Cave and Karst Science

The Transactions of the British Cave Research Association

BCRA

Volume 33 Number 3 For 2006

Collapse doline sediments, Dinaric Karst, Slovenia
Karst aquifer water chemistry, Zagros, Iran
Palmer's Chamber, Lamb Leer, UK
Grotta Del Cane, Naples, Italy
Poldi Fuhrich, 1898–1926
Forum

Cave and Karst Science - Notes for Contributors

Scope of articles

Authors are encouraged to submit articles for publication in *Cave and Karst Science* – the *Transactions of the British Cave Research Association* – under four broad headings...

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

Reports: Shorter contributions, normally 500–3,000 words, on aspects of karst or speleological science, as listed above, or more descriptive material, such as caving expedition reports and technical articles. The Editorial Board will review manuscripts unless the subject matter is outside their fields of expertise, in which case assessment by an appropriate expert will be sought.

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

Abstracts: Authors (or supervisors) of undergraduate or postgraduate dissertations on cave or karst themes are encouraged 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 are also welcome.

Prospective authors are welcome to contact the Editors (see Contents page for addresses), who will be pleased to advise on manuscript preparation.

The following notes are intended to help authors prepare their material in the most advantageous way. Time and effort are saved if the guidelines below are followed. Queries regarding the content or format of the material should be made before submitting the manuscript. On publication, authors will be provided with 20 reprints of their contribution, free of charge, for their own use.

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Abstract: Material should be accompanied by an abstract, stating the essential results of the investigation or the significance of the contribution, for use by abstracting, library and other services.

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Acknowledgements: Any person or organization that has given a grant or helped with the investigation or with preparation of the article should be acknowledged. Contributors in universities and other institutions are reminded that grants towards publication costs may be available, and that they should make related enquiries as early as possible. Some expedition budgets include an element to help publication, and the editors should be informed of this.

Speleological expeditions have a moral obligation to produce reports (contractual in the case of Ghar Parau Foundation awards). 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, preferably as appendices.

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Layout: Although material should be compatible with *Cave and Karst Science* 'house style' regarding headings, etc., do not attempt to match the layout. Text should remain in a single column with 'double-spaced' paragraph style. Character formatting (bold, italic, sub- and superscript) can be used, but please do not apply paragraph formatting, which will be stripped out during DTP.

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Tables, graphics and photos: Tables and diagrams should be referred to in the text, where necessary, as (Table 4), (Fig.3), etc. Photographs are welcomed, but should **not** be referred to in the text, except where essential and then only with the approval of the editors. Preferred approximate positions of tables, graphics and photos can be indicated by, e.g., <Insert Photo B>, or a pencilled note in the margin of paper manuscripts. A full list of captions should be submitted at the end of the manuscript, after a hard page break (or on a separate sheet of paper). Photo captions should include the photographer's name. Any material not created by the author(s) must acknowledge that permission is granted for its use.

Tables should be submitted in a separate file; numbered in sequence and provided with captions. Please use a simple format that is easy to edit. For example, use tabs or table cells rather than spaces to separate data, and do not merge table cells unless strictly necessary. Separate each table using a hard page break (or submit each table on a separate sheet of paper).

Graphical illustrations should be designed to make maximum use of page space. Maps must have bar scales only. Graphics should not use any colour. When submitting graphics, please bear in mind that the referees may request changes, so submission of a paper draft is advised. Various **Digital Graphics** formats are acceptable, but some are not recommended – e.g. MS Word's built-in facilities (autoshapes, text boxes and MS Draw) can cause problems. Vector formats are preferred but if a bit-mapped format is used it should have a resolution of at least 600 dpi (preferable 1200 dpi). Do **not** use a 'hairline' line-width, as this generally reproduces at a printer-default of one pixel, which is too narrow. The minimum line width should be at least 0.5pt (0.007″, 0.2mm, 4 pixels @ 600dpi) at final size. Type generally should not exceed 10pt nor be smaller than 6pt in the final version; 8pt type is preferred. **Paper Graphics** are acceptable, but they must be produced using opaque black ink (not pencil!) on high-quality material (cartridge paper, tracing paper, Kodatrace, etc.). If photo-reduction is contemplated, all letters and lines must be large and thick enough to allow for their reduction. Unless CAD-generated, lettering should be done by stencil, Letraset or similar methods, not hand-written.

Photographs should be in sharp focus and of good contrast. Prints (e.g. 150 × 100mm) and 35mm transparencies are acceptable. Digital photos must be of appropriate resolution – at least 300 dpi at final print size. They should not be edited before submission, as any necessary contrast adjustment and sharpening will be applied to suit the printing process, and this cannot be done if the photo is pre-adjusted). Preferred formats are LZW-compressed TIF, or JPG with minimal compression. Highly compressed JPGs may not be usable.

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Cover photo:

Velika dolina and Mala dolina (meaning great doline and small doline) create the classic view of the entrance of Škocjanske jame (the Škocjan caves) in Slovenia. They are large collapse features that perhaps should now be known as tiankengs. The main sink of the Reka river is away in the right distance, and the river re-emerges from the tall cave passage almost below the village church, before crossing both doline floors and finally flowing into the huge river passage in the main Škocjan cave, which lies almost beneath the camera. The pointed mountain in the far distance is Snežnik (1796m), the highest point in the Dinaric Karst of Slovenia. Papers by Trevor Shaw and Uroš Stepišnik in this Issue include information about the early exploration and survey of the Škocjan caves and dolines, and about investigations of other collapse dolines in the Dinaric Karst.

Photograph by Tony Waltham

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EDITORIAL

John Gunn and David Lowe

Here we are at the final Issue of Volume 33 of *Cave and Karst Science*, and perhaps predictably we are still one year behind the publication schedule.

To be honest, we are fed up of making excuses, but let's say simply that the principal reason remains the same. We can only produce a publication if and when we have suitable material to publish. That sounds so simple and yet, for reasons we do not understand, we have found it totally impossible to claw back slippage that began a long time ago, for reasons that we do understand and hence will not exhume here.

So what is going wrong? Is there a problem with cave and karst research in general?

Superficially the health of cave and karst science has never been better. Don't take our word for it but look first at the web sites for *Speleogenesis…*, *International Journal of Speleology*, *Journal of Cave and Karst Studies*, *Acta Carsologica* and half a dozen other top flight international publications, whose contents and abstracts we publish in *Forum* when space permits. If you don't do web sites, we don't mind – look at the hard copies instead. The story is the same. Moving from periodicals to recent text books, we need only say (alphabetically), Ford and Williams (*Karst Hydrogeology and Geomorphology*, Second Edition, 2007), Klimchouk (*Hypogene Speleogenesis: Hydrogeological and Morphogenetic Perspective*, 2007), Palmer (*Cave Geology*, 2007), Proudlove (*Subterranean Fishes of the World*, 2006). Cave and karst science in all its facets appears to be alive and well. The totality of the length, breadth, depth and quality of today's science is unquestionable. We have both quantity and quality, and both quantity and quality are currently expanding. But, sadly, at least from our point of view, despite various exceptions, cave and karst research in Britain appears to be in a far less healthy state and much of the expansion in knowledge is taking place elsewhere.

The problem is exacerbated by the fact that many professional researchers, and particularly those based in British universities, who might once have seen it as important to support the BCRA by publishing in *Cave and Karst Science,* are now driven by career-related factors to publish their results and ideas in higher-profile, commonly topic-specific, and generally big-budget journals that are listed on the all important 'Science Citation Index'. This means that articles of karst science significance are targeted instead upon journals dealing more generally with, for example, geomorphology, engineering geology, geochemistry or hydrogeology. We are not occupying self-righteous high ground when reporting this issue, as we too have been forced along the same road – it is quite simply unavoidable. An obvious related issue is that of time. Once forced onto the treadmill of publishing in the major international science journals, finding the time and energy to trickle occasional crumbs towards *Cave and Karst Science,* even when one has the best of intentions, isn't always practicable. Add to this the workload of editing the material, as we do, or acting as unpaid referees as many others do (see below), and the whole question of how to ensure input from professional researchers becomes still more difficult to answer. Nevertheless we will continue to seek the support of these researchers as best we can, in whatever ways they can.

Yet again we must reemphasise that one of our main planks in trying to take British cave and karst science forward has always been to encourage contributions from amateur researchers, of whom there are still many, and from those that we might describe as either pre-professional or post professional – i.e. from the ranks of the student and retired populations. We know that there are many out there who will never need to trundle the academic treadmill, those who perhaps will, one day, but have not yet felt the pointed stick, and those who, thankfully, have left the scourge of the treadmill behind. All of these individuals, groups and partnerships have observations, ideas and all manner of information that is of wide interest to the cave and karst world in general, but might never make it into an international journal or might be banished to obscurity in an ephemeral club publication. Each type of potential contributor represents fertile ground for a different reason, whether this is not being ready or confident to face the rigours of "big journal" publishing, feeling that their ideas deserve a wider audience than just their club mates, or thinking "I always intended to develop and write up that idea but never had time – until now."

Well – the offer remains. We will gladly do whatever we can to guide new (or rusty) authors through the publication process, whether the outcome be a fully refereed Paper, a less rigorously reviewed Report, or simply a Scientific Note or item of Correspondence in the *Cave and Karst Science Forum.* The corollary is, of course that we will not publish material that is either unfit, unsuitable or not yet ready, but we will provide sensible reasons why, and helpful suggestions about how to move things forward. A final rider is that we like to include a mix of material from as large a pool of authors as possible, but we do not turn things down simply on the basis that a productive author might submit material on a regular basis.

Moving on, BCRA is close to sorting out a variety of issues relating to membership costs and options, non-member subscriptions to *Cave and Karst Science*, and the future development of the journal itself. Authoritative details of costs and procedures will be circulated to all available addresses in the very near future. The next few issues of the journal will see a metamorphosis that will include continued availability in printed form with colour printing an available option for at least some of the inside pages as well as the covers. Necessarily though the subscription costs will rise to a realistic level to help cover the additional costs of colour printing and the reduced cost efficiency of printing smaller numbers to meet a reduced demand. For those who prefer it, or those who consider the new cover price of the printed journal too steep, a web-based option will also be phased in. To mitigate the possibility of confusion we will not attempt to provide fuller details here, but reiterate that they will be provided if not with this issue, then very soon.

Which brings us to the closing comments on Volume 33, which has gestated painfully slowly and yet has included a fascinating cross section of contributions, whose authors are thanked first for their submissions but then for both their faith and their patience. As usual we thank also the many referees who have worked hard and conscientiously to help maintain the quality and integrity of *Cave and Karst Science*. Of course we contribute to the review process ourselves, but our expertise and time only stretch so far, and we could not succeed without the help of our flexible Editorial Board, some of whom will referee several papers during the history of each Volume. This year we thank: Simon Bottrell, Anthony Day, Andrew Chamberlain, John Cordingley, Steve Craven, Jaimie Dick, Ian Fairchild, Derek Ford, Stephan Kempe, Jiri Krasny, Harry Long, Art Palmer, Graham Proudlove, Trevor Shaw, Tony Waltham, Robin Westerman, John Wilcock, Paul Wood, Chas Yonge and Paul Younger. Tony Waltham is also thanked for repeatedly coming to our rescue by providing selections of potential cover images, to make up for a surprising lack of suitable material among the articles we have published. Since our acknowledgements at the end of Volume 32, Rebecca Talbot has become Rebecca Bedson, and we both congratulate her and thank her for her continued DTP efforts to turn the mixed bag of material that we pass to her into formatted articles for publication. Last but by no means least we again thank Steve Summers and the staff of the Sherwood Press Group for their ongoing help and support in producing a high-quality printed product of which, we believe, they and the BCRA can be justifiably proud.

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The search for Palmer's Chamber, Lamb Leer, Somerset, United Kingdom.

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Key Words: Mendips, cave detection, geophysics, resistivity, microgravity.

Abstract: During the late 1930s and 1950s a series of geophysical resistivity measurements were acquired by Professor Leo Palmer of Hull University over the Lamb Leer cave system (referred to as Lamb Lair by Palmer), which is located within the Mendip Hills, Somerset. Through his surveys, Professor Palmer reportedly delineated a resistive zone that he believed to correspond to the location of the Great Chamber of Lamb Leer, a 30m-diameter cavity located at 35m below ground level. Additionally, he concluded that a further large cavern of similar size existed some 100m northeast of the Great Chamber. In an attempt to confirm the existence and establish the nature of "Palmer's Chamber", a series of resistivity and microgravity profiles were carried out during the summers of 2004 and 2006. The resistivity survey confirmed the presence of a resistive anomaly within the vicinity of "Palmer's Chamber"; however the resulting microgravity data do not suggest the presence of a mass deficiency feature that would be expected over a significant void.

(Received 26 April 07; accepted 29 May 07)

Plate 1: Professor Palmer (centre) and survey team with Geophysical Megger Earth Tester, August 1957 (courtesy of the MNRC). Roughly 45 years after this photo was taken a mineshaft (now know as Gibbets Brow) opened up almost directly below where Palmer stood.

BACKGROUND

Lamb Leer Cavern is located near the northerly edge of the Mendip limestone plateau, 2km south of Compton Martin, Somerset, and has intrigued both cave explorers and historians for the last three centuries. The cave was discovered just before 1676, when lead miners sinking a shaft in "the hill called Lamb" broke into a natural passageway and discovered "a very great vault" (Beaumont 1681). This "vault" is the main chamber of the cave (known as the Great Chamber) and with the floor of the cavern located at 60m below the surface, when first discovered it seems likely to be the deepest exploration of a cave anywhere in the world (Shaw, 1962). Lamb Leer was subsequently closed by the Landowner in 1982.

Before its closure, the cave was accessed via a 20m mined shaft that connects to a natural passage that slopes down towards the north. After 100m the passage passes through the "Beehive Chamber", a well-decorated chamber containing a large stalagmite boss, and ends with a 20m drop into the eastern side of the Great Chamber (also referred to as the main chamber). The Great Chamber is roughly 30m in diameter, and from here passages lead off west for about 60m to the Cave of the Falling Waters, and north into a complex of small phreatic tubes with some large rifts known as the St Valentine's Series (Irwin and Jarret 1999; Waltham *et al*. 1997).

The cave is developed in a fine-grained, chinastone, facies of the Clifton Down Limestone, dipping 15° east, and is transected by the west–east orientated Lamb Leer Fault, located towards the northern wall of the Great Chamber. This is an almost vertical fault zone of approximately 20m width with a downthrow of 60m to the south. However, apparent subhorizontal slickensides on the vertical plane in the roof of the Great Chamber suggest an additional horizontal displacement of unknown length (Stanton, 1966).

In 1938, Professor Lionel Palmer, the first Professor of Physics at Hull University, undertook a series of resistivity surveys over the area of Lamb Leer. This was one of the earliest attempts to locate caves using geophysical methods, and one of the first of a series of geophysical surveys undertaken by Palmer. The survey was carried out using a recently acquired Geophysical Megger Earth Tester manufactured by "Messrs. Evershed and Vignoles", purchased through a grant of £250 provided by the Royal Society. Palmer's surveys in 1938 identified an anomaly over the area of the Great Chamber and a second anomaly to the northwest which he interpreted as an "unknown chamber". This was subsequently referred to as "Palmer's Chamber". Unfortunately, shortly after identifying this "unknown chamber", the resistivity apparatus had to be returned to "Messrs. Evershed and Vignoles" for repair, and the survey was abandoned.

It was not until August 1957 that Palmer returned to Lamb Leer to characterize the "unknown chamber" with the same (although partially redesigned) resistivity apparatus. This time he enlisted the help of a local caving club (the Mendip Nature Research Committee) and Frome Grammar School. Together they undertook five full days of work comprising 35 geoelectrical traverses (constant depth) and 40 different depth soundings comprising 11 readings at each station. Through these surveys, Palmer concluded that, *"...a large chamber undoubtedly exists ...* [which is] *... nearer the surface than the main chamber of Lamb Lair ...* [and] *... it is probable that this new chamber is not smaller than Lamb Lair ...* [referring to the Great Chamber] *... and may well be considerably larger."* (Palmer,1958).

These results and interpretations provided a driving force behind the continual exploration of the cavern by most of the main caving clubs on Mendip, all keen to discover the route through to "Palmer's Chamber". To date this quest has never been realized and, with the closure of Lamb Leer in 1982, the search for "Palmer's Chamber" has all but ceased. The validity of Palmer's conclusions from

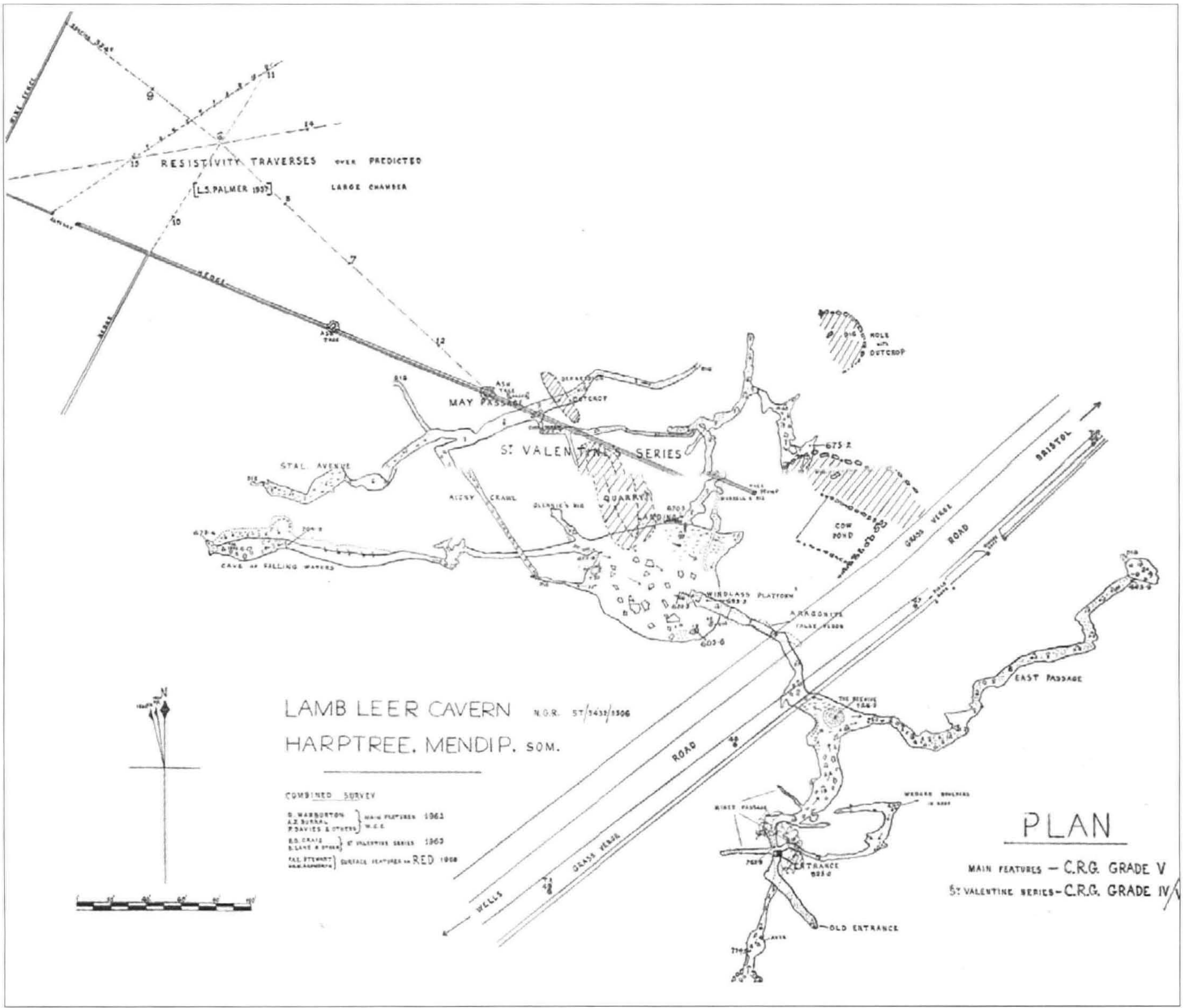

***Figure 1**: Survey of Lamb Leer Cavern showing the location of Palmers interpretations (courtesy of the MNRC). The Great Chamber is located to the north of the road, with "Palmer's Chamber" predicted to the north west of Lamb Leer*

resistivity surveys over Lamb Leer and at other sites in the Mendip Hills has been questioned by a number of workers (For example Mullen, 1992). Although the new chamber outlined by Palmer has never been found, he did outline a series of passageways up to 60m deep, just to the north of the Great Chamber. Subsequent exploration by cavers in this area has yielded a series of passageways known as the Valentine's Series at 40m depth.

GENERAL PRINCIPLES OF RESISTIVITY SURVEYING

The general underlying principles of geoelectrical (or resistivity) surveying remain the same as when Professor Palmer carried out his surveys and are best described in his own words:

> *"...an electrical current is sent into the earth through two electrodes C_1 and C_2 inserted into the surface to a depth of a few inches. The earth with the two current electrodes constitutes a form of a three-dimensional potentiometer over the surface of which is a potential 'pattern'. This pattern depends on the current distribution, which in turn depends on the variations of the electrical current throughout the half-space bounded by the earth's surface and extending downwards to infinity, the upper half-space being air of infinite resistivity."*
>
> *"The potential fall between any two points on the surface can be measured by the insertion of two additional probes or potential electrodes P_1 and P_2 at the points between which the potential is to be measured. The ratio of the measured potential difference to the current flowing is a function of some 'mean' and localised value of the earth's electrical resistivity."*
>
> *"This 'mean' value will depend on the variations of the electrical properties of those portions of the earth's crust through which the majority part of the current passes; whilst the electrode configuration on the surface will determine the location of the particular region" (Palmer 1959). Also known as the 'apparent resistivity', this 'mean' value can be equated to the actual resistivity of a zone only in the case of homogeneous isotropic ground."*

It is at this point that standard modern methods diverge from the techniques used during Palmer's era. Due to computational limitations during the 1950s, resistivity results could only be analysed through the plotting of the electrode distance against apparent resistivity. These graphs were then examined and compared with theoretical curves expected from different geological conditions, with anomalously high resistivity deflections from the background curve interpreted as relating to voids. The approximate depths to these anomalies were then determined by halving the distance between the current electrodes (Palmer, 1959). Unfortunately this technique is based upon the assumption that the subsurface is homogeneous and isotropic (i.e. uniform ground with no geological features except for the cave). In most cases the presence of faults or rockhead depressions invalidates this method of interpretation. These limitations were appreciated by Palmer who wrote in a similar survey at Pen Park Hole, "*...that the interpretation of complex variations is often extremely difficult unless* ... [the local geological structure] ... *can be recognised and its effect appreciated.*" (Palmer, 1959).

During the 1990s the method of geoelectrical surveying was revolutionised by the fundamental advance in computational power, which resulted in a significant improvement in both the acquisition and processing of resistivity data. Multi-electrode arrays could be deployed allowing larger datasets to be obtained in a fraction of the time, and the apparent resistivity dataset inverted to represent a true model of the subsurface resistivity. This inversion of the apparent resistivity dataset derives a 2-D model through dividing the subsurface into a number of rectangular blocks then determining the resistivity of each rectangular block producing an apparent resistivity pseudosection that agrees with the actual measurements, thus allowing complex geological structure to be appreciated.

RESURVEYING "PALMER'S CHAMBER"

Survey Design

During the summer of 2006, a series of resistivity profile lines was acquired using a 72-channel IRIS SYSCAL resistivity system over the known location of the Lamb Leer Main Chamber and within the area of "Palmer's Chamber". After an initial trial survey using different electrode arrays over the main chamber, it was decided to adopt a pole-dipole array using a 5m electrode spacing, as this appeared to provide the best compromise between depth of penetration and lateral resolution. Resistivity tomography allows the identification of air-filled voids through the electrical contrast between the relatively conductive limestone and the extremely resistive air-filled cave passage. Unfortunately, due to non-uniqueness of the resistivity survey technique, an anomalously high resistive zone does not necessarily indicate the presence of large voids, as it might also represent the presence of open fractures or more massive rock strata (McDonald and Davies, 2003).

As a result, the integration of microgravity data is essential in establishing whether anomalously high resistive zones are caused by fracture-free crystalline rock or air-filled voids. The microgravity technique is based on measuring localised variations in the Earth's gravitational field that are caused by subsurface materials of different densities. The presence of an anomalously low density body (such as an air-filled cavity) in the subsurface causes a localized low anomaly in the measured gravitational field. In order to determine the nature of the resistive zones, two microgravity profile lines were carried out and centred on both the Great chamber and "Palmer's Chamber" using a Scintrex CG3M microgravity instrument. Both the resistivity profile lines and gravity station elevations were surveyed and levelled using a Topcon total station.

Results

The results of the resistivity tomography and microgravity surveys are presented in Figures 2 and 3 as contoured scale sections of the subsurface representing changes in resistivity, and corresponding gravity profiles (Bouguer anomaly). The vertical and horizontal axes on the resistivity section respectively display elevation (m local datum) and chainage along each profile line. The resistivity contour scale used for these sections has been chosen to provide a contrast between anomalously high resistive zones and the relatively conductive limestone bedrock.

The resistivity and microgravity results shown in Figure 2 were centred over the known location of Lamb Leer's Great Chamber (130m-150m chainage), with the aim of calibrating and assisting in the interpretation of the results derived over "Palmer's Chamber".

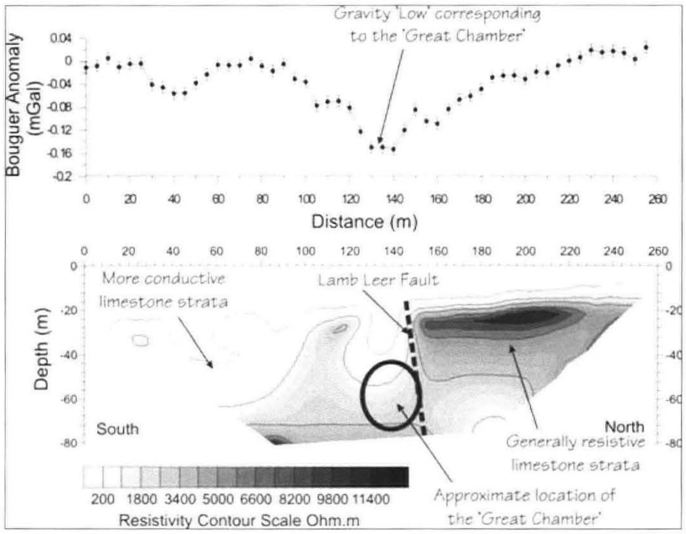

Figure 2: *Microgravity (above) and resistivity (below) surveys located over the Great Chamber of Lamb Leer.*

On inspection of the resistivity section, the principal feature appears to be a boundary between highly resistive limestone located to the north of the profile line, and relatively conductive material located to the south. This appears to be as a consequence of the Lamb Leer Fault (exposed in the Great Chamber) with the boundary at approximately 150m chainage representing the fault plane and the relatively conductive material to the south possibly associated with the zone of brecciation. The Great Chamber of the cave does not appear to be prominent in the resistivity section, and it is likely that an expression of the chamber has been either masked by the dominant influence of the fault or is beyond the detectability range of the survey. Considering the microgravity profile line, there appears to be a very significant gravity 'low' of around 150μGal over the location of the Great Chamber, which corresponds to the magnitude expected from a chamber of this depth and size.

Figure 3 shows both the resistivity and microgravity results of the profile lines positioned to target "Palmer's Chamber". The resistivity section displays similar characteristics to the resistivity section shown in Figure 2, and appears to show the continuation of the Lamb Leer Fault with highly resistive material to the north of the section and relatively conductive material to the south. The major

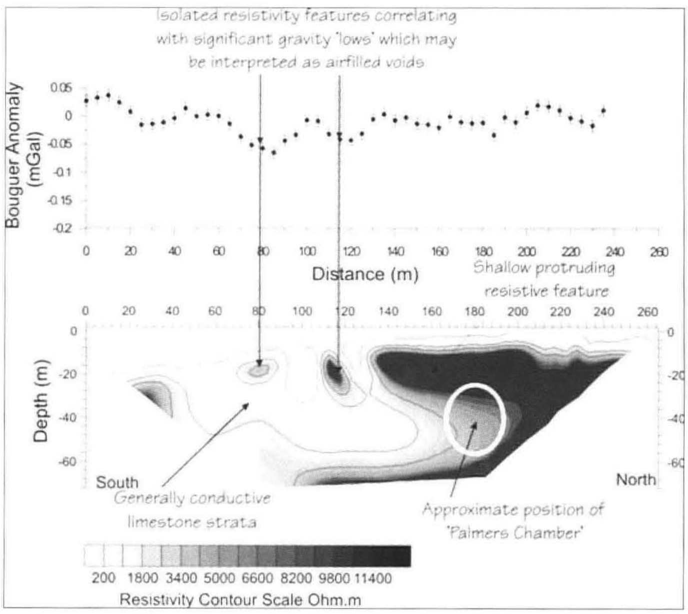

Figure 3: *Microgravity (above) and resistivity (below) surveys located over "Palmer's Chamber".*

difference between the two sections is the shallow resistive feature that protrudes, though appears to be separate from, the northerly resistive unit between 130m-205m chainage. This feature is in the approximate location of "Palmer's Chamber" and it is possible that it represents the feature mapped by Palmer. When considering the gravity profile line located over "Palmer's Chamber" (Figure 3) with respect to the gravity results derived over the Great Chamber (Figure 2), there does not appear to be a significant gravity 'low' over the location of this resistivity feature, suggesting that the anomaly does not represent a cavity as no mass deficiency is observed. Between 70m-90m and 110m-120m chainage two individual isolated resistive features are observed, both of which correlate with significant gravity 'lows'. Through modelling these features it can be shown that it is highly probable that these features represent unknown air-filled voids.

CONCLUSIONS

The very nature of a geophysical survey allows for a non-unique interpretation of results from a unique geological environment, and this is especially true when only a single geophysical technique is utilized. The ability to resolve subsurface features has been greatly improved by considering both gravity and resistivity techniques and measuring the two separate physical properties of the subsurface.

In order to address the question "*Does Palmer's Chamber exist?*", the resistivity surveys support the presence of a highly resistive zone at the location indicated by Professor Palmer, which in isolation would suggest that there is a chamber present. However, when considering the microgravity data the absence of a significant gravity 'low' similar to the 'low' observed over the Great Chamber would suggest that no significant chamber is present within the immediate location as described by Palmer. It therefore seems probable that the highly resistivity feature might correspond to an isolated section of the northerly highly resistive limestone unit, affected by the Lamb Leer Fault.

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REFERENCES

Beaumont, J. 1681. An account of Ookey hole and several other subterraneous grottoes and caverns in Somersetshire, etc. *Philosophical Collections of the Royal Society*, Vol.2, 1–8.

Irwin, D J and Jarrett, A. 1999. *Mendip Underground / A Cavers' Guide*. [Wells: Bat Products.]

McDonald, R and Davies, R. 2003. Integrated geophysical surveys applied to karstic studies. *First Break*, Vol.21, 32–35

Mullan, G. 1992. Resistivity Work, an Historical Perspective. *William Pengelly Cave Studies Trust Newsletter*, No.64, 1–2.

Palmer, L S. [September] 1938.*The detection of Caverns by earth-resistance measurements.* Report to the Royal Society.

Palmer, L S. 1958. Some results of a geoelectrical survey in the neighbourhood of Lamb Lair cavern. *Journal of the Wessex Cave Club,* 5, 67, 31–35.

Palmer, L S. 1959. Examples of geoelectrical surveys. *Proceedings of the Institution of Electrical Engineers*, Vol.106 (A), 27, 231–-243.

Palmer, L S. 1965. A Geoelectrical Survey in the Neighbourhood of Lamb Leer Cavern. *Mendip Nature Research Committee Journal,* Vol.I, 38–41.

Shaw, T R. 1962. Lamb Leer in the 17th Century. *Proceedings of the University of Bristol Spelaeological Society*, Vol.9, 183–187.

Stanton, W I. 1966. Basic geology of Lamb Leer Cavern. *Mendip Nature Research Committee Journal,* Vol.II, 79–80.

Waltham, A C, Simms, M J, Farrant, A R and Goldie, H S. 1997. Karst and Caves of Great Britain. Geological Conservation Review No.12. London: Chapman and Hall.]

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Loamy sediment fills in collapse dolines near the Ljubljanica River springs, Dinaric Karst, Slovenia.

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Abstract: Successful application of electrical resistivity imaging (ERI) techniques established that loamy sediment fills that floor collapse dolines in the hinterland of the Ljubljanica River springs near Vrhnika, Slovenia, locally reach more than 30m in thickness. Collapse doline development and transformation processes are discussed, and various characteristics and potential formational mechanisms of flat, loamy doline floors are considered. The loamy fills reflect sedimentation of suspended material from floodwaters that inundated the lower parts of the collapse dolines, whose flat floors lie at a consistent level as a result of water table oscillation related to the contemporary elevation of Ljubljansko barje at the karst system's outflow.

Key words: karst, collapse dolines, slopes, sediments, electrical resistivity imaging, ERI.

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INTRODUCTION

The Slovenian karst includes at least 330 major collapse dolines with volumes ranging from $0.03Mm^3$ up to $12.6Mm^3$. The larger collapse dolines are more common in areas of karst through flow, mainly in the hinterland of the larger ponors and in the catchments of major karst springs. On the Karst plateau collapse dolines are more common in the hinterland of the ponors of the Matarsko podolje area and in the Ljubljanica catchment.

The Ljubljanica, which collects its water from the extreme northwestern part of the Dinaric Karst, is part of the wider Sava River catchment area, which directs its waters towards the Danube. Its underground watershed is placed arbitrarily within the karst plateaus and mountains and therefore the limits of the Ljubljanica karst river basin cannot be precisely defined. Generally the line of the watershed is assumed to lie close to the highest karst ridges, but it is known that in karst areas the orographic watershed can differ fundamentally from the actual one, and can even change in different hydrological situations. The extent of the Ljubljanica karst river basin in the hinterland of the karst springs near Vrhnika is estimated to be 1100 to $1200km^2$ (Gospodarič and Habič, 1976).

Hundreds of collapse dolines of different shapes and sizes occur in the area of the underground Ljubljanica River. The area includes 128 larger collapse dolines with volumes between $0.2Mm^3$ and $11Mm^3$. These are found: in the area between Ljubljansko barje

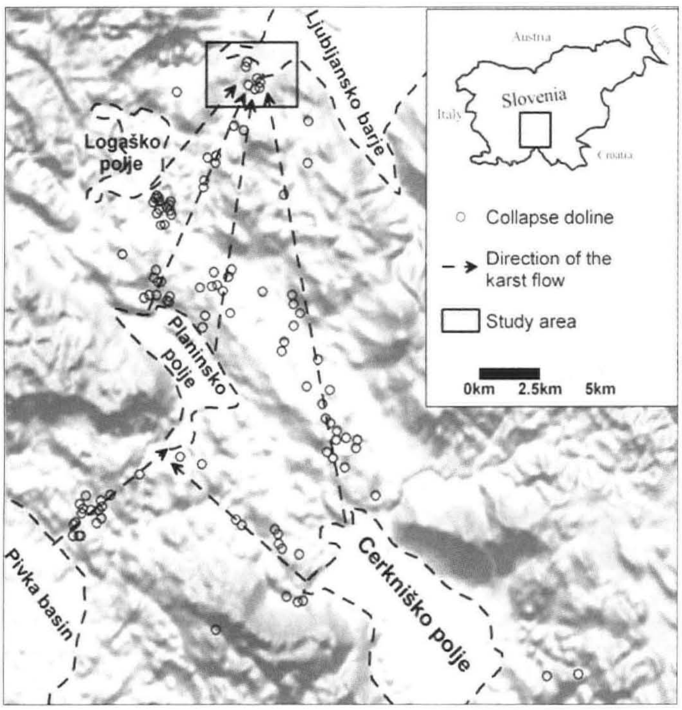

Figure 1: Collapse dolines in the area of the underground Ljubljanica River.

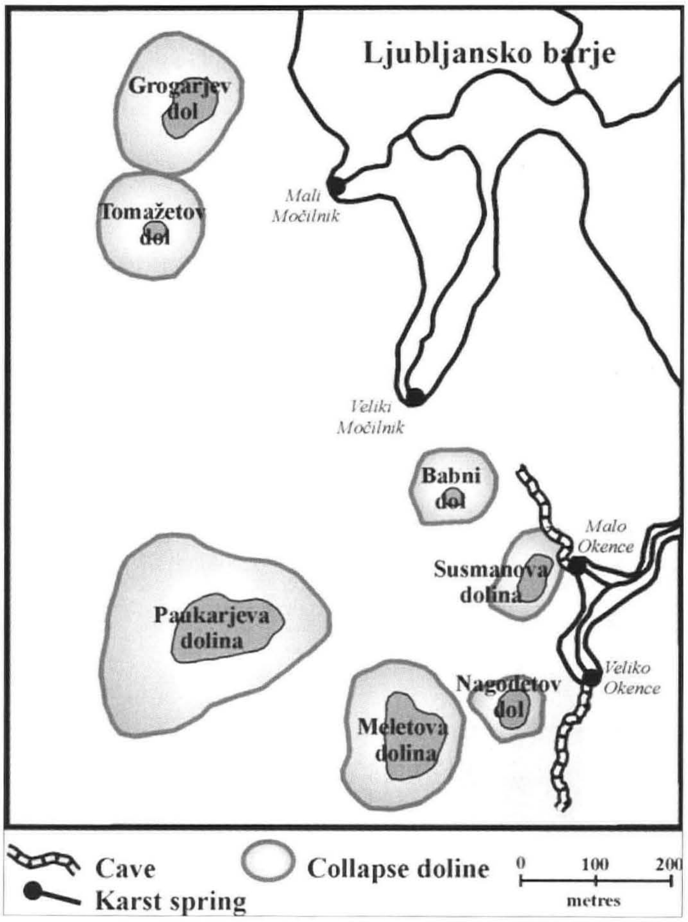

Figure 2: The collapse dolines near the Ljubljanica River springs.

Figure 3: Photograph of partly flooded Grogarjev dol

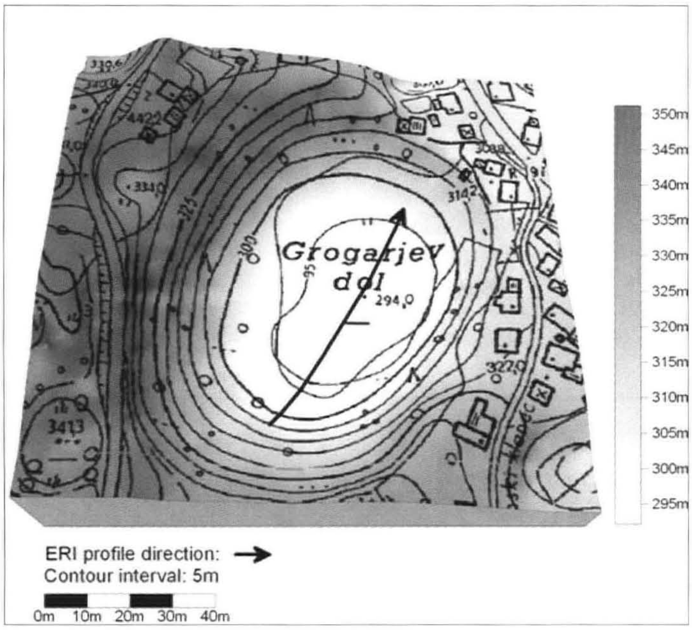

Figure 4: DEM of the Grogarjev dol, showing the ERI profile direction.

(Ljubljana Marsh) and Logaško polje; in the area between Logaško polje and Planinsko polje; in the flat karst surface of Logaško – Begunjski ravnik; in the area between Cerkniško polje and Planinsko polje; in the area between Postojnsko polje and Planinsko polje; in the area between Cerkniško polje and Loško polje and in the hinterland of the Ljubljanica River springs near Vrhnika (Fig.1).

Detailed geomorphic analysis of collapse dolines in the area near the Ljubljanica River springs focused on the slope development processes and the processes of formation of flat doline floors, which have been inundated by flood water and leveled by deposition of loamy material. The subsurface structure of the doline floors was established using Electrical Resistivity Imaging (ERI) techniques, with subsequent interpretation of the ERI data. A SuperSting R1/IP earth resistivity meter, developed by Advanced Geosciences, Inc., was used for data collection. Survey was conducted using a dipole-dipole array with 5m distance between two electrode pairs. The data were processed to generate two-dimensional resistivity models using EarthImager 2D resistivity inversion software. Minimum Root-Mean-Square (RMS) error in the survey was 2.59% and the maximum RMS error was 3.07%. This method is confirmed as being appropriate for providing a robust visualization of the epikarst structure and the subsurface structure of the collapse dolines (Stepišnik and Mihevc, 2007).

The application of this method in the study area revealed that the resistivity value for carbonate rock is more than 1000 ohm-m. For soil and weathered bedrock the resistivity values are approximately between 200 and 1000 ohm-m. Clayey material has resistivity values lower than 200 ohm-m.

COLLAPSE DOLINES

Collapse dolines are surface karst depressions of varied shape and size. Volumes of larger collapse dolines exceed the volumes of the largest known cave chambers in the area, so collapse doline formation cannot be related solely to a series of collapse processes within cave chambers and eventually on the surface (Habič, 1963; Šušteršič, 1973; Stepišnik, 2004, Waltham et al, 2005). Their origin is related to the concentric removal of material, with associated collapse of underground chambers, or with gradual removal of tectonically fractured carbonate bedrock above active cave passages (Habič, 1963; Mihevc, 2001; Stepišnik, 2004). Although collapse dolines have commonly been defined as depressions that are formed above cave chambers (e.g. Cramer, 1941; Gams, 1973; Šušteršič, 1973, Ford and Williams, 1989), a variety of speleogenetic mass removal processes contribute to their development.

Many morphological classifications of collapse dolines have appeared in published karstological literature. The most commonly applied subdivision of collapse dolines is into "immature" and "mature" or "degraded" (Habič, 1963; Šušteršič, 1984; Summerfield, 1996, Waltham *et al.,* 2005, Waltham, 2006). Collapse doline morphology is a result of the establishment of a balance between various geomorphic processes, whose dynamics, extent and duration inside the collapse dolines influence their size and shape. Changes involved depend upon rates of underground removal of the rock, slope angles and the mechanical properties of the bedrock, which are not uniform, even within a single collapse doline (Stepišnik, 2006).

Formation of smaller collapse dolines is related to cave chamber collapse. At the instant of collapse a qualitative modification takes place, as a subsurface karst feature become a surface karst feature. From this moment onward a combination of speleogenetic processes with a variety of exogenic geomorphic processes begins to operate.

Development of larger collapse dolines involves the gradual removal of material above active cave passages. The duration of the process defines the volume of the collapse dolines and the dynamics of the process defines the inclination and morphology of the slopes. Dominance of material removal over the rate of weathering of

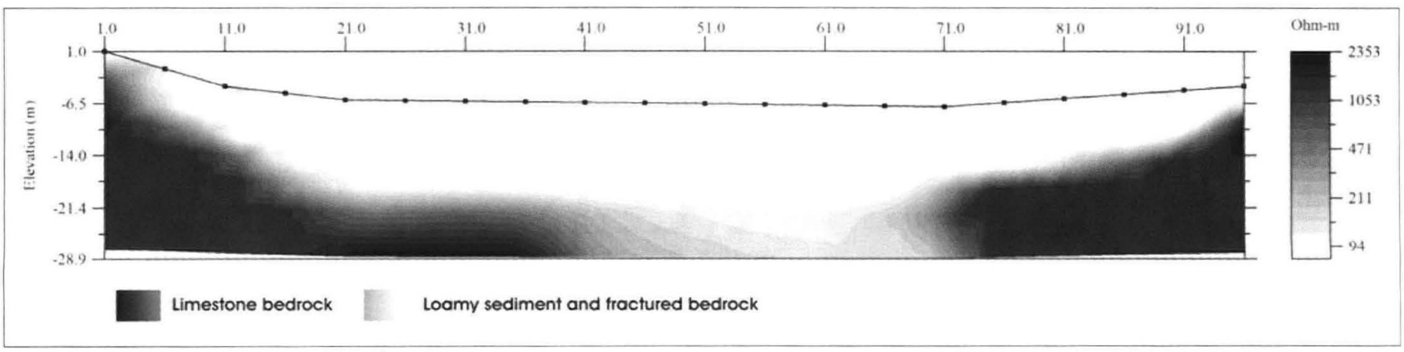

Figure 5: ERI profile of the Grogarjev dol.

bedrock on the doline margins results in the formation of steep slopes and walls.

Accumulations of mechanically derived material are present at the foot of steeper parts of the collapse doline slopes, either as scree, boulders or layers of weathered rock and soil mantle. The dynamics of the mechanical slope processes in such accumulated material relate strongly to the thickness of material and slope angle (Scheidegger, 1974). In contrast, on the karst surface vertically directed chemical denudation hinders the dynamics of mechanical slope processes while influencing the thickness of material on the slopes. At some point during slope development chemical denudation becomes the prevailing slope process and might completely take over from mechanical processes. This can be seen on slopes where mechanical slope processes are absent that are covered with grikes.

The term *active slopes* is used here to describe collapse doline slopes that include walls, scree or accumulated material, together with all slopes that are affected by ongoing mechanical mass removal. Where mechanical mass removal is not active and the process of chemical weathering dominates the slopes are termed *balanced slopes*. On these latter slopes the balance between mechanical weathering plus mechanical slope processes on the one hand and chemical denudation of bedrock on the other hand is established, and mechanical slope processes are generally inactive (Kaufman, 2003; Stepišnik, 2006).

Collapse doline floors are subjected to a number of processes that result in the development of a variety of floor morphologies. In collapse dolines undergoing ongoing removal of material above active cave passages the floors are rocky, with funnel-shaped depressions in accumulated talus. If the process of material removal is negligible or absent, concave floors occur, and these are filled with the finer fractions of weathered bedrock, commonly covered with soil. Smaller patches of loamy material are not uncommon on the floors of collapse dolines. If their floors lie tens of metres above piezometric level and there is no soil on the karst surface it must be concluded that the soil originated in now-demolished cave passages on the slopes that were completely filled with finer material. If weathered material has been completely removed or if the floor lies near the level of the piezometric surface, the lower parts of the collapse dolines are permanently or periodically filled with water or active water flow is present.

In most cases the floors of such collapse dolines are flooded only periodically, during periods of higher piezometric levels. If floodwaters contain a significant suspended load, sediment will eventually be deposited from a stagnant water body. Each ensuing flood will result in deposition of additional loamy sediment layers on the floor. The ultimate outcome of such sedimentation is the establishment of flat, loamy floors in collapse dolines (Stepišnik, 2003).

COLLAPSE DOLINES IN THE HINTERLAND OF THE LJUBLJANICA RIVER SPRINGS

A group of seven large collapse dolines occurs on the western margin of Ljubljansko barje, in the hinterland of the Ljubljanica River springs near Vrhnika (Fig.2). The bedrock in the area comprises thickly bedded Upper Jurassic limestone dipping at approximately 30 degrees towards the west. Hydrologically the dolines lie in an area of concentrated karst flow. Exploration of flooded cave systems has revealed that the currently active phreatic cave passages in the area do not lie beneath the collapse dolines but pass close by them. Cave channels do exist beneath the collapse dolines and were significant at the time of doline formation, but these are now fossilized with an infill of fine sediment (Ilič, 2002).

Morphologically these seven collapse dolines are very similar. Most of their slopes are balanced, and the slopes of Meletova

Figure 6: *Photograph of Paukarjeva dolina.*

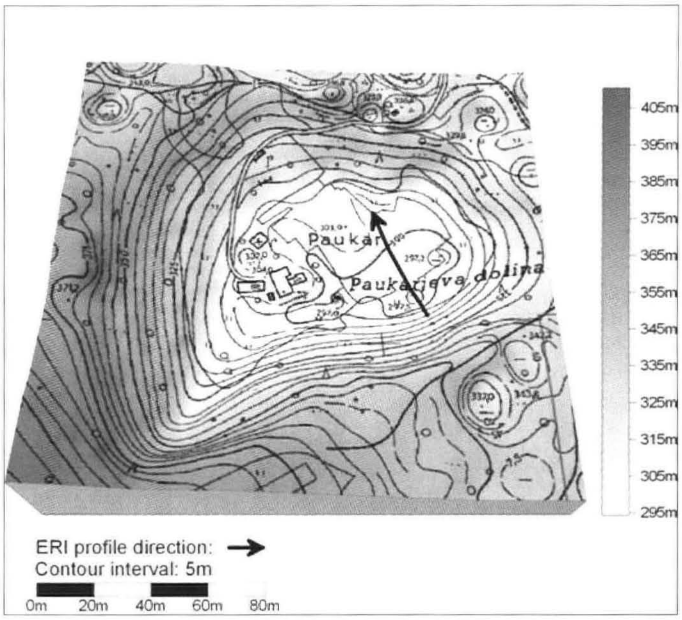

Figure 7: *DEM of the Paukarjeva dolina, showing the ERI profile direction.*

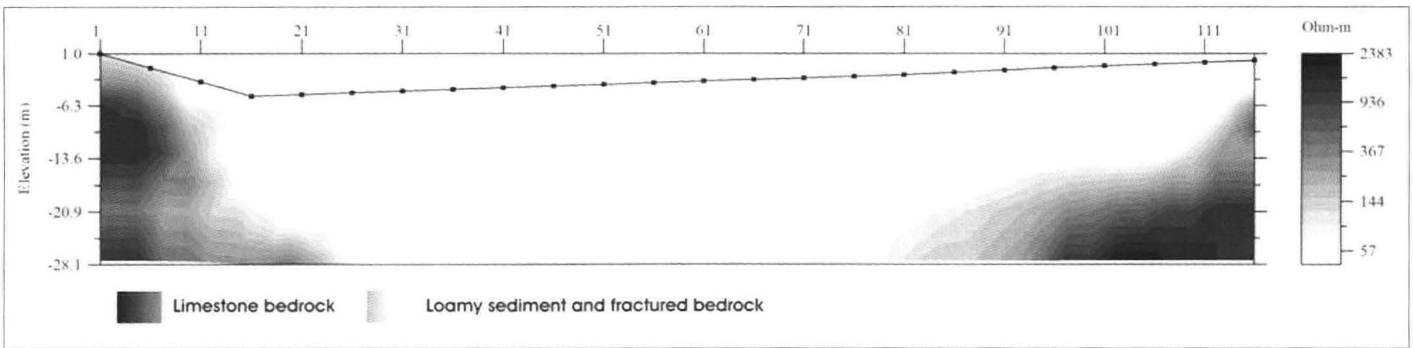

Figure 8: *ERI profile of the Paukarjeva dolina.*

Figure 9: Photograph of Meletova dolina

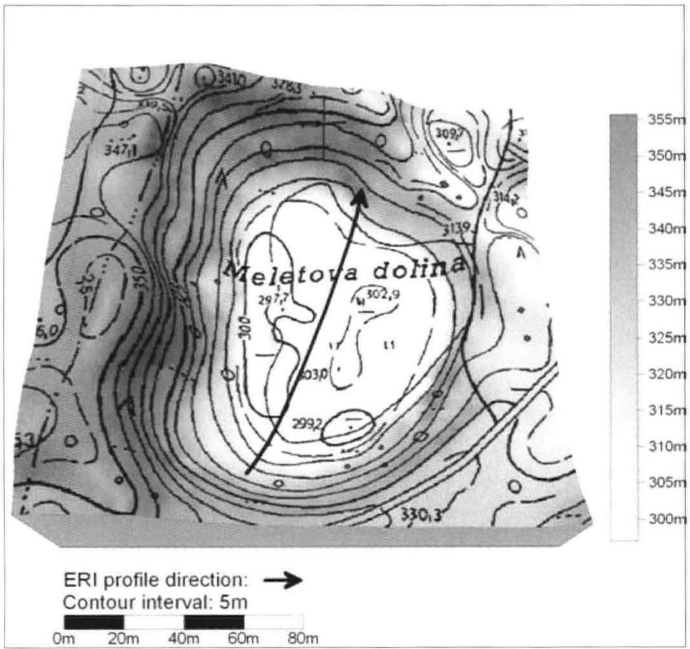

Figure 10: DEM of the Meletova dolina, showing the ERI profile direction.

dolina, Nagodetov dol and Babni dol include partly vertical rocky walls with scree at their feet. The floors of all seven dolines have been inundated and leveled by deposits of loamy sediment. The elevations of the floors vary between 294 and 304m above mean sea level.

Habič (1963) established that the floors of the collapse dolines in the hinterland of the Ljubljanica River springs are at similar elevations. He predicted that the cave system beneath the area was formed as a single level and that mass removal within cave chambers persisted until the moment of collapse. Recent investigations of the cave system and among the denuded caves in the area have revealed that the cave channels there are simply phreatic and they are not organized into a single level (Ilič, 2002; Stepišnik, 2003; Central Cave Register of Slovenia, 2007). On the other hand, the mechanism that results in water removal from caves at the instant of collapse doline formation is as yet unknown (Stepišnik, 2003).

Water table level in the area is related to the elevation of Ljubljansko barje, which at approximately 297m above mean sea level represents the lowest level of discharge from the karst area. The floors and lower parts of the collapse dolines are inundated at times of higher water table levels, and suspended loamy material is deposited from stagnating flood waters. Water table rises in this small area of the Ljubljanica River springs hinterland reach to approximately the same elevation in all of the collapse dolines, so flat loamy doline floors are created at a distinct single level (Stepišnik, 2003).

GROGARJEV DOL

Grogarjev dol collapse doline lies in the northeastern part of the study area. It is elongated north – south with a longer diameter of 175m and a shorter one of 145m. Its average depth is 35m and its volume is 0.35Mm^3. A narrow, 35m-high ridge separates it from the neighbouring Tomažetov dol collapse doline to the south.

The doline slopes are mostly balanced, but with some active parts in the eastern and southern slopes, where small sections of rocky walls and scree still appear. Its northern slopes have been modified by human activity. The floor has been inundated and its surface leveled by deposits of loamy material at an elevation of 294m.

At times of higher water table levels a lake appears in the doline, usually in the autumn and spring. The average depth of the lake is 6.5m and its surface reaches an elevation of 300.5m. Water carrying suspended material enters the doline via a group of small springs on the western side of the floor, and the water drains away at the lowest point of the doline at the foot of the eastern slopes towards one of the spring in Močilnik steephead valley which is around 150m to the southeast. It is active only at higher piezometric levels and its riverbed is at an elevation of around 293m.

ERI survey of Grogarjev dol revealed that the bedrock slopes of the collapse doline are covered with thin layers of less resistant soil and mechanically weathered rock. Weathered material thickness is greater in the lower part of the slope. The doline floor itself is filled with loamy sediment more than 22m thick. Beneath the loamy sediment limestone bedrock lies approximately 20m lower than the Ljubljansko barje surface. In the central part of the loam-covered bedrock floor there is an electrically less resistant vertical structure with resistivity values between 100 and 300 ohm-m, which might be a fault or a shaft that guided doline development (Figs 3, 4 and 5).

PAUKARJEVA DOLINA

Lying some 300m southwest of the Veliki Močilnik spring, the Paukarjeva dolina collapse doline has a long diameter of 275m and short diameter of 225m. Its average depth is 55m and its volume is 1.33Mm^3.

Its slopes are balanced, except for small sections on the southern side that are still active. The surface of loamy sediment fill in the

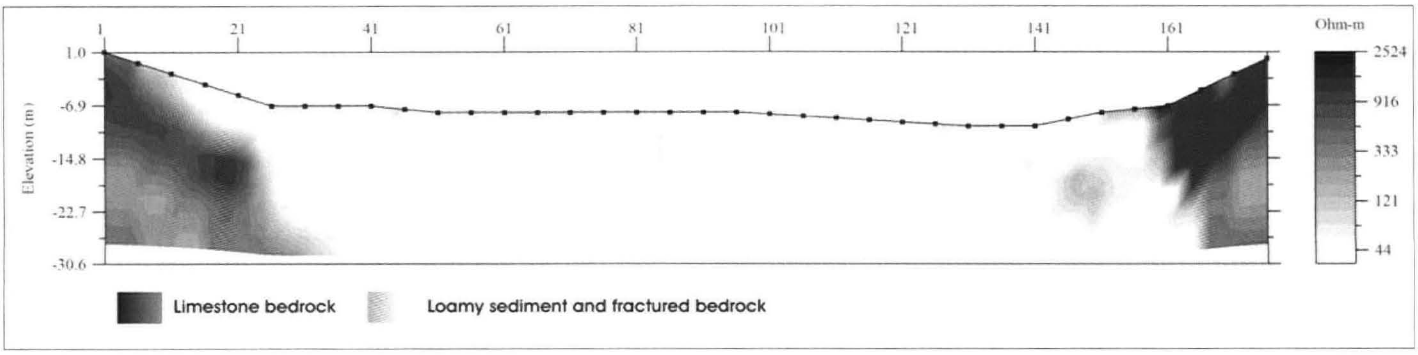

Figure 11: ERI profile of the Meletova dolina.

floor is slightly uneven, with its lowest point in the southern part of the doline at an elevation of 297m. During higher water table events the doline floor is partly flooded and small streams spring from the western side of the floor and sink on the opposite side.

Limited loamy material is found on the doline slopes up to an elevation of 305m, which is roughly the same level observed in the neighbouring collapse dolines. The uneven sediment distribution probably reflects the effects of secondary washing out of sections of the originally deposited material.

ERI survey of the doline revealed that in the eastern part the bedrock slope is covered by a thin layer of less resistant soil and weathered rock. The doline floor is infilled with loamy sediment exceeding 30m in thickness, and the underlying bedrock is more than 30m below the present elevation of Ljubljansko barje (Figs 6, 7 and 8).

MELETOVA DOLINA

Meletova dolina, one of the largest collapse dolines in the neighborhood, lies in the southern part of the study area. Its longer diameter is 200m and shorter diameter 135m, with an average depth of 33m and volume of $0.35Mm^3$.

Its eastern and northern slopes are generally balanced, whereas the other slopes are mostly active and have steep rocky walls in their upper sections, with scree in their lower sections extending down to the flat loamy floor. The surface of the sediment that covers the floor is slightly uneven. Its highest position is in the northeast side at an elevation of 302m and at its lowest on the western side, at an elevation of 297m. Depressions up to 2m deep in the loamy sediment beneath the scree are most likely a result of localized suffosion.

Loamy sediment infill is more than 30m thick in the doline floor. The subsurface structure of the floor sediment is similar to that described for Paukarjeva dolina (above). Considering the greater than 30m thickness of the loamy sediment fill, the bedrock floor must lie more than 30m below the level of Ljubljansko barje (Figs 9, 10 and 11).

NAGODETOV DOL

Nagodetov dol collapse doline lies 70m south of the Veliko Okence spring in the Retovje steephead valley and 50m northeast of Meletova dolina. It is the smallest and shallowest of the dolines in the study area. Its longest diameter is 85m and its shortest 65m, with an average depth of 18m and an approximate volume of $0.03Mm^3$.

Both the eastern and northern slopes are active, with steep rocky walls in their upper parts and scree lower down. All other slopes are mostly balanced. Deposits of loamy material have produced a completely flat floor at an elevation of 300.8m. The loamy sediment, which has low resistance (less than 50 ohm-m), is more than 15m thick, and the bedrock floor of the collapse must lie more than 12m below the level of Ljubljansko barje. The main water-filled phreatic cave passages behind the Veliko Okence spring lie approximately 50m east of the doline (Ilič, 2002).

Near the surface, in the eastern part of the doline floor, is a structure with a resistivity value of approximately 120 ohm-m. It consists of loamy material and limestone gravel derived from the scree in the eastern slope. Another structure with the same electrical resistivity at a depth of approximately 10m, also in the eastern part of the floor, most likely consists of similar material. The presence of this subsurface structure suggests there was contemporary sedimentation of the loamy material and slope process deposits during development of the flat, loamy sediment floor (Figs 12 and 13).

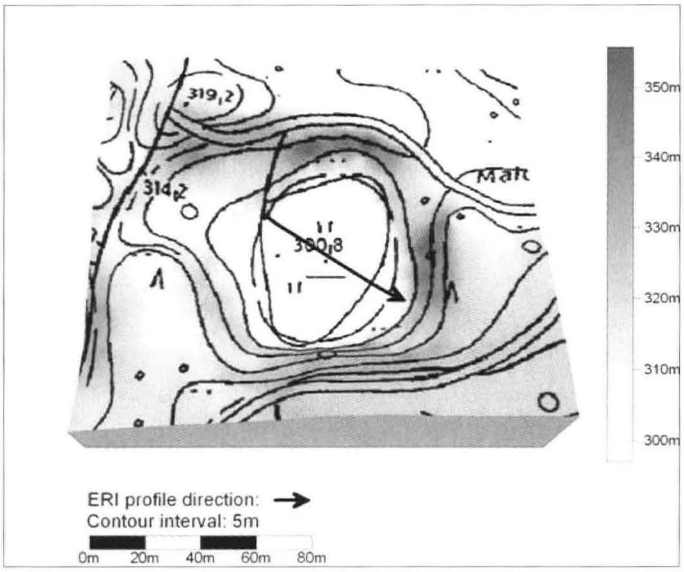

Figure 12: DEM of the Nagodetov dol, showing the ERI profile direction.

SUSMANOVA DOLINA

Susmanova dolina collapse doline lies near the steephead valley of Retovje and is separated from the Malo Okence spring by an 8m-high ridge. The asymmetrical doline is elongated north – south, with a 130m longest diameter, 70m shortest diameter, 18m average depth and a volume of $0.68Mm^3$.

The doline slopes are generally balanced; only in smaller sections on the south side are there patches of active slope. Just like the ground plan of the doline as a whole the loamy floor of the doline at elevation of 299m, is elongated, and it is completely flat.

The average water level at the Malo Okence spring is about 295m, which is only 4m lower than the flat loamy floor of the Susmanova dolina. Phreatic caves behind the spring extend north of the doline in the direction of the Veliki Močilnik spring (Ilič, 2002).

ERI survey of the doline revealed that its bedrock slopes are covered by a thin layer of less resistant soil and weathered rock. In the central part of the doline the thickness of the loamy sediment is approximately 23m. Within the northern and southern parts of the bedrock floor vertical structures with lower resistivity values, ranging between 100 and 500 ohm-m, might be either faults or shafts that influenced doline formation (Figs 14 and 15). On the basis of this evidence the bedrock floor of the collapse doline is at least 20m lower than the Ljubljansko barje flat.

CONCLUSIONS

Detailed investigation of collapse doline slopes and floors in the hinterland of the Ljubljanica River springs revealed:

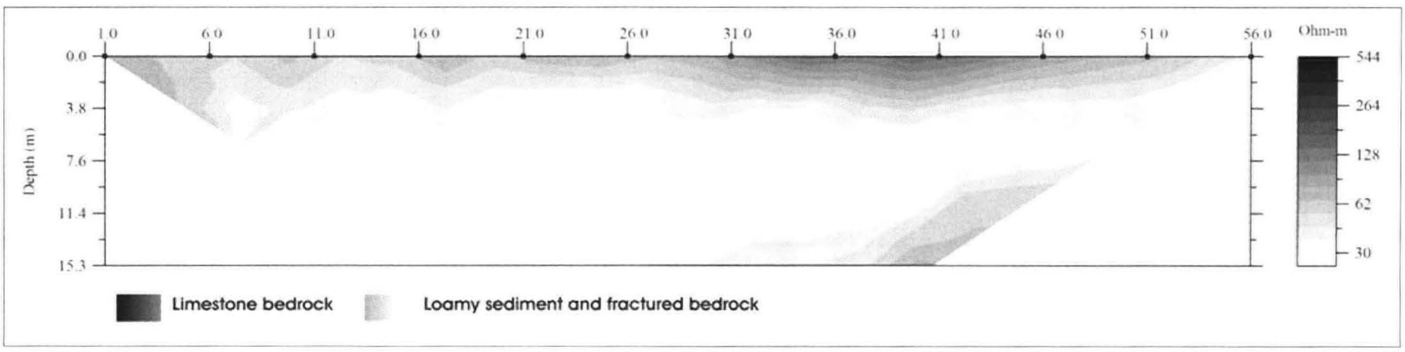

Figure 13: ERI profile of the Nagodetov dol.

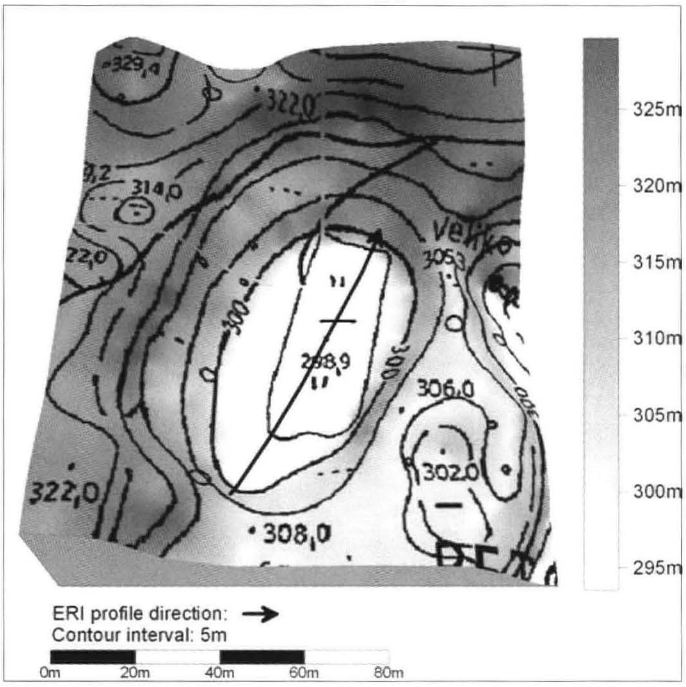

Figure 14: *DEM of the Susmanova dolina, showing the ERI profile direction.*

- Prevailing slopes are balanced. Slopes still affected by mechanical removal of the rock mass occur rarely.
- The collapse dolines were formed above active phreatic cave passages, which in recent times were located below the level of Ljubljansko barje. All explored active cave passages in the area are near collapse dolines. Cave passages that lead in the direction of collapse dolines are no longer active and are therefore filled with fine sediment.
- Successful application of the ERI method revealed details of the subsurface structure of the collapse doline floors.
- The doline floors were inundated and leveled by emplacement of an infill of loamy sediment. Deposition of the sediment occurred from stagnant water bodies, which formed lakes within the dolines during periods of higher water table levels. A similar process that remains active in the Grogarjev dol is the only known ongoing example of this type of deposition on the Slovenian karst.
- Doline floor elevations, which range between 294 and 304m above mean sea level, are related to the elevation of Ljubljansko barje, which currently lies at 297m.
- On the basis of the ERI derived data it appears that the thickness of loamy fill within the collapse dolines locally exceeds 30m, and the bases of all the fills that were studied extend below the current level of the Ljubljansko Barje flat. However, it is acknowledged that the interpretation of ERI derived data is based purely upon knowledge of surface structures and parameters. There is currently no accessible borehole information to provide ground truthing and calibration. Thus, the data are uncalibrated and some values, particularly at greater depths, might be inaccurate.

REFERENCES

Central Cave Register of Slovenia, maintained by the Speleological Association of Slovenia

Cramer, H. 1941. Die Systematik der Karstdolinen. *Neues Jahrbuch für Mineralogie, Geologie und Paläontologie*, Vol.85(1), 293–382

Ford, D C and Williams, P W. 1989. *Karst Geomorphology and Hydrology*. [London: Unwin Hyman.]

Gams, I. 1973. *Slovene Karst terminology*. [Ljubljana: Slovenska matica.]

Gams, I. 2004. *Karst in Slovenia in space and time*. [Ljubljana: Založba ZRC.]

Gospodarič, R and Habič, P. 1976. *Underground water tracing, investigations in Slovenia 1972–1975*. [Ljubljana: IZRK SAZU.]

Habič, P. 1963. Udorne vrtače – koliševke in podzemski tokovi. Treći Jugoslovenski speleološki kongres, Speleološki savez Jugoslavije, Sarajevo.

Ilič, U. 2002. Nove raziskave v Velikem in Malem Okencu. *Naše jame*, Vol.44, 124–131.

Mihevc, A. 2001.*The Speleogenesis of the Divača karst*. [Ljubljana: Založba ZRC.]

Pleničar, M. 1963. Tolmač osnovne geološke karte za list Postojna. [Ljubljana: Geološki zavod Ljubljana.]

Scheidegger, A E. 1974. *Theoretical Geomorphology*. [Berlin: Springer-Verlag.]

Stepišnik, U. 2003. Morfogenetske značilnosti vrhniških udornic. *Naše jame*, Vol.45, 34–47

Stepišnik, U. 2004. The origin of sediments inside the collapse dolines of Postojna karst (Slovenia). *Acta carsologica*, Vol.33(1), 237–244

Summerfield, M A. 1996. *Global geomorphology: an introduction to study of landforms*. [London: Longman.]

Šušteršič, F. 1973. On the problems of collapse dolinas and allied forms of high Notranjsko (Southcentral Slovenia). *Geografski vestnik*, Vol.45(1), 71–84

Šušteršič, F. 1984. Preprost model preoblikovanja udornic. *Acta carsologica*, Vol.12(1), 107–138

Waltham, T. 2006. Tiankengs of the world, outside China. Speleogenesis and Evolution of Karst Aquifers, Vol.4(1), 12pp.

Waltham, T, Bell, F and Culshaw, M. 2005. *Sinkholes and Subsidence, Karst and Cavernous Rocks in Engineering and Construction*. [London: Springer–Praxis.]

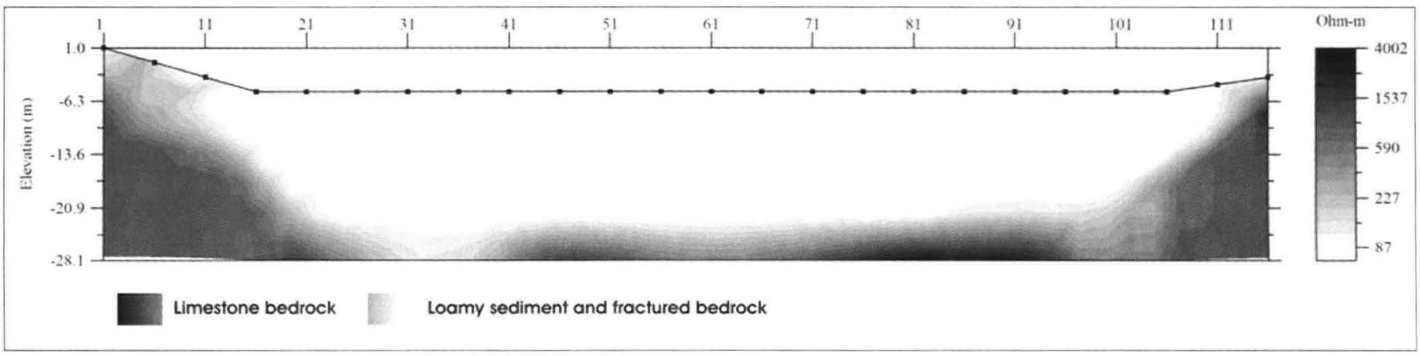

Figure 15: *ERI profile of the Susmanova dolina.*

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Lithological control on water chemistry in karst aquifers of the Zagros Range, Iran.

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Abstract: The Zagros Range of south-central Iran is characterized by long and regular anticlinal and synclinal folds. Most highlands are karstified limestone and dolomite aquifers, which are sandwiched between thick non-karstic marl, marlstone, marly limestone, gypsum and anhydrite formations. Hydrochemical data from 195 karst springs, emerging from five different karstic formations, were used to determine the factors controlling spring water quality. The size and boundaries of catchment area of each spring were determined using water balance and geological methods. The springs were classified based on water type and specific conductance; and discrimination analysis was performed on the major anions, cations, and the specific conductance of all the springs to confirm the proposed classification. The Piper diagram reveals bicarbonate, bicarbonate-dominant, sulphate-dominant, or chloride water type with specific conductances ranging from 190 to 13500μS/cm. The lithology of the neighbouring formations and its extent of outcrop into the catchment area of the karst springs have a major effect on water quality. Large exposures of marl, marlstone, and marly limestone on the catchment area of the karst springs can change bicarbonate water to bicarbonate-sulphate, whereas gypsum and anhydrite produce sulphate-type waters. Salt domes, and saline water from adjacent lakes or alluvial aquifers are the main sources for chloride-type water.

Key words: karst springs, hydrochemistry, aquifer, water quality, Zagros

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INTRODUCTION

The chemical composition and physical properties of karst springs reflect the processes operating in the relevant geological environment. The quality of karst water is a function of composition of precipitation, type of recharge water, lithology of karst aquifer rocks and neighbouring formations, type of flow (diffuse or conduit), saline water intrusion, and anthropogenic pollution (Appelo and Postma, 2005).

Raeisi and Karami (1996) and Keshavarz (2003) reported the average specific conductance of precipitation in the central-south of Iran to be 12.5μS/cm and 40μS/cm, respectively. The specific conductance of precipitation is significantly lower than the specific conductance of karst springs, such that the effect of precipitation is less important than that of the aquifer lithology on water quality (Hem, 1985; Ford and Williams, 1989; Raeisi and Karami, 1996; Lopez-Chicano *et al.*, 2001; Reghunath *et al.*, 2002; Tooth and Fairchild, 2003; and Güler and Thyne, 2004). Under this condition, the most intensive alteration of the chemical composition of rainwater occurs when it crosses the unsaturated and saturated zones.

More-developed karst drainage implies shorter residence times and thus, normally, lower mineralization. If the flow regime is mainly diffuse in a karst region, water flow is slow and the residence time in the aquifer is long. In this case, mineralization is generally greater (Appelo and Postama, 2005). The solubility of calcite and dolomite by dissociation in pure, de-ionized water is very low. Investigations have shown that most of the enhanced solubility of carbonate minerals that occurs is due to P_{CO2}. However, the maximum solubilities of calcite and dolomite at pH=7 are 500 and 480 mg/l, respectively, and their common ranges of abundance in karstic springs are both 10–300 mg/l (Ford and Williams, 1989). Dissolution of calcite and dolomite is limited to maximum values even in a diffuse flow. If the karst waters are not in direct contact with salt domes or gypsum/anhydrite evaporite formations, the water is bicarbonate-rich and the specific conductance is less than 500μS/cm (Raeisi and Moore, 1993). Andreo and Carrasco (1999) extended this limit to a range of 314 to 554μS/cm with water types of bicarbonate-calcium and/or magnesium. The dissolution of gypsum and anhydrite causes a high level of sulphate in groundwater, although other sulphate-bearing minerals may also contribute sulphate to the groundwater (Marfia *et al.*, 2004; Gunn *et al.*, 2006; Krothe and Libra, 1983). In carbonate terrains, concentrations of $CaCO_3$ higher than 350mg/l are nearly always a result of enrichment by sulphates or chlorides (Ford and Williams, 1989). Salt occurs as beds, but in some cases, the salt is in the form of salt diapirs or salt domes. The mixing of karst water with Na–Cl or $Ca–SO_4$ waters decreases the quality of karst water. Intrusion of saline water into a karst aquifer can significantly change the quality of karst water (Rezaei *et al.*, 2005). Anthropogenic processes, including groundwater pollution by liquid wastes or leachates from solid wastes, can also change the physical and chemical characteristics of karstic springs drastically (Aley, 2000; Li *et al.*, 2005).

Carbonate formations crop out over about 23% of the Zagros Range of Iran (Raeisi and Kowsar, 1997). Formations overlying and underlying the carbonates are composed of marl and/or gypsum, whereas the interlayers are halite in some parts of the Zagros Mountains. Salt domes are in direct contact with karst formations in some of the anticlines. The main issues to be addressed in this study include: a) classification of karst springs in the study area, b) determination of the main factors controlling karst spring chemistry; and c) hydrochemical comparison of various carbonate formations' effects on water quality.

GEOLOGICAL SETTING

The study areas lie in the Zagros Range, south-central Iran, within 51° to 56° E and 27° 40' to 31° 15' N (Fig.1). Climatologically, the area is an arid to semi-arid region with an average annual precipitation and temperature of 400 $mm.yr^{-1}$ and 20°C, respectively (Rahimi, 2006). The Zagros Range consists of three zones, namely the Khozestan Plain, the Simply Folded Zagros and the High Zagros (Darvichzadeh, 1991). The Khozestan Plain Zone consists of alluvial sediments, which cover all underlying formations. The Simply Folded Zagros consists of long, linear, asymmetrical folds. Anticlines are well-exposed and separated by broad valleys (Miliaresis, 2001). Fold axes have a northwest to southeast trend. The High Zagros is a narrow zone very close to the Main Zagros Thrust Fault, and it is crushed and intensively faulted.

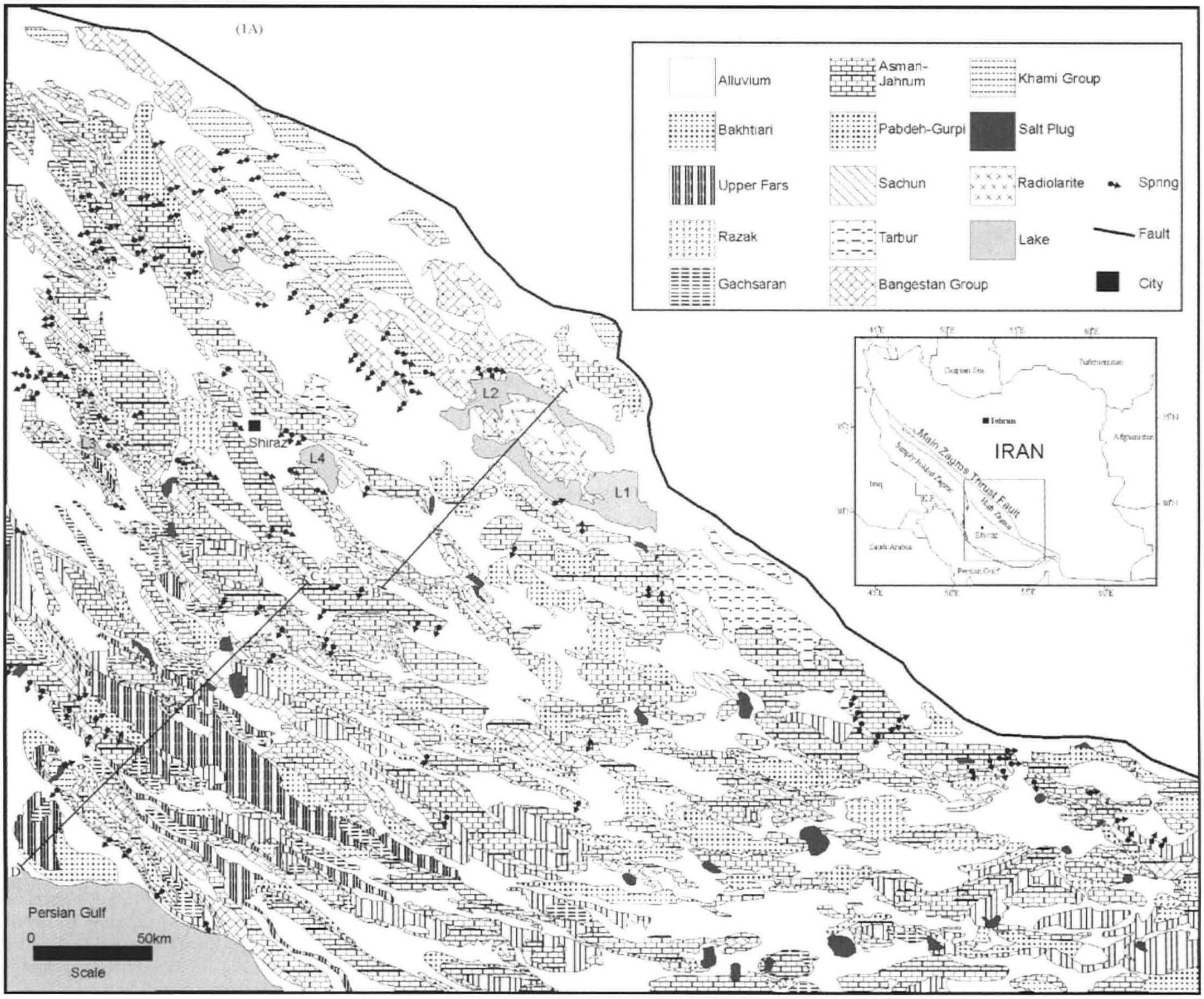

Figure 1(A)*: Location map (Boxes), geological map and location of springs. The lines AB and CD indicate the lines of cross-section illustrated in figures 1(B) and 1(C) respectively. Abbreviations: K.P: Khozestan Plain, L1: Bakhtegan Lake, L2: Tashk Lake, L3: Parishan Lake, L4: Maharlu lake. [Based on maps of the Oil Company of Iran.]*

Geometrically, the Zagros anticlines are cylindrical in form and generally plunge beneath younger sediments at both ends. The young sediments that overlie karstic aquifers, include permeable and impermeable beds. Sediments form a thick cover over the synclines situated between anticlines. Only the tops of the anticlines are uncovered and expose carbonate formations. At their bases karst aquifers are limited by impermeable formations (mostly marls). The main source of recharge is direct precipitation on the karstic aquifer body. The recharge is mainly autogenic (Ashjari and Raeisi, 2006). A combination of joints and bedding planes play a role in transferring the groundwater through the vadose zone to the phreatic zone. The impermeable formation below the karstic aquifer and/or interbedded shales and marls in karstic formations can block groundwater flow in a vertical direction. The steep slopes of the anticline limbs direct the flow away from the anticlinal crests via available pathways. A main conduit system may develop at the foot of the anticline, parallel to the strike where the branches of diffuse flow or small-conduit flow join each other. The direction of flow at the feet of the anticline's main conduit system depends mainly on the location of the discharge zones (Ashjari and Raeisi, 2006).

Details of the sequence of formations at outcrop in the study areas are presented in Figure 2. In the following sections the main outcropping formations are discussed in decreasing order of age (James and Wynd, 1965; Stocklin and Setudehnia, 1971; Darvichzadeh, 1991; and Alavi 2004).

The Surmeh Formation consists of dolomitic limestone and dolomites, overlain by the Hith Formation, which comprises anhydrite-gypsum with interbedded dolomites where best developed in the south of the study area near the Persian Gulf, but changes to dolomite or dies out across the rest of the study area. Next, the Fahliyan Formation is limestone, the Gadvan Formation comprises limestone interbedded with marl, and the Dariyan Formation is also limestone. The Kazhdumi Formation includes marl at the top overlying argillaceous limestone and marl towards the base, whereas the overlying Sarvak Formation has a basal 250m of argillaceous limestone with an upper 570m of limestone. Above this the Gurpi Formation comprises marl and shale and the Pabdeh Formation includes calcareous shale, marl, and lime mudstone with subordinate argillaceous limestone. In interior parts of the study area, the upper part of the Gurpi and all of the Pabdeh formations are replaced by the Tarbur and Sachun formations respectively. The Tarbur Formation consists essentially of massive limestone, with limestone-dolomite in some parts. Within the 1400m-thick Sachun Formation argillite, shale and evaporites (mainly gypsum) are intercalated with thin-bedded dolomite. Generally the Jahrum Formation, comprising dolomite interbedded with dolomitic limestone, overlies the Pabdeh Formation, but in the interior of the study area, it overlies the Sachun Formation. Across most parts of the study area the Jahrum and Asmari formations are not differentiated. The Razak Formation is mainly marl, interbedded with silty limestone, and the Gachsaran

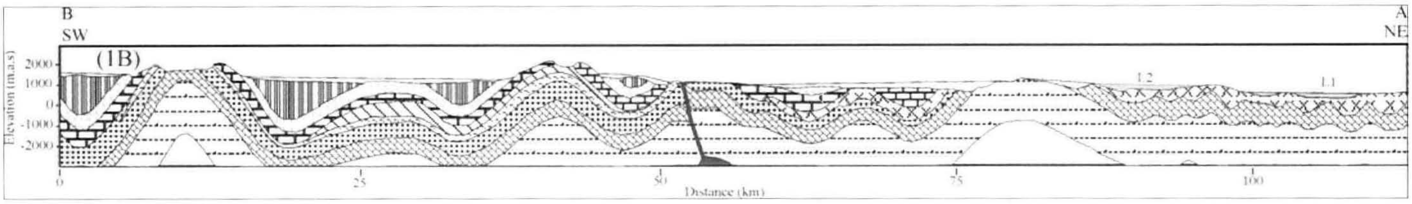

Figure 1(B): *Geological cross section drawn along the line AB shown on Figure 1(A). [Based on maps of the Oil Company of Iran.]*

Formation is composed of multiple sequences of variable thickness, and its lithology includes alternations of evaporites (gypsum, anhydrite and subordinate halite), shale, marl and (locally) conglomeratic calcarenite. Overlying the Razak and Gachsaran formations, the lower part of the Mishan Formation is the Guri Member, consisting of 112m of limestone with bands of marlstone and marl. The upper part of the Mishan Formation comprises marl alternating with bands of shelly limestone. Above this, the Aghajari Formation is composed mainly of carbonate-clast and polymict conglomerate, calcarenite, cross-bedded sandstone, siltstone, marl, and lime-mudstone, overlain by the conglomerate, sandstone, siltstone and shale of the Bakhtiari Formation.

METHOD OF STUDY

The data of this research are obtained from the Karst Research Centre of Iran, PhD and MSc theses of the Earth Sciences Department of Shiraz University, and the Fars Regional Water Organization (Naseri, 1991; Jahani 1994; Rajaei 1999; Rezaei 1998; Kowsar 1995; Pezeshkpour 1991; Raeisi *et al.*, 1993, 1998; Raeisi and Karami 1996, 1997; Rahnemaie 1994; Karst Research Centre of Iran 1993, 1995, 1996, 2000; Keshavarz 2003). The chemical analyses in the dataset were tested for Charge Balance Error (CBE):

$$CBE=100*[(\sum cations - \sum anions)/ (\sum cations + \sum anions)] \quad (1)$$

Only CBEs less than or equal to ±10% were accepted for this study. The next step included plotting the springs' locations on geological maps of 1/100,000 and 1/250,000 from the Oil Company of Iran. Then, the size of the catchment area of each spring was determined using the following equation (Karimi, 2003; Karimi *et al.*, 2005; Ashjari and Raeisi, 2006):

$$A=V/ (10^3*P*I) \quad (2)$$

In which A is the catchment area of the spring in (km^2), V is the total discharge of the spring during one hydrological year in (m^{3}yr^{-1}), P is the annual precipitation in (mm.yr^{-1}), and I is the recharge coefficient (dimensionless), which varies from 0 to 1. The recharge coefficient was estimated based on geological and climatic conditions, and previous researcher experiences such as Rahnemaie (1994); Karimi, (2003); Karimi *et al.*, (2005); Ashjari and Raeisi, (2006). In equation (2) it is assumed that there is no allogenic input and the variation of storage over one hydrological year is insignificant.

Then, the calculated surface area (A) was compared to the probable boundary of the spring catchment area, which was determined by the following assumptions and criteria (Karimi, 2003; Karimi *et al.*, 2005; Ashjari and Raeisi, 2006):

1. The catchment area is probably as close as possible to the spring;
2. The elevation of the catchment area must be higher than that of the related spring and possible catchment areas can be determined using the topographical map of the region;
3. There must be no impermeable formations crossing the aquifer and possibly disconnecting one part from the spring;
4. The water budget must be balanced for the total area of the main aquifer (or anticline), in other words, the catchment areas of all the subaquifers must be determined;
5. Geomorphology, geology, and tectonic settings must justify the catchment area;
6. The physicochemical parameters should be in agreement with the lithology of the related karst aquifers and adjacent formations; and
7. Available dye-tracing data may be used to confirm or refute the proposed boundaries.

The type of water was determined by the use of Piper diagrams. Discrimination analysis (DA) was applied on the major anions, cations, and specific conductances of all the springs. In DA, suppose that there are k distinct populations (samples) $\pi_1,...\pi_k$. The purpose is to classify an individual with observation $X=(x_1,...x_p)$ or a group of N individuals with observations $X^{\alpha}=(x_{\alpha 1},...x_{\alpha p})$, $\alpha=1,...,N$, on p different characters (in this case meaning the chemical parameters of a sample), characterizing the individual or the group, into one of π_1, ...π_k. When considering the group of individuals, the basic assumption is that the group as a whole belongs to only one population among the k given. Furthermore, it is assumed that each of π_i can be specified by means of distribution function of a random vector, whose components represent random measurements on the p

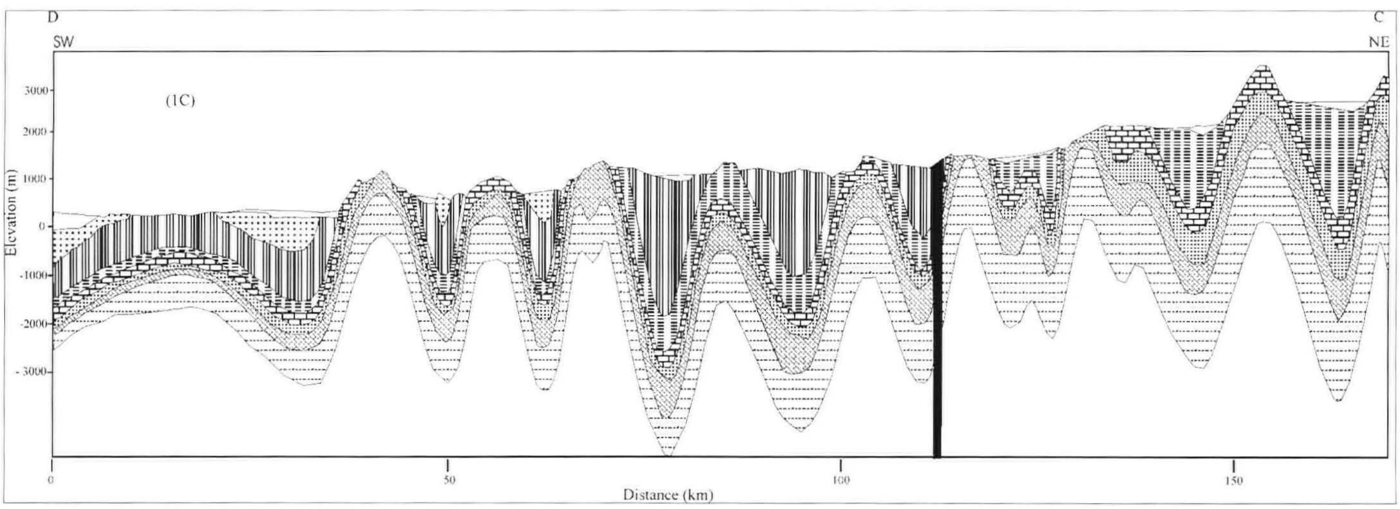

Figure 1(C): *Geological cross section drawn along the line CD shown on Figure 1(A). [Based on maps of the Oil Company of Iran.]*

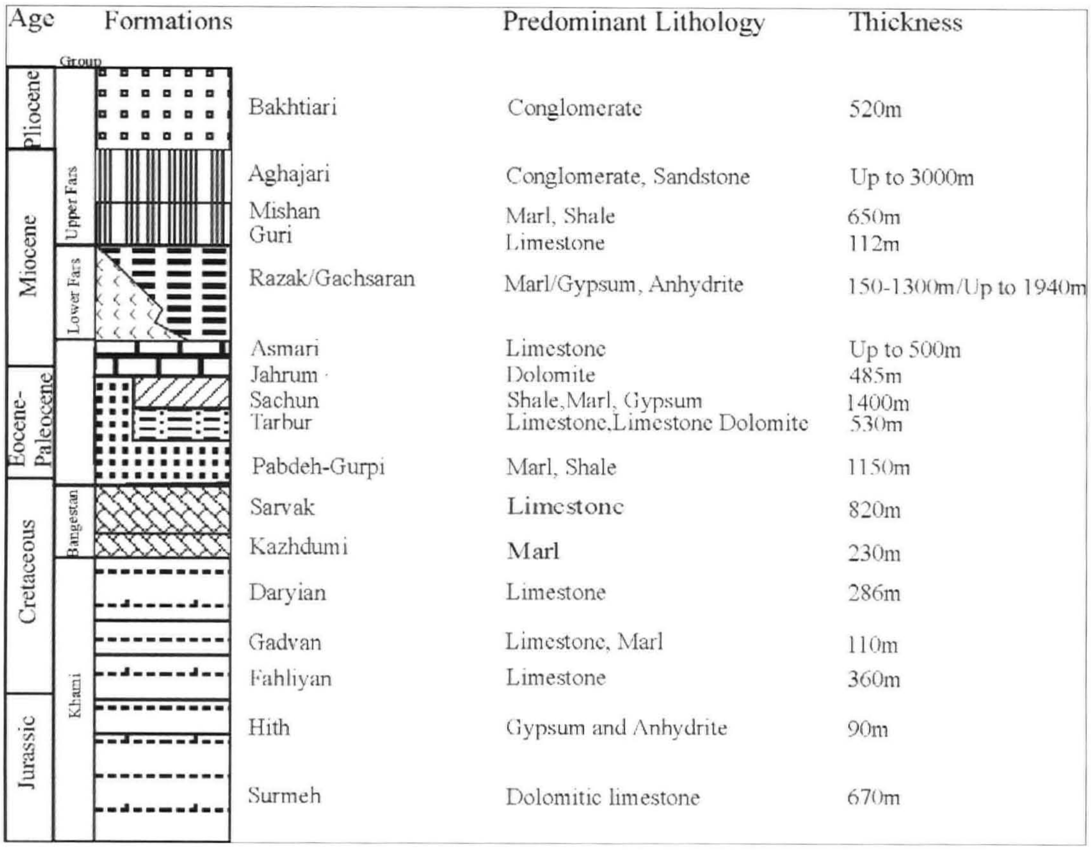

Figure 2: *Stratigraphical column through the Zagros, central-south Iran. [After Darvichzadeh, 1991; Alavi, 2004; McQuarrie, 2004).]*

different characters (Giri, 1977). The DA technique builds up a discriminant function for each group. It is a latent variable that is created as a linear combination of discriminating variables (chemical parameters), such that $L = b_1x_1 + b_2x_2 + ... + b_px_p + c$, where the b's are discriminant coefficients, the x's are discriminating variables, and c is a constant. This is analogous to multiple regression, but the b's are discriminant coefficients that maximize the distance between the means of the criterion variable for grouping. Note that the foregoing assumes the discriminant function is estimated using ordinary least-squares. The correlations of each variable with each discriminant function are presented by a structure matrix. That is, the correlations of each independent variable with the discriminant scores associated with each given discriminant function. The correlations then serve like factor loadings in factor analysis by considering the set of variables that load most heavily on a given dimension. The efficiency of discriminant functions can be tested by comparing the predictor variables follow multivariate normal distributions with predefined groups. For more discussion about DA application in water resources classification, see Ravichandran (1987), Alberto *et al.*, (2001), Lam-Hoai and Rougier (2001).

RESULTS

Numbers of springs were 120, 49, 18, 5 and 3 in the Asmari-Jahrum (AJ), Sarvak (Sa), Dariyan–Gadvan–Fahliyan (DGF), Tarbur (Ta) and Guri (Gu) formations respectively (Fig.1). The Daryian, Gadvan and Fahliyan formations constitute a single hydrogeological unit in the catchment area of the springs emerging from these formations. Differences in the number of springs depend on the extent of outcrop of the karstic formations in the study area. Outcrop areas of the AJ, Sa, DGF, Ta and Gu formations are 11303, 4560, 1685, 1215 and 806km^2, respectively. The springs were classified into four main groups based on the dominant type of water and the range of specific conductance (SC) (Table 1). The type of water is bicarbonate in Group B_1, bicarbonate-dominant in Group B_2, sulphate-dominant in Group S, and chloride in Group C. The first group (B_1) includes 112 bicarbonate karst springs with SC values of less than 500μS/cm. The sulphate and chloride concentrations are almost constant in Group B_1. The main reason for SC enhancement is the higher dissolution of bicarbonate ions (Fig.3). The chemistry of Group B_1 is mainly affected by the lithology of the karst formations and not by the neighbouring formations' lithology.

Of the 43 springs of Group B_2, 3 are bicarbonate, 36 bicarbonate-sulphate, and 4 bicarbonate-chloride. The SC ranges from 500 to 1160μS/cm (Table 1) in this group. Whereas the three bicarbonate springs plot in the bicarbonate region in the Piper diagram, they are very close to the chloride boundary, and therefore, they are almost of the bicarbonate-chloride type. The ratios of average bicarbonate, sulphate and chloride concentrations in Group B_1 to Group B_2 are 1.5, 4.7 and 4.3, respectively. Therefore, the main reason for SC enhancement in this group is sulphate and chloride concentrations (Fig.3). Water type in Group S is sulphate in 18 of the springs and sulphate-chloride in 8 of the springs. The SC ranges from 1160 to 1850μS/cm in this group. Bicarbonate concentration is almost constant in most of the springs and the main reason for the increase in SC is mainly the sulphate concentration (Fig.3). There are no springs in this group with SC in the range 1850 to 2300μS/cm. Group C consists of 14 chloride-type springs with SC ranging from 2300 to 13500μS/cm. In this case the main reason for SC enhancement is the chloride concentration (Fig.4). Discrimination analysis has been carried out on the major anions, cations and the SC of all the springs. The results confirmed the proposed classification, especially in Group B_1, S, and C (Table 2). Out of the 43 springs of Group B_2, 8 springs were misclassified as Groups B_1, and 2 springs were incorrectly designated as Group S. This was not unexpected because Group B_2 covers the transition between bicarbonate- and sulphate-type waters.

Each group of karstic springs was categorized on the basis of the type of karstic formations cropping out in its catchment area (Table 3). DGF and Ta were classified in Group B_1, Gu in Group C, Sa in Group B_1, B_2 and C, and AJ in Group B_1, B_2, S and C.

DARIYAN–GADVAN–FAHLIYAN FORMATIONS

Water type in the Dariyan–Gadvan–Fahliyan (DGF) formations is bicarbonate calcite (Fig.5A) with SC ranging from 364 to 451μS/cm (Table 3). Ca/Mg molar ratios can be used to differentiate limestone and dolomite groundwater sources. The relationship between Ca and Mg concentrations in the B_1 Group is shown in Figure 6. Ca/Mg molar ratios greater than 3 for most DGF springs demonstrate the limestone lithology of these formations. The bicarbonate type and SC values less than 451μS/cm in all karst springs emerging from DGF can be explained as follows:

Main groups	SC (µS cm^{-1})	Water Type	Number of springs	Ca	Mg	Na	HCO_3	SO_4	Cl	Q (LS^{-1})
B_1	<500	Bicarbonate	112	2.1	1.0	0.2	2.7	0.4	0.4	5 – 3112
B_2	500 – 1160	Bicarbonate, Bicarbonate – sulphate, Bicarbonate – chloride	43	3.2	2.5	2.1	4.1	1.9	1.7	5 – 2855
S	1160 – 1850	Sulphate, Sulphate – chloride	26	7.4	5.6	2.3	3.1	9.2	2.6	5 – 163
C	2300 – 13500	Chloride	14	12.5	9.4	30.8	2.3	11.0	42.0	5 – 98

***Table 1**. Classification of karst springs based on SC and water type. Unit of average ion concentration is meq/litre.*

1) the DGF lithology is limestone;
2) the Hith Formation changes into dolomite or dies out in the catchment area of the springs. Thus the underlying rock is the massive limestone of the Surmeh Formation. The contact lithology overlying the DGF formations is dark argillaceous limestone and marl of the Kazhdumi Formation, which is not capable of changing the water quality of the DGF formations significantly;
3) neither salt domes nor saline lakes are situated near the catchment areas of the springs.

SARVAK FORMATION

The numbers of springs emerging from the Sarvak Formation are 31, 11, and 7 in groups B_1, B_2 and C respectively (Table 3). The type of water in Group B_1 is bicarbonate and the SC ranges from 190 to 500µS/cm. The Ca/Mg molar ratio of most Sarvak springs is greater than 3, demonstrating the limestone lithology of these formation. The high water quality of Sarvak springs in Group B_1 is justified as follows:

1) The lower part of the Sarvak Formation consists of argillaceous limestone, which prevents hydraulic continuity with the underlying Kazhdumi Formation;
2) The contact lithology of the overlying Gurpi Formation is marl, which is effectively impermeable, limiting water flow from Gurpi to Sarvak. Water type in the Gurpi Formation is sulphate (Raeisi and Moore, 1993). Any effect of the Gurpi Formation on the quality of the Sarvak springs depends on the extent of the exposed area of the Gurpi. If the Gurpi crops out extensively in the catchment area of the springs, it may change the type of water from bicarbonate to bicarbonate-sulphate or sulphate. The large number of bicarbonate-type springs reflects the limited outcrop area of the Gurpi Formation in the catchment of those Sarvak springs classified in Group B_1;
3) The catchment areas of the springs are remote from salt sources.

In Group B_2, the SC of Sarvak springs ranges from 510 to 1160µS/cm and the water type is bicarbonate in 3 springs, bicarbonate-sulphate in 4 springs, and bicarbonate-chloride in 4 springs (Table 3). The Ca/Mg molar ratios of groups B_2, S and C are less than 3 in all karstic formations (Fig.7). The main source of sulphate ions in the four bicarbonate-sulphate springs is the effect of an extensive Gurpi Formation outcrop. The chloride concentration is so high in the three bicarbonate springs that it falls near the boundary of the chloride zone in the Piper diagram. Because of this, the water type can be considered as bicarbonate-chloride. The three bicarbonate and three bicarbonate-chloride springs are located near the high salinity alluvial aquifer adjacent to the saline Tashk Lake (Raeisi *et al.*, 1998). Intrusion of saline water from the adjacent alluvial aquifer increases the chloride concentration in the karst springs. Seven springs emerging from the Sarvak Formation belong to Group C. The SC of these springs ranges from 2720 to 9910µS/cm with an average chloride concentration of 49.8 meq/litre (Table 3). Four of these springs are located near the high salinity alluvial aquifer adjacent to the saline Tashk Lake (Raeisi *et al.*, 1998; Raeisi and Nejati, 2000), but the salinity of the adjacent alluvium is higher than that of the alluvium adjacent to the Sarvak springs of Group B_2. The three others chloride springs are near salt domes cropping out in the catchment of the karst springs.

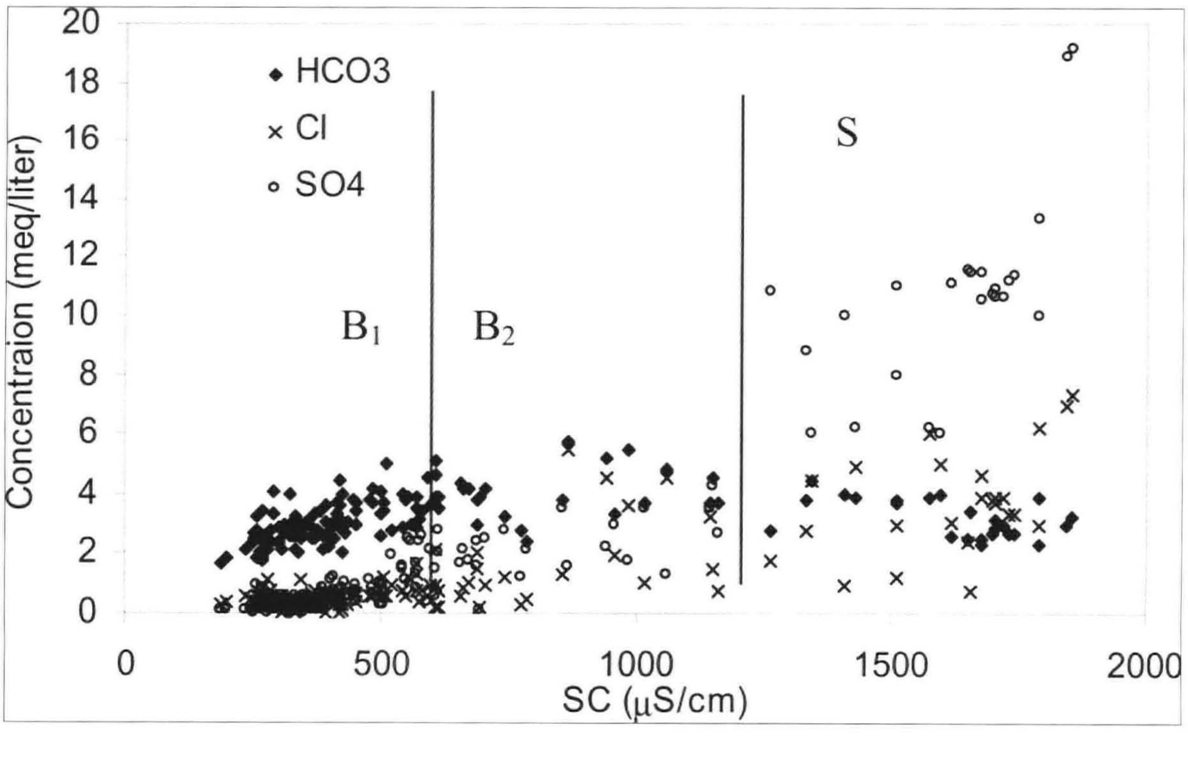

***Figure 3:** Variation of major anions with specific conductivity for springs with specific conductivity less than 2000µS cm^{-1}.*

Number of springs based on predefined criteria	Number of springs predicted by discriminant analysis				
Main groups	Total	B_1	B_2	S	C
B_1	112	108	4	0	0
B_2	43	8	33	2	0
S	26	0	0	25	1
C	14	0	0	0	14

Table 2. *Classification of springs based on major ions and SC using discriminant analysis.*

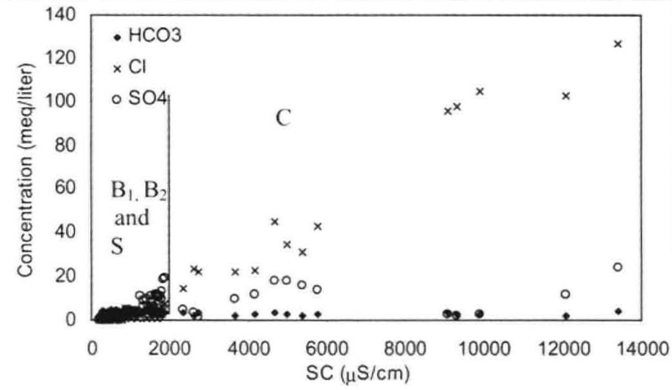

Figure 4: *Variation of major anions with specific conductivity for all springs.*

TARBUR FORMATION

Five springs emerge from the Tarbur Formation and all are classified in Group B_1. Ca/Mg molar ratio varies from 1 to 3 in all of the Tarbur springs, the SC ranges from 249 to 356μS/cm and the water type is bicarbonate-calcium-magnesium (Table 3). As explained above, the underlying marl of the Gurpi Formation does not affect the water quality significantly. Additionally, the Gurpi Formation outcrop is limited in the catchment area of these springs. The contact lithology of the Sachun Formation above the Tarbur consists of marl, marlstone and silty limestone. The high water quality of the Tarbur springs implies that they are not affected by the adjacent formations and that the catchment areas of the springs are not close to a source of salt.

ASMARI–JAHRUM FORMATIONS

A total of 120 karst springs emerge from the combined Asmari–Jahrum (AJ) formations, comprising 58, 32, 23, and 7 in groups B_1, B_2, S and C respectively (Table 3). Ca/Mg molar ratios vary from 1 to 3 in 46 of the AJ springs in Group B_1, reflecting the dolomite and limestone lithology of these formations. The Ca/Mg molar ratio of less than 1 in twelve of the AJ springs is most probably due to extensive flow of water in the dolomite part of the AJ formations. Ca/Mg molar ratios in groups B_2, S and C are less than 3 in all springs. The AJ overlies the Pabdeh and Sachun formations in the catchment area of 102 and 18 of the springs, respectively. The underlying Pabdeh Formation does not affect the water quality of the AJ karst springs significantly because the lithology of the Pabdeh at the contact with AJ is marly limestone. Additionally, the Pabdeh Formation is exposed only in the catchment areas of 27 springs classified in Group B_1.

In cases where the AJ formations overlie the Pabdeh Formation, the overlying Razak or Gachsaran formations determine the spring quality. There are 55, 23 and 1 springs in groups B_1, B_2 and C respectively where there is a boundary between the Pabdeh and Razak formations (Table 4). The high number of springs in groups B_1 and B_2 is related to the contact lithology of the Razak Formation, which is mainly alternating layers of marly limestone and silty marlstone. The effect of the Razak Formation on the water quality depends on the extent of the Razak Formation outcrop on the AJ formations. As the exposed area increases, the springs are categorized as Group B_2 instead of B_1. Intrusion of saline water changed the type of water from groups B_1 or B_2 to Group C in one spring.

In 23 cases the Pabdeh Formation underlies and the Gachsaran Formation overlies the AJ formations. The contact lithology of the Gachsaran Formation is anhydrite and gypsum with thin interbeds of limestone and marl. The numbers of springs in groups B_1, B_2, S and C are 3, 9, 8 and 3, respectively (Table 4). High numbers of karst springs in groups B_2 and S reflect the deleterious effect of the Gachsaran Formation. The distribution of springs in groups B_1, B_2 and S depends on the extent of Gachsaran Formation outcrop area on the AJ formations or the change of Gachsaran lithology due to extreme mobility and being responsive to differential pressures (Stocklin and Setudehnia, 1971). The SC of three Group C springs with overlying Gachsaran Formation lies between 2350μS/cm and 12100μS/cm, with an average chloride concentration of 47.0 meq/litre. Salt domes cropping out in the catchment area of these springs are the source of the salinity.

In 18 springs the combined AJ formations are bounded by the underlying Sachun Formation and the overlying Razak Formation. Fifteen of these springs are classified in Group S and three in Group C (Table 4). SC ranges from 1260 to 1850μS/cm in Group S. Massive gypsum and marls of the Sachun Formation at the contact with the AJ formations are the main cause of water deterioration in Group S. The Razak Formation is not the cause of low water quality because, as discussed, the springs emerging from the AJ formations sandwiched between the Razak and Pabdeh formations are classified in groups B_1 and B_2. SC of three springs in Group C ranges from 5670 to 5750μS/cm. Salt dome outcrops in the catchment area of these springs are the source of chloride. Water type of the AJ springs

Main groups	Karst formations	Water type	SC (μS cm^{-1})	Q (LS^{-1})	No. of springs	Ca	Mg	Na	HCO_3	SO_4	Cl	Ca/Mg
B_1	DGF	HCO_3 – Ca	364 – 451	14 – 344	18	2.2	0.6	0.4	2.6	0.2	0.5	4.3
	Sa	HCO_3 – Ca	190 – 500	5 – 3112	31	2.1	0.4	0.2	2.2	0.3	0.4	5.3
	Ta	HCO_3 – Ca – Mg	249 – 356	5 – 30	5	2.1	1.2	0.2	2.8	0.2	0.4	1.7
	AJ	HCO_3 – Ca – Mg	260 – 500	5 – 2855	58	2.0	1.6	0.2	3.0	0.5	0.4	1.6
B_2	Sa	HCO_3 – Cl HCO_3 – SO_4 HCO_3	510 – 1160	5 – 127	11	3.6	3.0	3.3	5.0	2.0	2.7	1.2
	AJ	HCO_3 – SO_4 HCO_3	500 – 1060	5 – 2800	32	2.8	2.1	0.8	3.2	1.7	0.7	1.3
S	AJ	SO_4 SO_4 – Cl	1260 – 1850	5 – 163	23	9.0	5.5	3.2	3.0	10.3	3.8	1.6
	Gu	SO_4	1190 – 1510	5 – 20	3	5.8	5.7	1.4	3.1	8.2	1.4	1.0
C	Sa	Cl	2720 – 9910	12 – 66	7	10.7	10.1	35.0	2.5	8.0	49.8	1.1
	AJ	Cl	2350 – 13500	12 – 98	7	14.3	8.8	26.6	2.1	13.2	34.5	1.6

Table 3. Water types, number of springs, discharge, SC range and major ions of karst formations in each group. Unit of concentration is meq/litre.

Main Groups	Underlying Formation		Overlying Formation		Type of water	SC Range ($\mu S\ cm^{-1}$)
	Formation	No. of Springs	Formation	No. of Springs		
B_1	Pabdeh	58	Razak	55	$HCO_3 - Ca - Mg$	260 – 500
			Gachsaran	3	$HCO_3 - Ca - Mg$	350 – 390
B_2	Pabdeh	32	Razak	23	$HCO_3 - SO_4$	500 – 1010
			Gachsaran	9	$HCO_3 - SO_4$	520 – 1150
S	Pabdeh	8	Gachsaran	8	SO_4 (6), $SO_4 - Cl$ (2)	1270 – 1680
	Sachun	15	Razak	15	SO_4 (9), $SO_4 - Cl$ (6)	1260 – 1850
C	Sachun	3	Razak	3	Cl	5670 – 5750
	Pabdeh	4	Gachsaran	3	Cl	2360 – 12100
			Razak	1	Cl	13500

Table 4. *Number of springs in each spring group in each formation overlying and underlying the combined Asmari-Jahrum formations.*

is bicarbonate-dominant, except where affected by neighbouring evaporite formations, salt domes and/or saline water intrusion.

GURI MEMBER

The three karst springs of the Guri Member of the Mishan Formation are categorized in Group S, with SC values ranging from 1190 to 1510µS/cm and an average sulphate content of 8.2 meq/litre (Table 3). Ca/Mg molar ratios of the springs are less than 3, which is unexpected in the Guri Member with its limestone lithology. In spite of the dominant limestone lithology of the Guri Member, the presence of bands of marlstone and marl, the small thickness (112m) of the Guri Member among the other studied karst formations, and the lithologies of adjacent formations (marl and gypsum in the Gachsaran Formation and marls in the Mishan Formation) contribute to a relative increase of sulphate concentration and the absence of bicarbonate water-type.

CONCLUSION

The water quality of karst springs depends on the lithology of neighbouring formations. If the lithologies of the neighbouring formations are marlstone, silty limestone, argillaceous limestone, marly limestone and/or marl with limited outcrop area on the karst formations, the water quality is not reduced. In such cases, the chemistry of karst springs is controlled mainly by the lithology of the water route inside the karst formation and the type of water is bicarbonate (Group B_1). As the marl or marly limestone on the karst formations increases, the water type may change from bicarbonate (Group B_1) to bicarbonate-sulphate (Group B_2). If gypsum and anhydrite are the contact lithology of neighbouring formations, the water type is bicarbonate-sulphate (Group B_2) or sulphate (Group S) depending upon the extent of the outcrop area of gypsum and anhydrite on the karst formations. Intrusion of saline water from neighbouring lakes or alluvial aquifers into karst aquifers, and the mixing of saline water from salt domes with the karst water are the main sources of chloride-type waters. It appears that the lithology of overlain and underlain formations can influence the chemical characteristics of karst water, provided that the layers have elevated marl, gypsum and/or salt. To what extent the chemical influences exerted by overlain or underlain formations affect the karst water needs more data, because the influences of the layers are to some

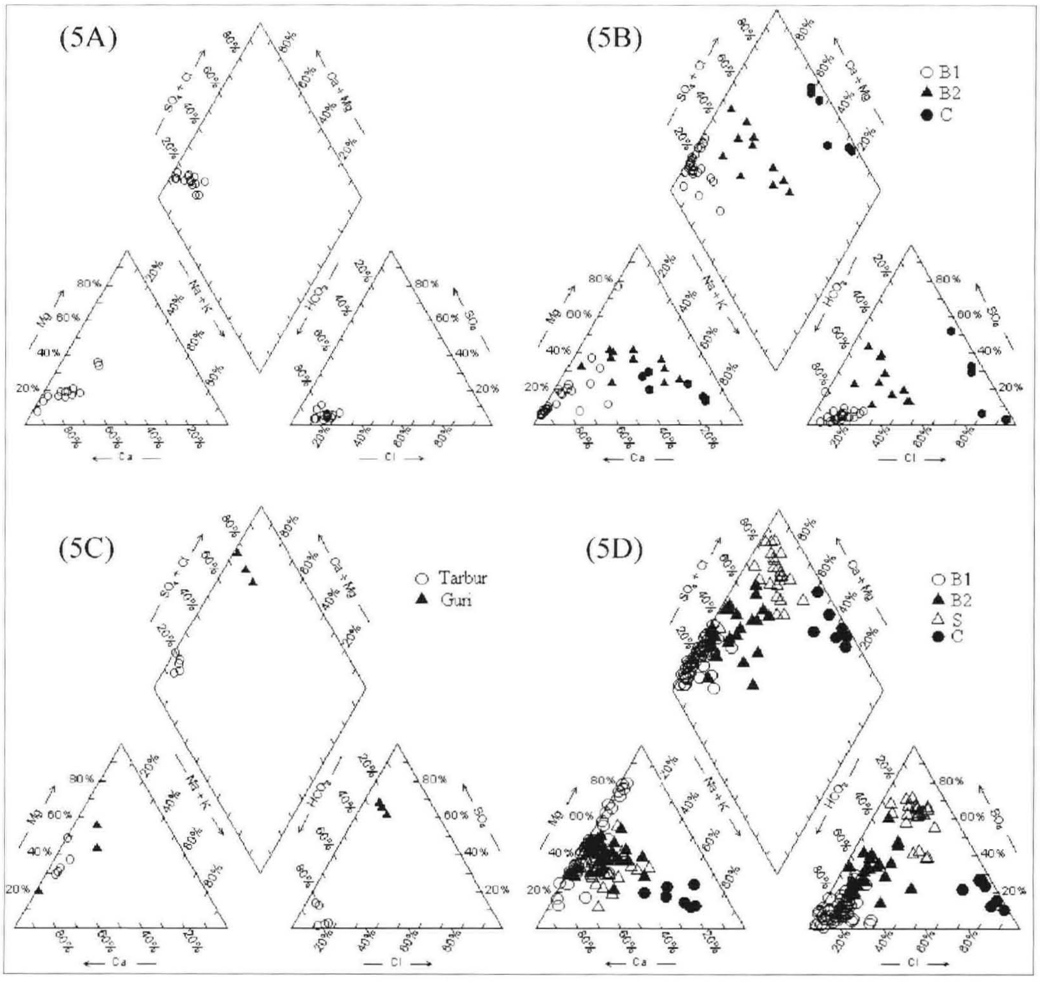

Figure 5: *Piper diagram for springs of A) Dariyan-Gadvan-Fahliyan, B) Sarvak, C) Guri and Tarbur, and D) Asmari-Jahrum formations.*

extent similar. The karst water is influenced by surface drainage entering the aquifer and by subsurface contact with neighbouring layers.

Ca/Mg molar ratios of groups B_2, S and C are less than 3 in all karstic formations, which is unexpected in the Sarvak Formation and Guri Member with their limestone lithology. It can thus be concluded that the Ca/Mg molar ratio can distinguish the type of lithology of the water route in karstic springs if the water type is bicarbonate and the SC is less than about 500μS/cm.

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REFERENCES

Alavi, M. 2004. Regional stratigraphy of the Zagros Folds-Thrust Belt of Iran and its proforeland evolution. *American Journal of Science*, Vol.304, 1–20.

Alberto, W D, Del Pilar, D M, Valeria, A M, Fabiana, P S, Cecilia, H A and De los Angeles, B M. 2001. Pattern recognition techniques for the evaluation of spatial and temporal variations in water quality, a case study: Suquia River Basin (Cordoba–Argentina). *Water Resources*, Vol.35, 2881–2894.

Aley, T. 2000. Water and landuse problems in areas of conduit aquifers. 481–484 *in* Klimchouk, A B, Ford, D C, Palmer, A N and Dreybrodt, W (eds), *Speleogenesis: Evolution of Karst Aquifers*. [Huntsville: National Speleological Society.]

Andreo, B and Carrasco, F. 1999. Application of geochemistry and radioactivity in the hydrogeological investigation of carbonate aquifers (Sierras Blanca and Mijas, southern Spain). *Applied Geochemistry*, Vol.14 (3), 283–299.

Appelo, C A J and Postma, D. 2005. *Geochemistry groundwater and pollution (2nd edition)*. [Amsterdam: Ben Akkerman.] 649pp.

Ashjari, J and Raeisi, E. 2006. Influences of anticlinal structure on regional flow, Zagros, Iran. *Journal of Cave and Karst Studies*, Vol.68(3), 118–129.

Darvichzadeh, A. 1991. *Geology of Iran*. [Tehran: Amirkabir.] 901pp.

Ford, D C and Williams, P W. 1989. *Karst geomorphology and hydrology*. [London: Unwin Hyman.] 601pp.

Giri, N C. 1977. *Multivariate statistical inference*. [New York: Academic Press.] 420pp.

Güler, C and Thyne, G D. 2004. Hydrologic and geologic factors controlling surface and groundwater chemistry in Indian Wells–Owens Valley area, southeastern California, USA. *Journal of Hydrology*, Vol.285(1–4),177–198.

Gunn, J, Bottrell, S H, Lowe, D J and Worthington, S R H. 2006. Deep groundwater flow and geochemical processes in limestone aquifers: evidence from thermal waters in Derbyshire, England, UK. *Hydrogeology Journal*, Vol.14, 868–881.

Hem, J D. 1985. *Study and interpretation of the chemical characteristics of natural water*. [U.S. Geological Survey Water-Supply: Paper 2254] 264pp.

James, G A and Wynd, J G. 1965. Stratigraphic nomenclature of Iranian Oil Consortium Agreement area. *Bulletin of American Association of Petroleum Geologist*, Vol.49(12), 2182–2245.

Jahani, H R. 1994. *Role of lineaments in groundwater flow in folded karst area*. Unpublished MSc thesis, Department of Geosciences, Shiraz University.

Karimi, H. 1998. *Hydrogeological and hydrochemical evaluation of springs and piezometers of Podenow anticline, Firoozabad*. Unpublished MSc thesis, Department of Geosciences, Shiraz University.

Karimi, H. 2003. *Hydrogeological behavior of the Alvand Basin karst aquifers, Kermanshah* . Unpublished PhD thesis, Department of Geosciences, Shiraz University.

Karimi, H, Raeisi, E and Zare, M. 2005. Physicochemical time series of karst springs as a tool to differentiate the source of spring water. *Carbonate and Evaporites*, Vol.20(2),138–147.

Karst Research Centre of Iran. 1993. *Comprehensive study and research in water resource of the Maharlu Basin (Fars)*. Vol.1–4.

Karst Research Centre of Iran. 1995. *Comprehensive study and research in water resource of the Bakhtegan Basin (Fars)*. Vol.1–6.

Karst Research Centre of Iran. 1996. *Comprehensive study and research in water resource of the Kazerun area and Persian Gulf Beach Basin*. Vol.1–4.

Karst Research Centre of Iran. 2000. *Comprehensive study and research in water resource of the Haji-Abad Basin (Hormozgan)*. Vol.1–5.

Keshavarz, T. 2003. *Study on the karstic artesian aquifers in Khersan 3 dam site*. Unpublished MSc thesis, Department of Geosciences, Shiraz University.

Kowsar, N. 1995. *Speleogical and hydrogeological study of Shapour cave*. Unpublished MSc thesis, Department of Geosciences, Shiraz University.

Krothe, N C and Libra, R D. 1983. Sulfur isotopes and hydrochemical variations in spring waters of southern Indiana. *Journal of Hydrology*, Vol.61, 267–283.

Lam-Hoai, T and Rougier, C. 2001. Zooplankton assemblages and biomass during a 4-period survey in a northern Mediterranean coastal lagoon. *Water Resources*, Vol.35, 271–283.

Li, S, Liu, C, Tao, F, Lang, Y and Han, G. 2005. Carbon biogeochemistry of ground water, Guiyang, Southwest China. *Ground Water*, Vol.43(4), 494–499.

Lopez-Chicano, M, Bouamama, M, Vallejos, A and Pulido-Bosch, A. 2001. Factors which determine the hydrogeochemical behavior of karstic springs. A case study from the Betic Cordillera, Spain. *Applied Geochemistry* , Vol.16, 1179–1192.

McQuarrie, N. 2004. Crustal scale geometry of the Zagros fold-thrust belt, Iran. *Journal of Structural Geology*, Vol.26, 519–535.

Marfia, A M, Krishnamurthy, RV, Atekwana, E A and Panton, W F. 2004. Isotopic and geochemical evolution of ground and surface waters in a karst dominated geological setting: a case study from Belize, Central America. *Applied Geochemistry*, Vol.19, 937–946.

Miliaresis, G C. 2001. Geomorphometric mapping of Zagros Ranges at regional scale. *Computers and Geosciences*, Vol.27, 775–786.

Naseri, H R. 1991. *Hydrogeological study of karst springs of Drudzan Dam catchment*. Unpublished MSc thesis, Department of Geosciences, Shiraz University.

Pezeshkpour, P. 1991. *Hydrogeological and hydrochemical evaluation of Kuh-e- Gar-Barm-Firooz springs*. Unpublished MSc thesis, Department of Geosciences, Shiraz University.

Raeisi, E and Karami, G. 1996. The governing factors of the physicochemical characteristics of Sheshpeer karst springs, Iran. *Carbonates and Evaporites*, Vol.11, 162–168.

Raeisi, E and Karami, G. 1997. Hydrodynamic of Berghan karst spring as indicators of aquifer characteristics. *Journal of Cave and Karst Studies*, Vol.59(3), 112–118.

Raeisi, E. and Kowsar, N. 1997. Development of Shapour Cave, Southern Iran. *Cave and Karst Science*, Vol.24(1), 27–34.

Raeisi, E and Moore, F. 1993. Hydrochemistry of Karst spring from two carbonatic units in Zagros sides of Iran. *Journal of Sciences, Islamic Republic of Iran*, Vol.4(4), 302–307.

Raeisi, E and Nejati, M H. 2000. Study of the source of salinity in the Gomban karst spring, southern Iran. *Carbonates and Evaporites*, Vol.15 (2), 115–120.

Raeisi, E, Pezeshkpour, P and Moore, F. 1993. Characteristics of karst aquifers as indicated by temporal changes of the spring's physicochemical parameters. *Iranian Journal of Scienceand Technology*, Vol.17(1), 17–28.

Raeisi, E, Rezaie, M and Zare, M. 1998. The source of low quality of karstic springs, Rahmat Anticline, Iran. *Proceedings of Geological Society of Iran, 3rd, Shiraz, Geosciences Department of Shiraz University*, 231–234.

Rahimi, M. 2006. *Effect of rainfall, temperature, geological factors and baselevel of erosion on characterstics of Asmai-Jahrum Formations in central south of Iran*. Unpublished MSc thesis, Department of Geosciences, Shiraz University.

Rahnemaie, M. 1994. *Evaluation of infiltration and runoff in the karstified carbonate rocks*. Unpublished MSc thesis, Department of Geosciences, Shiraz University.

Rajaei, A. 1999. *The study on watertightness of karstic formations in Mirzayeh Shirazi (Kavar) Dam*. Unpublished MSc thesis, Department of Geosciences, Shiraz University.

Ravichandran, S. 1987. Water quality studies on Buckingham Canal (Madras, India) a discriminant analysis. *Hydrobiologia*, Vol.154, 121–126.

Reghunath, R, Sreedhara-Murty, T R and Raghavan, B R. 2002. The utility of multivariate statistical techniques in hydrogeochemical studies: An example from Karnataka, India. *Water Resources*, Vol.36, 2437–2442.

Rezaei, M. 1998. *Hydrogeology of chloride karstic springs in Rahmat anticline*. Unpublished M.Sc. thesis, Department of Geosciences, Shiraz University.

Rezaei, M, Sanz, E, Raeisi, E, Ayora, C, Vázquez-Suñé, E and Carrera, J. 2005. Reactive transport modeling of calcite dissolution in the fresh-salt water mixing zone. *Journal of Hydrology*, Vol.311(1–4), 282–298.

Stocklin, J and Setudehnia, A. 1971. *Stratigraphic Lexicon of Iran*. [Geological Survey of Iran: Report 18-1971] 370 pp.

Tooth, A F and Fairchild, I J. 2003. Soil and karst aquifer hydrological controls on the geochemical evolution of speleothem forming drip waters, Crag Cave, southwest Ireland. *Journal of Hydrology*, Vol.273, 51–68.

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Poldi Fuhrich (1898–1926): female pioneer of severe cave exploration.

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Abstract: Poldi Fuhrich (1898–1926) of Salzburg became one of the leading cave explorers of the 1920s, a remarkable achievement for a woman at that time. Each year from 1919 to 1925 she was in the front line of new exploration in Austria's Eisriesenwelt. In 1925 she was one of the surveyors in the Poulnagollum river cave in Ireland, and she also visited caves in France, Germany, Moravia, Dalmatia, Slovenia and Brazil. Her unpublished documents and photographs from 1921, when she was working deep in Škocjanske jame, reveal much about Robert Oedl's surveying methods and about their Slovene assistants. At the age of 28 she died in a cave accident while exploring the Lurgrotte in Austria.

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INTRODUCTION

Poldi Fuhrich[1] was probably the first woman anywhere in the world to take part in especially difficult exploration, some of it original, in many caves. It was at a time (1919–1926) when women were still not encouraged to participate in such activities.

As will be seen, she was a key member of the team extending the great Eisriesenwelt ice cave in Austria, a cave that was testing the then limits of exploration techniques. She worked also in the far reaches of the exceptionally difficult Škocjanske jame river cave in Slovenia, and she met her death at the age of 28 during exploration of the long Austrian cave Lurgrotte. In addition, she joined explorers in many other parts of Europe and in Brazil, to visit their caves. Personal recollections emphasize her enthusiasm, personality, ability, strength and courage. The impression she made in Ireland in 1925 remains particularly vivid.

Her work is considered in more detail below, but at this stage it is appropriate to place her activity in the context of what was normal for women at that time. Women were not altogether excluded from cave exploration in the 1920s, as they were from most golf clubs for example, but many cave clubs would not accept them as members, in the same way as many scientific societies had previously excluded them. In England the University of Bristol Spelaeological Society was unique when it was formed in 1919, in that women were admitted[2]. The Küstenland (Trieste) section of the Deutscher und Österreichischer Alpenverein, which explored Škocjanske jame from 1884 until World War I, did accept women members, but they did not participate in the exploration.

Until 1919 the few women to make difficult explorations were taken, or lowered by winch, into known caves. Perhaps the first of these was made by Lady Elizabeth Berkely Craven[2a] who, in 1786, was taken into a cave on the Greek Island of Antiparos. There were two rope ladders, and a rope handline was necessary in other steep places. Notable also was Lily Ellen May Johnson (1879–1963), who went down the English caves Eldon Hole (61m) in 1904, Gaping Gill (103m) in 1904 and 1908 and Alum Pot (73m) in 1908[3]. All these descents would have been made by winch or rope ladder. In 1921, when Poldi was at the height of her power, Dina Dobson (1885–1968) of Bristol was noted for being the first woman to descend the 12m ladder pitch with a waterfall in Swildon's Hole[4]. In 1930, after Poldi Fuhrich's achievements were known, Hela Krajač (b. 1889) descended the 120m pitch of Jama Varnača in the Velebit (Dalmatia)[5].

Among the Salzburg explorers of Eisriesenwelt from 1919, however, women, though a minority, were not an exception[6, 7]. Besides Poldi, there was Marta Biebl (1902–1998) who later married Friedrich Oedl (1894–1969) who led the explorations of the cave and arranged it for public visits. She was the mother of the late Friedrich Oedl (1925–2006), an important source of information for this paper. A Kathe Oedl is also listed among the explorers of 1919[6].

Nevertheless, in the wider world women cave explorers were still regarded as rarities, if not curiosities. Thus even in 1934 the survey of Poulnagollum cave in Ireland was reported as "by two Austrians (one a lady)"[8]. One of her obituaries[9] stated *"she is the first internationally known woman cave explorer"*.

It must be emphasized here, however, that Poldi's reputation is not dependent on her being female. She earned it by her own achievements and personality during the seven years before her

Figure 1. *Poldi Fuhrich, a portrait by A Asal in 1922[27]. A close friend[9] makes much of her normally joyous nature, so it seems she did not like sitting for a formal portrait.*

Figure 2. *A silver version of this badge (27mm wide) was awarded to Poldi Fuhrich in 1924. In recent years a similar badge in bronze, with the Society's name replaced by 'Ursus spelaeus', has been used as a membership badge.*

untimely death. It was all the more remarkable because at that time she was not following a normal path, for there were no previous examples to follow. She had the good fortune to be among colleagues, some of the foremost cave explorers of the period, who did not regard her as an oddity and who accepted her gratefully for what she was.

Sources for this study are sparse. Apart from the informative obituaries, there are printed accounts of the Eisriesenwelt and Lurgrotte explorations and, for the former, there are lists of participants in each of the main expeditions[6]. There also exists one short manuscript account[10] written by Poldi, summarizing her activities in 1924. For her part in the Škocjanske jame work of 1921 nothing has been published except a single paragraph in some Austrian newspapers[11], but it can be deduced in the unpublished doctoral thesis[12] of her colleague Robert Oedl, and from a remarkable series of original photographs by his brother Friedrich[13] (often called Fritz, the more familiar version of the name). A list of some of his photographs is held by the Verein für Höhlenkunde in Salzburg and this provides the dates on which they were taken.

It is for this reason that special attention is given here to Škocjanske jame. Not only do these sources provide vivid information and images of Poldi's activities there, but they also give previously unpublished information about the surveying undertaken there by Robert Oedl in the following year.

In addition to these sources there is almost certainly other unpublished material that has not yet been located. As Poldi wrote her summary of what she did in 1924[10], it is likely that similar acccounts exist somewhere for other years. A diary is known to have been written for her 1925 visit to caves in Brazil, but it cannot now be found; and if there is one diary, there are probably others. Perhaps this paper will stimulate Austrian karst historians to search further.

POLDI FUHRICH

Leopoldine Fuhrich[14, 15] (Fig.1), almost always known as Poldi, was born at Salzburg in 1898, some time before 22 May[16]. In November 1922 she was listed in the membership list of the Speleological Society of Wien as a student at Wien University[17], where she studied zoology, botany and physical education[9]. At one time she taught

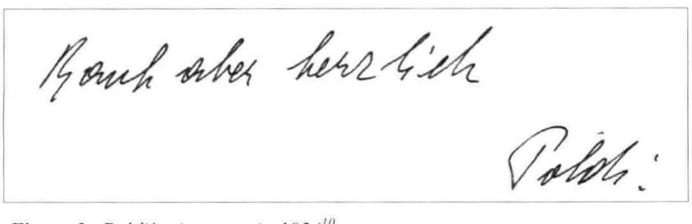


Figure 3. *Poldi's signature in 1924[10].*

biology and physical training at the Realgymnasium (high school) for girls at Hietzing in Wien. Her teaching was enhanced by stories of her own experiences in Austria and abroad, and she was considered one of the hardest working and most capable of the young women teachers. She enjoyed athletics and was a capable mountain walker and skier[14]. Her biological interests from university remained, for the fauna and flora of Lurgrotte were one of the reasons for her fatal visit there in 1926[18].

At the age of 21, in 1919, she joined in the first of her major exploring expeditions in the now 40km-long Eisriesenwelt, the largest ice cave in Austria. She hardly ever missed explorations in that cave and soon she was familiar with many other Alpine caves[14]. In Eisriesenwelt she made some explorations by herself and she frequently substituted as a cave guide there[9].

As her reputation grew, she was invited to karst regions in other countries including Ireland and Brazil. These experiences broadened not only her knowledge of caves but also of exploration techniques[14]. In August 1924 at the early age of 26 she was awarded the silver Höhlenplakette (cave badge) (Fig.2) of the Hauptverband Deutscher Höhlenforscher at a meeting in Nürnberg[15].

Her obituary writers[9, 14] emphasize her positive outlook on life, her humour, infectious enthusiasm, single-mindedness when appropriate, and modesty: *"she hated it when her achievements were lauded in public"*[9]. She must have been a great personal loss, as well as a loss to the cave world.

Poldi's summary of her 1924 cave activities[10], sent to her friend and colleague Erwin Angermayer (1888–1963) provides us with a specimen of her handwriting (Fig.3).

Her cave work is, of course, the subject of the rest of this paper, and her death in the Lurgrotte on 23 May 1926 will be described.

ROBERT OEDL

It is convenient also to summarize the life of Robert Oedl at this stage, for he was a colleague of Poldi, working with her in Eisriesenwelt for several years and having her as his professional companion during his 1921 visit to Škocjanske jame. He and Erwin Angermayer were probably the people closest to her, influencing her and in turn being affected by her energy and enthusiasm.

Franz Robert Oedl was known only as Robert Oedl[17] until quite late in life when he started to use the Franz as well[19, 20]. He was born in the same year as Poldi (1898)[20] and died in his 80th year on 10 January 1978[21, 22, 23, 24]. He had begun exploring caves in 1913 while still at school. After serving in the Navy in World War I he graduated as an engineer at the Technical University of München in 1922 and in 1924 he gained his engineering doctorate there for his thesis on Škocjanske jame[12]. This was based on work he did there in September 1921 (with Poldi) and April 1922, and involved much surveying both underground and in the dolines on the surface. He is seen in Figs 7 and 10.

Already in 1920 he had been surveying in Eisriesenwelt where he, too, was one of the exploring team for many years. In 1923 he was appointed to manage the state-owned tourist caves of Dachstein, exploring, surveying and preparing them for tourists[25]. In 1955 he commissioned the cable car system at Eisriesenwelt to facilitate access to the cave.

EISRIESENWELT, 1919–1925

The entrance to this, perhaps the most important ice cave in the world, is at an altitude of 1656m, 34km from Salzburg. First noticed in 1879, serious exploration started in 1913 but was halted by World War I. From 1919 one or more expeditions took place each year and Poldi was certainly part of the exploring team in 1919[6], 1920[26], 1921[27], 1922[6], 1924[10] and 1925[26]; and probably also in 1923. These expeditions were at the then limits of technically possible. The dates of discovery of the very extensive new passages and halls are recorded on the successive versions of the 1:3000 published survey by Walter Czoernig and Robert Oedl: thus to the Dom des Grauens in 1919[28], to Tropfsteindom in 1920[29], to the Trümmerhalle in 1921[29], etc. One place is named Poldi Dom[6]; another, Poldischluf.

Also present in 1924 was the Australian, George Elliot Barton[10, 30], who is mentioned again in connection with Poldi's visits to Moravia, Dalmatia, Brazil and Ireland.

ŠKOCJANSKE JAME, 1921–1922

Poldi Fuhrich was at Škocjan from 6 to 16 September 1921, together with Robert Oedl, who was working for his doctoral thesis. With them was Robert's older brother Friedrich (1894–1969)[31], who took many photographs[13], which are valuable for placing just where in Škocjanske jame they were working and who was there with them[32]. Among those present was Anton Meeraus (1892–1979)[33], formerly of the Deutsche und Österreichische Alpenverein Küstenland section at Trieste and then of its successor, the Circolo Alpino Trieste, who made the visit possible. Meeraus had already in 1913 been adding to the earlier survey of the cave made by Hanke and Marinitsch[34, 35]. He was also involved in the Eisriesenwelt exploration, where the Meeraus Labyrinth, discovered in 1921, was named after him.

Nineteen of Friedrich Oedl's photographs show Poldi Fuhrich, Robert Oedl and Anton Meeraus in the cave[13]. Those taken deep inside the cave are known to have been taken on 9 September[27]. In Fig.4 a wooden boat[36] is being carried down to the underground river at the far end of Martelova dvorana (Martel Hall) to enable the explorers to pass across the Martelovo jezero (Martel Lake) into Marchesettijeva dvorana. In Fig.5[37] the boat is afloat in Mrtvo jezero (Dead Lake), even further into the cave; and in Fig.6 the explorers, still with bare feet after the boat journey, are attempting to climb up a fissure in the Mrtvo jezero chamber, using some of the driftwood that commonly accumulates there. Poldi Fuhrich is prominent in all three of these pictures.

It should be remembered that the distance from the cave entrance to Mrtvo jezero (Figs 5 and 6) is 2080m and that the way there is so difficult that it took six years of exploration (1884–1890) for the original explorers to reach it. Much of the route uses narrow ledges with iron handrails some 20m above the river on the vertical walls of the canyon whose total height varies from 75m to 146m. The 1921 explorers' boat would have avoided these for part of the way, but it was still a difficult journey.

The two Oedl brothers were in the cave again at Easter 1922. They were then mainly occupied with surveying[38], though some had already been done in the previous year when Poldi was with them (see Fig.7). This little-known survey work deserves special attention here.

Besides the intrinsic difficulties of surveying in a large cave, they operated under extra constraints because of the sensitive political situation close to the new Jugoslav/Italian border so soon after the end of the war. Despite formal approval from the Italian consulate in Münich to bring their instruments into the newly Italian territory, they found it prudent to use unobtrusive apparatus so as to attract little attention, especially when working on the surface in daylight.

Time for surveying was also limited as there was also much other work to do, such as research and photography. It was impossible to resurvey the whole cave and, in any case, they recognized the quality of the previous Austrian work by Hanke and Marinitsch. So, for much of the cave they made only repeat measurements to verify the accuracy of the earlier survey. They used theodolites and steel tapes where the survey points were roomy enough. When tripods could not be used, hand-held Brunton pocket compasses and clinometers were used. These checks generally confirmed the previous survey, though it is strange that they did not detect the gross error where it gave the wrong orientation to the Hanke Kanal passage. They did however resurvey the dry passiages of Tiha jama and also the very end of the river cave from Martelova dvorana to Mrtvo jezero (Fig.8). In this last the orientation of the passage is correct, in contrast to the Hanke-Marinitsch plan.

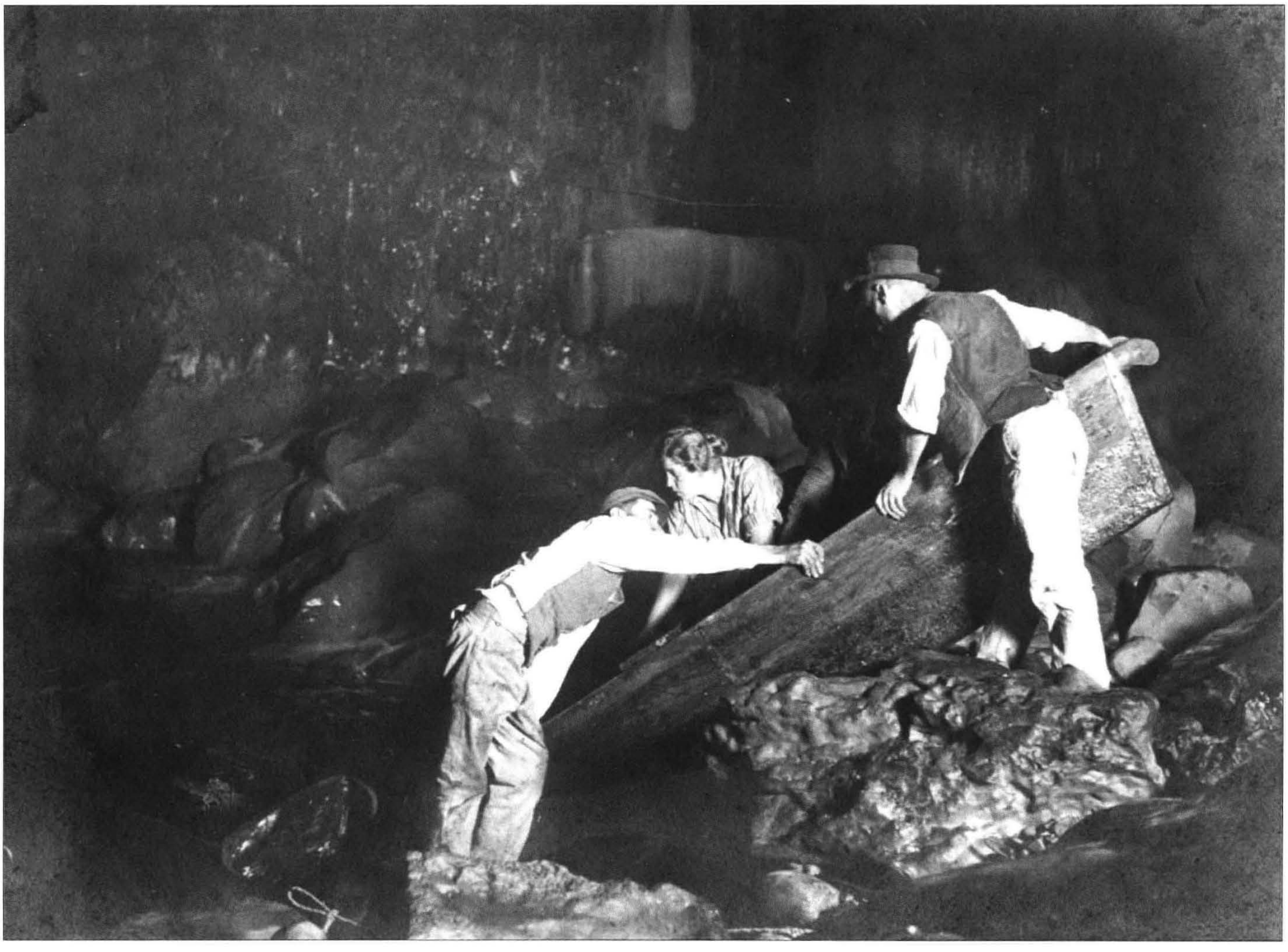


Figure 4. *Moving the boat towards the river in Martelova dvorana, 9 September 1921[27] (photograph by F Oedl). From left to right: Franc Cerkvenik, Miklov; Poldi Fuhrich; Janez Delez, Žvnkov.*

Figure 5. The boat on Mrtvo jezero, 9 September 1921[27] (photograph by F Oedl). From left to right Anton Meeraus; Poldi Fuhrich; Franc Cerkvenik, Miklov.

Oedl considered that the two main dolines, Velika and Mala dolina, had not previously been mapped in sufficient detail. He did not have time for a full tachymetric survey so he combined a theodolite survey with a stereophotogrammetric record, using a stereo-comparator for the plate pairs. The resulting plan and elevation[39] included also the large underground chambers Schmidlova dvorana, Rudolfova dvorana and Svetinova dvorana, but these are not based on stereophotogrammetry. Even his newly made plan of the Mrtvo jezero area (Fig.8) marks the locations of camera positions and directions as if the technique were used there also.

Oedl's detailed measurements of the great passages near the entrance enabled him to construct a 3-dimensional model of that part of the cave at a scale of 1:500. The model itself at the Deutsches Museum at München was destroyed by bombing during World War II, but a photograph of it survived (Fig.9). Škocjanske jame seems to have inspired production of hollow models of that kind, including one, at the same scale, made in 1894 by Franz von Hopfgartner, who was a member of the Section Küstenland, which was surveying the cave at that time. The original is in the Civici Musei di Storie ed Arte in Trieste and a copy of it is displayed in the museum at Škocjanske jame. Unlike Oedl's later model it is almost entirely restricted to the land surface and the great dolines. Another model showing the whole length of the cave, was made between 1929 and 1933 for exhibition at the first Italian Congreso Speleologico Nazionale, held at Trieste in 1933[40]. Both these models are now exhibited in the museum of Park Škocjanske jame, but of course not the one made by Robert Oedl. Such models seem to be unknown elsewhere, although "negative" models (i.e. with the cave shown as solid and the surrounding rock as empty space) were produced in Australia by Oliver Trickett, one before 1912 and another about 1920[41].

Also present with the 1921 party were at least three local cave workers or guides, shown standing in Fig.10 as well as being involved in the activities recorded in Figs 4, 5 and 6. Commonly these people were left unnamed in the contemporary literature. Often they are just described as "Grotten-Arbeiter" (cave workers) or are mis-named[42]. Those who accompanied Poldi Fuhrich and the Oedls have now been positively identified by showing enlarged copies of the photographs to the older inhabitants of the villages of Škocjan and Matavun who remembered them in later life. These invaluable independent sources were Janko Gombač (b. 1917) and his wife Milka, Milena Lipold (b. 1922) and Albina Bak.

Another difficulty arises in distinguishing between different people of the same names, for there were several branches of these families in the villages and two of the three helpers in 1921 had identical names. They are distinguished locally by adding the name of the family house, e.g. Vnckov, after an early owner of the house. As these names are not shown on the houses, the present house number is added here. The three Slovene companions of the Austrians were:

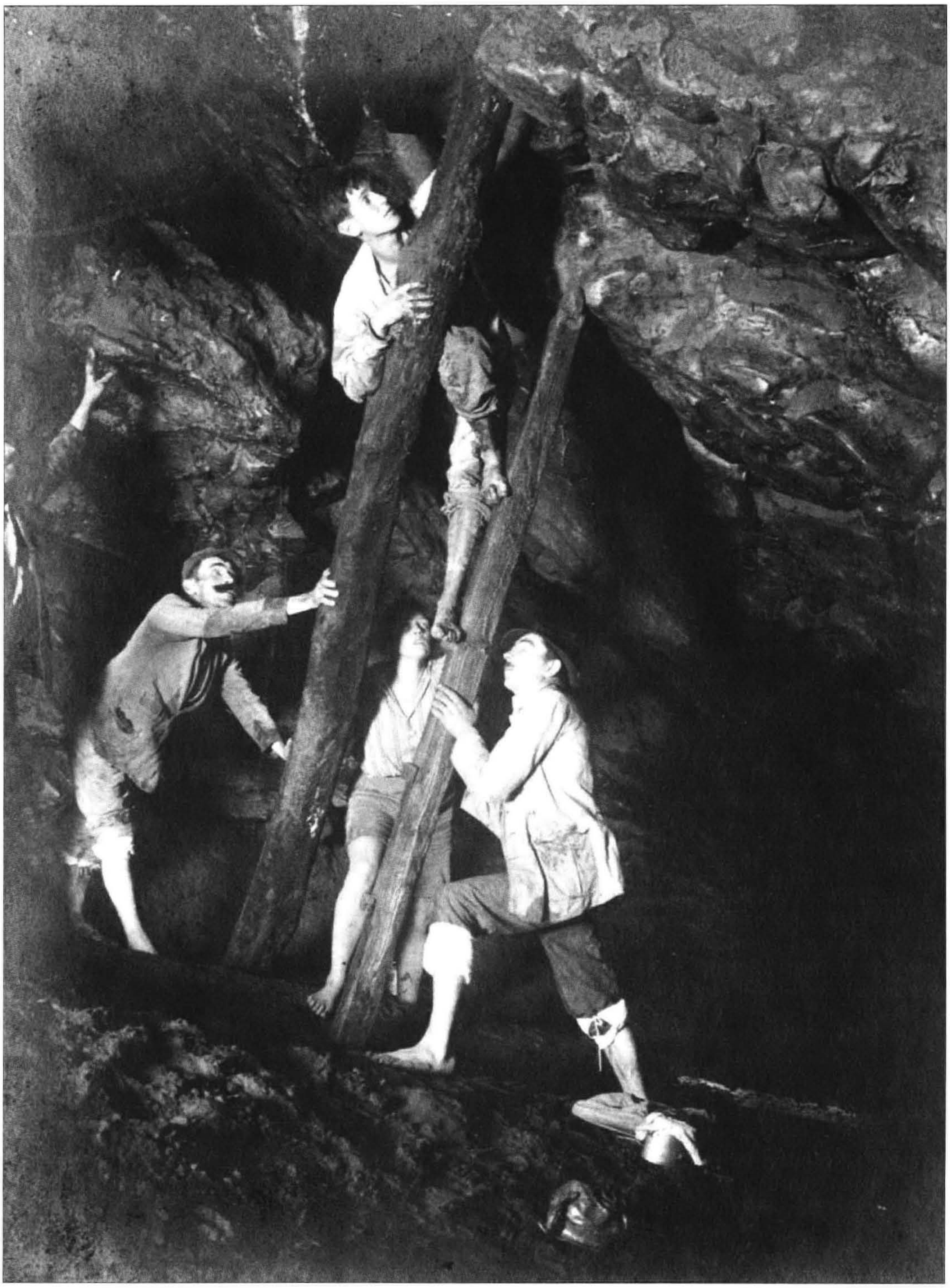
- Franc Cerkvenik, Miklov (Matavun 6) 1875–1948. (He was sometimes called by the nickname Mikulič);
- Franc Cerkvenik, Vnckov[43] (Matavun10) 1897–1924[44];
- Janez[45] Delez, Žvnkov (Škocjan 10) 1889–1968.

GERMANY, CZECH REPUBLIC, FRANCE, DALMATIA AND PERHAPS SLOVENIA ALSO, 1922–1925[12]

Grouped together in this section are some foreign visits by Poldi Fuhrich about which very little is known.

The fact that she visited karst caves in Germany is mentioned in obituaries[9, 14] but no year or other information is given.

Figure 6. Climbing near to Mrtvo jezero, using driftwood from the river, 9 September 1921[27] (photograph by F Oedl). From left to right: Franc Cerkvenik, Miklov; Poldi Fuhrich; Anton Meeraus (above); Franc Cerkvenik, Vnckov.



In 1922 she went to Moravia and Bohemia[46] and then returned to Moravia in 1924, accompanied this time by George Elliot Barton[46A]. Her own manuscript report[10] states that in that year she saw Absolon's karst museum in Brno and visited the caves of Sloup, Macocha, Kateřinska *"and the newly discovered Masaryk Cave"* in the Punkva system. *"Development work in these caves is very interesting"*. She went also into the undeveloped Hugonova Cave (Rudicke Propadán near Rudice): *"most interesting: one climbs down about 60–70m on ladders into the active river cave. There one walks for about an hour in the stream between high flowstone-covered walls with magnificent stalactites. They are working to extend the cave"*. Another cave she saw was the "Stierhöhle" (Býčí skála).

Some French karst was seen in 1923[46] and she herself[10] recorded that in 1924 she went to caves in southern France including Padirac, Lacave and Saute de la Pucelle, as well as to others at Rocamadour.

In 1925, probably in June or July, she was in Dalmatian caves with Friedrich Oedl and George Elliot Barton[47]. There is an unconfirmed report that she was in Slovenia also about that time. Walter Klappacher of Salzburg stated that *"a year before the Lurgrotte accident [i.e. in 1925] she became giddy when climbing [the ladder] out of Kačna jama"*[47A]. Certainly it would have been easy for the party to have gone to both Dalmatia and Slovenia in the same journey, as the two regions are quite close[47B]. Klappacher's source is evidently in the extensive archives of the Verein für Höhlenkunde in Salzburg, but it cannot readily be located[47C], so this question must be left unresolved at present. The main objective of this paper, to make the achievements of Poldi Fuhrich more widely known, is not affected, and an intriguing further study has been identified for a future researcher.

BRAZIL, 1923

Poldi visited karst in Brazil in 1923[46]. The copy of her obiturary by Angermayer[9] sent to me by the late Friedrich Oedl has a short manuscript addition (perhaps by him) where Brazil is mentioned: *"with Eliot Barton"*. Another obituary[14] states that she wrote up this visit in *"an extremely interesting diary"*. Alas, it has not been

Figure 7. *In Matavun village with surveying equipment and a rope ladder, 8 September 1921*[27]*. From left to right: Robert Oedl; Anton Meeraus; Poldi Fuhrich; Friedrich Oedl.*

possible to locate the diary, but it might still exist in Salzburg. Barton's presence in Brazil in that year is confirmed by Martel[48], who says that at the end of 1923 he received news about it from him[49].

George Elliot Barton[50] was an Australian who studied at Cambridge University from 1921 to 1924[51]. He had fought at Gallipoli in World War I[25] so he must have been born before 1890. He was a friend of Robert Oedl, who wrote *"he was a prominent, tough fellow who disappeared during an expedition into Tibet"*[25]. In Austria he worked with Robet Oedl in Eisriesenwelt and the Dachstein caves[52], and he explored caves in Mallorca[53], England, France, Dalmatia and Sumatra[54], and also in Ireland as we shall see.

IRELAND, 1925

The visit made by Poldi Fuhrich and Friedrich Oedl[55], Robert's elder brother, to Ireland during August 1925[56] is the only occasion for which we have an independent account of what they did and of the impression that Poldi, in particular, made on their English host, E A Baker. Opportunity will be taken to reprint extracts from his book.

Dr Ernest Albert Baker (1869–1941) was about 56 at the time, a literary historian, head of the London University School of Librarianship, and a well-known climber and cave explorer. It was George Elliot Barton[54] who brought the two Austrians to join Baker and himself for their visit to the karst of County Clare in Ireland, where they were to explore the long river cave of Poulnagollum.

As will be seen, Poldi was one of the surveyors of this wet cave. The main survey, plan and cross-sections, was first published in 1926 with a short report by Baker[57]and then again in his better-known book of 1932[58]. The visit was also the subject of a lecture given by Baker in 1928[59]. The survey covers a total passage length a little over 1500m according to a modern survey[60], which confirms the general accuracy of the 1925 work. With the addition of other passages surveyed in less detail, Baker gives an overall measured length of 8km. The total length now known is 10.3km[60]. Besides the survey work, Poldi also contributed seven of the photographs published in the book, one of them taken underground in the stream passage (Fig.11).

In the quotations from Baker's book[47] below, Poldi's name has been printed as Führich, with the umlaut as in the book, although this is not correct.

> [p.187] *Dr. Oedl and Miss Führich were as tough as he [Barton] and practised the same self-reliance. The three of them found me in the dining-room at Paddington, and I was presented to the lady. My luggage, comprising a sackful of rope ladders, had been deposited near the door, and whilst I was disengaging my things from the pile, Miss Führich, who already had an enormous Austrian rucksack weighing probably 50 lb. on her back, and another of similar weight and dimensions in one hand, picked up my sack of ladders in the other, and strode gaily off to the train. I could not but feel that Poulnagollum was as good as conquered. ...*
> [p.189] *Early next morning we descended the pot-hole, with plenty of spare rope for emergencies, and started work. Oedl and Miss Führich at once began a survey; Barton and I, as the spearhead of the party, went forward. The river was running strongly, but this was no disadvantage, except that it was very chilly ... Moving rapidly, we reached the point attained in 1912, and pushed forward into the unknown ...* [p.195] *we had been underground nearly twelve hours.*
>
> *The next few days were otherwise but hardly less actively employed. There were a host of swallets and minor fissures to be examined round about, to complete our knowledge of this huge water-system. ...*
> [p.196] *Another visit was paid to Poulnagollum five days later, principally in order to complete the survey. ... I left the other three now to go on with the survey, and spent the day photographing outside. They were fourteen hours below – presumably not without food – and obtained all the horizontal and vertical measurements necessary for the map eventually produced by Dr. Oedl. This comprises the main cavern to a point well beyond the junction, together with the tributary cave that starts from Poulnaelva. But they also followed up and surveyed, though not in such minute detail, a number of subsidiary passages, and found that these made a total extent of five miles, three times as much as either the underground system at Mitchelstown or that at the bottom of Gaping Ghyll, till now the two longest caverns known in the British Isles.*
>
> *Our next business was to deal with the long range of sea-caves in the limestone coast of the cliffs of Moher.*

LURGROTTE, 1926

Although Poldi Fuhrich made herself familiar with many of the caves of Europe and even of Brazil, most of her more difficult exploration was done relatively close to her home town of Salzburg. Eisriesenwelt, for example, was only 34km away. She did not know the Lurgrotte, which is not far from Graz and about 130km from Salzburg, so at Whitsun 1926 she went to some of the more difficult parts of the cave. With her was the very experienced Austrian cave explorer Hermann Bock (1882–1969)[62] and her friend Nandl ("Anni") Sandtner.

The cave is about 5km long altogether and can be penetrated from its upper entrance at Semriach to the Peggau entrance where the stream emerges. It was at the Semriach end of the cave that the visit took place in which Poldi fell 22m[63] to her death. The following account is based on Bock's own description[18].

They entered the cave on the evening of Saturday 22 May. The exploration involved several vertical descents and they took with them 60m of wire rope ladders and three ropes with a total length of

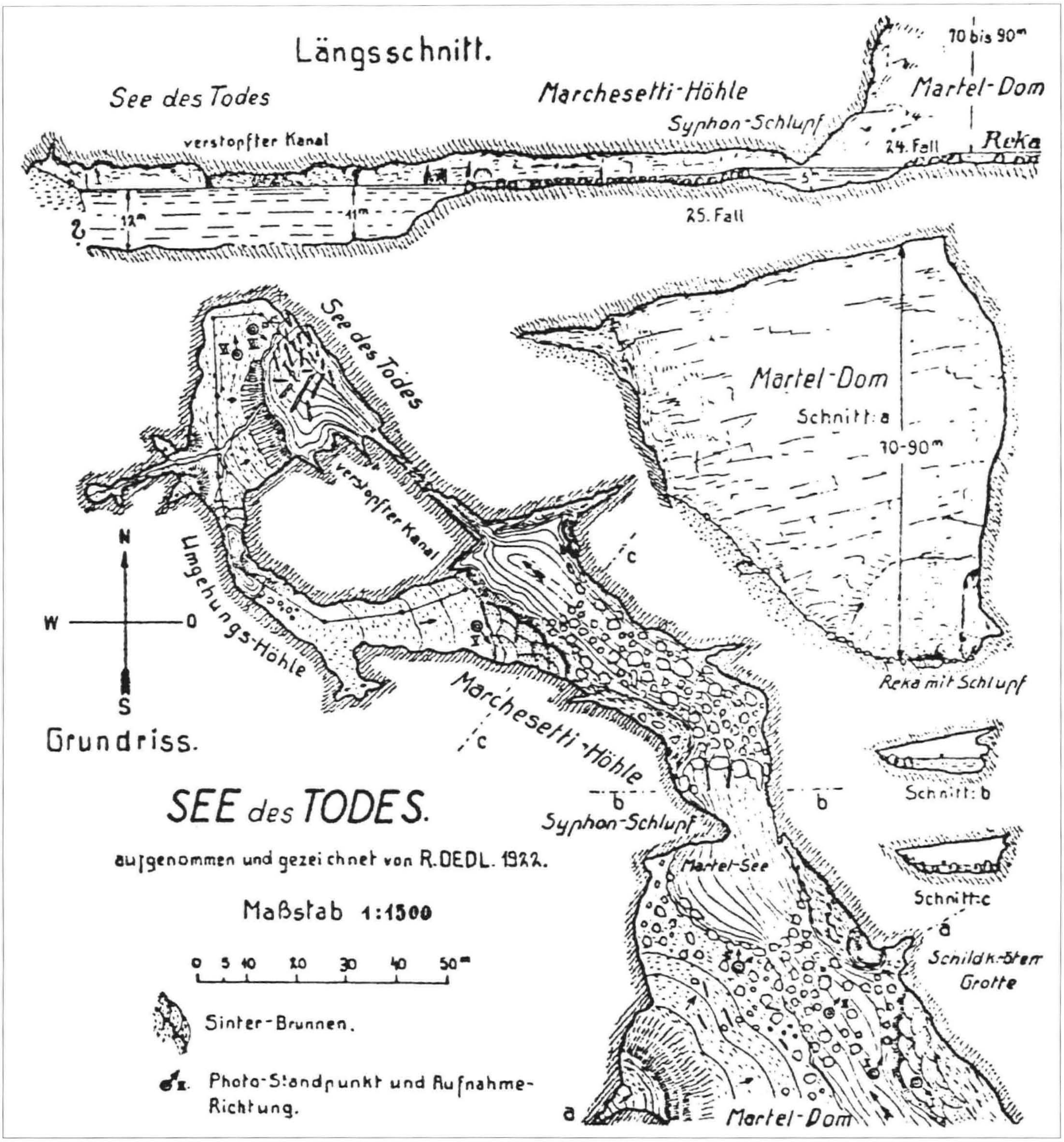


Figure 8. *Robert Oedl's unpublished survey of Mrtvo jezero ('See des Todes') and the approach from Martelova dvorana ('Martel-Dom'), made in 1922.*

100m. That was all they could carry. As there were only three of them it was not possible for the last person down and the first person up to be secured on a safety line; but this was not unusual there.

They descended the 40m-deep Geisterschacht (Fig.12) by ladders with no difficulty and found that the water in the Gnomenteich pool was thigh deep. Nevertheless they continued down the next two pitches to what was then called the Dom der Silur (Silurian Hall), now renamed the Poldi-Fuhrich-Dom. The gorge continued downstream for 300m to where they found that the sump was free of water so they continued as far as the Kletterabgrund beyond it, 1300m from the entrance. Poldi and Anni wanted to go further, but they decided to return because of the risk of being cut off by water. Bock and Poldi took it in turns to lead up the pitches. Thus it was Poldi who led up the first part of the Geisterschacht without a safety line.

The accident itself is described in Bock's own (translated) words[64]:

> *We climbed to a 4m high ledge to shorten the ascent as much as possible. The ladder hangs free for 4m, then it leans against the sloping and much grooved rock so that you move up a wall with easy grips. The exit went through a flat, broad hole and posed no special problems.*
>
> *Poldi climbed swiftly up, maybe a bit too fast. After some time – I thought she had reached the top and was resting – she fell, without crying out, in a wide curve into the deep. We saw nothing of it and only heard a swish and a hard impact. At first we thought that a stone or piece of wood of the stairs*

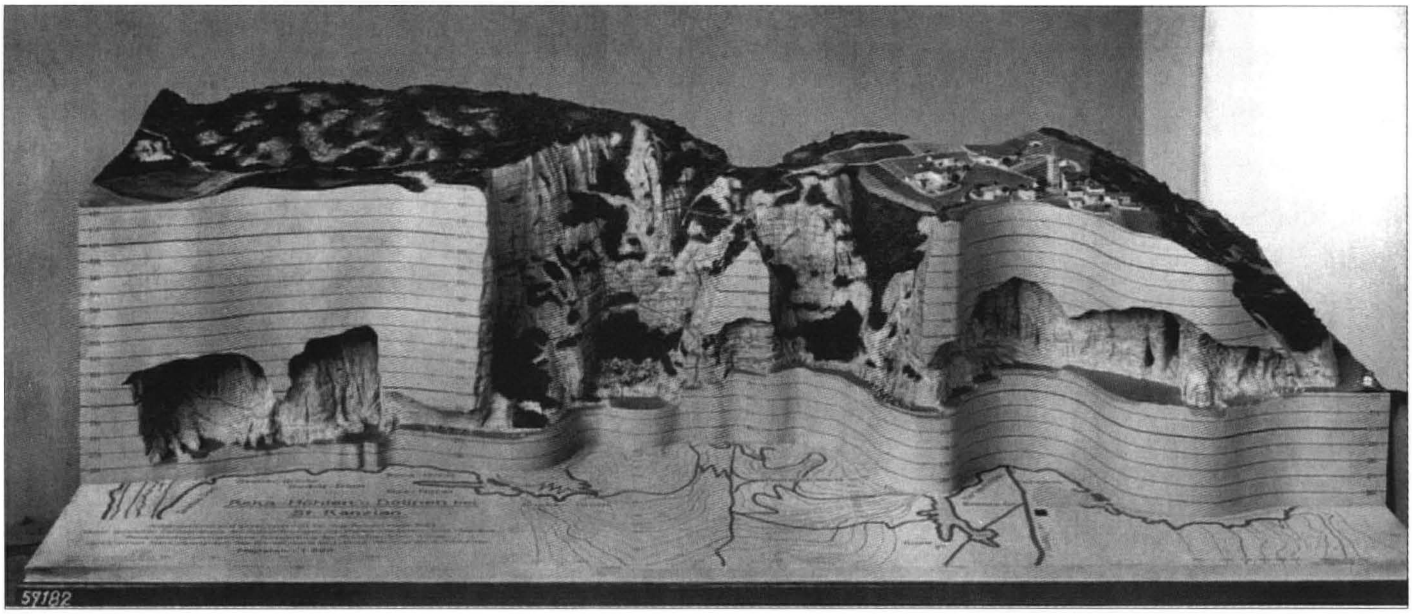


Figure 9 *The model (now destroyed) of part of Škocjanske jame made in 1924 by Robert Oedl at a scale of 1:500. From the right are shown the caves, Mahorčičeva, beneath the village of Škocjan; then Mala and Velika dolina with the natural bridge between them; then the first part of the main cave, as far as Svetinova dvorana. The size of the model was 162cm by 71cm by 50cm. (Photo No.2069 of the Deutsches Museum, München).*

destroyed by high water in 1910 had passed through a side shaft. Our calling brought no response. Then I saw from the extreme end of the ledge something dark lying in the water ... As quickly as possible I climbed down and found Poldi with her upper body in the water, the legs still on the coarse gravel. She was facing down and under the level of the shallow water. When I lifted Poldi she at first showed no signs of life, bleeding only a little from the mouth. She appeared completely uninjured in head, hands, and upper body and soon opened her eyes. I called to Miss Sandtner to come quickly. We settled Poldi as well as we could in a spot free of water whereby I took care that her legs would be straight when she fully woke up to save the accident victim all unnecessary pain. Apparently she had landed on her feet and sustained multiple fractures.

Soon Poldi regained full consciousness but had no recollection of how the accident happened; she did not even know she had fallen. Most probably she lost consciousness from an attack of vertigo even before leaving the ladder and did not regain consciousness until the cold of the water awakened her. She asked us to put padding under her back and knees. It was then that I suspected she might have serious internal injuries. Her lamp had landed a few feet further where the water was a bit deeper; only by the gas bubbles rising could I locate it. After changing the squashed burner it was still serviceable.

While Miss Sandtner remained with Poldi, whom we had covered with every piece of clothing we could spare, I hurried to climb up to organize help. The fall had happened at 2:20 a m [on Sunday 23 May]. At 3 a m I had reached the sons of the owner of the Lurgrotte (Leopold, Georg, and Peter Schinnerl) whose abode is in Pöllau, 70m above the cave entrance. They were the first helpers. One I sent to Semriach to the fire department and to the local paramedic and the doctor. With the others I returned with blankets and warm milk to the site of the accident. Poldi was fully conscious and complained about wetness and cold. At 5 a m four men of the fire department, the paramedic and the doctor had arrived. When we had put on emergency bandages Poldi had fallen asleep because of the warm blankets and a bit of rum we gave her. Her breathing was calm and we had hopes of saving her life. She woke up again but after I could say only a few words to her, she closed her eyes for ever.

(translated by Rudolph Reinbacher)

The reason for the fall was unknown. Poldi was in good health and not tired. The ladder was in good condition and was used immediately afterwards by Bock when he went to summon help. Perhaps a moment's inattention, or vertigo as Bock suggests.

She was buried three days later, on 26 May, in the family tomb in the cemetery of Salzburg. Guides from Eisriesenwelt carried the coffin; Hermann Bock made a moving speech at the graveside and as a last salute threw his "badge of honour" of the Hauptverband Deutscher Höhlenforscher into the grave[9]. This would have been a cave bear badge like the one awarded to Poldi.

Early newspaper reports of the accident occurred in newspapers of 25 and 26 May[65]. The first obituary appeared in the Salzburger Volksblatt on 29 May[9]. It was written by her close colleague and friend, Dr Erwin Angermayer, and was also printed separately on a single sheet with her name bordered in black. Another informative appreciation, also used here as a source, appeared several years later in the Viennese "Women's Review"[14]. A black-edged tribute appeared in the journal of the Association of German Cave Explorers, published in Berlin in 1926[66], demonstrating the respect in which she was held internationally. Another obituary appeared in the Hungarian publication Barlangkutatás[67].

A bronze commemorative plaque was placed on the wall at Poldi Brunnen, near the entrance of Eisriesenwelt (Fig.13). She is further commemorated by the naming of a Poldi Dom in Eisriesenwelt, the larger Poldi Führich Dom[68] close to where she fell in Lurgrotte, and a memorial tablet at the top of the shaft where she died in the Lurgrotte.

CONCLUSION

So, an early end to a promising life. And not just a promising life but a life that had already achieved much and one whose merits had been recognized and appreciated in her lifetime. Her exploration abilities and the way in which she inspired others were already fully developed. What did not have time to mature was the broad view arising from her already wide experience of karst and caves and people.

Nevertheless the world has something to be grateful for, that Poldi existed. After 80 years in obscurity her work deserves to be widely known.

Figure 10. *The exploring party in Škocjanske jame on 9 September 1921 (photograph by F Oedl). From left to right: Poldi Fuhrich; Franc Cerkvenik, Vnckov; Robert Oedl (seated); Franc Cerkvenik, Miklov; Janez Delez, Žvnkov; Friedrich Oedl (seated); Anton Meeraus.*

The research necessary for this appreciation has not only gathered together what little printed information exists. It has also, by using unpublished sources, brought to light such significant work as the Oedl's surveying techniques in Škocjanske jame. It has led also to belated identification and recognition of the hitherto anonymous Slovene cave workers there.

ACKNOWLEDGEMENTS

Nearly all the German texts used here were translated by Rudolph Reinbacher of California. Robert Oedl's surveying methods were discussed with Franjo Drole, of the Karst Research Institute in Postojna, who has resurveyed the whole of Škocjankse jame using modern techniques in recent years. Pino Guidi has made available his extensive knowledge of Trieste-based explorers. Identification of the cave guides who assisted the 1921 party at Škocjan was achieved with the help of Darja Kranjc and Borut Peric, who talked with Janko and Milka Gombač, Milena Lipold and Albina Bak. Rosana Cerkvenik, also of Park Škocjanske jame, has similarly questioned members of that extended family.

The late Dr Friedrich Oedl (1925-2006), son of the photographer Friedrich, provided copies of Poldi's 1924 manuscript and of two key obituaries and of the photograph used here as Fig.1. His helpful letters and discussions contained more useful information. It was he who presented the album of photographs[13] to the director of Park Škocjanske jame. His son, also Friedrich (b. 1960), has also provided information.

Dr Margareta Benz-Zauner of the Deutsches Museum in München traced the photograph (Fig.9) of the now destroyed model of Škocjanske jame made in 1924 by Robert Oedl. Roland Winkelhöfer of Dresden provided photographs of the cave bear badge and the memorial at Eisriesenwelt. I am especially grateful to Albin Debevec, Director of Park Škocjanske jame, for permission to reproduce several photographs from the album of 1921.

The quality of many of the illustrations owes much to Igor Lapajne, by whose skill the small greyish prints in the photograph album[13] have been made into vivid pictures of real people. And last, to give it prominence, is my appreciation of Chris Ballinger, who turns all I have done into electrons so that it can be published.

Subsequent to the original acknowledgements above, I must also express my appreciation of the contributions of referees Professor Stephan Kempe and Dr Stephen Craven, both of whom improved the original manuscript by raising several important points of detail.

REFERENCES AND ENDNOTES

1 Not Führich, with an umlaut, as printed in Baker, E A, 1932. Caving [;] episodes of underground exploration. [London: Chapman and Hall.] pp.184–189 & opp. pp.122, 194, 196 and 204.

2 Shaw, T R. 1969. History of the University of Bristol Spelaeological Society. Proceedings University of Bristol Spelaeological Society, Vol.12(1), 9–30 (pp.16–17).

2A Craven, E [B]. 1789. A journey through the Crimea to Constantinople. [London: Robinson.] Pp.246—253.

3 Craven, S A. 2004. Male chauvinism at Alum Pot: the unrecorded presence of Miss L E May Johnson on 19 September 1908. The Yorkshire Ramblers Club Bulletin (22), 16–22 (p.18).

4 Tratman, E K. 1968. Dina Portway Dobson-Hinton, M.A., Litt.D., F. S.A. [obituary]. Cave Research Group of Great Britain Newsletter (111), 13–14.

5 Božić, V. 1997. Ženski dubinski speleološki rekordi Speleolog, Zagreb (42/43) for 1994–1995, 25–30.

6 Angermayer, E. 1928. Die Eisriesenwelt im Tennengebirge bei Werfen (Salzburg). 2nd edition. Wien: Speläologisches Institut.

Figure 11. The main stream passage in Poulnagollum, Ireland, photographed by Poldi Fuhrich in August 1925 "near the farthest point reached"[61].

[Natur- und höhlenkundliche Führer durch Österreich, Vol.5], pp.35–37.

7 Oedl, F. 2003. Letter dated [13 December] to the author.

8 Palmer, W T. 1934. The complete hill walker[,] rock climber and cave explorer. [London: Pitman.] p.207.

9 Angermayer, E. 1926. Poldi Fuhrich † Salzburger Volksblatt, 29 May. This obituary was also printed separately in two columns on one side of a single sheet.

10 [Fuhrich], P. 1924. Tätigkeitsbericht 1924. 2pp of manuscript. The original is with the Oedl family in Salzburg.

11 Grazer Tagespost, 30 Sept. 1921 (also reprinted in an unidentified newspaper and in Wiener Volkszeitung 1922).

12 Oedl, [F] R. 1924. Der unterirdische Lauf der Reka. Eine karsthydrographische Studie über das Höhlen- und Dolinengebiet von St. Kanzian und Divaca auf der Triester Karsthochfläche. Unpublished thesis submitted for the degree of Doktor der technischen Wissenschaften at the Technische Hochschule at München. Copies of this thesis are held at the Karst Research Institute at Postojna and at the World Heritage Site, Park Škocjanske jame.

13 Oedl, F. [1921]. 96 Photo und Ansichtskarten von Adelsberger, Cirkvenitzer und Karsthöhlen gewidmet von Herrn Dr. Fritz Oedl [sic]. An album (350 x 257 mm) of 20 leaves containing 79 photographic prints of the karst and caves of Škocjan, in the possession of Albin Debevec, director of the Park Škocjanske Jame. Photographs from it are reproduced here with his permission.

14 Prantl, G. 1933. Poldi Fuhrich (1898–1926). Frauen-Rundschau Organ des Bundes Österreichischer Frauenvereine, Wien, September.

15 Mitteilungen über Höhlen- und Karstforschung, Berlin, Jahrgang 1924 (pub. 1925): 24. The badge is mistakenly described as of gold in the anonymous Hungarian report: Absturz einer österreichischen Höhlenforscherin in der Lurgrotte. Barlangkutatás, Budapest, Vol.14–15, 1927:97.

16 None of the obituaries (see notes 9 and 14) state the date of her birth. It is however known that she was 28 years old when she died on 23 May 1926[9].

17 Die Gründung der Speläologischen Gesellschaft in Wien. Speläologisches Jahrbuch, Wien. Vol.4 (1–2) 1923, [1] – 2.

18 Bock, H. 1926. Tödlicher Absturz der Höhlenforscherin Poldi Fuhrich in der Lurgrotte bei Semriach. Mitteilungen über Höhlen- und Karstforschung, Berlin, Jahrgang 1926 (Heft 3), [66]–70 (p. [66]).

19 Liste des participants. Actes du 6[e] Congrès international de Spéléologie, Olomouc – ČSSR 1973 (pub. 1975) Vol.1, p.84).

20 He signs his full name under his portrait in Die Höhle, Wien, Vol.37 (2) 1986, p.109.

21 Robert Oedl. UIS-Bulletin, Union Internationale de Spéléologie, Vol.2(16) for 1977, pub. 1978, p.10.

22 Vale Dr ing. Robert Oedl. The British Caver, Vol.69, 1978, 73–74.

23 Bergthaller, A and Trimmel, H. 1978. Baurat h.c. Dr. Dip.-Ing. Robert Oedl zum Gedenken. Die Höhle, Wien, Vol.29(2), 64–65.

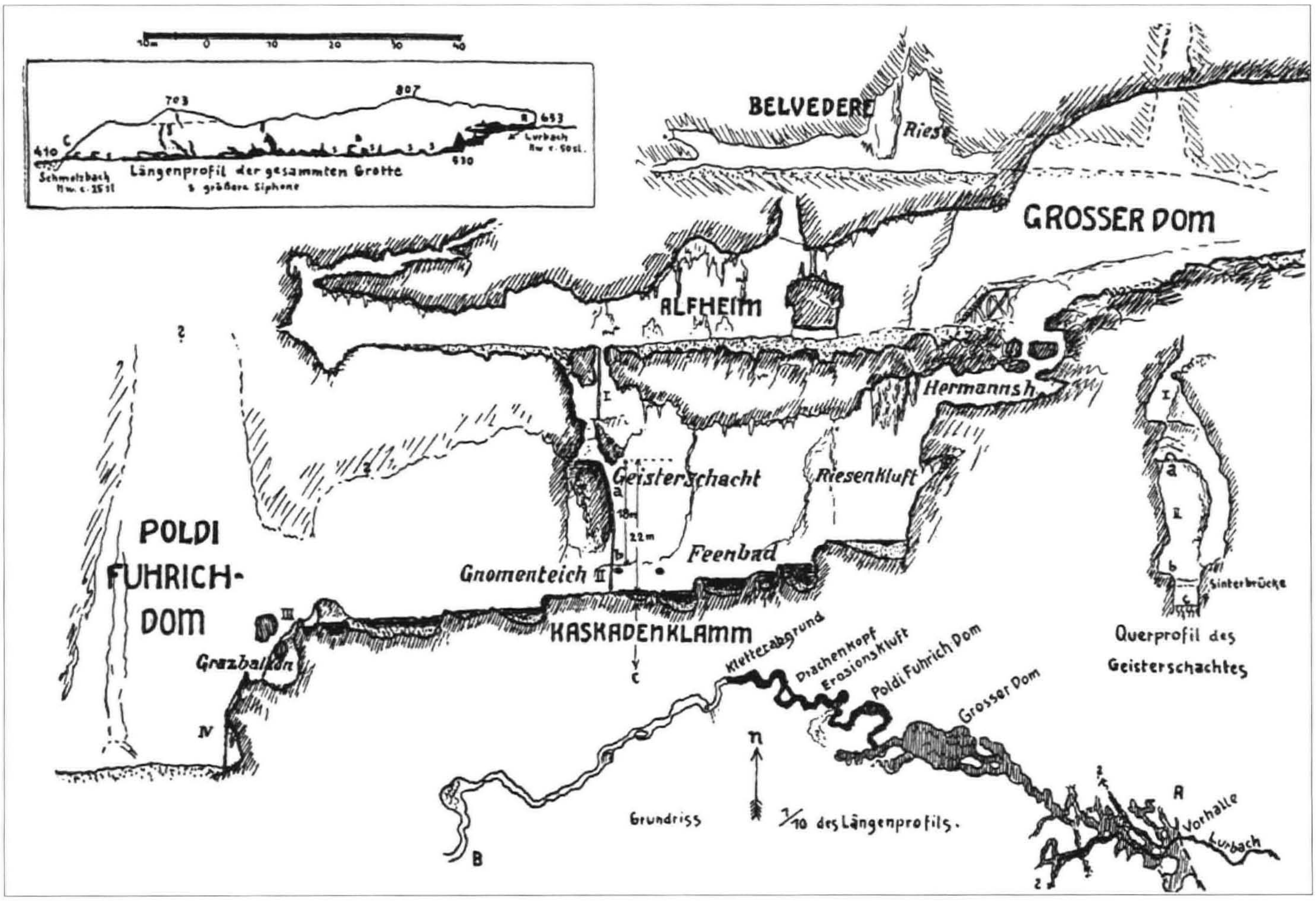


Figure 12. The Semriach end of the Lurgrotte[63]*, where the fatal visit was made in 1926.*

Figure 13. *The memorial tablet at Poldi Brunnen near Eisriesrenwelt (photograph by Roland Winkelhöfer, July 2007).*

24 Habe, F. 1979. V spomin Dipl. Ing. Dr. Roberta Oedla. Naše jame, Ljubljana, Vol.20 for 1978, 114–115.

25 Oedl, F R. 1976. My explorations in the Dachstein caves system 50 years ago. Proceedings of the 6^{th} International Congress of Speleology 1973, Vol.3, 229–234.

26 Günther, W and Oedl, F. [1995]. 75 Jahre Schauhöhle Eisriesenwelt. Salzburg. pp.26 (with a photograph showing Poldi in the 1919 team) and 27.

27 Bilderverzeichnis [des Vereines für Hohlenkunde in Salzburg] (a manuscript list of 36 photographs of the period 1919–1925).

28 Angermayer, E et al. 1926. Die Eisriesenwelt im Tennengebirge (Salzburg). Wien, Speläologisches Institut, Tafel 1 [Speläologische Monographien, Vol.6].

29 Angermayer, E. 1928. Op. cit. (note 6), Tafel 1.

30 Czoernig-Czernhausen, W. 1926. Die Höhlen des Landes Salzburg und seiner Grenzgebirge. Salzburg, Verein für Höhlenkunde in Salzburg, p.75 [Spelaeologische Monographien, Vol.10]. An English translation was published in Cave Science, Settle, Vol.3(24), 1955, p.381.

31 Morocutti, A. 1969. Dr. Friedrich Oedl zum Gedenken. Die Höhle, Wien, Vol.20(2): 59–60.

32 Oedl, [F] R. 1924. Op. cit. (note 12), pp.3, 4.

33 Oedl, [F] R. 1924. Op. cit. (note 12), pp.4, 18.

34 Oedl, [F] R. 1924. Op. cit. (note 12), p.315.

35 Oedl, [F] R. 1923. Auswertungsmöglichkeiten von Höhlenvermessungen. Speläologisches Jahrbuch, Wien, Vol.4: [138] – 144, p.140.

36 The boat is of such a strange shape that at one stage it was wondered if some farm equipment had been modified but Janko Gombač (b. 1917) of Matavun is certain that it was specially made for the purpose. The small projections at the corners would have aided in carrying it over dry ground.

37 The photograph reproduced in Fig.5 from the album (note 13) was first published in 1922 in F Oedl. Die Höhlen der Ostalpen, pp.16–28 in Max Rohrer, (Ed.), Die Höhle in Sport Wissenschaft und Kunst. [München: Alpenfreund.] p.16.

38 Oedl, [F] R. 1924. Op. cit. (note 12), pp.316–325.

39 Oedl, [F] R. 1924. Op. cit. (note 12), Taf. IV.

40 This model is illustrated in Atti del I Congresso Speleologico Nazionale, Trieste, 10–14 giugno, 1933. p.124.

41 Middleton, G J. 1991. Oliver Trickett doyen of Australia's cave surveyors 1847–1924. [Sydney: Sydney Speleological Society.] pp.108, 113 [Sydney Speleological Society Occasional Paper No.10].

42 Žiberna, J. [1981]. Divaški prag. Divača, p.153.

43 The house name Vnckov was originally spelled Venckov, but the "e" is not sounded so that local spelling is used here.

44 Milena Lipold, his daughter, remembers that she was two years old when he died. All these dates have been confirmed by Darja Kranjc from church records.

45 Also known as Ivan. The names are interchangeable.

46 Angermayer, E. 1933. Zur Geschichte der Höhlenforschung in Salzburg. Speläologisches Jahrbuch, Wien, Vol.13–14 for 1932 and 1933, 1–12 (p.9).

46A Angermayer, E. 1925. Verbandsnachrichten – Verbandsmitglieder – Oesterreich. Mitteilungen über Höhlen- und Karstforschung, Berlin, Jahrgang 1925, 5–8 (p.8).

47 Baker, E A. 1932. Caving episodes of underground exploration. London: Chapman and Hall. p.184.

47A Klappacher, W. 2007. e-mail to Rudolph Reinbacher, about 1 June 2007.

47B The existence of postcards sent from Škocjan by two of their Salzburg friends, Robert Oedl in March 1925 and Walter Czoernig in June[13], tend to support this.

47C Klappacher, W. 2007. e-mail to Rudolph Reinbacher 18 July.

48 Martel, E A. (1924). Les récentes explorations souterraines (1914–1923). Revue de Géographie Annuelle, Paris, Vol.11(4) for 1923, 1–56, (pp.32, 40).

49 No correspondence between Barton and Martel is known to have survived (Martel, E A. 1997. La plume et les gouffres Correspondance d'Edouard-Alfred Martel, (de 1868–1936). Lozère).

50 Not Elliot Georg Barton as in the membership list of the Speläologische Gesellschaft in Wien (note 17), nor yet C[laude] G Barton as named by E A Baker (note 47).

51 Craven, S [A]. 1999. Two speleological Bartons. Descent, (147), p.38.

52 Martel, E A. 1924. Op. cit. (note 48), pp.21, 23–24.

53 Martel, E A. 1924. Op. cit. (note 48), pp.32–33.

54 Baker, E A. 1932. Op. cit. (note 47), pp.18, 184–185.

55 The possibility was considered of it being Robert Oedl, a qualified and experienced surveyor and Poldi's usual companion, who was present, not his brother. After all, Baker had given the wrong initials (C G) to Barton and mis-spelled Fuhrich on the same page that he introduced Dr Oedl. But no: Friedrich's obituary[3] confirms that it was indeed he that was in Ireland.

56 Not 1923 as misprinted in Speläologische Jahrbuch (note 46).

57 Baker, E A. 1926. Caving in County Clare. 37th Annual Report [for 1925] of the Wells Natural History and Archaeological Society, 40–42.

58 Baker, E A. 1932. Op. cit. (note 47), pp.[190] – [191].

59 Summarized in 40th Annual Report [for 1928] of the Wells Natural History and Archaeological Society: 14 (the year 1925 is misprinted as 1927).

60 Tratman, E K (Ed.). [1969] The caves of north-west Clare, Ireland. [Newton Abbot: David and Charles.] p.166.

61 Baker, E A. 1932. Op. cit. (note 47), opp. p.194.

62 An account of Bock's life appeared when he was 80 years old: Maurin, V. 1962. Oberbaurat Dipl.-Ing. Hermann Bock 80 Jahre alt. Die Höhle, Wien, Vol.13(4), 91–95.

63 Anon. 1926. Die Abgründe in der Lurgrotte bei Semriach. Mitteilungen über Höhlen- und Karstforschung, Berlin. Jahrgang 1926 (Heft 3), 70–72. This is a precise description accompanied by the survey reproduced here in Fig.12. Other sources state that the fall was of only 20m.

64 Bock, H. 1926. Op. cit. (note 18), pp.68–69.

65 For example Tagespost Graz, 25 and 26 May 1926.

66 Poldi Fuhrich. Mitteilungen über Höhlen- und Karstforschung, Berlin. Jahrgang 1926 (Heft 3), [65].

67 Anon. 1927. Absturz einer österreichischen Höhlenforscherin in der Lurgrotte. Barlangkutatás, Budapest, Vol.14–15, p.97.

68 It is just called the Fuhrich Dom in the more modern literature, e.g. H Trimmel and R Jantschitsch. [c. 1994]. Lurgrotte Semriach..., pp.10, 12.

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The Grotta Del Cane (Dog Cave), Naples, Italy.

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Abstract: The Grotta del Cane (Dog Cave) has been well known since antiquity because of a carbon dioxide layer, which is toxic for animals but not for a man standing erect. In this report we cite some important accounts by visitors during the last two millennia, together with a modern description of its features and current methods of minimizing hazards of such cave environments.

Key words: Grotta del Cane, Dog Cave, carbon dioxide.

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INTRODUCTION

The Grotta del Cane (Dog Cave) is a famous cavity near Naples, Italy (Fig.1). It has been known since Roman times and many visitors have described it vividly. But until now, the speleological literature has lacked a modern review of its history and its current status. Its fame is due to carbon dioxide, which enters the cave through a crevice a short distance inside. An opening in the ground from which exhalations of carbon dioxide, oxygen and nitrogen rise is called a fumerole or mofette (Himus, 1954), the latter term also being used to describe the emitted gases themselves. Proprietors of the cave formerly demonstrated the anaesthetic effect of the gas on small dogs whose faces were close to the floor, where the concentration of CO_2 is high. Seemingly they died, and then were resurrected when they were removed from the cave and thrown into the nearby Lake of Agnano (drained in 1866).

HISTORY

The earliest reference to Grotta del Cane apparently is in "Naturalis Historiae", a monumental work by Pliny the Elder (77 A.D.) published in the First Century A.D.:

> *Spiritus letales aliubi aut scrobibus emissi aut ipso loci situ mortiferi, aliubi volucribus tantum, ut Soracte vicino urbi tractu, aliubi praeter hominem ceteris animantibus, nonnunquam et homini, ut in Sinuessano agro et Puteolano, spiracula vocant , alii Charonea, scrobes mortiferum spiritum exhalantes.*
>
> [the deadly vapours released by holes or causing death on account of the soil characteristics, in some places only of birds, as in Soratte Mt. close to Rome, in other places to any animals with the exception of man, as in the area of Sinuessa and Pozzuoli, are called fumaroles and also Charon's passages, as holes releasing deadly vapours] (translation by the authors).

Pliny's citation of both the Pozzuoli area and death caused only to animals and not to man clearly identifies Grotta del Cane. When in a standing position, humans' heads are above the layer of carbon dioxide. After more than a millennium of seeming silence, interest in the cave became evident in the XVI Century. Benedetto di Falco (1535) wrote about the entrance to a *"small and miraculous cave with a strong smell of sulphur or another unknown quality of the soil, so that any animal entering the cave suddenly dies."* Subsequently, John Evelyn (1620–1706) visited the *"Grotta del Cane or Charon's Cave"* in 1645. Evelyn was an educated man who attended Oxford University and travelled widely in Europe. In his diary (Evelyn, 1952), in addition to recounting the standard anaesthetizing of unfortunate dogs, he embellished his account with second-hand tales of human experiments when a *"poor creature whom Peter of Toledo caused to go in; likewise some Turkish slaves; two soldiers, and other foolhardy persons, who all perished, and could never be recovered by the water of the lake, as are dogs"*. A few years later, Georgius Agricola (1549) described the cave as a narrow passage sloping downward for seven feet where *"deadly vapours kill any animal"*.

About a century later, Athanasius Kircher visited the cave in 1638 and began a series of important experiments and observations. Published later (Kircher, 1668), his results may be considered the first scientific study of the cave. Kircher first repeated the anaesthetizing of a dog. Tied to a pole, the animal was introduced into the cave and immediately retrieved when it became unconscious. Then it was put into the nearby lake where it suddenly recovered completely – as usual.

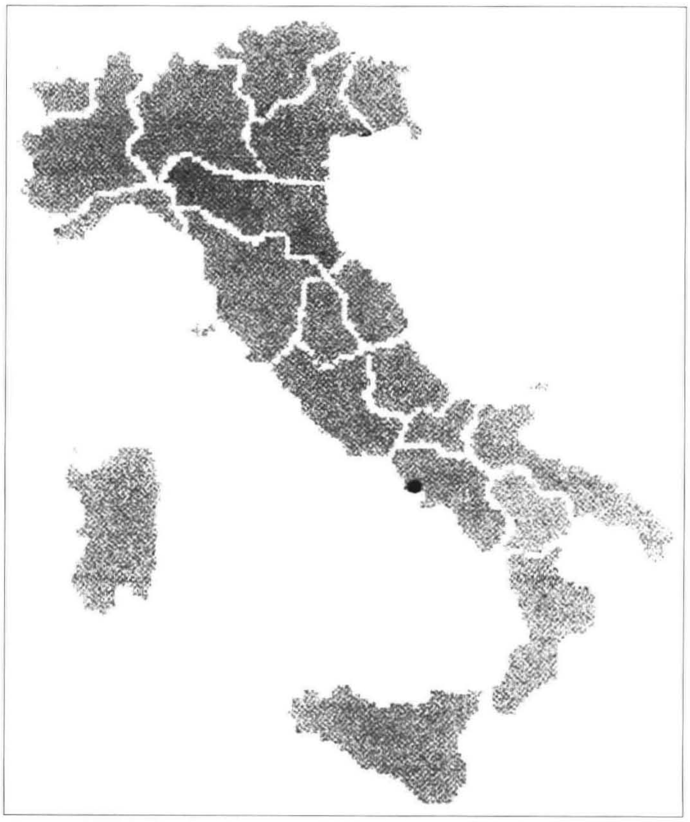


Figure 1. *Location of the Grotta del Cane, near Naples, Italy.*

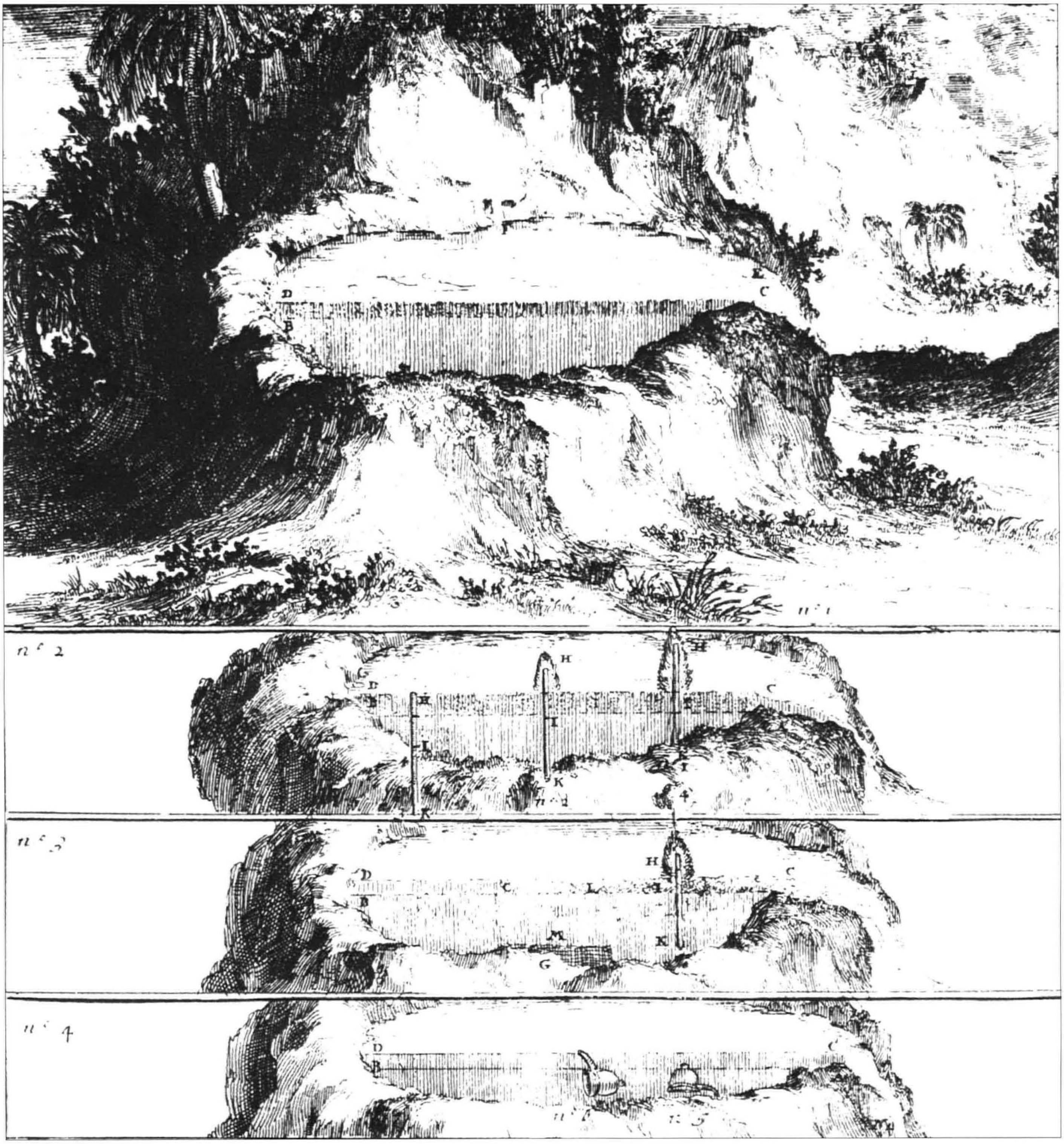


Figure 2. The "Grotta de Cani" (Dogs' cave) as reported by Kircher (1669). These elevations are quite different from the real cave, as compared with the modern survey. No.1 – See Observation I; No.2 – See Observation II; No.3 – See Observation III; No.4 – See Observation VI.

But Kircher was in his 30s at that time, and eager to understand what was happening. He put his head into the cave and felt the effects of the noxious gas at once, concluding that he survived only because he backed out immediately, thus confirming the effects of the vapours released into the cave. He returned on Sunday, October 26, 1664 with a contingent of more than 50 people *("Doctors, Counts, Marquises, Dukes, Princes, Prelates, Bishops")* as witnesses to his work. Being a Jesuit he chose to dedicate his report to the Bishop John Caramuel. For his book, he commissioned a view of the cave (Kircher, 1669, p.190), reproduced here as Fig.2. The engraver, however, failed to understand the special nature of the cave, as comparison of this figure with a modern survey (Fig.4) demonstrates. Nevertheless, the original illustration points out some especially important features summarized in Kircher's nine observations:

Observation I:

A wooden gate closes the cave and some money must be given to the peasant who owns it. It is artificial and measures 8 feet high, 6 feet wide and 12 feet long; it was not possible to examine it closely and it may be larger. Below a certain level (dashed part in the upper part of section 1) the wall is humid, while above this level the wall is dry, locally cold and locally warm to touch and also through one's shoes.

Observation II:

Notwithstanding the opinion of other people, Doctor-in-law Franciscus Andreae boldly entered the cave with a lighted torch. The torch burned regularly above the level reported above; when lowered the flame went out but started again when the torch was lifted. If the torch was totally lowered below the cited level, no flame reappeared when the torch was lifted.

Observation III:
Behaviour of smoke was as follows: When the flame is above the cited level, the smoke rose as usual. But when the flame was lowered, a layer of smoke spread out and immediately moved to the floor.

Observation IV:
The torch used in Observation II was dry before and after the observation and therefore it was not extinguished by water.

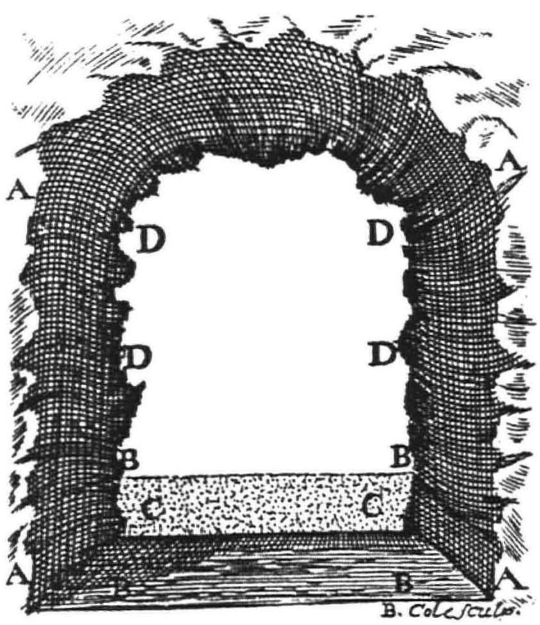
Observation V:
A sponge was left on the floor of the cave for a long time, but no drop of moisture was obtained when it was retrieved.

Observation VI:
Above the cited level, a mirror revealed no condensation but, when lowered, it showed some condensation as from a human breath. This condensation disappeared in a short time. Then a still was placed with its end toward the soil; no water was detected inside but on the outside surface some condensation appeared. Subsequently the still was reversed, with its end above the cited level. Then some condensation appeared inside, but the amount was less than one drop. When tasted, some detected an acid taste, others no taste at all.

Observation VII:
A dog was introduced into the cave. When its head was above the cited level, nothing happened. But when its head was lowered, the dog tried desperately to get away. When tied to a club to keep it close to the bottom, it seemingly died. When plunged into the lake, it showed a few signs of life and when pulled to the shore it rose, looked around and ran away to avoid a repeat performance.

Observation VIII:
The invisible material below the cited level is lighter than water but heavier than air. A frog imprisoned close to the floor became unconscious but after a longer time than required for the dog. When brought outside the frog recovered and moved away in the grass.

Observation IX:
A strip of gunpowder was laid from the entrance to the lower part of the cave. When lighted it burned totally, and the smoke behaved as in Observation III.



A. A. A. A. *Feralis Cavernæ facies & ingreſsus.*
B. B. B. B. *Altitudo ſpatii lethiferi & viri-deſcentis muri coloris.*
C. C. *Æther ſubtiliſſimus & inſenſilis in horizontali linea à toto antri ambitu in cavitatem ejuſdem ingrediens.*
D. D. D. D. *Regio Cryptæ ſuperior in qua animantia vitâ fruuntur.*

Figure 3. *A view of the "Deadly Cavern" by Connor (1695). A.A.A.A. – Details and entrance of the Deadly Cavern; B.B.B.B. – Level of the deadly space and the greenish colour of the wall; C.C. – Thinnest and slightest ether along a horizontal line within the whole cave; D.D.D.D. – Higher section of the cave where animals can survive.*

A medical doctor named Thomas Cornelius collected some soil on the lowest part of the floor to be analysed later at home (but no results are reported in Kircher's book). The Marquis de Arenis intended to obtain a sample of the gas below the cited level, but his servants forgot to bring a container (*"as happens everywhere"*, Kircher commented). Carried out with the cooperation of many persons including experts of different disciplines, Kircher's research nevertheless must be considered especially notable for his period. A few years later, near the end of the XVII Century, another medical doctor (Bernard Connor, 1695) visited the site. He also witnessed the usual anaesthetizing of an unfortunate dog in the cave, then called *"Deadly Cave"*. In his book he also included an illustration of the cave with details on distribution of the noxious gas (Fig.3). Several years later, Peter Tolstoi (sent by Czar Peter to Venice to study naval science), travelled in southern Europe and visited the cave: *"On the right side on one mountain is carved a niche of a width that one man can pass... In this niche from the earth arises a toxic vapour that will quickly kill any living man, cattle, beast or bird on the ground* (but) *just four* arshins *[c.1 metre] above this infectious vapour a man can enter this niche freely"*. He also performed the usual tests with a dog, which recovered after its bath in the nearby lake, and with torches, which *"immediately went out"* when lowered close to the ground (Tolstoi, 1987). Some years later, Pompeo Sarnelli (1752) mentioned that in this area, *"as the baths are useful to man, so such mofettes are noxious"*.

During the following year, Sylvanus Urban (1753) described Naples and its environs, including some second-hand accounts. According to the description of an unknown *"Italian author"*, he recorded the size of the cave as 14 palms high, 6 wide and 16 deep. In addition to the usual reactions of animals when introduced into the cave, he recounted: *"If a pistol be fired near the bottom it gives no report, whence it is concluded either that there is an entire vacuum at the bottom or that the air is there extremely subtle."* According to the remarks of a Mr Addison (another traveller), a pistol cannot be fired at all in the cave and *"it is much more probable that the effects of the grotto upon animals and lighted torches are owing to stagnated vitiated air or to unctuous or viscous vapours arising from the bottom of it, than to a vacuum or subtlety of the air."* Urban also quoted the account of another traveller, a Mr Saunders, that the *"suffocating vapour"* in the cave *"rises, however, only about 11 inches; and if the head of any creature be ever so little above that, it receives no hurt from it. The people who shew us this, affect to make it miraculous. But anyone who knows a little chemistry, will find nothing so wonderful in it."*

Mr Saunders then added another interesting point: since no speleothems (*"stony icicles"*) are present, he attributes this to some action of the vapour, which should *"rise higher than the eleven inches, tho' in less quantity and not so concentrated"*.

Then, in order to test this hypothesis, *"my curiosity tempting me to stay much longer than travellers usually do in this place, I felt the ill effects of it in a pain in my breast for three days."* He further added that in the cave, below the height of eleven inches, a glittering mineral covers the wall *("which the English miners call Mundich")* that, when tasted, *"was plain vitriol."*

In 1760, Johann Georg Keyssler (spelled Keysler in the English editions of his book [Shaw, 2000]) reported that: *"there is a cottage where lives a man who makes it his business to keep dogs in order to*

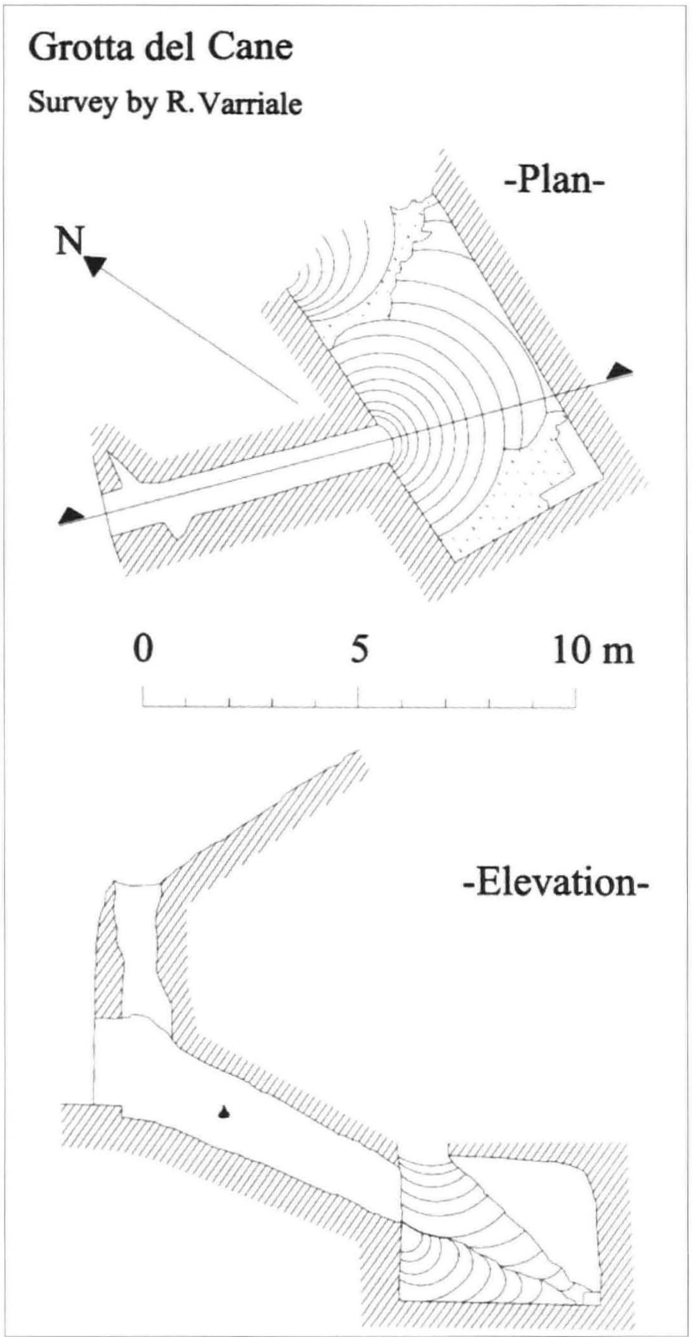


Figure 4. *Survey of the "Grotta del Cane". Modified from Varriale (2002). The black triangle at 2.5m from the entrance in the elevation is a crevice releasing the CO_2.*

shew strangers the surprising effects of this grotto, and is generally rewarded with five or six carlini" (Keylser, 1760). He added that the time of recovery is different for vipers and frogs, and included the accounts given by John Evelyn (above), while adding a new embellishment: an ass somehow inserted into the cave by order of Charles VIII, King of France, supposedly died in a short time.

In 1782, the Abbé C de Saint Non mentioned the *"experiments (with dogs) on the still air or better on the foul air continuously emerging from the floor to a height of about one and one-half feet"*.

The first analysis of the gas appears to have been that of the Abbé Pasquale Panvini, who identified it as carbon dioxide (Panvini, 1818). He stated specifically that older authors had exaggerated the effects of the gas; he put his face close to the soil and took several breaths. He noticed that his nose begin to itch and stopped the experiment after some difficulty breathing. In his opinion, the carbonic acid was due to the decomposition of pyrites producing sulphuric acid, which had reacted with limestone to release CO_2. The presence of CO_2 was confirmed in 1832 by James Dwight Dana, a noted professor-to-be of geology at Yale University (Gilman, 1899).

Clarke (1836) reported a detailed abstract of a memoir by the Abbé Breislak L Spallanzani projected these experiments, but being prevented from undertaking them by his duties, his friend the Abbé Breislak, who resided near the spot, engaged in the task. According to him a considerable decrease of the emission of deadly air had occurred since the time of Pliny. The height of the mephitic vapour varies according to the temperature of the atmosphere and the diversity of winds, but it is estimated to be at a mean of 8 inches (20cm). The temperature at the entrance of the cave at a height of about 3 feet (90cm) was 62–64°F (17–18°C), but close to the ground rose to 80–82°F (27–28°C). A chemical analysis of the mephitic air gave 10% of oxygen, 40% of carbon dioxide and 50% of nitrogen. The magnetic field was the same inside and outside the cave and because the air is a conductor it was not possible to detect any electric field. A reaction between turpentine oil and sulphuric or nitric acid in a vessel immersed in the layer of mephitic air resulted in a lively flame as in the open atmospheric air. Phosphoric matches immersed in the *"mephitis"* produced a short and transient flame. Another experiment was made with a table immersed for four–fifths of its length in the *"mephitis"*. A train of gunpowder laid on the table had a cylinder of phosphorus adjacent to the lower end of the gunpowder. When this one was ignited at the upper end the combustion reached the lower end and the phosphorus burned with a bright flame until it was totally consumed. Therefore the Abbé deduced that the mephitic air is *"unfit for the respiration of animals or the inflammation of common combustible substances"* but *"readily allows that of phosphorus"*.

In 1865 Alexander Dumas described a visit to the cave at a time when its keeper kept two dogs to show its effect to visitors. Numerous other pre-World War II accounts also are on record.

PRESENT STATUS

Shortly before World War II the authorities prohibited the abuse of dogs. In 1958 the cave gate was removed and the cave became a site for waste disposal, degrading its environment. Municipal authorities eventually raised the ground level in front of the cave by several metres, to prevent the entrance of children: behaviour typical of many bureaucrats, who find it easier to shut off access than to care for an important monument. Fortunately, this action was overridden by responsible local citizens and institutions. Using funds provided by the Ministry of University and Scientific Research, restoration of the cave was completed in 2001, with the removal of several cubic metres of rubbish by the cavers of the Centro Ricerche Speleologiche di Napoli. The excavation was conducted using archaeological techniques but only modern materials were found. (Varriale, 2002; 2005). Unfortunately local bureaucrats continue to ignore the importance of the cave and its ultimate fate is uncertain. It is to be hoped that detailed meteorological studies of the cave will be completed and published in the foreseeable future.

PHYSICAL FEATURES AND METEOROLOGY

The dimensions and morphology of the cave are shown in Fig.4; dimensions asserted by ancient writers referred only to the entrance passage. It is mainly (perhaps totally) artificial, excavated in Greco-Roman times. Presumably it was intended as a steam room (*"sudatorium"*). Evidently local CO_2 emissions were minor or entirely lacking at the time of its excavation; levels of volcanic activity in this area are notoriously subject to change.

At the time of excavation, the inner chamber received light and possibly some ventilation from a chimney, which now is filled with rubble. Because of subsequent adverse environmental conditions in this inner room, this chimney was only rediscovered during the recent removal of rubbish from the cave. Fig.5 shows measurements of air temperature, CO_2 and N_2 concentrations at that time (Varriale, 2001). Two special hazards of the cave are thus its atmospheric hypercarbia (elevated CO_2) and hyperthermia (elevated temperature). Human physiological observations in Hawaii have shown that the safe working time for healthy adults in normocarbic 45°C caves is about 45 seconds at a time (Halliday, 2000). Longer exposures require very careful sublingual thermometry with immediate oral or intravenous replacement of fluids and electrolytes as needed. In Grotta del Cane, volunteer speleologists remained in

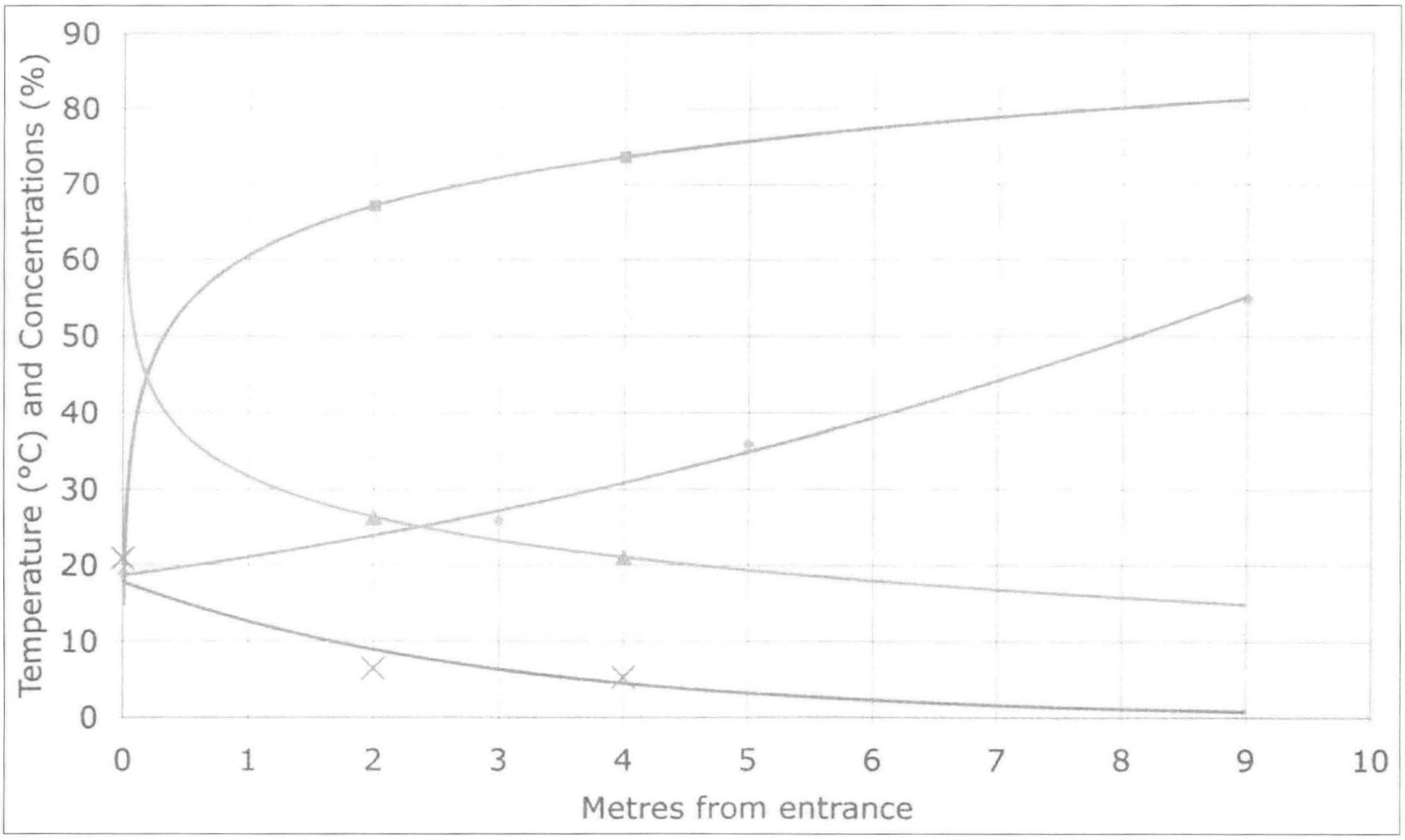


***Figure 5.** Measurements of temperature (dots), CO_2 concentration (squares), N_2 concentration (triangles) and O_2 (X). (Varriale, 2006).*

the inner room for as long as five minutes despite breathing difficulties and heavy condensation on instruments (abnormal pulse rates were not recorded). This may have been possible because of unrecorded thermostratification of the cave's atmosphere, a feature commonly observed in hyperthermic caves in Hawaii.

The cave's hypercarbia is of the dilutional type characteristic of volcanic regions. In the presence of adequate partial pressure of O_2, approximately 20% CO_2 is required to produce unconsciousness in this scenario (Smith, 1997). This is in contrast to the commoner form of hypercarbia resulting from replacement of atmospheric O_2 by CO_2 by respiration or oxidation of organic material. In that scenario, cave studies are feasible only up to 6% CO_2/15% O_2 (Howarth and Stone, 1990) without auxiliary oxygen, and require tolerance of uncomfortably rapid breathing, which itself may eventually cause fatal exhaustion. Newly developed portable oxygen devices and portable fingertip oximeters, now available at affordable prices, might be very useful in such environments.

Layering of the very high concentration of CO_2 released into the cave about 30cm below the entrance has caused a noticeable brownish discoloration of the cave walls, perhaps due to the presence of extremophilic micro-organisms; above this level, the walls are white. Connor documented a similar phenomenon in 1695, but at that time its colour was perceived as greenish, suggesting that slightly different environmental conditions were present at that time. In both 1664 and 2000, open flames produced white fog. This may be attributed to formation of condensation nuclei in a supersaturated atmosphere. It is hoped that more detailed meteorological studies will be conducted, and then published in the foreseeable future.

CONCLUSIONS

The Grotta del Cane is a notable historical monument, first recorded in the first century of our age. After several decades of modern oblivion, local speleologists restored the cave by cleaning out rubbish. This volunteer group faced and overcame severe working conditions. Unfortunately local bureaucrats have not accepted the historic and phenomenological importance of the cave and its ultimate fate is uncertain.

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REFERENCES

Agricola, G. 1549. De animantibus subterraneis liber. Apud Frobenium et Episcopum, Basilaee.

Clarke, C C. [=R. Phillips?]. 1836. The wonders of the world. Babcock and Co., Charleston: 123–127.

Connor, B. 1695. Dissertationes medico-physicae. Oxonii.

Dumas, A. 1865. Impressions de voyage-Le Corricolo. Paris.

Evelyn, J, 1952. The diary of John Evelyn. Vol.1. London: J.M. Dent and Sons Ltd, New York: E.P. Dutton and Co. Inc.

Falco, B. 1535. Descrittione dei luoghi antiqui di Napoli e del suo amenissimo distretto.

Gilman, D C. 1899. The life of James Dwight Dana. Harper and Brothers Publishers, New York and London.

Halliday, W R. 2000. Mapping caves in Kilaluea (sic - Kilauea is correct) Caldera: proposed standards and guidelines. *Hawaii Speleological Survey Newsletter*, # 7, June 2000.

Halliday, W R and Cigna, A. 2006. Two 1851 accounts of Grotta del Cane. *Journal of Cave and Karst Studies*, p.170.

Himus, G W. 1954. *A Dictionary of Geology*. Penguin Books, p.96.

Howarth, F G and Stone F D. 1990. Elevated Carbon Dioxide levels in Bayliss Cave, Australia: implications for the evolution of obligate cave species. *Pacific Science*, Vol.44, No.3, 207–218.

Keysler, J G. 1760, Travels through Germany, Bohemia, Hungary, Switzerland, Italy and Lorrain. Vol. 3, London.

Kircher, A. 1668. Mundus Subterraneus in XII libros digestus. J. Janssonium à Waesberge & Filios, Amstelodami, 190–194.

Panvini, P. 1818. Il forestiere alle antichità e curiosità naturali di Pozzuoli, Cuma, Baja e Miseno. Napoli, Gervasi, 12–16.

Plinius, C S. 77 AD. *Naturalis Historia*. Book. 2, cap. XCV. Giardini, Como, 1984.

Saint Non, C de. 1782. Vojage pittoresque ou description des royames de Naples et de Sicilie.

Sarnelli, P. 1752, Guida de Forestieri curiosi de vedere le cose notabili de Pozzoli, Baja, Miseno, Cuma. Napoli.

Shaw, T R. 2000. *Foreign travellers in the Slovene karst. 1537–1900*. ZRC, Postojna.

Smith, G K. 1997. Naked flame tests for CO_2 in limestone caves and the

effect of CO_2 and O_2 on humans. Papers, 1997 Australian Speleological Federation Conference, Quorn, South Australia, 40–52.
Tolstoi, P. 1987. The Travel Diary of Peter Tolstoi. Northern Illinois University Press. De Kalb, p.191.
Urban, S. 1753. Of the baths of Naples and Pozzuoli. *The Gentleman's Magazine, London*, Printed by E Cave, 16–17.
Varriale, R. 2002. La Grotta del Cane. Report of Centro Ricerche Speleologiche di Napoli.
Varriale, R. 2005. *La Grotta del Cane*. p.183 *in* N Russo, S Del Prete, I Giulivo and A Santo (Eds), Grotte e speleologia della Campania. Fed. Spel. Campana, Sellino Editore, Avellino.
Varriale, R. 2006. Personal communication.

ISSN 1356-191X

Forum

Readers are invited to offer thesis abstracts, review articles, scientific notes, comments on previously published papers and discussions of general interest for publication in the Forum of *Cave and Karst Science*.

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SCIENTIFIC NOTES

GEOTHERMAL SPELEOGENESIS

The topic of speleogenetic inception and passage enlargement under geothermal conditions is somewhat out of context for the recent book by Klimchouk (2007) and the review by Faulkner (2007). Some additional thoughts are therefore considered separately here.

The question of modifying the present models of limestone dissolution in $CaCO_3$ / H_2O / CO_2 systems to cover speleogenesis in geothermal environments has started to be addressed by several authors and teams. Worthington (2001; 2004) proposed a geothermal viscosity reduction along deeper unconfined meteoric flow paths, and therefore increased flow rates and greater enlargement. However, this seems to be an uncertain argument, because it ignores the reduction in geothermal gradient caused by the cooling of the bedrock by the downward-flowing cold meteoric water itself, as discussed by Sippel and Glover (1964), Jeannin *et al.* (1997), Luetscher and Jeannin (2004) and Lismonde (2004). The first of these papers concluded that a 'normal' geothermal gradient could only be maintained if the velocity of the downward-flowing water is $<3ma^{-1}$. This equates to a velocity of c. $10^{-5}cms^{-1}$, which, from the graphs presented by Faulkner (2006, Fig. 3) is far too low to reach the breakthrough point for any conduit. Thus, the rise in temperature in local unconfined phreatic geometrical arrangements is insignificant, even within pre-breakthrough (laminar) flow regimes. For deep explorable stream passages, the lack of anecdotal evidence of rises in temperature from cavers and cave divers is hardly necessary to deny the possibility of effective geothermal heating. Additionally, Badino (2005) calculated that the cooling of the lowest conduits of a system by local meteoric flows effectively shields upper levels from geothermal heat. The efficiency with which flowing meteoric water exchanges heat with conduit walls was also demonstrated in the opposite sense by Ford (1984, p343), who described fast groundwater circulation within karstic limestones in permafrosted areas in Canada.

Andre and Rajaram (2005) considered karst inception by *rising hot geothermal waters of carbonic acid* with laminar flow in a single limestone fracture, apparently in unconfined conditions. They modelled the heat exchange between the rising water as it is cooled by the bedrock (thereby increasing the calcite saturation concentration upward along the fracture) and found that aperture growth rises almost uniformly until a *'maturation time'* that is somewhat analogous to the breakthrough time of meteoric systems. However, they calculated that the enlargement rate could then decrease, because an increasing flow rate would warm the bedrock further, creating a more-isothermal flow, thus reducing calcite solubility and dissolution rates at high saturation. Clearly, this treatment does not model Klimchouk's (2007) *confined* setting for an aquifer that only permits a constant flow rate, and their model also did not account for the buoyancy effects. This avoidance of buoyancy is common to all other numerical models of early conduit formation, as Klimchouk (2007) observed, but Dijk and Berkowitz (2000) have found experimentally that its effects make flow systems far more unpredictable than commonly assumed, at least for fractures in halite with fast dissolution in unsaturated waters.

References

Andre, B J and Rajaram, H. 2005. Dissolution of limestone fractures by cooling waters: Early development of hypogene karst systems. *Water Resources Research*, Vol.41, doi:10.1029/2004WR003331.
Badino, G. 2005. Underground drainage systems and geothermal flux. *Acta Carsologica*, Vol.34(2), 277–316.
Dijk, P E and Berkowitz, B. 2000. Buoyancy-driven dissolution enhancement in rock fractures. *Geology*, Vol.28(11), 1051–1054.
Faulkner, T. 2007. Review of Hypogene Speleogenesis. *Cave and Karst Science* (This issue).
Faulkner, T. 2006. Limestone dissolution in phreatic conditions at maximum rates and in pure, cold, water. *Cave and Karst Science*, Vol.33(1), 11–20.
Ford, D C. *Karst groundwater activity and landform genesis in modern permafrost regions of Canada*. 340–350 in LaFleur, R G (Editor), *Groundwater as a geomorphic agent*. [Boston: Allen and Unwin.]
Jeannin, P-Y, Liedl, R and Sauter, M. 1997. Some concepts about heat transfer in karstic systems. *Proceedings of the twelfth International Speleological Congress*, 1, 195–198.
Klimchouk, A B. 2007. *Hypogene Speleogenesis: Hydrogeological and Morphogenetic Perspective*. National Cave and Karst Research Institute Special Paper No.1. 106pp.
Lismonde, B. 2004. Geothermal flux with deep karstic waters: the surprise relating to transitory phenomena. *Karstologia*, 44, 51–55.
Luetscher, M and Jeannin, P-Y. 2004. Temperature distribution in karst systems: the role of air and water fluxes. *Terra Nova*, Vol.16, 344–350.
Sippel, R F and Glover, E D. 1964. The solution alteration of carbonate rocks, the effects of temperature and pressure. *Geochimica et Cosmochimica Acta*, Vol.28, 1401–1417.
Worthington, S R H. 2001. Depth of conduit flow in unconfined carbonate aquifers. *Geology*, Vol.29(4), 335–338.
Worthington, S R H. 2004. Hydraulic and geological factors influencing conduit flow depth. *Cave and Karst Science*, Vol.31(3), 123–134.

End

Trevor Faulkner
Cheshire, UK.
26 August 2007

CORRESPONDENCE

Dear Editors
It was nice to see Mark Dougherty's article on compass sighting errors in *Cave and Karst Science*, Vol.33, No.2.

A major problem is that a person's eyes cross when sighting on a close object; for instance, while concentrating on the compass. I can cross and uncross my eyes independently of focusing and get errors from -5 to +15 degrees when I use two eyes.

References:

Bartholomew, Roger V. [Fall] 1988. "Use One Eye With the Suunto". *Compass and Tape*, Vol.6, No.2, 16–20.
Neff, Brad. [Winter] 1988. "A Trigonometric Analysis of Suunto Sighting Error". *Compass and Tape*, Vol.3, No.3, 60–61.
Thrun, Robert. [Fall] 1988. "Don't Use Two Eyes With Your Suunto". *Compass and Tape*, Vol.6, No.2, p.25.

Bob Thrun

BOOK REVIEWS

CAVE GEOLOGY. By Arthur N Palmer. Published by Cave Books, 4700 Amberwood Drive, Dayton, Ohio OH 45424-4602, USA. 2007. 454pp, 561 photos, 250 maps and diagrams, A4 hardback. ISBN 978-0-939748-66-2. $38.95.

This is a fabulous book, at a ridiculously low price, from arguably the best technical writer in the world of caves and karst. Art has been working on it for years; it is his *magnum opus* that relates so much of his vast experience. And it has turned out to be well worth waiting for. His writing is (as usual) succinct, perceptive, comprehensive and authoritative, and the words explain everything so very clearly. Then the pages contain a huge library of excellent photos (nearly all by Art himself, and many with his wife – and long-time caving companion – Peggy there for scale), which, together with a great pile of cave surveys (mostly black-line), make the book a must-have on their own.

Books on caves or karst have to have a certain amount of overlap. This one is unashamedly centred on the caves, with only minimal reference to the surface landforms of karst. So Ford and Williams will remain as the key text on karst, but Palmer has now stepped in with the key text on caves. Scientists and students will all want their own copies, but this is also a must for every serious caver – because the science is so accessible at a readable level. Art Palmer is a teacher, and it shows; he presents his information so well, even including sections on the techniques that yield the data (notably in chapters 1 and 14), from cave surveying to water tracing and more. But it is his concise explanations of complex subjects that are so much to be valued; they include: the nature of the karst water table; groundwater hydraulics; Reynolds Number and Manning Equation; interpreting flow data from cave wall scallops, and many more.

Chapter 2 introduces cave country, with an overview of the key elements of surface karst and then an excellent round-up of the world's cave regions and great caves. Chapter 3 is a solid introduction to the bits of geology needed to understand caves. Chapters 4 and 5 are splendid overviews of the hydrology and chemistry of karst waters. With due deference to the erudite Wolfgang Dreybrodt (who thinks and writes on a higher plane than most mere mortals), this is the best overview going of the chemical processes that drive karst dissolution. Chapter 6 covers all the morphological features of caves, with concise explanations at all points.

Chapter 7, on speleogenesis and the origin of caves, could be accused of being a little thin on the real origins of caves (though it develops very clear concepts on the subsequent evolution of caves). It refers to hydraulic thresholds, strong acids and inception horizons, but all rather briefly, when this is the major area of current debate; perhaps the obvious fracture permeability of granite is adequate reason to worry less about how the water first got there to start dissolving the limestone.

Chapters 8 and 9, on the hydrological and geological controls of cave patterns, are both excellent chapters, written from Art's greatest strengths. Groundwater controls cover dendritic caves, maze caves, diffuse recharge, artesian flow, hypogene caves, saltwater, thermal water and sulphuric acid – with the last of these dwelling on the now-famous caves of Villa Luz, Frasassi and Lechuguilla. The geological controls include rock types, rock structure, porosity and stress release, before heading off to paragenesis and vadose captures. Cave levels (not always level) get the full treatment, with so much learned from the complexities of Mammoth Cave where bedding guides individual passages with vadose/phreatic transfers that identify the true genetic levels (just as in our own Leck Fell Master Cave, though that example does not feature in the book), and there is also due reference to the underflow concept developed by Steve Worthington.

Chapters follow on cave minerals (with many answers and many questions), lava caves (but no word on their lack in flood basalts), and an unusually thorough consideration of weathering processes in caves. The time chapter covers dating, palaeo-climates and inferences for landscape evolution, and has a fascinating story on the long history of the huge Black Hills caves in South Dakota. A final chapter delves briefly into the applications of cave studies, with a scatter of examples including sinkhole collapses and groundwater pollution. It rounds off a book that contains a massive amount of information.

This might have read like an enthusiastic review; it was meant to; this is an excellent book. Don't give up on it because it's lost in the depths of Ohio, as it's well worth chasing down a copy.

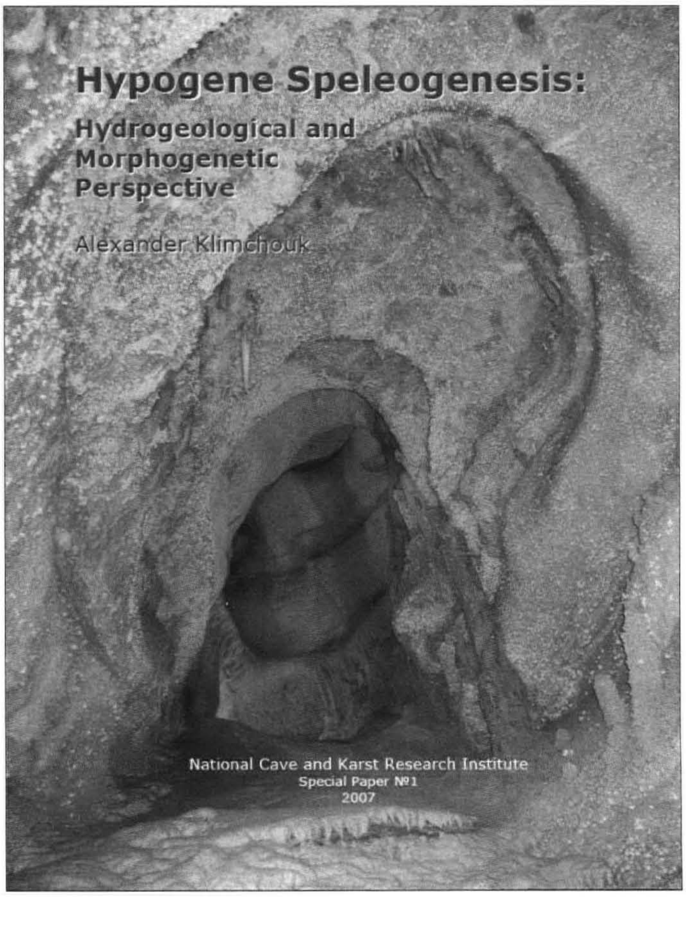
Tony Waltham
Nottingham.

HYPOGENE SPELEOGENESIS: HYDROGEOLOGICAL AND MORPHOGENETIC PERSPECTIVE by Dr Alexander B Klimchouk, National Cave and Karst Research Institute Special Paper No.1, 2007, 106pp. Available for $35 plus $6 domestic shipping or $13 international shipping. Payable by Visa, MC, AMEX, or Discover cards via sales@nckri.org or by calling 001-505-835-6168, or by cheque written to "NCKRI" and sent to NCKRI/E&ES, Attn: Lisa Majkowski, New Mexico Tech, 801 Leroy Place, Socorro, New Mexico, 87801, USA. ISBN-10 0-9795422-0-0; ISBN-13 978-0-9795422-0-6

This important new work draws together the increasing evidence from around the world that *hypogene* speleogenesis is a widespread phenomenon. The concepts discussed include those of confined deep-seated karstic aquifers and hydrothermal and strong acid dissolution. These have been considered in the past (e.g. in Klimchouk *et al.*, 2000: Chapter 5.2), but not so thoroughly nor with such powerful arguments for a revision of current thinking in several areas. The book also provides an insight into Russian and other east European texts that are otherwise not very accessible to an English language readership. In the text below, clarifications suggested by this reviewer are inserted in square parentheses.

Definitions

Following Ford (2006), the author defines 'hypogene' speleogenesis from its hydrogeological setting rather than from dissolutional mechanisms as: "*The formation of caves by water that recharges the*



soluble formation from below, driven by hydrostatic pressure or other sources of energy, independent of recharge from the overlying or immediately adjacent surface". The key words are "*from below*", because the concept assumes that the soluble formation is commonly and initially *confined* by less soluble lithologies through which the water rises vertically to regain the surface. This creates *cross-formational* or *transverse* [phreatic] speleogenesis from the water rising through the strata of the dissolving rock, in contrast to the 'epigenic' *lateral* or *longitudinal* [phreatic and / or vadose] speleogenesis that occurs in local unconfined settings, where the water flows through a soluble formation all the way to the surface. This latter setting is the one that has dominated most previous explanations for the development of karst cave systems.

Settings

The hypogenic setting incorporates the discharge regimes of regional or intermediate flow systems. Most water is ultimately derived from downward percolation of meteoric water along distant major divides and discharged upwards to the surface via non-karstic rocks, commonly at river valleys and other low areas where tectonically-weakened zones increase permeabilities. It is the *least permeable* units that dominate the system for cross-formational flow, because their fractures constrain the flow rates, not the enlarging conduits in the soluble formation. Flows can reach depths of 1000–1500m and so might become heated geothermally, creating steep thermal gradients on rising upwards and cooling. There is no genetic relationship with the overlying surface or with *adjacent* groundwater recharge. However, lateral hydraulic connections create maze systems in the soluble beds that only extend for a few hundred metres in any single direction [although it is not clear why there is such a universal constraint].

Hypogene caves form distinctive passage morphologies in soluble rocks that appear to be independent of lithology, because similar forms occur in both carbonates (including even marbles) and evaporites (gypsum and halite). In plan and in section, these caves develop as 2D (single- and multi-level) and 3D network and spongework mazes and irregular chambers that are strongly controlled by (commonly rectilinear) fracture patterns, and *never* form dendritic branchwork caves. Thus, the overall passage densities, cave porosities and passage areal coverages are about one order of magnitude greater in these confined rather than in unconfined settings, with no appreciable parameter differences between caves in limestone or gypsum in confined settings. The multi-level stories are thought to form simultaneously, rather than ageing upwards as in 'epigenetic' caves that follow lowering water levels, although 'master levels' might give a misleading impression of successive 'lateral' cave-forming flows. The maze passages commonly have many lateral blind terminations and abrupt variations in cross-sections.

Within the enlarging conduits, flow regimes are commonly sluggish without forming wall scallops. Supply from such high karstic storage to artesian risings is commonly steady and independent of climate and weather, with little temporal variation of chemical parameters. Three different cave flow regimes are identified, giving passage morphologies that are convincingly well illustrated: recharge from rising inlets from less permeable strata at floor level (which might be obscured by sediments), throughflow along rising wall channels and ceiling half-tubes, and discharge via rising outlet tubes into the confining lithology. Ceilings also display distinctive cupolas that might also terminate in outlets and there can be evidence of underwater stoping upwards. Thus, hypogene transverse flow differs from previously-held views about regional flow, which assumed little communication with adjacent aquifers. The author argues, apparently for the first time, that the conduit enlargement is commonly driven by *buoyancy dissolution* that is driven by solute or thermal density differences. Thus, dissolution is stronger along conduit roofs [which can be similar to the epigenic case, where sediments drift to the floor], explaining the formation of rising wall channels and cupolas. Additionally, as water cools on ascent, it can dissolve more calcite in limestone settings (hydrothermal speleogenesis) [which is important at low flow rates and high solute concentrations]. The cave sediments are commonly autochthonous clastic clays and silts without larger allogenic deposits. Exotic minerals are common, but not speleothems until removal of caprocks and lowering of water levels. Moreover, uplift and denudation of basinal strata can bring the caves into an epigenic environment where hypogenic features can be over-printed by scallops and allochthonous sediments. Rapid recent uplifts and neotectonic activity can be important in re-directing flows [as also applies to enhanced fracturing in the epikarst].

Arising hypotheses

The author asserts that hypogene systems include many of the largest and longest caves in the world, which were commonly thought to be 'epigenic'. Hypogene speleogenesis should also explain the existence of several deep and large but unexplored cavities revealed by boreholes, wells and mines. Arising from his general observations and deductions, he hypothesises that hypogene speleogenesis might provide an alternative explanation for maze caves to that provided by Palmer (1991) in supposedly-meteoric systems, especially in low-gradient systems with low flow rates and low hydraulic gradients. He notes that this is an alternative to diffuse recharge through insoluble caprock, which should not create multi-storeys. When upward flow across the karst formation is limited by permeability of the feeding and receiving formations, it suppresses speleogenetic competition [because there is no positive feedback of favourable large conduits capturing the flow], allowing dissolution equally along structural features to create complex 2D and 3D mazes. Thus, the author believes that *"most"* maze caves in the world were formed in confined conditions [although the numbers of maze caves formed by the Palmer (1991) process at high flow rates and with short 'breakthrough' times in 'epigenic' situations are not quantified]. Hypogene speleogenesis might also include many settings previously thought to originate from palaeokarst, including at oil fields [potentially reducing their assumed ages]. Ceiling half-tubes formed by buoyancy effects might be a better explanation than paragenesis in some situations and cupolas might have formed by buoyancy dissolution rather than later by condensation-corrosion in vadose conditions. Ascending hypogenic transverse speleogenesis can explain many features, even in the well-studied caves of the Guadalupe Mountains (USA), without needing to invoke sulphuric acid dissolution, although this might be a supplementary mechanism. The author concludes that karst zones and their function in basinal groundwater systems are predictable but that, because of inheritance, speleogenesis requires each separate stage to be specified.

Commentary

Whilst reading the text, this reviewer made several personal observations, as summarised below. Some might seem detailed and pedantic, but could be useful for readers previously familiar primarily with precursor literature written in English.

Speleogenesis occurs in many different hydrogeological environments and timescales and relies on many different physical and chemical mechanisms, so that precise specification of new terms is essential. Klimchouk attempts to distinguish two major inland cave forming environments: 'hypogenic' with 'transverse' flow (as specified above and also equated in places with 'deep-seated', i.e. karst with no surface exposure, although its depth range is not specified), and 'epigenic' with 'lateral' flow (equated with 'unconfined'). This leads to some confusion, because Lowe and Waltham (2002) define 'epigean' as forming on the surface, 'endogean' and 'epikarst' as being immediately below the surface and 'hypogean' as being deeper than the endogean. Thus, Klimchouk seems to describe all the classically-described cave systems of the world as being formed on, or perhaps at, the surface, without distinguishing them from the epikarst and despite many non-hypogenic dendritic systems reaching depths greater than a kilometre. Klimchouk himself suggests replacing his use of 'epigenic' by 'hypergenic', a word used in eastern Europe to denote processes caused by near-surface descending water. He also refers to 'unconfined' settings as 'vadose' in the Abstract and in the Epilogue, whereas many are, of course, phreatic. A way to resolve the confusion might be to accept that soluble formation aquifers can be both shallow or deep *and* confined or unconfined, and indeed that they can also be 'half-confined', with recharge from clastic strata but discharge through soluble strata and vice versa. It would then be clear that vauclusian risings supplied via long karst conduits and synclinal structures such as the Carboniferous limestone beneath the South Wales coalfield are both deep and unconfined, at least at their extremities, whilst misleadingly obeying the given hypogean definition. A statement on p8 that *"Principal categories of karst-forming environments ..... can be adequately understood and classed only within the context of regional groundwater flow systems"* seems to be too sweeping, because it denies the important role of the epikarst (e.g. Klimchouk, 2000) and the thousands of short caves in marble stripe karsts (e.g. Faulkner, 2001).

Another difficulty is that the reader has to take some ideas and concepts on trust, especially early in the document, and the text should provide more references. For example: the early mixing of examples for gypsum and limestone environments is initially alarming, although it becomes justified later; on p.9, one wonders by which processes water from distant recharge areas can rejuvenate aggressiveness, but this is explained by the various types of mixing corrosion on p.32; the term 'free convection mechanism' is introduced early, without explanation, although it transpires later that it means 'buoyancy'. Also on p.9, the word *"hydrosomes"* is used, for which this reviewer cannot easily find a definition. The statements *"rate of vertical water exchange remains more stable than the rate of lateral flow"* and *"The rate of upward percolation across confining beds under valleys is generally higher than the rate of downward percolation in the vicinity of topographic divides"* appear on p.14. It would be informative to learn how the author knows these things: are they measured, experimental, theoretical or assumed results? Understanding of the 'breakthrough' concept is assumed, without giving an appropriate reference (e.g. Dreybrodt, 1990). [Incidentally, *"discharge increases...dramatically after breakthrough"* (p.25) should be *"at breakthrough"*, because flow rate increases less dramatically before and afterwards (Dreybrodt, 1990)]. In section 3.6, three processes that increase the solubility of gypsum are listed and it is stated that *"it is generally believed that creation of significant caves, where these acids* [derived from H_2S] *provide the dissolution mechanism depends mainly upon rejuvenation of aggressiveness by mixing or cooling"*, without references. Similarly, the role of *"large scale (regional) convection cells driven by density gradients in groundwater circulation"* is stated in section 3.8 to be *"generally recognised"*, without giving examples. Earlier on the same page, a role for buoyancy during dissolution in *unconfined* systems is discounted, without considering a possible role there prior to breakthrough. It would also be useful if some examples of relict hypogenic caves over-printed by epigenetic processes were suggested on p.84. The epigenic replacement of sulphate rocks by calcite and sulphur (mentioned on p.89) needs further explanation, supported by relevant equations. The reader would also like to know what the evidence is for *"microbially-mediated transformation of methane to simple organic compounds"*, as stated on p.90.

The book contains, surprisingly, little discussion of the geomorphological approach of Lowe (1992), who identified deep inception horizons that perhaps date from the time of diagenesis and who had already discussed vertical upward *"cross-stratigraphical"* drainage during inception. The *"Recognition of the ultimate control on confined speleogenesis by transmissivities of adjacent non-soluble aquifers"* on p.13 was essentially proposed by Lowe (1992) and this should be acknowledged in several places. Similarly, the physico-chemico approaches for limestone dissolution during inception and conduit enlargement (e.g. Palmer, 1991; Dreybrodt *et al.*, 2005) are sparingly mentioned. Does the author think that there is an inception phase prior to 'breakthrough' in these environments? Are the answers the same for limestone, gypsum and halite lithologies? Or, is 'breakthrough' never reached, with conduits slowly enlarged over millions of years (as proposed by Dreybrodt and Gabrovsek, 2000 for low gradient limestone unconfined aquifers) in all these rock types? These questions, together with possible rates of conduit enlargement and relevant timescales, could have been posed, even if their answers are presently unavailable for a book that is intended to be a springboard for future research. Footnote 3 on p.97 about a widely-reported 5–15mm constraint on conduit size at breakthrough is incorrect, especially in regional and confined settings with low flow rates, according to Faulkner (2006).

The future

The observations above pale into insignificance against the immense accomplishment of *Hypogene Speleogenesis*, which is essential reading for karst researchers. It represents a comprehensive new paradigm that Alexander Klimchouk has been constructing over many years of exploration and research, and his arising hypotheses challenge many established ideas, as discussed above. As if the physics and chemistry of pre- and post-breakthrough dissolution in 'simple' $CaCO_3$-H_2O-CO_2 systems are not complex enough, the quantitative explanation of speleogenesis in the various hypogene systems discussed qualitatively by Klimchouk might take decades of research to elucidate: every one of these systems could differ geologically and involve a complex and variable suite of temperature-dependent chemical reactions that might need to be considered 'cave by cave'. Even more challenging, we can now anticipate an integration of studies that relate hypogenic speleogenesis with metamorphism, mineralization and metasomatic chemical reactions and dissolutions and with the formation of sulphur deposits and hydrocarbons in oil and gas fields.

Klimchouk notes that there are still few analyses that link regional speleogenesis with regional hydrogeological and geomorphological evolution (as also applies in Britain) and that this linkage should be assisted by the re-interpretations of many known caves, especially those where epigenic processes have followed hypogenic processes. There might be no obvious examples of such 'overprinting' in British caves, but a re-evaluation of British maze caves, which occur in various lithologies, based on the concepts of *Hypogene Speleogenesis*, would be extremely beneficial. For example, could the high-level maze passages in Ogof Ffynnon Ddu have been initiated in this way?! (However, the presence of scallops and the *apparent* absence of hypogene diagnostic features in the five maze caves accessible within Devis Hole Mine, UK, as described and illustrated by Harrison, 2007, might make such a determination problematical in this case).

In common with nearly all previous studies of karst hydrogeomorphology, Klimchouk only considers *interglacial* speleogenesis, as implied in Fig.14 on p.29. Page 29 also discusses a *"common misconception"* in the literature that hypogenic karst is peculiar to arid climates. However, the most northerly of his many illustrations of hypogene speleogenesis are a cave near Krasnoyarsk, Siberia, at c.56°N and Knock Fell Caverns, UK, at c.55°N. Thus, few of his examples have been covered by Quaternary icesheets. Because planetary glacial conditions lasted for some 90% of the Pleistocene, as can be inferred from (e.g.) Huybers (2007), we must now also consider whether much of his reported long-term hypogene cave development occurred during (normal!) wetter conditions, when water levels were higher south of the northern hemisphere icesheets and any permafrost. In this case, the caves might then become relict episodically during interglacials, as at present, rather than only after uplift and denudation, especially as glacial erosion is also not relevant to most of his examples. It is also interesting to note that Osborne (2007), whilst ascribing speleogenesis by slowly-rising groundwaters to Cathedral Cave, New South Wales, Australia, recognised at least ten significant phases of hypogene speleogenesis, rather than its development occurring in a single continuous, but long-duration, process. The drawing together of explanations of hypogene speleogenesis within wider understandings of regional geological and geomorphological evolution, planetary climate change and the appropriate local chemistry should provide fascinating studies for karst research for at least a century.

References

Dreybrodt, W. 1990. The role of dissolution kinetics in the development of karst aquifers in limestone: a model simulation of karst evolution. *Journal of Geology*, Vol.98(5), 639–655.

Dreybrodt, W and Gabrovsek, F. 2000. *Dynamics of the evolution of single karst conduits*. 184–193 *in* Klimchouk, A B, Ford, D C, Palmer, A N and Dreybrodt, W (Eds), *Speleogenesis: Evolution of karst aquifers*. [USA: National Speleological Society.]

Dreybrodt, W, Gabrovsek, F and Romanov, D. 2005. *Processes of speleogenesis: a modeling approach.* [Postojna – Ljubljana: Zalozba, ZRC.] 376pp.
Faulkner, T. 2001. Cave development in central Scandinavia. *Proceedings of the thirteenth International Speleological Congress.* Paper 155, 4pp (Abstract p.106).
Faulkner, T. 2006. Limestone dissolution in phreatic conditions at maximum rates and in pure, cold, water. *Cave and Karst Science,* Vol.33(1), 11–20.
Ford, D C. 2006. *Karst geomorphology, caves and cave deposits: A review of North American contributions during the past half century.* 1–14 *in* Harmon, R S and Wicks, C W (Eds). *Perspectives on karst geomorphology, hydrology and geochemistry.* GSA Special Paper, Boulder, Colorado.
Harrison, T. 2007. Further phreatic cave systems in Swaledale, north Yorkshire, UK. *Cave and Karst Science,* Vol.33(2), 65–72.
Huybers, P. 2007. Glacial variability over the last two million years: an extended depth-derived age model, continuous obliquity pacing and the Pleistocene progression. *Quaternary Science Reviews,* Vol.26, 37–55.
Klimchouk, A B. 2000. The formation of epikarst and its role in vadose speleogenesis. 91–99 *in* Klimchouk, A B, Ford, D C, Palmer, A N and Dreybrodt, W (Eds), *Speleogenesis: Evolution of karst aquifers.* [USA: National Speleological Society.]
Klimchouk, A B, Ford, D C, Palmer, A N and Dreybrodt, W (Eds). 2000. *Speleogenesis: Evolution of karst aquifers.* [USA: National Speleological Society.]
Lowe, D J. 1992. *The origin of limestone caverns: an inception horizon hypothesis.* PhD Thesis. Manchester Metropolitan University.
Lowe, D J and Waltham, A C. 2002. A Dictionary of Karst and Caves. *BCRA Cave Studies Series* (10) 40pp.
Osborne, R A L. 2007. Cathedral Cave, Wellington Caves, New South Wales, Australia. A multiphase, non-fluvial cave. *Earth Surface Processes and Landforms.* (In press).
Palmer, A N. 1991. Origin and morphology of limestone caves. *Geological Society of America Bulletin,* Vol.103, 1–21.

Trevor Faulkner
24 August 2007

THESIS ABSTRACT

The challenge to the sustainable development of the caves and surrounding region of the Cradle of Humankind Heritage Site.

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Submitted in part fulfilment of the requirements for the Masters Degree in Business Leadership, November 2006

Graduate School of Business Leadership
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Supervisor: Mr Greg Dalton

The Cradle of Humankind World Heritage Site is one of the latest additions to South Africa's list of environmentally, economically and scientifically valuable regions. The area is known as the Cradle and has seen a dramatic increase in the use of this term as a marketing tool to help develop the region as a tourism centre. However this very development and the growing Gauteng urbanization together with specific events such as the rise of acidic mine water is placing the area under serious threat.

The focus of the Cradle is the caves of the regions and the scientific data they contain. The caves are accessible in a large part to many parties such as caving groups, commercial cavers, formal and informal tourists in the caves, scientists and use of the caves for cultural activities. All these events are controlled only by the self imposed standards of the individuals in questions. As a result there has been a decrease in the condition of some caves. The effect can be described in terms of the tragedy of the commons as outlined by G Hardin. Simply put this tragedy is the result of individuals seeking personal benefit, be it financial, scientific, cultural or adventure as they utilise the caves as a common or publicly accessible resource. The negative impacts of such use are attributed to other users if they are even acknowledged. As a result the deterioration is shared by all but the benefits gained only by the individual.

The opinion of many parties actively looking at this issue has been summarized and expanded on with reference to many scientific and academic articles. The problem is defined as how to develop the Cradle in a sustainable manner, that is to prevent further damage to the caves and hence the Cradle's reputation, without simply banning access to the very resource that is the reason for the region's development.

A short description of what caves are and why they are important is developed into a description of the current economic activity that can be measured, as well as two potential health hazards to those entering caves which may impact on the tourist image. Histoplasmosis capsulatum is a fungal lung infection found in many but, so far, not all Cradle caves; whereas the presence of radon gas from natural sources has been measured it has not been investigated in depth.

The importance of collaboration and the effect of a lack of collaboration is seen as being one of the Cradle's weaknesses. As the many interested parties pursue their own, often overlapping, interests the pressure on those interested from the increased activity and development of the area is creating tension. In an effort to explore how this tension might be used creatively it is suggested that a measurement of the problem, as seen in the changing environment of the caves, be utilized. The implications of sustainable development are explored and the difficulties of this are described, whilst the need to follow or include the best practices worldwide is seen as a way forward.

A particularly useful comparison is made between the Western Cape Peninsular, the United Kingdom National Parks and the Canadian Oak Forest regions. The areas have similar problems to the Cradle and have approached those problems that might have useful suggestions for the Cradle.

A list of recommendations for further consideration for both the Cradle and the caves specifically is given. The emphasis is on fewer key parameters to be identified leading to a measurement system. This system can then be used to support further research on specific issues.

If action is not taken soon to co-ordinate and focus on the challenges to the Cradle then it will be too late to preserve the best examples of the region and difficult to develop the Cradle sustainably into the world-class tourist, residential, archaeological, spelaeological and visual wonder that it is.

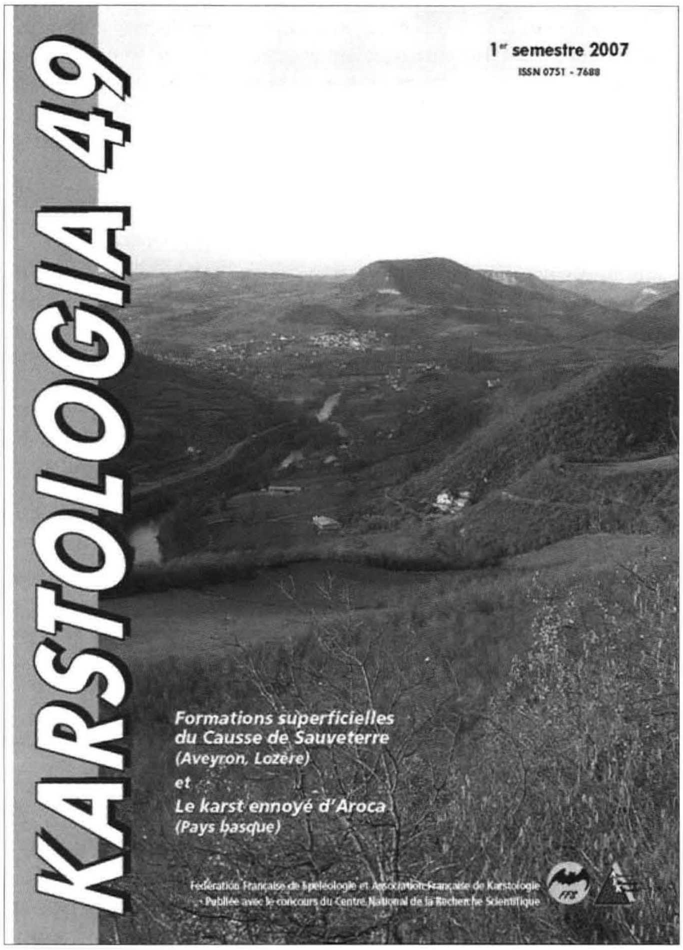
ABSTRACTS FROM KARSTOLOGIA 49

Laurent BRUXELLES, Régine SIMON-COINÇON, Jean-Louis GUENDON et Paul AMBERT
Formes et formations superficielles de la partie ouest du Causse de Sauveterre (Grands Causses, Aveyron et Lozère). p.1–14

MORPHOLOGY AND SUPERFICIAL FORMATIONS OF THE WESTERN PART OF THE CAUSSE DE SAUVETERRE (GRANDS CAUSSES, AVEYRON AND LOZÈRE, FRANCE). In 2002, the Natural Regional Park of Grands Causses has coordinated a hydrogeological study of the western part of the Causse de Sauveterre, the northernmost of the Grands Causses. A multidisciplinary approach (geology, geomorphology, geochemistry and hydrology) was used to delineate the catchment area of the main springs and to estimate the vulnerability of karstic aquifers.

The Grands Causses are situated in the southern part of the French Massif Central. The landscape is characterised by huge limestone plateaus cut by deep canyons.

The morphologic study of the western part of the Causse de Sauveterre (Causse de Massegros and Causse de Sévérac), combined with analysis of superficial formations, allows us to identify the main steps of landscape evolution. The discovery of bauxite and of many outcrops of Upper Cretaceous sandstone confirm that the Coniacian ingression invaded some paleo-landscapes developed within a long period of continental evolution which was initiated at the end of the Jurassic. During the Tertiary, many residual formations form covers of the limestone plateaus. We can distinguish alterites developed from different formations of the



stratigraphic series (clay with cherts from Bajocian, dolomitic sand from Bathonian and Callovian, sandy clays from Cretaceous deposits) from some allochtonous deposits which can be found in some parts of the Causse de Massegros. These formations are found in association with morphological features (shelves, poljés, fluvio-karstic valleys, sinkholes) and are more or less responsible of their development. Furthermore, some volcanic rocks cut through or even reused some of them. With the deepening of canyons and the base level drop, horizontal morphologies are preserved only where superficial formations are abundant and thick enough to maintain crypto-corrosion. Elsewhere, karst unplugging removes most of the superficial formations, and the karstic evolution tends to show a vertical development of morphologies and caves. Some springs, which benefit from a favourable lithologic, structural and hydrologic context, are more competitive and expand their catchment area at the expense of the other springs. Many superficial features express this dynamism on the plateau and allow us to determine the most sensible areas for water pollution and the most fragile ones for human activities.

Key words: karstic morphology, superficial formations, alterites, Upper Cretaceous, volcanism, hydrogeology, Causse de Sauveterre, Grands Causses, France.

Fouzia BENSAOULA
Etude de la karstification à partir des données de forages: le cas des Monts de Tlemcen (Algérie). p.15–24

Study of karstification from borehole data. The case of the Tlemcen mountains. The Tlemcen mountains are the second largest carbonate massif in the north-west of Algeria, after the one of the Saida mountains. It is a large horst structure trending NE-SW, composed mainly of Upper Jurassic and Lower Cretaceous formations. The aquifers within it constitute the main water resource of the area. They are tapped by more than 160 boreholes, which constitute a great tool for studying the karst, especially its phreatic part. In the holes made by conventional drills, the total loss of drilling mud indicate karstification. The registration of the altitude of those losses permit to recognize the fissured and karstified levels. Three different aspects of karstifications were observed: an important fracturation, seen by complete loss of drilling mud during the drilling, important caves, observed by the free fall of drilling tools, and caves filled by karstic sediments, found thanks to diagraphies and the study of material brought up by the drilling.

A statistical analysis of these data permitted to evidence the following elements:

- The dolomitic facies is much more dominant than the limestone facies;
- The frequency of incidences slowly decreases with depth;
- The fracturation is most important in the first 120 to 130 m below the top of the karstified formations, although it does not disappear at depth.

In the breakdown zone of Tlemcen, situated in the northern piedmont part of the Tlemcen mountain, 26 boreholes permitted to draw an isopach map of the thickness of the karstic cover as well as the top of the karstified formation. This one shows two hollow zones below 100 m depth in the SW and NE parts. The top of the Jurassic carbonates shows a very irregular surface which might correspond to a karstic paleorelief that was drowned by the Miocene transgression. Finally, the last map shows a karstified surface that can possibly be connected to a pseudo-paleo-piezometric surface.

Key words: Tlemcen mountains, boreholes, loss of drilling mud, karstification, cartography, breakdown zone of Tlemcen.

Cécile HAVRON , Jean-Marc BAELE et Yves QUINIF
Pétrographie d'une altérite résiduelle de type « fantôme de roche » p.25–32

Petrography of a residual alterite « ghost-rock ». Classically, the karstogenesis begins with a phase of dissolution along fissures. Progressively, the fissure broadens and more water flows. Some fissures transform in more important void, sometimes galleries. The fundamental fact is that the removal of bed-rock is total, the greatest part by solution (carbonates, calcium and magnesium, sodium and potassium...), the rest one like solid phase (clay minerals, quartz...). We call this process "total removal". But another karstification process exists: the « ghost-rock » formation.

The first phase of the « ghost-rock » formation begins with an isovolumic alteration of the bed-rock. The insoluble parts remain while the soluble parts are evacuated with underground water. This insoluble part is constituted by clays minerals, silica phase, sparite like fossils, or big crystals and forms a residual alterite. That is the "ghost-rock formation". This is the case for the present example which is a residual alterite in a very pure wackestone. This object presents like a volume of alterite confined in the intact bed-rock. We study this ghost-rock by a petrographic analysis. The macroscopic approach emphasizes the great porosity of the ghost-rock which is very crumbly. The border between the ghost-rock and the bed-rock is very irregular, emphazising the petrophysic differences.

The microscopic approach shows in the ghost-rock a general collapse of the structure where subsist only the best crystallized grains. The alteration increases to the detriment of the little crystals, saving the bioclasts, or to the detriment of the fissures. One detects also another phase which is constituted by gypsum. The examination using the electron microscope shows that the bed-rock is formed by well soldered grains, crystals, primary pyrite. On the other hand, the ghost-rock is characterised by a great porosity, secondary pyrite, corrosion gulfs on crystals. This is the indication that the acid function comes from sulfuric acid by oxidation of the sulfide. This is the reason of the presence of gypsum. After the alteration, the organic matter present in the bed-rock (black limestone) can reduce the gypsum in secondary sulfide. The conclusion is that the formation of the ghost-rock can develop in a pure limestone, and non only in a limestone with silico-clay skeleton. This ghost-rock represents the first stage of the genesis: an isovolumic alteration, without macroscopic void, before a collapse of the weathering rock.

Key words: karst, weathering, ghost-rocks, microscopic analysis.

Cyril FLEURANT, Gregory TUCKER et Heather VILES
Modèle d'évolution de paysages, application aux karsts en cockpit de Jamaïque. p.33–43

Landscape evolution model, example of cockpit karst terrains, Jamaica.
A model of cockpit karst landscape evolution is presented. After explaining implementation of dissolution processes of limestone in the landscape evolution model CHILD, we develop a model of limestone denudation based on epikarst theory processes. The model takes into account an anisotropic dissolution in space and time according to what is observed in reality or described by scenarios of cockpit karst landscape evolution. This model requires a fracture's network to take into account subsurface flow. Then, dissolution and thus fractures widening are computed and show a positive feedback between dissolution and flow. The relation between subcutaneous dissolution of fractures and denudation of the topography is introduced by means of an empirical equation associated with epikarst processes: the denudation is taken to be proportional to the dissolution in the subcutaneous zone. Simulated cockpit karst terrains are compared with real landscapes by means of morphometric criteria. Results of the model are very close to reality which hence confirms the importance of anisotropic dissolution processes and above all could be a numerical validation of the epikarst processes to describe cockpit karst genesis.

KEY WORDS: erosion, dissolution, karst, fracture, landscape, modelling.

Nathalie VANARA, Alain PERRE, Marc PERNET, Serge LATAPIE, Stéphane JAILLET et Olivier MARTINE
Aroca (domaine marin côtier, Pays basque, France): un karst continental ennoyé par les transgressions maritimes quaternaires. p.43-55

AROCA (LITTORAL, BASQUE COUNTRY, FRANCE): A CONTINENTAL KARST DROWNED BY QUATERNARY MARITIME TRANSGRESSIONS. The rocky formations in shallow areas of the Atlantic coast are hardly known. Studies are rare because of the difficulties of direct observation (diving in always agitated, troubled water, depth between –20 and –40m).

Our first step was to make a detailed topography of a submarine plateau named Aroca, 4km off Socoa harbour (bay of Saint-Jean-de-Luz). This plateau was already known for having a large variety of forms within a small surface (150 x 100m). We gave names to most remarquable formations and defined five main characteristic zones:

- in the exokarstic domain:
  - 1/ a top surface with channels;
  - 2/ a dismantled surface with pinnacles;
- in the endokarstic domain:
  - 3/ caves, galleries, arches;
- at the limits:
  - 4/ three inclined plans, west, north and east;
  - 5/ a cliff to the south.

A typology of forms shows a predominance of ablation reliefs: aplanation, over-deepened channels, covered rooms and galleries, arches, residual pinnacles. Deposit accumulations regroup chaotic breakdown blocks, pebble accumulations and sand covers.

Statement of explanations requires recognition of the nature and age of the outcrops and succession of erosional agents during the Pleistocene. Rocks are dated from Ypresien (limestones) to Bartonian (marls). Continental erosion during sea regressions is responsible of caracteristic landforms and deposits; for example wall banks, allochthonous pebbles. The currently active marine erosion during sea transgressions is due to storms, tide, dissolution, biochemical action (lithophages) and gravity.

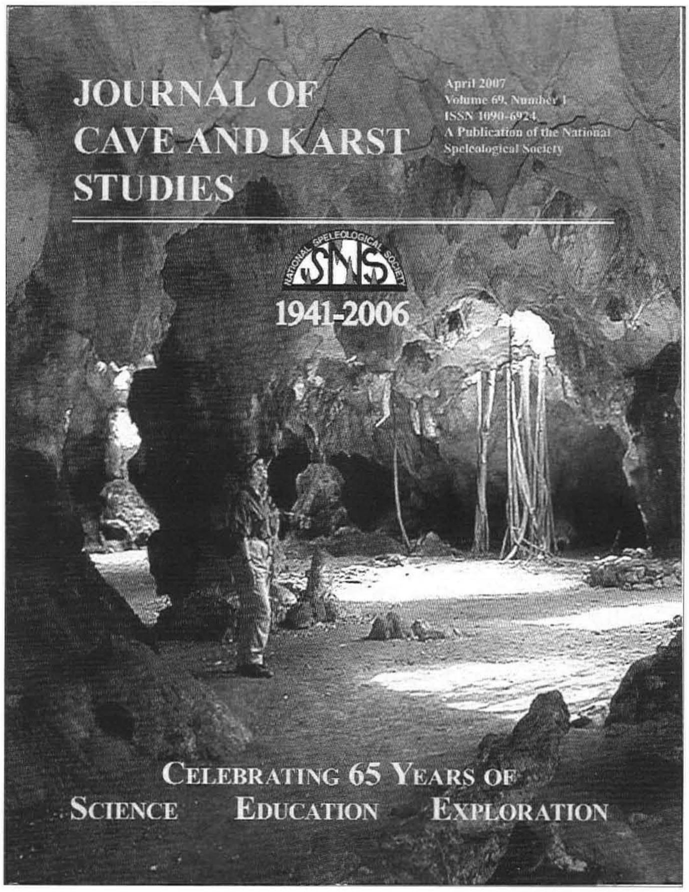
We propose a paleogeographic reconstitution. After an essentially calcareous sedimentation in Eocene and an essentially marly sedimentation in Oligocene, the sea recedes during Miocene. From then, the platform, henceforward above the water, is subject to meteoric erosion. In Pliocene, evolution of the massif is isovolumic (under a marly cover and with a low hydraulic gradient). During the lower and middle Pleistocene, the erosion of the marly cover goes on. During the upper Pleistocene, the wurmian (–18000 BP) marine regression allows entrenchment of the hydrographic system thanks to an increase of hydraulic gradients (classic functional karst). From 15000 years onwards, a general transgression of sea level happens by successive steps. During the Boreal, a break in transgression allows the formation of a paleo-shore at –20 to –30m, inducing a peneplanation phase in the tidal or infratidal zone. From 7500 BP onwards, a a rapid transgression from –23 to –8, then a slower one from –8 to the present level stops karstification on the massif.

At present, only marine abrasion is active and tends to obliterate the previously built landforms.

KEY WORDS: littoral zone, submarine limestone plateau, marine regressions/trangressions, paleogeographic reconstitution, Tertiary, Quaternary, Basque coast, Atlantic Pyrenees, France.

OTHER RECENT KARST PUBLICATIONS

[**Note**: the content of this section is heavily space-dependent as well as dependent upon information availability at the time of publication. Hence it is not claimed that coverage is exhaustive. Where possible omissions will be rectified in later issues.]



Journal of Cave and Karst Studies
of the National Speleological Society
Volume 69(1), April 2007

1941–2006: Celebrating 65 Years of Science, Education,& Exploration

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Helictite
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ABSTRACTS

Ian D Clark: The abode of malevolent spirits and creatures – Caves in Victorian Aboriginal social organization. pages 3–10.

A study of Aboriginal associations with Victorian caves finds that there is a rich cultural heritage associated with caves. This association has been found to be rich and varied in which caves and sink holes featured prominently in the lives of Aboriginal people – they were often the abodes of malevolent creatures and spirits and some were associated with important ancestral heroes, traditional harming practices, and some were important in the after death movement of souls to their resting places. Aboriginal names for caves, where known, are discussed.

Garry K Smith: Tectonic and Talus Caves at Pilchers Mountain, New South Wales. Pages 11–20.

There are fourteen known caves within the Pilchers Mountain Environmental Protection Reserve, in New South Wales, Australia. The reserve contains five main chasms which run generally East–West for approximately one kilometre, over a total width of half a kilometre.

The chasms and caves were formed by massive sandstone block separation along sub-parallel joint planes. Movement of the blocks toward the valley floor was aided by the dip of the sandstone layers and presence of underlying shale bands which acted as slip planes when lubricated by groundwater. There are two distinct types of caves at Pilchers Mountain, "tectonic" caves formed by the movement of large blocks of bedrock, and "talus" caves amongst large breakdown rocks and boulders. The chasms provide a micro-climate which supports a pocket of dense, high canopy, subtropical rainforest, and the caves are home to populations of bats and other fauna.

The European history of Pilchers Mountain is detailed in chronological order from the early 1800s to the present day. A Plan of Management is in the process of being formulated by stakeholders and interested parties to ensure the continued preservation of the reserve.

Ken G Grimes: Microkarren in Australia – a request for information. Pages 21–23

Microkarren are the smallest class of visible karren. They are finely-sculptured solutional forms, typically recognisable within a one centimetre grid. They come in a variety of patterns, of which fields of moderately to strongly sinuous microrills about 1mm wide and several decimetres long are the most conspicuous type. A descriptive terminology is suggested. Their genesis is uncertain, but appears to involve solution by thin films of water (dew, sea-spray or light rain) with surface-tension effects. In Australia their best development seems to be in the tropical monsoon (seasonally dry) and arid areas. However, these cryptic forms are poorly recorded and it is too early to make definite statements about their distribution. This note is a request for people to watch for them and report any sightings.

RESEARCH FUNDS AND GRANTS

CAVE SCIENCE AND TECHNOLOGY RESEARCH INITIATIVE (CSTRI)

The British Cave Research Association has allocated £25,000 to this initiative for the period 2006 to 2010, to promote research in four cave science themes, namely speleogenesis, archaeology and palaeontology, biology, and technology. There will be an emphasis on the publication of ideas and the findings of the research. The objectives of the initiative are:

a) to encourage research activity by cavers and cave scientists who may have no (or limited) support from research establishments,
b) to stimulate new research which could contribute significantly to any aspect of caving – this will include 'technology' as well as the traditional 'earth sciences',
c) to support research that is unusual, is particularly innovative, or is likely to be of great interest or benefit to cavers,
d) to assist in the purchase of necessary consumable items or scientific equipment,
e) to provide a contribution to funds for travel in association with fieldwork, or to visit laboratories that can provide essential facilities,
f) To provide financial support for the preparation of scientific reports and presentations.

Proposals will be considered by an Awards Panel that will be involved in regular monitoring of sponsored projects. Elections to the Panel will be every four years on a staggered basis. Closing dates for applications are April 1st, August 1st, December 1st but where the requested funding is less than £200, there is a 'fast-track' application procedure, for which only basic information and a short outline of the project are needed. Fast-track decisions can usually be made within a few weeks of the receipt of an application. Further details of the fund, including rules, guidelines and an application form can be found on the web site at **bcra.org.uk / grant_aid** or from the fund administrator, David Checkley (**D.Checkley@bcra.org.uk**), 36 Copperfield Road, Cheadle Hulme, SK8 7PN, United Kingdom.

GHAR PARAU FOUNDATION (GPF)

Expedition Awards

A total of at least £1,200 is available annually, to one or more 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 pure exploration in remote or little known areas. Closing dates for applications are 31 August and 31 January. Further information about the awards can be found on the web site at **bcra.org.uk / grant_aid** or from the GPF secretary, David Judson (**D.Judson@bcra.org.uk**), Hurst Barn, Castlemorton, Malvern, WR13 6LS, United Kingdom.

The E K Tratman Award

An annual award is 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 (see above for contact details), not later than 31 January each year.

UK CAVE CONSERVATION EMERGENCY FUND (UKCCEF)

The UKCCEF is a charitable fund administered by the British Cave Research Association. The objectives of the Fund are to support projects that further the conservation of caves and cave features. Reference to a cave or cave feature is intended to include historic mines, caves and other places of speleological interest within the United Kingdom. Further details of the fund are available at **bcra.org.uk / funding**

PUBLICATIONS

BCRA Publications are obtainable from Ernie Shield (**publications@bcra.org.uk**), Village Farm, Great Thirkleby, Thirsk, Y07 2AT, United Kingdom. Information about BCRA publications is on the web site at **bcra.org.uk / pub**

CAVE AND KARST SCIENCE

Published three times annually, this is a scientific journal comprising research papers, reports, reviews and discussion forum, on all aspects of speleological and karstological investigation, including geology and geomorphology, archaeology, biospeleology, exploration and expeditions.
Editors: Dr D J Lowe (**D.Lowe@bcra.org.uk**), c/o British Geological Survey, Keyworth, Nottingham, NG12 5GG, United Kingdom, and
Professor J Gunn (**J.Gunn@bcra.org.uk**), Limestone Research Group, University of Huddersfield, Queensgate, Huddersfield, HDI 3DH, United Kingdom.

SPELEOLOGY

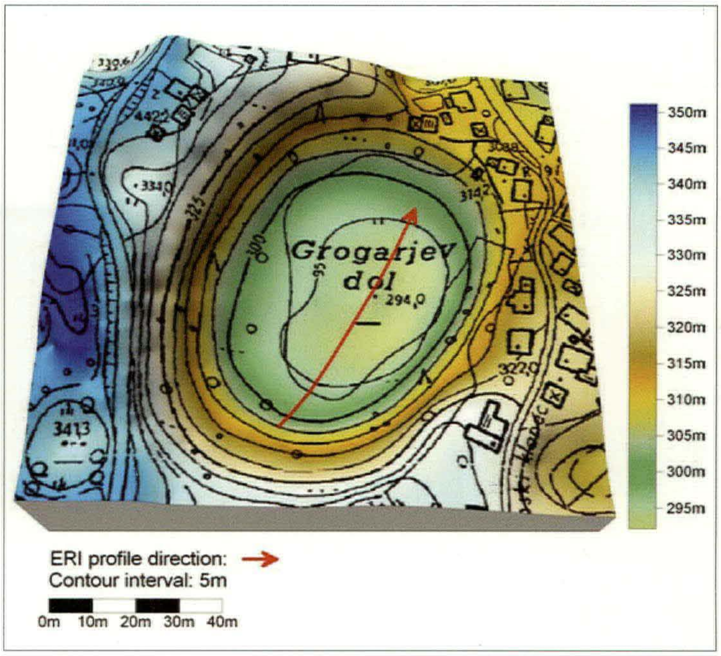
Published three times annually and replacing BCRA's bulletin *'Caves & Caving'*, this magazine promotes the scientific study of caves, caving technology, and cave exploration. The magazine also acts as a forum for BCRA's special interest groups and includes book reviews and reports of caving events. *Speleology* is issued free to members of the British Caving Association.
Editor: Erin Lynch (**speleology@bcra.org.uk**), [China] +86 773 8813651
UK editorial office: David Gibson (**D.Gibson@bcra.org.uk**), 12 Well House Drive, Leeds, LS8 4BX, United Kingdom.

CAVE STUDIES SERIES

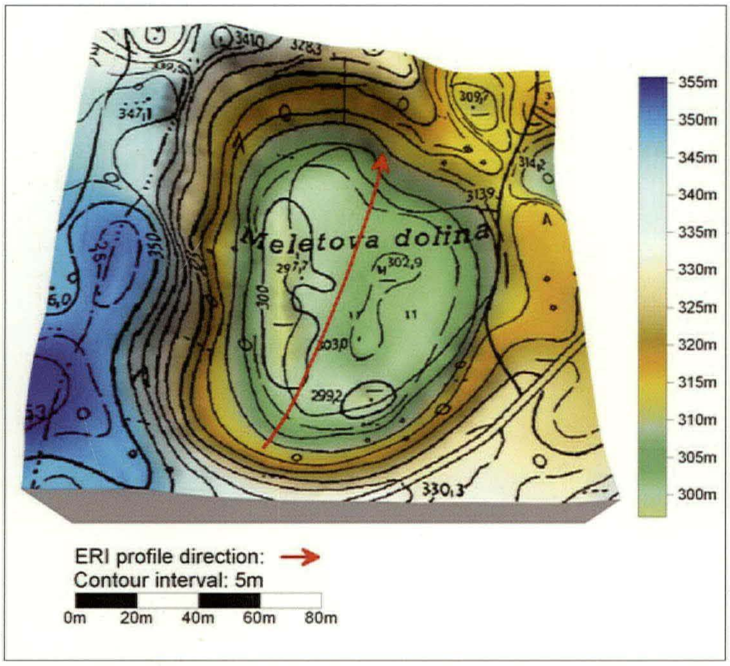
A series of booklets on various speleological or karst subjects. An up-to-date list of titles in print can be found on our web site. The editor is always willing to consider new topics for inclusion in the series.
Series Editor: David Judson (**D.Judson@bcra.org.uk**), Hurst Barn, Castlemorton, Malvern, WR13 6LS, United Kingdom.

BCRA SPECIAL INTEREST GROUPS

These are organized groups within the BCRA that issue their own publications and hold symposiums, field meetings, etc. Further information can be found at **bcra.org.uk / sig**
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 and organizes seminars and field meetings.
Explosives Users' Group provides information to cavers using explosives for cave exploration and rescue, and liaises with relevant authorities. The Group operates an Internet discussion group and organizes seminars and field meetings.
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 newsletter, Compass Points, and organizes seminars and field meetings.

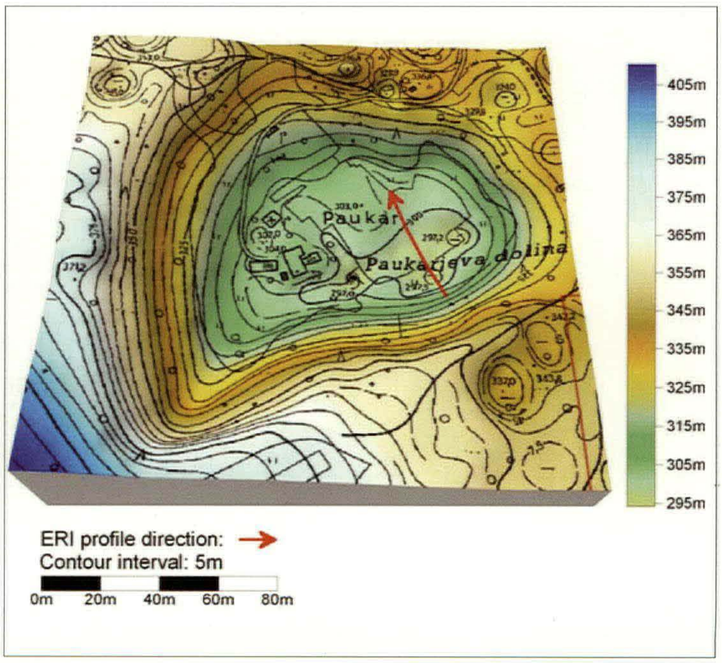


Grogarjev dol (above)
and digital elevation model (right)



Paukarjeva dolina (above)
and digital elevation model (left)

Meletova dolina (above)
and digital elevation model (right)



Collapse dolines in Slovenia; see pp 105-110