in secondary porosity development, both microporosity in the rock matrix and macroporosity in the form of cavities. The geological controls on secondary microporosity development have been presented previously in Goldstrand and Shevenell (1997). The objectives of this study are: (1) to identify the geochemical and spatial factors that influence secondary porosity development; (2) to identify how these factors are influenced by the scale of observation; (3) to identify controls on the heterogeneity of the karst aquifer; and (4) to evaluate how these factors influence groundwater flow.

GENERAL GEOLOGICAL AND HYDROLOGICAL SETTING

Geological setting

Bear Creek Valley is located in the upper plate of the Whiteoak Mountain thrust fault (Fig. 1) within the Valley and Ridge province of the southern Appalachian fold and thrust belt, east Tennessee. The bedrock of the Bear Creek Valley and adjacent ridges consists of Cambrian and Ordovician carbonate and clastic sedimentary rocks (King and Haase 1987; Hatcher et al, 1992). The majority of the waste management areas within the Bear Creek Valley are located in the Nolichucky Shale and Copper Ridge Dolomite, which drain into the karstic Maynardville Limestone in the valley floor. During well drilling, a cavity was noted when an obvious drop of the drill string occurred. The drilling results show that numerous, small (<1.5m in height), totally submerged, interconnected cavities are common within the Maynardville Limestone. Many of these cavities are partially to totally mud-filled.

Bedrock strike in the area varies from N47°E to N67°E and dips average 43° towards the southeast (King and Haase, 1987). The Nolichucky Shale forms part of the central floor of the Bear Creek Valley and is gradationally overlain by the Maynardville Limestone; both formations are part of the Conasauga Group. The Maynardville Limestone forms the southeastern floor of the Bear Creek Valley and is gradationally overlain by the ridge-forming Copper Ridge Dolomite; both formations are considered part of the Knox aquifer in this region (Solomon et al, 1992).

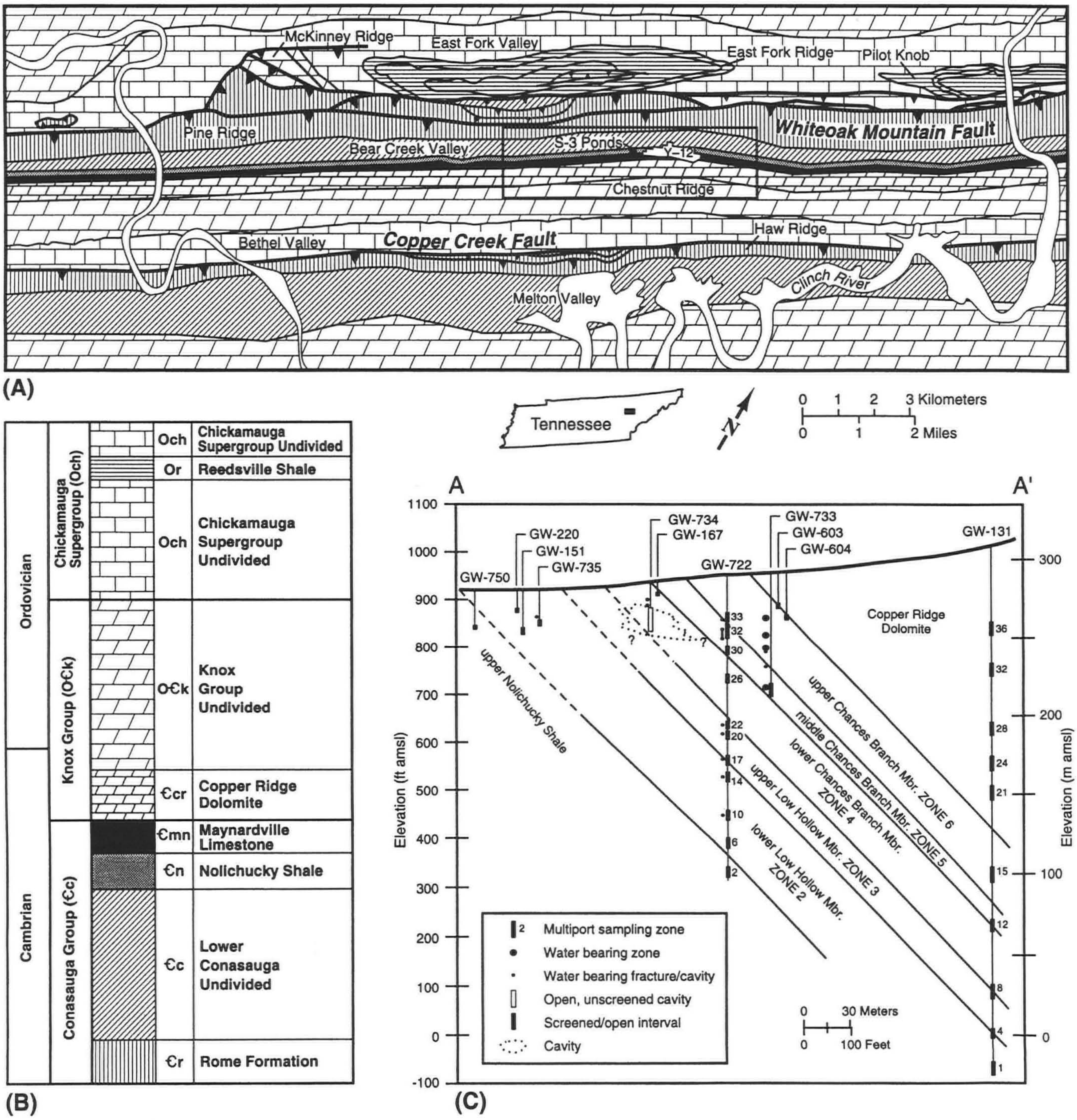

Figure 1. Location and generalized geological map for the Y-12 Plant area, Bear Creek Valley, and Chestnut Ridge. The inset box in Fig. 1(A) shows the location of Figure 2. Figure 1(B) shows a stratigraphical column of the units identified in 1(A) and serves as a key to the symbols in 1(A). Figure 1(C) is a cross section showing the general geology perpendicular to strike. This particular cross section is located just east of the '2' in Y-12 of Figure 1(A), and the cross section location is identified more clearly in the enlargement of the Y-12 area in Figure 2.

The Maynardville Limestone ranges in stratigraphical thickness between 116 and 127m in the Bear Creek Valley (Hatcher et al, 1992; Shevenell et al, 1992). Based on gamma-ray log signatures, the uppermost Nolichucky Shale and the whole of the Maynardville Limestone have been divided into six zones (Shevenell et al, 1992). Zone 1 comprises the upper part of the Nolichucky Shale and was not part of this study. The Maynardville Limestone is divided into five geophysically distinct zones numbered 2 to 6, with zone 2 at the base and zone 6 at the top of the formation. Detailed lithological descriptions and discussions of secondary porosity development appear in Goldstrand and Shevenell (1997), a brief summary of which is included here. The Maynardville Limestone represents an upward shallowing carbonate platform sequence from sub-tidal (zone 2) to supratidal (zone 6) palaeoenvironments (Weber, 1988; Goldstrand 1995). Rapid facies changes occur laterally in the sub-tidal portion of this carbonate platform (i.e., zones 2, 3, and 4) where examined in detail in the area of the Burial Grounds (Fig. 2). However, facies in zone 6, and to a lesser extent zone 5, are generally uniform throughout The Bear Creek Valley. The Maynardville Limestone-Copper Ridge Dolomite contact is gradational with mottled, irregularly bedded, dolomitic limestone within the uppermost Maynardville Limestone grading upward into cherty dolostone of the Copper Ridge Dolomite.

Geophysically the contact between the Nolichucky Shale and Maynardville Limestone is placed immediately above the highest right deflection on the gamma-ray log (defining the location of the last major shale interbed within the Nolichucky Shale) and at the bottom of the comparatively constant carbonate baseline (Shevenell et al, 1992). Lithologically, this contact can be either abrupt or gradational within the Bear Creek Valley. Where the contact is gradational, the contact is placed where the limestone to shale ratio becomes >50% within the ribbon-bedded lime mudstone below the lowermost massive limestone.

Several fracture sets have been identified in the Bear Creek Valley area, with a prominent fracture set oriented parallel to and along bedding planes (Sledz and Huff, 1981; Ketelle and Huff, 1984; Rothschild et al, 1984; Hatcher et al, 1992). A second prominent set of fractures is also parallel to strike but perpendicular to bedding (Hatcher et al, 1992), with the frequency of fracturing decreasing with depth within the bedrock (Solomon et al, 1992). Within the Oak Ridge area there is a strong correlation between fracture spacing and bed thickness (i.e. an increase in fracture spacing in thicker beds; Hatcher et al, 1992).

Although no major faults are present in the immediate study area, minor thrust faults (duplicating 3- to 6-m sections of strata) have been observed in core. These faults provide zones of preferred groundwater flow and cavity development. Within the Burial Grounds area (Fig. 2) cavities (up to 1m high) have developed along fault planes. Grout that was placed in cavities in one well during well completion attempts was encountered in a second well located 50m down dip, showing that these cavities are hydrologically connected along the fault plane.

Hydrological setting

Hydraulic head data indicate that groundwater flow into the Maynardville Limestone is from the adjacent ridges in an approximately strike perpendicular direction. Flow in the Maynardville Limestone is parallel to strike, suggesting that the Maynardville Limestone acts as a hydraulic drain for the Bear Creek Valley. Within the Bear Creek Valley a shallow groundwater and surface water divide is located near the northwestern end of the Y-12 Plant in the area of the S-3 ponds (Geraghty and Miller Inc. 1987; 1990; Fig. 2). Northeast of the divide, groundwater flows toward Upper East Fork Poplar Creek, and southwest of the divide the groundwater flow is southwestwards towards Bear Creek. The surface water in the Bear Creek Valley and groundwater in the Maynardville Limestone are interconnected, with gaining and losing reaches of the stream and springs discharging from the Maynardville Limestone into Bear Creek (Geraghty and Miller Inc. 1985). A large number of dissolution cavities are present in the Maynardville Limestone underlying Bear Creek (Shevenell et al, 1992; Shevenell and Beauchamp, 1994). Locally, intermittent rapid flow through these features occurs in response to precipitation events (Shevenell, 1996).

METHODS

Data pertaining to facies and lithological variations within the Maynardville Limestone were obtained from core and geophysical data from 17 cored boreholes throughout the Bear Creek Valley (Goldstrand, 1995). All depth data referenced in the following sections are depths below ground surface. See Goldstrand and Shevenell (1997) for a detailed description of the lithological variability and geological controls on microporosity development within the Maynardville Limestone.

To define the distribution, connectivity, and extent of the karst system, a drilling program was initiated and all historical drill hole data were consulted to identify locations and sizes of cavities and fractures (Shevenell et al, 1992; Shevenell and Beauchamp, 1994). Most of the wells penetrated multiple lithological zones, yet attempts were made in most cases to complete the open or screened intervals so that the well monitored only one lithological zone (See Table 1 for listing of lithological zones in each well completion interval). The type of water inflow to the well encountered during drilling was noted as the borehole was advanced. Most cavities are identified by an obvious drop of the drill string during drilling through a

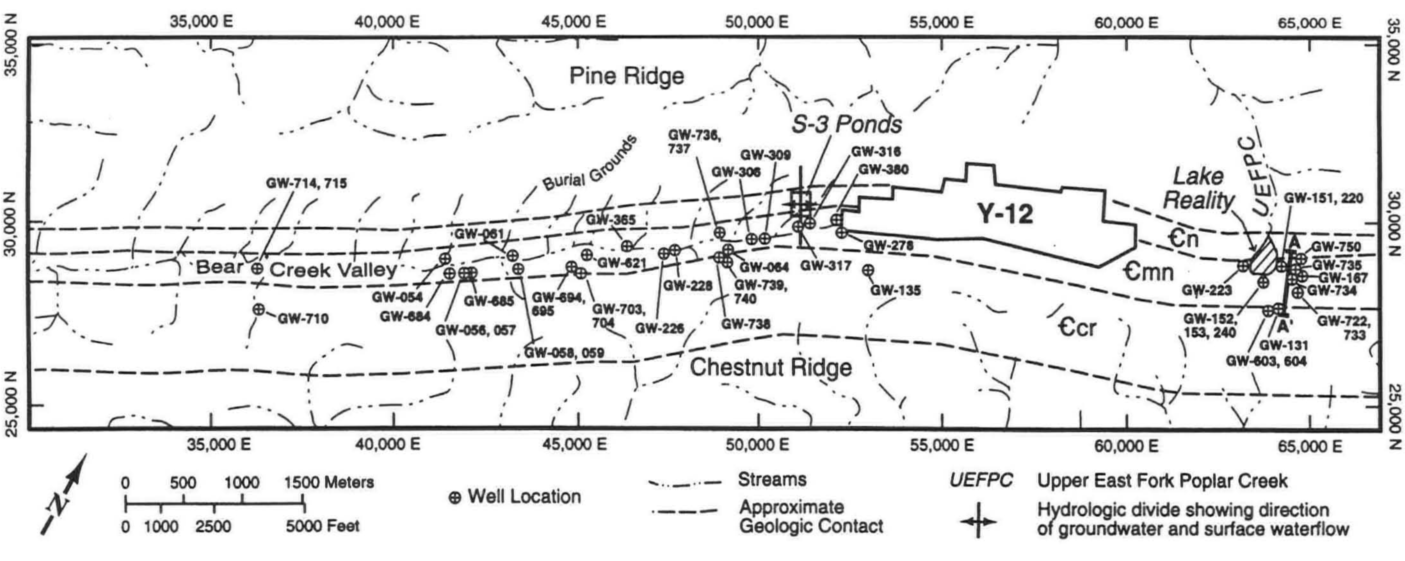

Figure 2. Generalized geological map of the Y-12 Plant vicinity showing core hole and well locations and approximate formation contacts for the Copper Ridge Dolomite, Maynardville Limestone, and Nolichucky Shale. Cross section line A-A' shows the location of the cross section depicted in Figure 1(C). See Figure 1 (B) for key to geological symbols.

Table 1. Well completion data and aquifer parameter data for wells analysed with the hydrograph analysis method.

Well	Hydrograph Group	Depth (m)	Water Zone	Elevation (m)	Screen/Open Interval Depth (m bgs) Top	Bottom	Completion Interval in Єmn zone	Ave T (m^2/d)	Std Dev T	Ave S_{y1}	Std Dev S_{y1}
GW-054	1	11.0		271.3	10.7	11.3	5	26.7	25.4	2.81E-03	4.77E-03
GW-056	1	16.8		270.3	16.2	16.8	6				
GW-057	1	7.6		270.4	6.4	7.0	6	6.7	7.1	1.04E-03	2.54E-04
GW-058	1	13.8		277.3	12.8	13.5	6	5.8	3.6	1.24E-03	1.15E-03
GW-059	1	8.0		277.4	7.0	7.6	6	4.3	0.5	4.14E-04	1.42E-05
GW-061	2	8.0		274.6	6.1	7.5	2	4.1	0.7	3.61E-04	1.38E-05
GW-131-01		328.5	w	307.4	0.0	0.0	2				
GW-131-04		306.6	f?	307.4	0.0	0.0	2				
GW-131-08		279.4	f?	307.4	0.0	0.0	3/4				
GW-131-12		239.5	f?	307.4	0.0	0.0	4/5				
GW-135-06		348.2	f	358.4	0.0	0.0	2				
GW-135-11		294.2	f	358.4	0.0	0.0	3				
GW-135-19		222.9	w	358.4	0.0	0.0	6				
GW-151		3.6		278.4	26.2	29.3	2				
GW-152		5.3		280.0	3.7	5.1	2				
GW-153		18.3		280.0	15.2	18.1	6				
GW-167	3	9.2		283.4	7.9	9.2	4	25.9		2.11E-03	
GW-220	1	13.8		278.3	10.7	13.6	2	6.2	4.3	1.75E-04	1.69E-05
GW-223		27.6		277.1	24.4	27.4	2				
GW-226		16.8	w	286.8	13.7	16.8	2	6.5	2.9	4.08E-03	7.33E-05
GW-228		30.5	c	287.8	24.4	30.5	6				
GW-240		9.0	f	280.3	7.3	8.8	6				
GW-278		6.4	w	303.3	4.9	6.4	2				
GW-306		17.8	f	301.7	14.6	17.7	2				
GW-309		11.6	f	300.5	8.2	11.3	2				
GW-316		24.4	f	318.5	21.0	24.2	6				
GW-317		40.2	f	323.4	36.6	39.8	6				
GW-365		45.7	f	284.5	38.6	45.7	2				
GW-603	2	22.9	w	292.5	19.8	22.9	6	10.1	0.0	8.32E-04	8.43E-05
GW-604	2	34.3	w	292.5	31.4	34.3	6	10.3	0.1	1.00E-03	6.90E-04
GW-621	1	13.1	c	281.4	7.6	12.3	4	1.2	0.8	1.28E-03	3.65E-04
GW-684		39.5	c	273.0	34.8	39.1	6				
GW-685	1	42.2	w	271.1	27.0	40.6	6	7.2	9.3	2.04E-03	2.55E-03
GW-694	3	62.3	f	286.2	47.0	62.3	4	2.4	1.2	2.11E-03	9.55E-04
GW-695	3	19.0		285.7	15.9	19.0	6	3.7	0.5	2.93E-03	4.25E-04
GW-703	3	55.5		290.2	41.2	55.5	5				
GW-704	2	78.0	w	287.2	75.0	78.0	4	2.6	0.4	2.30E-03	2.42E-04
GW-710	3	227.0		276.8	164.5	227.0	5/6				
GW-714	3	44.0	w	265.9	35.1	44.2	4	3.9		2.13E-03	
GW-715	1	13.0	c	265.9	10.1	13.1	6	16.1	13.2	1.33E-04	8.19E-05
GW-734	1	31.0	c	285.8	18.1	31.4	4	26.0	15.1	7.33E-04	3.58E-04
GW-735	1	24.0	w	280.9	20.7	23.8	2	33.4	9.4	1.59E-03	3.71E-04
GW-736	3	31.0	f	291.9	28.0	31.3	2	4.4	3.4	4.90E-03	3.68E-03
GW-737	3	27.0	f	291.9	24.1	27.3	2	6.2	2.0	6.10E-03	4.19E-03
GW-738	3	27.0	c	298.9	20.4	26.7	6	1.4	1.0	2.35E-03	4.20E-04
GW-739	3	98.0	w	311.2	88.2	67.1	4				
GW-740	3	58.0	f	310.0	50.5	57.9	6				

Note: Group refers to the group categorized based on hydrograph data. Blank entries have no hydrograph data.

particular interval accompanied by an increased flow of water. When cores were taken, cavities were identified when there was poor core recovery. A fracture is indicated when an increased flow of water is noted and cuttings show evidence of fractures (e.g. haematite stains). Water zones from matrix intervals are noted when slow flowing water occurs without any indications of the presence of cavities or fractures.

Cross-borehole tests were conducted between August and November, 1993, when storm influence was at a minimum, in an attempt to identify preferred flow directions. These tests were conducted in five areas within the Bear Creek Valley by injecting water in one well in an area and monitoring the water level responses in up to 10 nearby wells at distances of 8 to 180m from the injection well. Hydrographs were also obtained from more than 40 wells in the Maynardville Limestone in the winters of 1993-1995 when the influence of storm events was greatest (Shevenell, 1996). In this previous work it was assumed that three segments on a recession curve from wells in a karst aquifer represent drainage from three types of storage: conduit, fracture and matrix portions of the aquifer. Shevenell (1996) presents a scheme to analyze well hydrographs quantitatively in karst terranes when corresponding stream or spring discharge rates are not available. Estimates of transmissivity (T) and specific yield (S_y) in different portions of the flow regime are obtained with the use of water level hydrographs. The continuum T is calculated following the work of Atkinson, 1977, where the continuum T is defined as the average, non-conduit T of the aquifer. From these calculations, the distribution of T and S_y in the Maynardville Limestone was obtained. In addition, historical geochemical data from waters sampled four times per year were compiled and the aqueous speciation model SOLMINEQ (Kharaka et al, 1988) was used to calculate saturation indices in order to evaluate which portions of the aquifer were subject to dissolution reactions (Shevenell, 1994).

RESULTS

Hydrological observations

Hydrograph data from numerous wells indicate that some wells are dominated by conduit flow, whereas others are not (Shevenell, 1996). Conduit development is extensive at shallow depths (<35m), but cavities are generally lacking below this depth. However, there is a considerable amount of heterogeneity in the shallower (<35m) portions of the aquifer. Hydrographs provided significant insight into the behaviour of flow in different portions of the karstic Maynardville Limestone. The data presented herein provide information on the large scale heterogeneity in the aquifer. For instance, a deeper well (GW-739) responds to one particular storm, but a shallower well (GW-740) only 30m away does not respond to this same storm, showing the highly heterogeneous nature of this karst flow system.

Observed responses of the monitored wells to precipitation events are summarized below. Techniques used to estimated specific yield (S_y) and transmissivity (T) from hydrograph data are described in Shevenell (1996). In this paper, wells are divided into three groups as a function of their hydrograph responses, and hence, their flow behavior. Group 1 wells are classified as those with a significant contribution from conduit flow and these wells show three distinct slopes on their recession curves (Fig. 3). Group 2 wells are classified as those with some contribution from conduit flow. Although these wells also show three distinct slopes on their recession curves, the three slopes are more nearly equal to one another than in the Group 1 wells, conduit flow is less important than in Group 1 wells, and dissolutionally enlarged features are likely to be smaller and more similar in size to nearby fractures (Fig. 4). Group 3 wells show no influence from conduit flow, have only one or two slopes on the recession curve, and are restricted to portions of the aquifer dominated by fractured and matrix intervals (Fig. 5). Of the wells for which hydrograph data are available, 56.4% showed characteristics of Group 3 wells, 7.7% are characterized as Group 2 wells, and 35.9% fall into the Group 1 category indicating that a significant fraction exhibit quick flow through karst features. The depths of the Group 1 wells range from 5.6 to 60m (Table 1), whereas the Group 2 wells range in total depth from 7.5 to 78m, and Group 3 wells range in depth from 8.2 to 227m. Each of the groups span a relatively wide range in depths, with no conduit, quick flow observed below 78m.

Hydrographs were obtained from 40 wells over a wide range of depths. Table 1 lists the zone and depth at which the wells are completed with overlying materials having been cased off. In order for S_y and T to be calculated using methods described in Shevenell (1996), at least two distinct slopes must be present on a hydrograph recession curve. All hydrograph data for which S_y and T could be calculated are from wells at depths <91m. Six wells at depths >91m were monitored, but none showed two or three slopes from which T and S_y could be calculated. In zone 2, nine wells were monitored, and 10 wells were monitored in both zones 6 and 4. Only four wells were completed in zone 5 and one deep well in zone 3. The S_y and T could not be calculated for the zone 3 well because it had only one slope on the recession curve. Hence, generalized interpretations regarding zone 3 can not be made because (1) there is only one well in this study for which any type of data are available, and (2) this is a deep well not influenced by conduit flow. Nevertheless, other generalizations regarding the specific zones can be made with the available data.

Figure 6 shows the distribution of calculated continuum T by Maynardville Limestone zone and the depth and group into which the wells fall. This plot indicates that the shallower wells (circles) generally have the higher T values, and the deeper wells (triangles) commonly have lower T values. This is reasonable, because fractures and cavities are probably smaller at depth, due to increasing pressures, and there will be less dissolutional enlargement of macro-secondary porosity features with depth due to less active flow. However, data from some wells do not follow this general trend strictly because the aquifer is highly heterogeneous. For instance, even at shallow depths, a relatively large range in T values was found (e.g. $0.8m^2/d$ in a 12m well (GW-621), and $26.7m^2/d$ in an 11m well (GW-054)).

Group 1 wells have the highest calculated T (average $12 \pm 10.9m^2/d$); Group 2 wells have intermediate T values (average $9 \pm 4m^2/d$); Group 3 wells have the lowest T (average $6 \pm 7m^2/d$), although all groups have a fairly wide range in calculated T. This can be seen on Figure 6, in which Group 1 wells (black symbols) with clear conduit influences generally have higher continuum T than Group 3 wells (open symbols), which have no contribution from conduit flow. This generalization does not hold universally because shallow wells that do not intersect conduits commonly have higher continuum T by virtue of their location in the shallow, more active, flow system, with continuum T tending to decrease with increasing depth. Hence, shallow non-conduit, but fractured, areas may have similar continuum T to areas where conduits are more important. Thus, depth is a very important controlling factor of conduit development and continuum T. These data also indicate that zone 2 has calculated T over a slightly wider range than the other zones, suggesting that heterogeneity within this zone may be somewhat greater than within the other zones. Zone 6 shows the smallest range, indicating less heterogeneity.

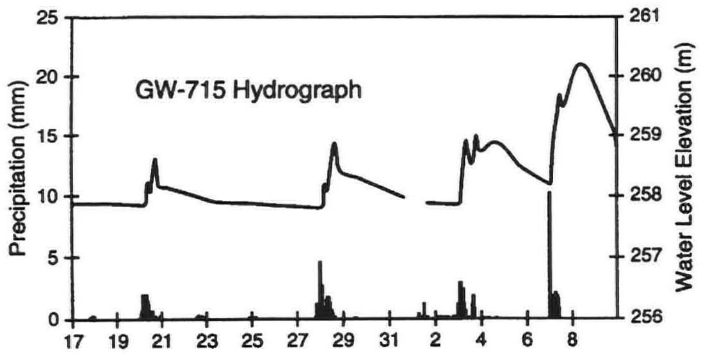

Figure 3. Water level and precipitation data versus time for the GW-715 well (Group 1 well example), from Shevenell, 1996.

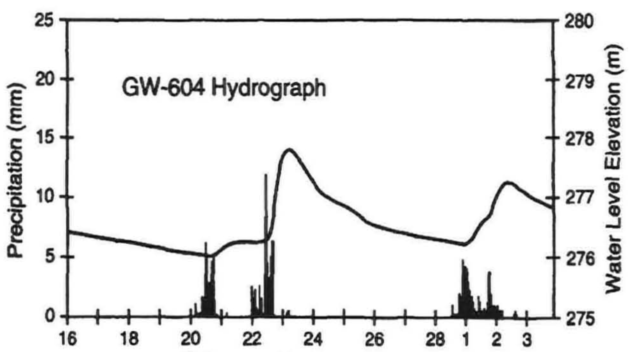

Figure 4. Water level and precipitation data versus time for the GW-604 well (Group 2 well example), from Shevenell, 1996.

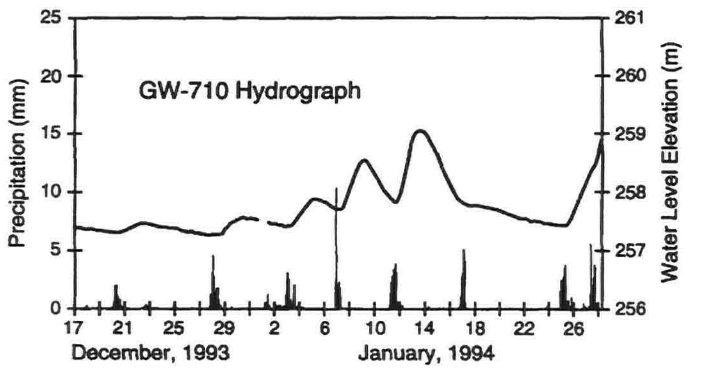

Figure 5. Water level and precipitation data versus time for the GW-710 well (Group 3 well example), from Shevenell, 1996.

Similar trends can be identified when viewing S_y as a function of depth and Group (Fig. 7; where S_y is for the first slope on the recession curve, which is the S_{yl} of cavities, or fractures if cavities are not present). Group 1 wells, which are the most influenced by conduit flow, have average $S_{yl} = 9.82 \times 10^{-4} \pm 8.04 \times 10^{-4}$; Group 2 wells, which are more influenced by smaller conduit features, have average $S_{yl} = 1.61 \times 10^{-3} \pm 7.99 \times 10^{-4}$; and Group 3 wells, which are not influenced by conduit flow, have average $S_{yl} = 3.08 \times 10^{-3} \pm 1.41 \times 10^{-3}$. As can be seen, there is considerable overlap in the calculated S_{yl} between the groups, due to the heterogeneous nature of the karst aquifer. Nevertheless, in all zones, Group 1 wells generally have lower S_{yl} values than wells that are more dominated by fracture and matrix flow. This is reasonable because the specific yield of karst portions of the aquifer should be lower than the matrix dominated portions due to the lower overall porosities. Because conduit development is more extensive at shallower depths, they probably contribute to the total porosity to a greater extent than do smaller conduits at deeper levels, and thus, the S_y of the continuum is lower. This general trend of increasing S_y from Groups 1 to 3 (open symbols) in all zones is much more consistent than are the depth relationships noted on Figure 7, because, S_y is a strong inverse function of the presence of cavities. Although matrix porosity is composed of smaller features, there are considerable greater numbers of them. Thus, there is much greater matrix porosity than porosity associated with cavities.

Data from the hydrograph analyses also indicate that zone 2 is more heterogeneous in its S_y values than the other Maynardville Limestone zones. When considering wells from all zones, it is clear that there can be a wide variation in S_y over all depths in the Group 1 wells, which are all influenced by conduit flow (Fig. 8) with most of the variability at the shallower depths. However, the calculated S_y of the Group 3 show a considerably smaller scatter, suggesting reduced heterogeneity in areas of fracture and matrix flow. The same is the case for the calculated transmissivities (Fig. 6). This suggests that the S_y of the matrix portion of the aquifer, which is not subject to significantly enhanced permeability through dissolution to create karst features, does not change appreciably with depth in any of the Maynardville Limestone zones. Based on porosity measurements in core (Goldstrand and Shevenell, 1997), microporosity also does not vary appreciably with depth. The non-conduit portions of the aquifer are considerably less heterogeneous than the conduit dominated portions of the aquifer. A similar relationship of T in Group 3 wells is also observed where the majority of the T for Group 3 are near $5 m^2/d$ (Fig. 9). Only one well in Group 3 shows elevated T, and this is a shallow well (depth = 9.2m, GW-167) located in the most active part of the flow system in the valley floor. The T of the Group 1 wells, on the other hand, show considerable scatter over the entire depth range, though deeper wells generally have lower T than shallower wells, as noted above (Fig. 9). Hence the variability in T and S_y in the Group 1 wells can be attributed to variations in the extent of conduit development in different portions of the aquifer, and to their depths.

Depth controls on conduit development have also been investigated by compiling all known water zones encountered during drilling of 133 different wells that penetrated any portion of the Maynardville Limestone (data from Jones et al, 1992). Data related to the type of water zone (cavity, fracture or matrix water) encountered during drilling were included in the compilation. Many of the wells at Y-12 were drilled to very shallow depths (<15m), and realistic generalizations on depth dependencies over a wide range of depths cannot be made. Therefore, a subset of the data was selected such that all data from wells drilled to >30m were included (Goldstrand and Shevenell, 1997). Figure 10 shows a bar diagram of these data comparing the abundance of water zones that are cavities versus those that are slower water zones in more matrix dominated intervals. These data show that cavities are much more important and common at the shallower depths than slow flow water zones. As depths increase, the frequency of cavities decreases substantially, and they are [eventually] absent at depths > 78m, whereas the other types of slow flow water zones increase significantly and dominate flow at depths below ≈35m. Hence, large size (macro) secondary porosity development is strongly depth dependent, with decreasing development with increasing depth. This is in contrast to the lack of depth dependency observed in the microporosity. Hence, the scale of observation is critical in defining secondary porosity development.

Results from cross-borehole tests are summarized from Shevenell et al (1995) and used to evaluate preferential quick flow directions. A summary of possible flow paths between injection and monitor wells is made based on the location of well completion interval relative to one another and the relative water level responses. Rapid water level rises and recessions are observed in the quick flow areas, whereas slower, diffuse flow is characterized by long responses showing broad curves for water level rise

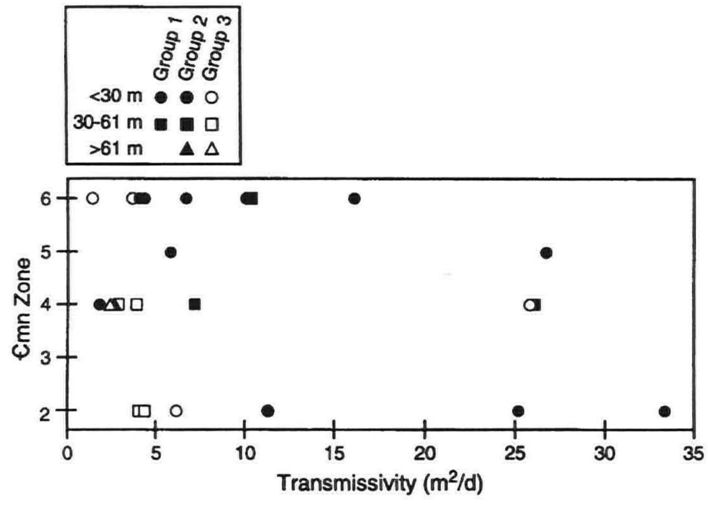

Figure 6. Calculated transmissivity by well group and depth for the five Maynardville Limestone lithological zones.

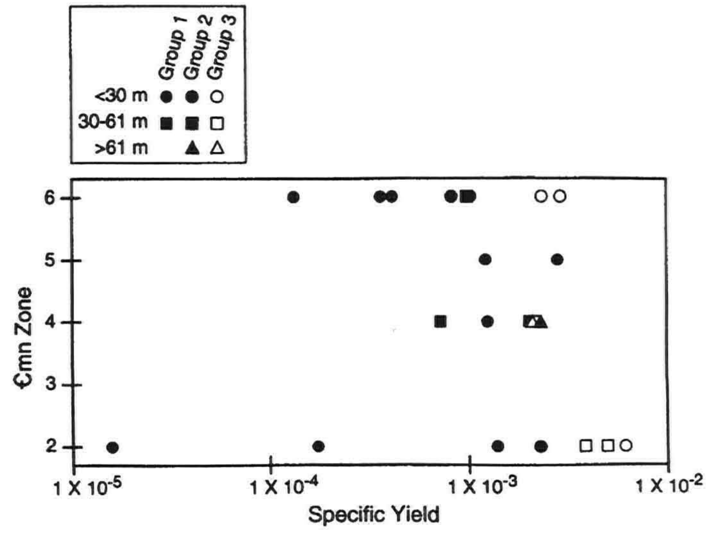

Figure 7. Calculated specific yield by well group and depth for the five Maynardville Limestone lithological zones.

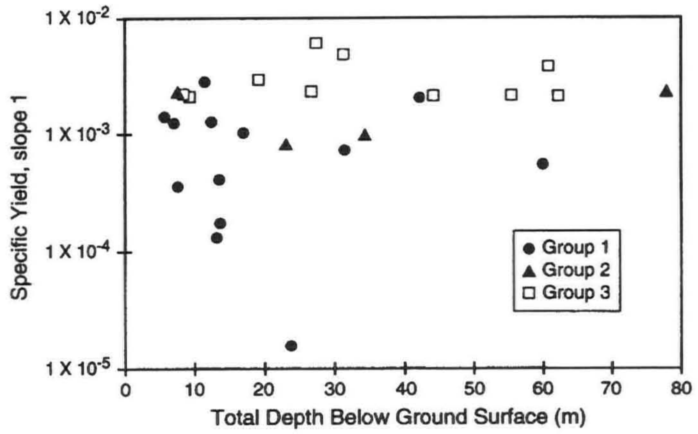

Figure 8. Calculated specific yield versus total depth by well group in the Maynardville Limestone.

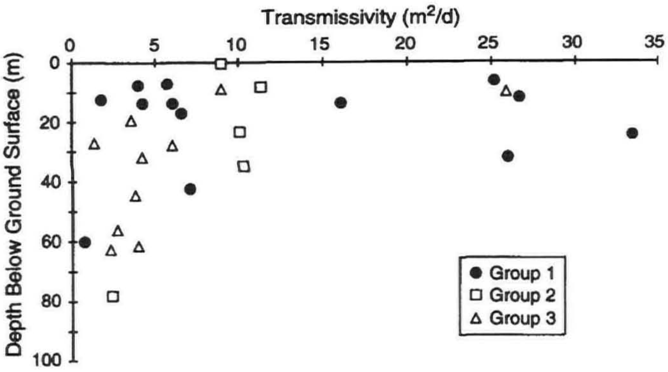

Figure 9. Transmissivity (m2/d) versus depth below ground surface in wells for which hydrograph data are available.

and fall. Most wells located at different elevations, perpendicular to strike and across strata from the injection well did not show a hydrological response to the injection, even at distances <60m. When wells are located at the same elevations (at depths <35m), rapid responses are generally seen, even when the monitor well is located across strata and perpendicular to strike. Relatively rapid responses suggestive of quick flow are also seen regularly in wells along the dip plane with one another, regardless of whether they are along strike, perpendicular to strike or at some angle to strike.

All monitored wells noted to contain cavities in their completion intervals showed a response to injection. The zones noted with fractures or cavities, rather than simply slow flowing matrix waters, showed the quickest responses to injection, as expected. This is true except for GW-703. This well is located perpendicular to strike and across strata from the injection well, suggesting that conduits and fractures may not be well connected in this direction.

Fractures and dissolutionally-enlarged fault planes are also important pathways for groundwater flow in the Bear Creek Valley. Dissolution along fault planes in the Burial Grounds area provides conduits for groundwater flow to deeper levels. Cavities intersected during drilling, present along small-scale thrust faults, are connected to cavities intersected in another well, 50m down dip, (Goldstrand, 1995). Bedding-parallel and strike-parallel fractures are the most permeable sets of fracture orientations in the area (Hatcher et al, 1992). Hydraulic connectivity along these fracture orientations is substantiated in the cross-borehole tests.

In summary, rapid fluid velocities can be expected along dip through cavities and fractures, and at shallow depths in all lithologies and at various angles to strike. The hydrologic connections roughly parallel to dip appear to be most prominent within zone 2. The cross-borehole data support the observations of cavities encountered during drilling, and lithological observations in core, both of which indicate significant secondary macroporosity (cavity) development at shallow depths, with significantly fewer karst features with increasing depth. Significant quick flow can be expected throughout the Bear Creek Valley, yet the directions of this flow may vary locally from site to site. In any hydrological modelling of this aquifer, considerably higher hydraulic conductivities should be assigned to the shallow (<35m) depths when modelling a large-scale problem. Smaller scale problems should take into account the higher hydraulic conductivities expected in along strike and dip directions.

Geochemical observations

Aqueous speciation modelling was conducted for waters from numerous wells in the Maynardville Limestone (Shevenell, 1994) using SOLMINEQ (Kharaka et al, 1988), and the results of these simulations are summarized here. Twenty-five wells for which there were at least two available chemical analyses with charge balances less than 5% were selected (Table 2). The SI columns in Table 2 summarize the saturation indices for calcite and dolomite, with '+'indicating supersaturation, '-' indicating undersaturation, 'sat' indicating saturation, and '+,-' indicating that the saturation indices have varied between super- and under saturation between sampling events. The saturation indices (SI) are calculated to

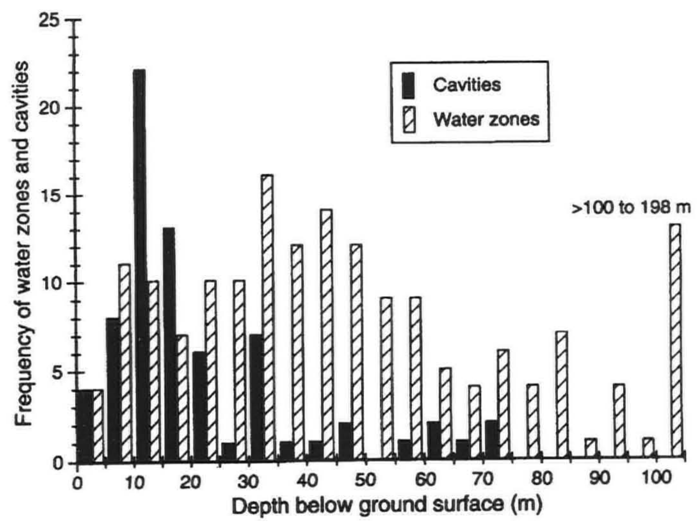

Figure 10. Frequency of water zones in the Maynardville Limestone for wells drilled to depths >30m.

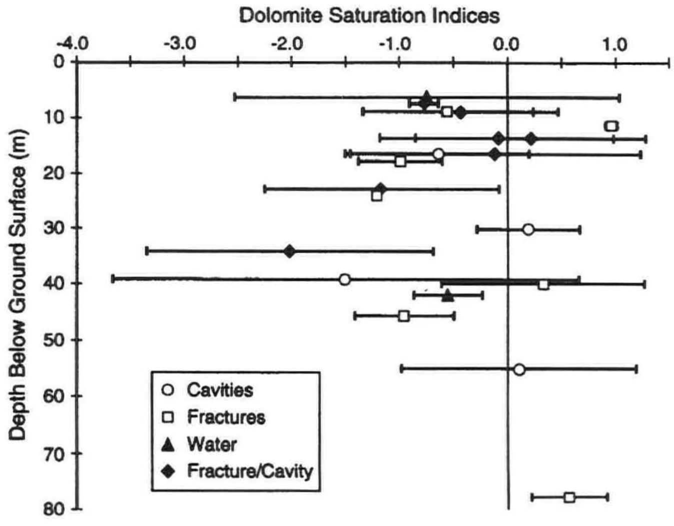

Figure 11. Dolomite saturation indices as a function of depth and water zone type.

determine which well waters are undersaturated with respect to calcite and dolomite, and hence may be actively enlarging karst dissolution features. Note, data for calculated dolomite equilibrium constants in SOLMINEQ were substituted with values for dolomite from Langmuir (1971). Consistent undersaturation with respect to calcite is suggestive of relatively young, quick flowing water because only a few days are typically required to reach calcite saturation. SI of anhydrite and gypsum are also included to determine which waters are undersaturated with respect to these minerals, and hence, may be actively dissolving to form microporosity.

In some wells, it is unknown which type of water zone occurs in the completion interval (e.g. GW-151) because no notations were made on the drilling logs. It is possible to ascertain the type of water zone in some cases in which hydrograph data are available in the individual wells. Wells in which hydrograph recession curves had two or three distinct slopes are suggestive of drainage from fractures and conduits (Shevenell, 1996), and these wells are identified in Table 2 with "f/c". The dolomite SI (and their standard deviations) are plotted on Figure 11 by depth and water zone type occurring in the completion interval. Most fractures and cavities show a wide range in SI values from super- to under-saturation (for both calcite and dolomite) indicating active dissolution is possible during at least some time periods, probably during periods of active flushing of conduits and fractures during precipitation events. The data points on Figure 11 with relatively small ranges in SI values have only two or three analyses available from which to calculate the standard deviation. Very shallow water zones (e.g. GW-278) in the most active part of the flow system also show a wide range in SI dolomite (and calcite; Table 2). The deepest well depicted on Figure 11 (GW-704, 78m) shows consistent supersaturation with respect to dolomite and calcite, indicating that less active dissolution may be occurring at greater depths than occurs in the more active, shallow (<35m) flow system, where conduit development is much more prevalent. Table 2 also lists two wells for which only one analysis is available for each of the packed off, multiport monitoring ports. Both wells monitor zones deeper than 222m and show slightly increasing dolomite and calcite SIs with depth, and decreasing anhydrite and gypsum SIs.

Table 2 also lists anhydrite and gypsum saturation indices. Microporosity development is controlled by de-dolomitization and dissolution of evaporite minerals (i.e. anhydrite and gypsum) based on lithological and petrographical observations. Geochemical modelling shows that evaporite dissolution is likely to be active in the matrix intervals at all depths, although waters at depth are somewhat less undersaturated with respect to these minerals than are the shallower waters in the more active flow system. Where there are multiple analyses, the standard deviations are quite small for anhydrite and gypsum in comparison to those for calcite and dolomite at the shallower depths, indicating that the saturation state with respect to anhydrite and gypsum does not vary appreciably through time. Relatively constant dissolution of these minerals in matrix intervals at all depths is likely, whereas periodic dissolution of calcite and dolomite occurs at shallow depths. The results of the geochemical modelling are consistent with the observations made related to micro- and macroporosity development with depth and lithology.

CONCLUSIONS

Secondary microporosity is strongly dependent on lithology, yet is largely independent of depth (Goldstrand and Shevenell, 1997). In contrast, secondary macroporosity (cavities) is strongly depth dependent

Well	Depth (m)	Єmn Zone	Water Zone	Charge Balance		# anal	Calcite			Dolomite			Anhydrite		Gypsum	
				Min	Max		SI	Ave	Stdev	SI	Ave	Stdev	Ave	Stdev	Ave	Stdev
GW-151	3.6	2		-4.31	3.39	8	+,-	0.08	0.40	+,-	-0.03	0.90	-2.66	0.03	-2.29	0.02
GW-152	5.3	2		-1.79	-1.75	2	+	0.78	0.00	+	1.28	0.01	-3.12	0.23	-2.74	0.22
GW-278	6.4	2	w	-3.61	-0.40	4	+,-	0.00	0.89	+,-	-0.76	1.78	-2.62	0.09	-2.27	0.07
GW-057	7.6	6	f/c	-3.30	2.08	2	-	-0.16	0.06	-	-0.77	0.13	-2.33	0.06	-1.95	0.04
GW-240	9.0	6	f	-3.38	1.21	7	+,-	-0.21	0.39	+,-	-0.55	0.79	-2.84	0.20	-2.48	0.19
GW-167	9.2	4	f/c	-0.97	1.38	2	+,-	0.29	0.44	+,-	-0.44	0.90	-3.06	0.58	-2.83	0.82
GW-309	11.6	2	f	-0.98	-0.89	3	-	-0.14	0.02	-	0.95	0.05	-1.54	0.15	-1.15	0.14
GW-058	13.8	6	f/c	-3.57	1.60	4	+,-	0.04	0.52	+,-	-0.11	1.08	-2.47	0.06	2.10	0.05
GW-220	13.8	2	f/c	-4.33	1.88	4	+,-	0.20	0.52	+,-	0.21	1.06	-2.73	0.06	-2.38	0.06
GW-226	16.8	2	c	-4.66	3.99	6	+,-	-0.06	0.44	+,-	-0.64	0.85	-2.20	0.08	-1.88	0.20
GW-056	16.8	6	f/c	-4.65	4.14	6	+,-	0.18	0.66	+,-	-0.12	1.35	-2.53	0.15	-2.15	0.15
GW-306	17.8	2	f	-1.39	4.56	4	+,-	-0.18	0.19	-	-0.99	0.39	-2.25	0.16	-1.88	0.17
GW-153	18.3	6		-4.61	1.55	12	+,-	0.12	0.40	+,-	0.17	0.81	-2.38	1.85	-2.58	0.09
GW-603	22.9	6	f/c	-3.28	4.72	6	+,-	-0.38	0.52	-	-1.17	1.09	-2.89	0.54	-2.58	0.72
GW-316	24.4	6	f	3.96	4.98	2	-	0.56	0.02	-	-1.21	0.02	-3.24	0.10	-2.87	0.10
GW-223	27.6	2		-3.75	2.90	5	+,-	-0.04	0.36	+,-	-0.64	0.69	-2.19	0.07	-1.84	0.08
GW-228	30.5	6	c	-4.32	1.31	2	+,-	0.15	0.29	+,-	0.18	0.47	-2.05	0.17	-1.65	0.16
GW-604	34.3	6	f/c	-4.43	4.35	4	-	-0.89	0.60	-	-2.03	1.33	-3.56	0.59	-3.29	0.81
GW-684	39.5	6	c	1.78	4.92	3	+,-	-0.63	1.02	+,-	-1.52	2.16	-2.81	0.26	-2.42	0.26
GW-317	40.2	6	f	-1.98	4.47	4	+,-	0.19	0.51	+,-	0.31	0.93	-3.24	0.21	-2.88	0.19
GW-685	42.2	6	w	-1.50	4.34	4	-	-0.15	0.15	-	-0.56	0.31	-2.52	0.03	-2.16	0.03
GW-365	45.7	2	f	-2.77	-1.09	3	+,-	-0.26	0.24	-	-0.97	0.46	-2.01	0.05	-1.63	0.05
GW-703	55.5	5	c	-2.15	3.50	3	+,-	-0.01	0.57	+,-	0.09	1.08	-2.96	0.08	-2.58	0.08
GW-704	78.0	4	f	-4.08	-4.96	3	+	0.28	0.17	+	0.54	0.35	-2.75	0.09	-2.37	0.09
Variations with depth for two wells with one analysis at each depth.																
GW-131-12	239.5	4/5	f?		-2.21	1	sat	-0.04		sat	-0.03		-2.25		-1.93	
GW-131-08	279.4	3/4	f?		-8.77	1	+	0.08		+	0.19		-2.15		-1.81	
GW-131-04	306.6	2	f?		-4.53	1	+	0.31		+	0.71		-1.92		-1.62	
GW-131-01	328.5	2	w		-2.83	1	+	0.24		+	0.50		-1.67		-1.34	
GW-135-19	222.9	6	w		-3.45	1	+	0.38		+	0.72		-2.71		-2.36	
GW-135-11	294.2	3	f		-6.94	1	+	0.43		+	0.64		-0.77		-0.46	
GW-135-06	348.2	2	f		-5.79	1	+	0.45		+	0.67		-0.45		-0.12	

Note: Water zones are identified as follows: w = slow flow matrix water, f = fractures, c = cavities.
'+' indicates supersaturation, '-' indicates undersaturation, 'sat' indicates saturation, and '+-' indicates that the saturation indices have varied between super- and under-saturation.

Table 2. Summary of saturation indices for filtered water samples collected in the karst Maynardville Limestone.

and lithologically independent. Pre-existing fractures and bedding planes are more important in macroporosity development at the shallow depths than they are in microporosity development at any depth. The reason for the contrast in depth and lithological dependencies between micro- and macroporosity can largely be attributed to the very active flow of groundwater through cavities and fractures at shallow depths in contrast to the more restricted flow in the matrix intervals at both the shallow and deeper levels. The processes controlling these differences relate to different geochemical reactions occurring between the two regimes, with calcite and dolomite dissolution being important in cavity formation, and gypsum and anhydrite dissolution being important in microporosity development.

In the Maynardville Limestone, several important factors control the development of microporosity and cavity formation: 1) lithological controls of secondary microporosity, 2) depth below the ground surface related to the active groundwater system that influences cavity development, for macro-porosity, and 3) structural controls (dissolutional enlarged fractures and faults). Core data from the Bear Creek Valley indicate that porosities in the Maynardville Limestone are lithologically (microporosity) and depth (macroporosity) dependent. Two interrelated diagenetic processes are the major controlling factors on microporosity development in the Maynardville Limestone: dissolution of evaporite minerals and de-dolomitization. Both these diagenetic processes produce mean matrix porosities of 1.3 % in the dolomitic upper part of the Maynardville Limestone to depths of approximately 180m bgs (Goldstrand, 1995). The microporosity formed by de-dolomitization may also explain the decrease in porosity stratigraphically lower in the Maynardville Limestone. The upper part of the Maynardville Limestone (zone 6) has the highest porosities and consists mostly of dolostone and dolomitic limestone, whereas the middle and lower parts of the formation (zone 5 through 2) are mostly limestone. Dissolution of gypsum and anhydrite nodules is responsible for the development of vuggy porosity within the upper part of the Maynardville Limestone (up to 10.3%). De-dolomitization (replacement of dolomite by calcite) is chemically related to the dissolution of gypsum within the Maynardville Limestone and Copper Ridge Dolomite (Saunders and Toran 1994; Goldstrand, 1995) and is an important factor in microporosity development in the dolomitic parts of these formations. Carbonate mud dissolution in the thrombolitic limestone facies, abundant in the lower Maynardville Limestone is also an important process forming secondary porosity. De-dolomitization within the stromatolitic dolomite facies has produced the highest microporosities within the Maynardville Limestone.

Mean matrix porosities in zones 5 to 2 of the Maynardville Limestone range from 0.8 to 0.5% (Goldstrand, 1995). Although, moldic porosity related to de-dolomitization is locally common (e.g. dolomitized ooids in zone 5), much of the porosity is related to dissolution of carbonate mud interbeds. Dissolution of intra-algal carbonate mud lithologies produces thin, elongate dissolution zones or fenestral porosity. Oxidation of pyrite also produces moldic porosity, but is only of minor importance in parts of zone 2 located above approximately 35m bgs.

A large number of cavities have been intersected at the shallower depths during drilling activities in nearly all zones of the Maynardville Limestone in the Bear Creek Valley (Shevenell et al, 1992). Therefore, any of the Maynardville Limestone zones within approximately 35m of the ground surface are likely to contain cavities that allow rapid groundwater flow and contaminant transport (Goldstrand and Shevenell, 1997). Zone 6 could be an important stratigraphical unit in the Maynardville Limestone for groundwater flow and contaminant transport because of the abundance of vuggy and moldic porosities. There are large variations in the thickness and lithology in the lower part of the Maynardville Limestone (zones 2, 3 and 4 in the Burial Grounds region). The direction and velocity of strike-parallel groundwater flow may be altered in this area within the lower Maynardville Limestone. The cross borehole testing and hydrograph analyses were useful in identifying general trends in the locations and directions in which quick flow may be more dominant. Quick flow is common at shallow depths (<35m) in all directions, and this supports the observations of cavity occurrence during drilling, and lithological observations in core. These both indicate significant secondary porosity and cavity development at shallow depths, with significantly fewer karst features at increasing depths.

Rapid fluid velocities can also be expected in various directions along the plane of dip in all lithologies and at various angles to strike. Hence, in any hydrological modelling of this aquifer, considerably higher hydraulic conductivities should be assigned to the shallow (<35m) depths when modelling a large-scale problem. Models should also account for the higher hydraulic conductivities expected in along strike and dip directions.

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RESEARCH FUNDS AND GRANTS

THE BCRA RESEARCH FUND

The British Cave Research Association has established the BCRA Research Fund to promote research into all aspects of speleology in Britain and abroad. Initially, a total of £500 per year will be made available. The aims of the scheme are primarily:

a) To assist in the purchase of consumable items such as water-tracing dyes, sample holders or chemical reagents without which it would be impossible to carry out or complete a research project.
b) To provide funds for travel in association with fieldwork or to visit laboratories which could provide essential facilities.
c) To provide financial support for the preparation of scientific reports. This could cover, for example, the costs of photographic processing, cartographic materials or computing time.
d) To stimulate new research which the BCRA Research Committee considers could contribute significantly to emerging areas of speleology.

The award scheme will not support the salaries of the research worker(s) or assistants, attendance at conferences in Britain or abroad, nor the purchase of personal caving clothing, equipment or vehicles. The applicant must be the principal investigator, and must be a member of the BCRA in order to qualify. Grants may be made to individuals or groups (including BCRA Special Interest Groups), who need not be employed in universities or research establishments. Information about the Fund and application forms Research Awards are available from The BCRA Administrator (address at foot of page).

GHAR PARAU FOUNDATION EXPEDITION AWARDS

An award, or awards, with a minimum of around £1000 available annually, to overseas caving expeditions originating from within the United Kingdom. Grants are normally given to those expeditions with an emphasis on a scientific approach and/or exploration in remote or little known areas. Application forms are available from the GPF Secretary, David Judson, Hurst Farm Barn, Cutler's Lane, Castlemorton Common, Malvern, Worcs., WR13 6LF. Closing date 1st February.

THE E.K.TRATMAN AWARD

An annual award, currently £50, made for the most stimulating contribution towards speleological literature published within the United Kingdom during the past 12 months. Suggestions are always welcome to members of the GPF Awards Committee, or its Secretary, David Judson, not later than 1st February each year.

BRITISH CAVE RESEARCH ASSOCIATION PUBLICATIONS

CAVE & KARST SCIENCE - published three times annually, a scientific journal comprising original research papers, reviews and discussion forum, on all aspects of speleological investigation, geology and geomorphology related to karst and caves, archaeology, biospeleology, exploration and expedition reports.
Editors: Dr. D.J. Lowe, c/o British Geological Survey, Keyworth, Notts., NG12 5GG and Professor J. Gunn, Limestone Research Group, Dept. of Geographical and Environmental Sciences, University of Huddersfield, Huddersfield HD1 3DH.

CAVES AND CAVING - quarterly news magazine of current events in caving, with brief reports or latest explorations and expeditions, news of new techniques and equipment, Association personalia etc.
Editor: Hugh St Lawrence, 5 Mayfield Rd., Bentham, Lancaster, LA2 7LP.

CAVE STUDIES SERIES - occasional series of booklets on various speleological or karst subjects.
No. 1 *Caves & Karst of the Yorkshire Dales;* by Tony Waltham and Martin Davies, 1987. Reprinted 1991.
No. 2 *An Introduction to Cave Surveying;* by Bryan Ellis, 1988. Reprinted 1993.
No. 3 *Caves & Karst of the Peak District*; by Trevor Ford and John Gunn, 1990. Reprinted with corrections 1992.
No. 4 *An Introduction to Cave Photography;* by Sheena Stoddard, 1994.
No. 5 *An Introduction to British Limestone Karst Environments;* edited by John Gunn, 1994.
No. 6 *A Dictionary of Karst and Caves*; compiled by Dave Lowe and Tony Waltham, 1995.

SPELEOHISTORY SERIES - an occasional series.
No. 1 The Ease Gill System-Forty Years of Exploration; by Jim Eyre, 1989.

CURRENT TITLES IN SPELEOLOGY - from 1994 this publication has been incorporated into the international journal Bulletin Bibliographique Speleologique/Speleological Abstracts; copies of which are available through BCRA.

BCRA SPECIAL INTEREST GROUPS

SPECIAL INTEREST GROUPS are organised groups within the BCRA that issue their own publications and hold symposia, field meetings etc.
Cave Radio and Electronics Group promotes the theoretical and practical study of cave radio and the uses of electronics in cave-related projects. The Group publishes a quarterly *technical journal* (c.32pp A4) and organises twice-yearly field meetings. Occasional publications include the *Bibliography of Underground Communications* (2nd edition, 36pp A4).

Explosives Users' Group provides information to cavers using explosives for cave exploration and rescue, and liaises with relevant authorities. The Group produces a regular newsletter and organises field meetings. Occasional publications include a *Bibliography* and *Guide to Regulations* etc.

Hydrology Group organises meetings around the country for the demonstration and discussion of water-tracing techniques, and organises programmes of tracer insertion, sampling, monitoring and so on. The group publishes an occasional newsletter.

Underground Photographer Magazine. This magazine was first published in December 1995, 48pp A4 with black and white photos. Subsequent editions have colour photos and articles on cave photography topics.

Speleohistory Group publishes an occasional newsletter on matters related to historical records of caves; documentary, photographic, biographical and so on.

Cave Surveying Group is a forum for discussion of matters relating to cave surveying, including methods of data recording, data processing, survey standards, instruments, archiving policy etc. The Group publishes a quarterly newsletter, Compass Points (c.16pp A4), and organises seminars and field meetings.

Copies of publications, information about Special Interest Groups, the BCRA Research Fund application forms, etc. are obtainable from the BCRA Administrator: B M Ellis, 20 Woodland Avenue, Westonzoyland, Bridgwater, Somerset, TA7 OLQ.