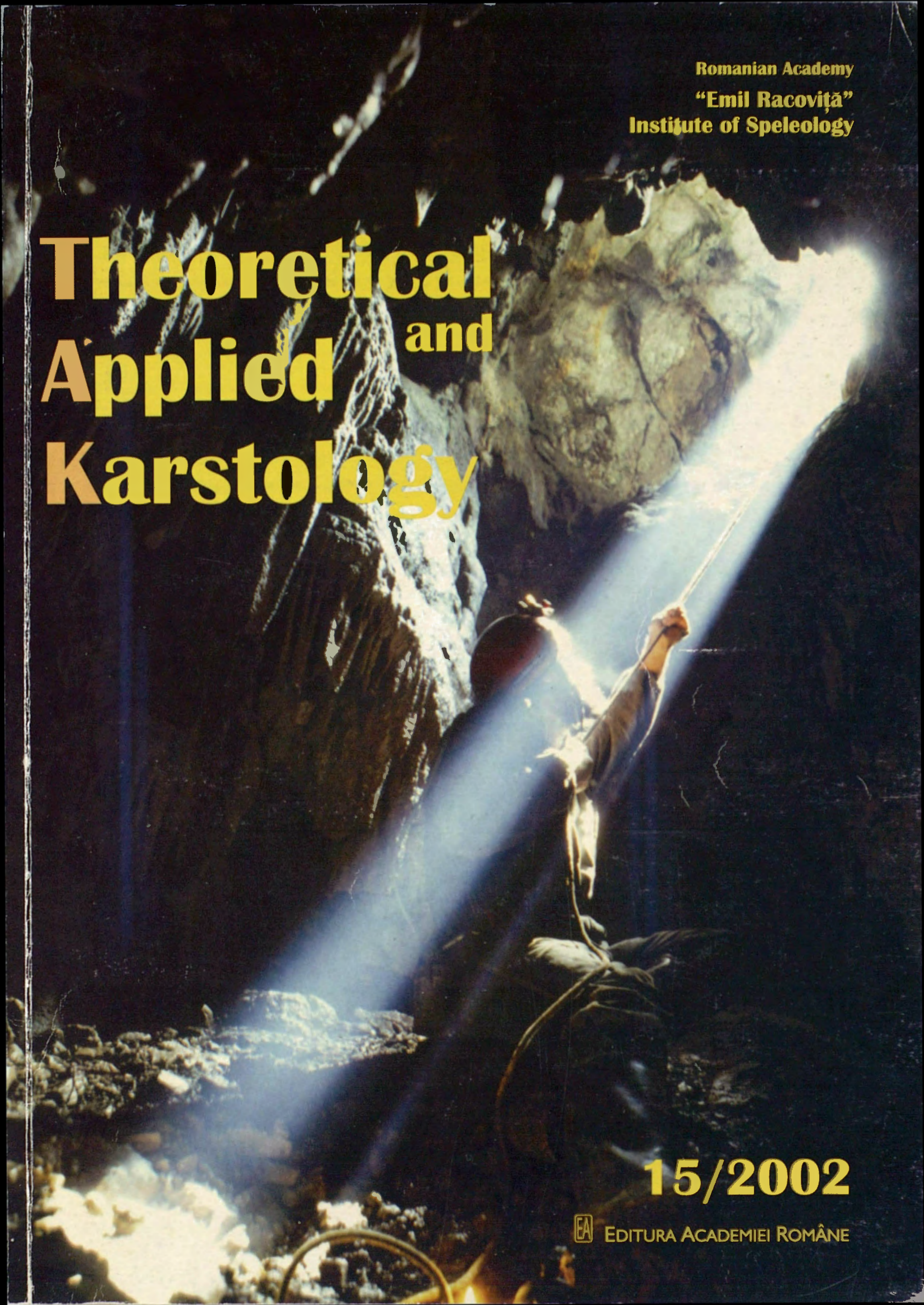
Theoretical and Applied Karstology, Volume 15, 2002

Silviu Constantin

Romanian Academy
"Emil Racoviță"
Institute of Speleology

Theoretical and Applied Karstology



15/2002

EDITURA ACADEMIEI ROMÂNE

Theoretical and Applied Karstology

Volume 15

Theoretical and Applied Karstology

vol. 15/2002

ISSN: 1012-9308

Indexation: Georef

Theoretical and Applied Karstology (TAK) is an annual journal dedicated to the karst and caves sciences. The first four issues were published by the "Emil Racovita" Institute of Speleology, as a series, between 1983 and 1991. Since 1992, TAK has been edited by the Institute and published by the Romanian Academy's Publishing House.

TAK publishes original contributions (review articles, research papers, short notes and book reviews) covering the whole range of karstology and physical speleology: karst geology and mineralogy, chemistry and physics of karst processes, karst geomorphology, karst hydrology and hydrogeology, speleo-chronology and landscape evolution, speleogenesis, climate and subterranean environment, speleo-paleontology, engineering and environmental problems in karst, karst managment, etc. The Editors welcome the submission of contributions from all over the world.

The "Emil Racovita" Speleological Institute encourages the exchange between TAK and specialized journals. Past TAK issues are also available to the Institute. Please address any inquiries concerning publication exchanges, orders, subscriptions, and any article submission to:

Theoretical & Applied Karstology Editorial Board
Institutul de Speologie "Emil Racoviță"
str. Frumoasă 11, C.P. 220-12, R-78114 Bucureşti, Romania.
tel/fax: +40-21-2128951; +40-21-2113874
email: karstology@yahoo.com
http:// www.geocities.com/karstology

Cover photographs: Cristian Lascu

Language revisions: Rodica Florescu

DTP Editor: Silviu Constantin

This volume was kindly supported by:

Outdoor Project SRL

the Romanian Society for Speleology and Karstology

Journals of the Romanian Academy Publishing House may be ordered to:

Editura Academiei Române, Calea 13 Septembrie nr. 13, P.O.Box 5-42, Bucharest, Romania. tel:+40-21-4119008.

Rodipet S.A.: Piața Presei Libere 1, P.O.Box 35-57, Bucharest, Romania. fax:+40-21-2226407; tel: +40-21-2224126.

Orion Press Impex 2000 SRL: P.O.Box 77-19, Bucharest 5, Romania. tel: +40-21-3018786; fax:+40-21-3350296.

Calea 13 Septembrie 13, P.O. Box 5-42, 76117 Bucureşti, România. tel:+40-21-4119008

Romanian Academy
"Emil Racoviță" Institute of Speleology

Editura Academiei Române
București, 2002

Theoretical and Applied Karstology

Volume 15/2002

Contents

Editor's Page

With its 15th issue, TAK resumes its annual appearance in a continuation of our efforts to increase the frequency of publication and, at the same time, to bring as much valuable karst science as possible on readers' desk, on a regular basis.

The contents of this volume partially relies on the papers presented at the XVIIIth International Symposium of "Theoretical and Applied Karstology" which was held in Băile Herculane, between May 24–28, this year. I'll use the privilege of this editor's page to say a few words about this event.

There were many pros and cons in our decision to re-organize this symposium in 2002. Serious logistical difficulties were foreseen as we could not rely on (almost) any sponsor support; to this we had to add the general lack of enthusiasm of most 'senior-organizers' of TAK and the transformation of our traditional partner, "Prospecţiuni" S.A., into a privately-owned company showing now little (if any!) interest for karst resources research... On the other hand, we have been strongly encouraged in our efforts by professor John Gunn, the president of the IGU Karst Commission, who considered this symposium very appropriate for the commission's annual meeting. And, finally, we've got a new partner for the organization, the Romanian Society for Speleology and Karstology with its young and enthusiastic staff. We said then: "OK, let's do it!" It was in January 2002 and the symposium was scheduled for the end of May, that is less then five months to organize an international meeting... not an easy bet, you will agree!

After only six weeks of intensive emailing and web contacts things become more encouraging: we got expressions of interest from more than 50 colleagues from abroad, including the majority of the members of the IGU Karst Commission. Some of our worries faded away and we started to wonder if we wouldn't need a larger meeting room... Two weeks before the symposium we had received over 45 papers and "firm registrations" from about 30 colleagues from abroad and more than 60 Romanians. And then, the cancellation emails started to fill my Inbox...

Finally, the symposium begun with a little more than 50 participants, among which, 15 colleagues from Brazil, Iran, Ireland, Italy, Moldova, Russia, Slovenia, South Korea, UK, US, and Yugoslavia. Unfortunately, most of the members of the IGU Karst Commission also cancelled their participation on a very short notice, and the annual meeting was no more held. A reduced participation did not necessarily mean a decrease of interest or a lower scientific level: it just made the reunion more informal and increased a bit the time for discussions and debates. However, as an organizer, I cannot hide that seeing the number of "firmly registered" participants being reduced to almost a half during the last ten days before an event, was a very frustrating experience.

I wouldn't mention this "inside-TAK" story if I didn't have the feeling that many of those absences were not necessarily a matter of *force majeure*. I am afraid of a certain trend in the scientific world, which encourage the registration to a venue and the submission of abstract(s), followed by a last-minute cancellation, preferably after the abstracts' volume was published... In my opinion, there are at least two factors that have led to this strategy: on the one hand, the generally high registration fees and additional expenses, which discourage students and scientists from poorer countries to even think about participation — sometimes even in spite of some grants. On the other hand, the publication of *extended* abstracts (which can be reported as "published papers" while keeping the "good stuff" for a "serious journal") certainly encourages this policy of "submit and disappear"...

If the above be true, then less people joining our meetings would mean even higher participation fees — which will further discourage people to physically participate in a conference. It seems to me like a vicious circle and I wonder if the scientific world doesn't need a serious discussion on this matter. As for myself, I continue to believe that scientific debates at a symposium, during the meetings and coffee-breaks, or late-night in hotel rooms and, especially, those during the field-trips are the life-blood of successful science and the best keys to future partnerships. I hope I'm not just a dreamer...

Therefore, I'd like to use this opportunity to thank again our colleagues that joined the last TAK meeting. Some of them also participated in the four-day-long TAK excursions (a novelty of this edition) and I hope they enjoyed that bit of Romania they saw during those days at least as much as I enjoyed being in the field with them.

A final word that I must add to this editorial is perhaps the most difficult to write. The great absent of this year TAK Symposium was dr. Costin Rădulescu, the director of our Institute and also the former director of our journal. He really hoped to be with us in Herculane but, at that time, he was forced to stay in hospital, facing the progressive weakness of his body. Only one month after the symposium, dr. Rădulescu passed away. Beginning with that day, our institute has become poorer...

As a TAK editor during the last ten years, I will certainly miss longtime his discrete, yet very efficient, contribution and supervision. But, knowing him as a modest and sensible person, I am quite sure that at this point of my phrase he would have gently wave his hand and said "Oh, no... please stop..."

...we dedicate this TAK issue to the memory of dr. Costin Rădulescu. And we will continue to dedicate our efforts to all of you, colleagues and friends of the underworld.

Silviu Constantin

In Memoriam

Constantin (Costin) Rădulescu

1932-2002

This year, the "Emil Racoviţă" Institute of Speleology has suffered an irreplaceable loss by the unexpected decease of dr. Constantin (Costin) Rădulescu.

Born on February 23, 1932 in Bucharest he completed his university studies at the Faculty of Biology, Bucharest University, between 1951 and 1955. During this time his dedication was stimulated by professor Margareta Dumitrescu who encouraged and supported him to pursue the studies on Mammals paleontology.

In 1956, while preparing his PhD thesis he started systematic excavations in caves from Central Dobrogea such as: "La Adam", Bordeiul de Piatră, Casian, Cheia, Gura Dobrogei. He also participated in the field campaigns from some caves in the Carpathians: Colţul Surpat, the caves no. 1 and 2 from Tătaru Massif, Cioclovina, etc.

In 1958 he becomes a researcher at the "Emil Racoviţă" Institute, where he will work until the very last moment of his life. After the submission of his PhD thesis entitled "*Contributions to the anatomic comparative study of the modern and fossil artiodactylia from Romania and their importance for the stratigraphy of the Upper Pleistocene*" (1963) he started extensive studies on Quaternary mammals.

Gradually, the field of his research will extend also to the sediments outside the subterranean environment. Between 1960 and 1963 he started the research of the stratified deposits from the Dacian Basin (the middle course of the Olteţ valley), between the localities of Tetoiu and Irimeşti, where remains of Plio–Pleistocene large mammals were abundant. The results came rapidly: two new genres were described here: *Paradolicopithecus arvernensis geticus* and *Mitilanotherium inespectatum*.

During 1962 and 1975, together with Petre-Mihai Samson and Henriette Alimen he worked in the Braşov Depression where he carried out paleo-biological and paleo-environmental studies. Beginning with 1978 his activity was mostly dedicated to the study of fossil remains from Pliocene and Lower Pleistocene deposits from the western area of the Dacian Basin (Drănic, Izvoru); here, many associations of micro-mammals with important stratigraphic and evolutionary significances have been described.

Under his guidance the first fauna associations of micro-mammals from the Crişul Alb valley have been described, including five new taxa. It is worth noticing also the discovery of a new genus of Eocene Embritopodian (*Crivadiatherium*) with two species, as well as that of a species of an Oligocene Indricotheriidian (*Benaratherium gabuniai*).

One of the last topics of his researches was related to the anatomy and physiology of the Mesozoic multituberculates and their paleoenvironmental significance. Several studies have been elaborated on this issue and a new family, two genera and two species (*Barbatodon transylvanicus* and *Kogaionon ungureanui*) have been described.

Costin Rădulescu published over 150 scientific papers describing mammalian fauna important both from morphological and paleoenvironmental viewpoints, that cover a time span of over 60 Ma, from the Upper Cretaceous to the Holocene.

His exceptional scientific knowledge promoted him as a member of many Romanian and international scientific societies, such as: the Sub-commission for Loess Stratigraphy and the Sub-commission for the Neogene/Quaternary limit of INQUA, the International Commission for non-marine Tertiary of the IUGS, the Sub-commission for Environment Protection of the Romanian UNESCO Commission.

For all his merits, on May 31, 1993, the General Assembly of the Romanian Academy elected him a corresponding member as a supreme recognition of his scientific value.

Behind these scientific achievements, Costin Rădulescu was a kind, sensitive, warm-hearted and delicate man. If one could figure a person that knows no selfishness, hate and hard feelings that would probably be the image that we, at the institute, will always treasure.

Emanoil Ştiucă

Theoretical and Applied Karstology, 15 (2002), pp. 7–26

TAK Reviews

Speleology in the Third Millennium: Achievements and Challenges*

Paolo Forti ¤

Italian Institute of Speleology, University of Bologna, Via Zamboni67, 40127 Bologna, Italy.

Abstract

Men have visited caves for a long time, but speleology started about 20 000 yr BP when the human frequentation of caves was no longer "accidental". The development of caving activities may be subdivided into three periods: **prehistory** (in which no written report exists), **protohistory** (in which documentation is available but speleology is not yet that of today) and **history** (which conventionally started with E. A. Martel).

Nowadays caving activities are split into several branches which may be grouped in four categories: *explorative*, *scientific*, *social* and *documentary speleology*. In the present paper after a short overview on the development of caving activities from prehistory until present day the challenges and goals for the third millennium are outlined, the main problems speleology will have to face being:

- exploration of the ice caves in Antarctica and of the volcanic caves in the space;
- scientific multidisciplinary investigation of special cave ecosystems;
- extensive search for new drinking water supply and new principles in medicine;
- environmental protection and sustainable tourism.

Key words: cave history, cave science, cave tourism, cave safeguard.

La spéléologie au troisième millénaire: réalisations et perspectives

Résumé

L'homme a visité les grottes depuis longtemps mais la spéléologie a commencé il y a 20000 années, quand la fréquentation des grottes a cessé d'être «accidentelle». Le développement de l'activité spéléologique peut être sous-divisé en trois périodes: la ***préhistoire*** *(dont on n'a pas de témoignages écrits), la* ***protohistoire*** *(il y a des sources documentaires mais la spéléologie n'est pas encore la science d'aujourd'hui) et l'****histoire*** *(qui commence, conventionnellement, avec E. A. Martel).*

Aujourd'hui les activités spéléologiques sont sous-divisées dans quelques branches qui peuvent être groupées dans quatre catégories: spéléologie explorative, scientifique, sociale *et* documentaire. *Dans ce travail, après un court exposé sur le développement des activités spéléo depuis la préhistoire jusqu'à présent, on discute les perspectives et les buts actuels pour le troisième millénaire. Les principales directions de recherche dans la spéléologie sont:*

- *l'exploration des grottes de glace de l'Antarctique et des cavités volcaniques de l'espace;*
- *investigations scientifiques multi-disciplinaires des écosystèmes particuliers;*
- *recherches extensives pour de nouvelles sources d'eau potable et de nouveaux remèdes médicaux;*
- *protection de l'environnement et tourisme.*

Mots-clés: histoire de la spéléologie, spéléologie scientifique, tourisme spéléologique, protection des cavernes.

Introduction

The word *Speleology* comes from the two Greek words (σπελαιων and λογοσ) literally meaning the science of caves (Shaw, 1992) and therefore it should be applied only to scientific researches performed inside natural cavities.

Anyway it is actually normally utilized in a broad significance, to define 'any activity' voluntarily performed by a person inside a cave (Fig. 1), ranging from pure or applied science to documentation, from exploration to social.

Surely human frequentation of caves started over one million years BP, but: *when did a man become a true "caver"*?

* Opening Conference at the XIII International Speleological Congress, Brasilia, July 2001.

¤ corresponding author. *E-mail address*: Forti@geomin.unibo.it

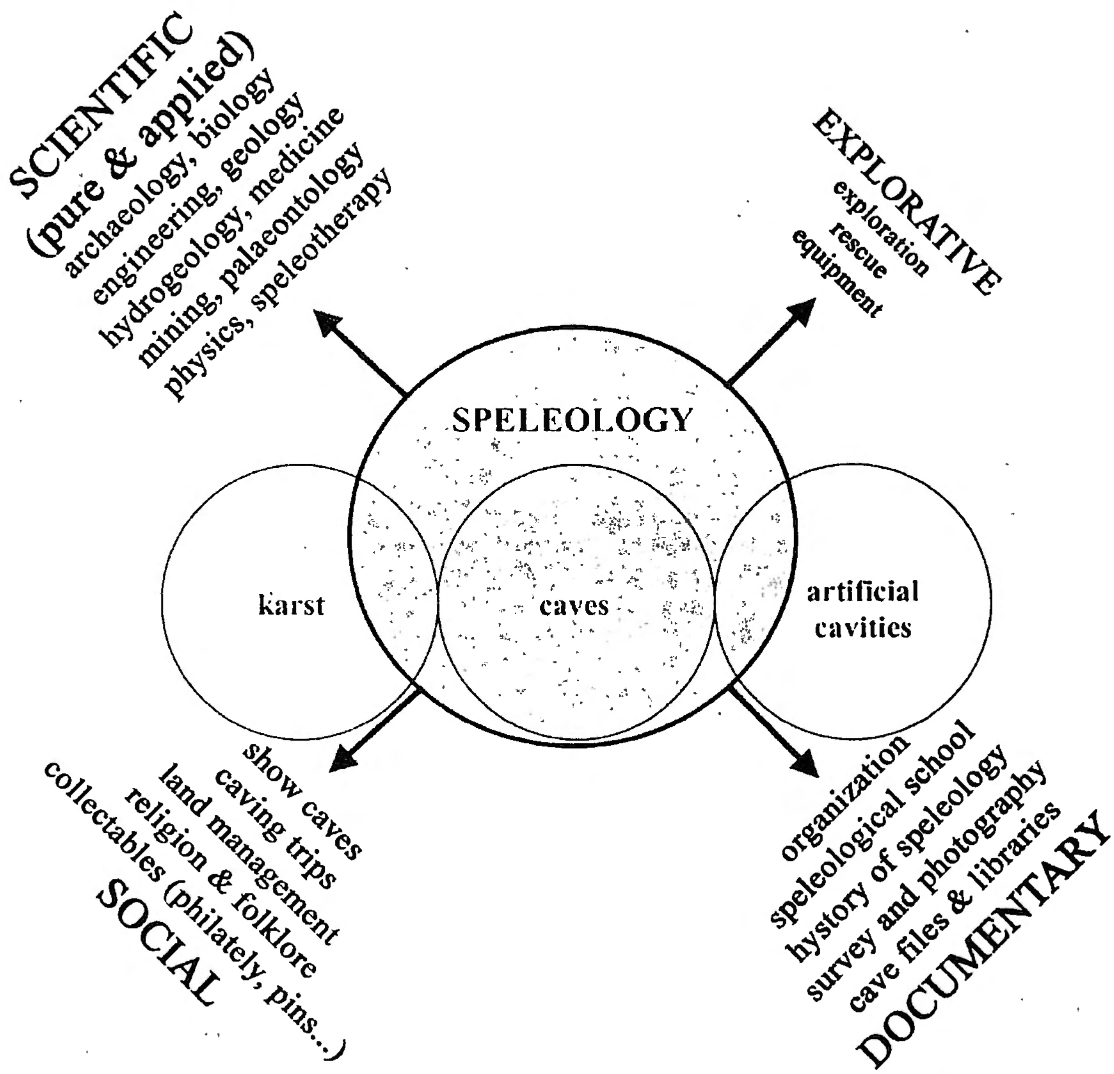


Fig. 1. Diagrammatic representation of the four main branches of speleology and of the environments in which they may be active.
Représentation schématique des quatre branches principales de la spéléologie et des leurs domaines d'activité.

Human frequentation of caves was purely accidental: most of the time our ancestors utilised just cave entrances for their needs (shelters, burial, etc.) without any acknowledgement of the cave environment itself: in other words, men had no interest to enter a cave just due to its cave nature and therefore, in reality, they did not perform any caving activity.

Probably the first time when men started to consider caves as a peculiar place was only some tens of thousands years ago and the first reason to 'go caving' was to perform religious rites, as testified by scores of painted caves spread in France, Italy, Spain, etc. (Fig. 2).

In the last 20 000 years caving activities grew in number and types but it is only during the last 100–150 years that "modern speleology" has developed.

The aim of this paper is to present a short overview on the main changes speleology underwent from its beginning up to present.

The principal achievements of this rather young activity will then be used as a basis for our attempt to answer a question intriguing most of cavers: *what will speleology become in the just begun third millennium*?

Fig. 2. Paintings in the Cervo cave (Apulia, Italy).
Peintures rupestres dans la grotte Cervo (Apulia, Italie).

The development of caving activities

The evolution of Speleology may be subdivided in three main periods as follows:

Prehistory

A period during which no reports of caving activities have been produced: it started 30–20 000 yr BP and ended around 2000 yr BP.

Proto-history

The period in which caving documentation exists but speleology was not yet the activity we presently know. It is worldwide accepted that this period ended with the beginning of the activity of E. A. Martel.

History

The last and rather brief period during which organisation and goals remained practically unchanged.

The prehistory of Speleology

As already said in the introduction, men have gone inside caves even deeply since at least one million years ago, to search for shelters and later for burials. But, according to its definition, the prehistory of speleology started only since they begun to 'use' the cave for a specific purpose (holy places) in the Palaeolithic time (30,000–10,000 years BP) (Shaw, 1992) or as flint mine, as in Koonalda Caves (Australia) (Wright, 1971, Tankersley *et al.*, 1997).

Later (< 5,000 yr BP) men started exploring caves to search for specific materials (minerals) they had no chance to find outside: niter was mined in the caves near Tigri river by Assyrians since 4000 yr BP as food stabilizer (Forti, 1983), while at the same time the Indians of the region of Mammoth Cave (USA) went deep into the caves to search for mirabilite (purgative) and gypsum (fertilizer) (Broughton, 1972).

The proto-history of Speleology

The proto-history of speleology starts only about 3,000 years BP in the Middle East and lasts until Martel gave rise to the modern speleology. Anyway even if the whole period covers something less than three millennia, it is reasonable to split it into two sub-periods: the boundary being during the XVIth Century when the first book completely dedicated to a cave was printed (Buchner, 1535); a couple of years later the first truly scientific researches on caves were performed.

From 3,000 years BP to 1535

The very first documented speleological exploration of a cave took place in Mesopotamia, where, not far from its source, the river Tigris flows through a natural rock tunnel. Tiglath Pileser, King of Assyria had his portrait carved at the entrance together with an inscription in 3100 BP (Opitz, 1929).

Later, a subsequent Assyrian King, Shalmaneser, in 853 or 852 BC had his men exploring three caves nearby the stream cave. The event is also reproduced in a bronze band of the gate of his royal palace in Balawat, now exhibited in the British Museum. Anyway the best, and rather unknown in literature, monument of an Assyrian king visiting a cave (Fig. 3) is just at the entrance of Shapur Cave not far from Persepolis in Iran (Forti, 1993).

Fig. 3. The monolith 8 m-tall at the entrance of the Shapur Cave, Iran, representing the Assyrian King Shapur I after his visit to the cavity.
Le monolithe (8 m haut) à l'entrée de la grotte de Shapur, Iran, représentant le roi assyrien Shapur Ier après sa visite dans la cavité.

About 2700 yr BP (GILL, 1991) Jews adapted natural shafts and cave passages to bring the water of the Ghion spring within the walls of Jerusalem.

Chineses started visiting caves some centuries B.C. and their early exploration of caves are always related to search for health care: stalactites, stalagmites, moonmilk and fossil bones were collected inside caves and then used to prepare medicines (SHAW, 1992). This medical use of cave material is still popular in Chinese traditional pharmacopoaeia. No detailed records of such explorations are known to survive, except for a description of stalagmites *in situ* made by Ko Hung about 2300 yr BP (KO HUNG, 1946).

Greek and Roman literature supply several cave descriptions but most of them are clearly fantasies and absolutely unrealistic reports. Anyway it is sure that several persons, for different reasons, visited caves, and left some detailed descriptions.

Among those worth mentioning is the Greek Aristotle (384–322 BC), who described several caves with underground rivers and wrote about the origin of caves and speleothems (SHAW, 1992) and the Latin Titus Lucretius Carus (95–51 BC), who included many interesting references to caves, ranging from hydrogeology to erosion, from earthquake to volcanic caves (on Etna Volcano) and their environment, in his poem entitled "*De rerum natura*" (= about the nature of things) (CIGNA, 1993).

Moreover the "tassellated pavings" (Fig. 4) found in many part of the Roman Empire, sometimes reproduced the caves world rather accurately (FORTI, 1998), providing evidence of its frequentation by the Romans.

After the decay of the Roman Empire, the interest in caves became completely lost and the major part of the responsibility belongs to the Christian Religion which, unlike most other religions, identifies the underground as the "Devil's Kingdom".

Therefore, for more than one thousand years, caves had interest only for monks, witches, alchemists, robbers, etc...

During this time, the documents related to cave explorations are very few and absolutely unreliable, even if some of them are quite accurate, like that related to Cheddar Hole, England, written by Henry of HUNTINGDON in 1135:

> .... *Chedder-hole, where there is a cavern which many persons have entered, and have traversed a great distance under ground, crossing subterranean streams, without finding any end of the cavern...*

The scientific interest for caves and its environment was preserved in countries with non-Christian religions, as testified by Abu Ali Ibn Sînâ (Avicenna) who tried to explain the development of stalactites between 1021 and 1023 (AVICENNA, 1929).

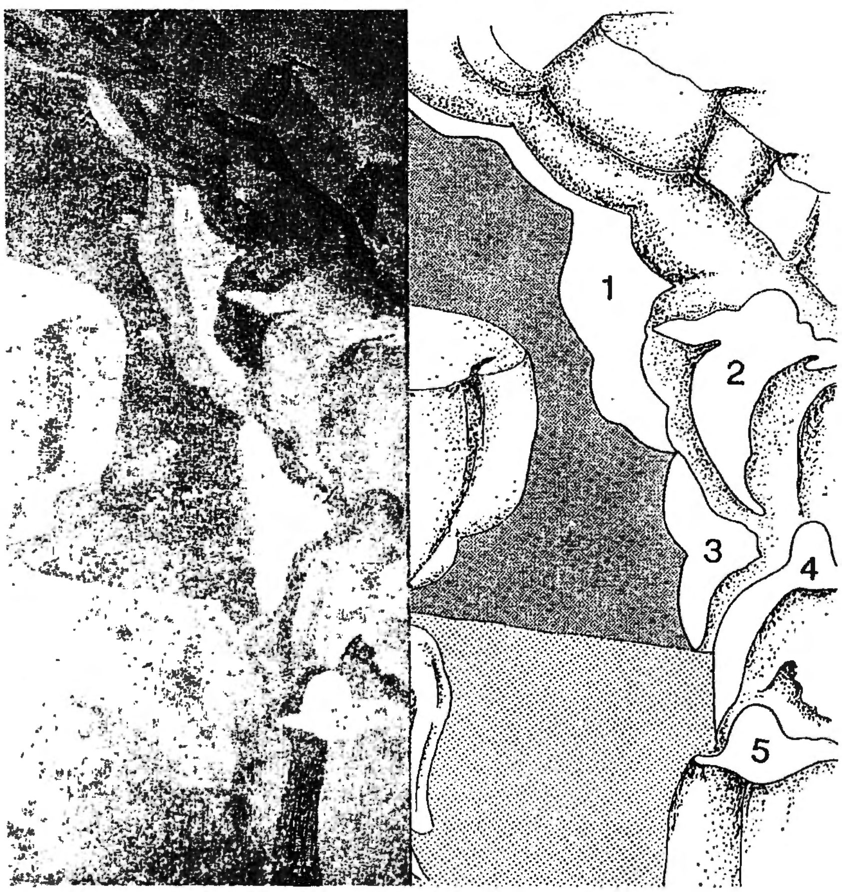


Fig. 4. Portion of a tessellated paving of the "Villa del Casale" (Piazza Armerina, Sicily, III Century) (left), where speleothems are represented very clearly: in the sketch on the right speleothems are put into evidence.

Partie du pavement de la «Villa del Casale» (Piazza Armerina, Sicile, IIIe siècle) (gauche), où les spéléothèmes sont representés très clairement; voir aussi l'esquisse à droite).

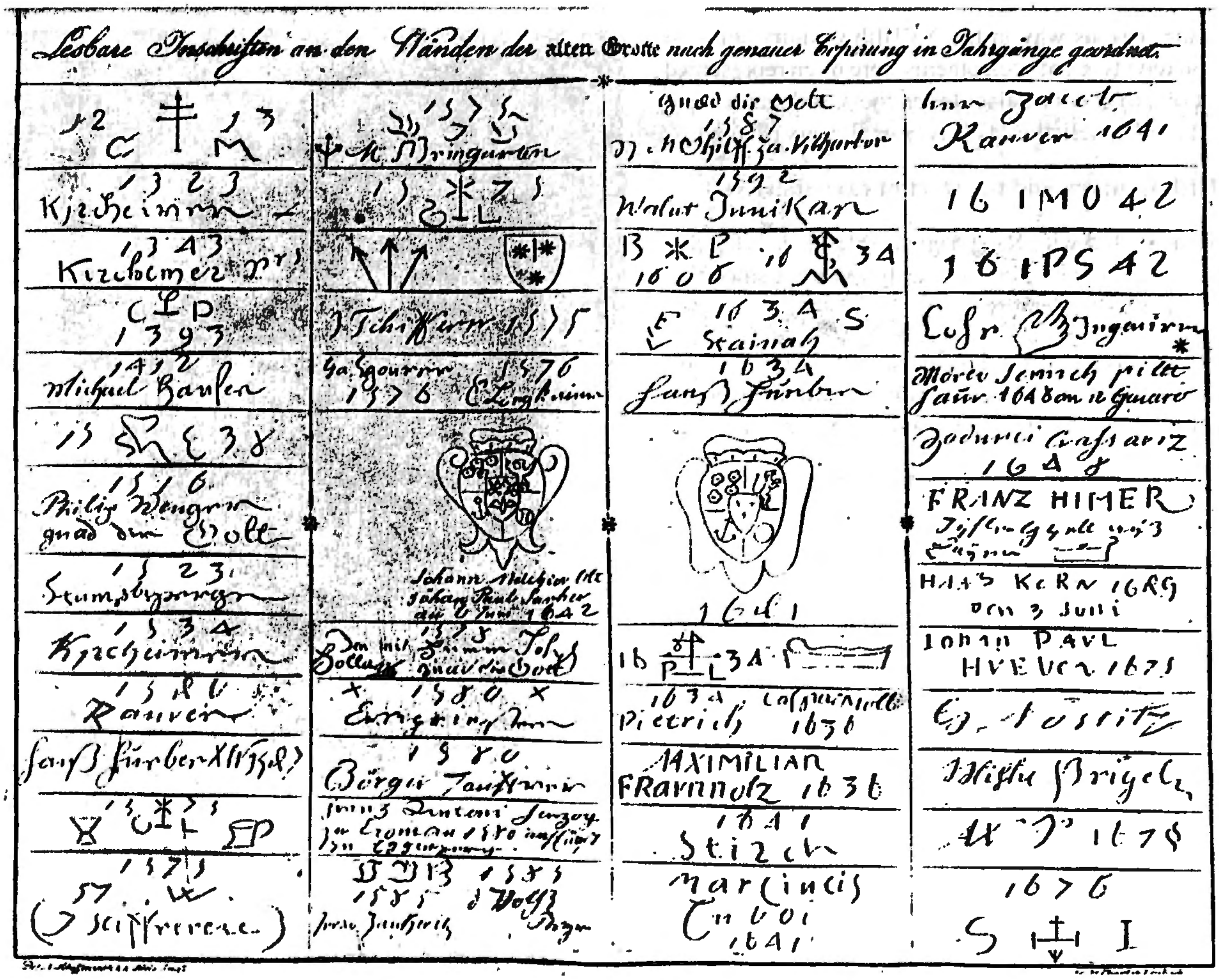


Fig. 5. The famous "historical inscriptions" of Postojna cave grouped in an engraving of the XIXth century (Hohenward, 1830).
Les fameuses «inscriptions historiques» de la grotte de Postojna groupées dans une gravure du XIXe siècle (Hohenward, 1830).

Anyway in all this period most of the traces of speleological activities are restricted to dated inscriptions over the cave walls like the world renowned ones in Postojna (Fig. 5).

After 1535

The blackout of speleology lasted all the Middle Age and part of the Renaissance. Only in the XVIth Century the interest in caves of travellers and later of scientists started again, as testified by the first printed book fully dedicated to a cave trip (Buchner, 1535): the single copy still existing of this 4 - pages pamphlet on the exploration of Breitenwinner Höle in Germany is currently conserved in the State Library in Ulm.

In 1590 the first description and speleogentic theory for the volcanic caves of Mt. Etna (Sicily, Italy) was reported (Filodei de Homodeis, 1590) and eighty years later a first detailed description of the behavior of the air currents inside the cave was given by Johannes Herbinius (1670).

But the book which is generally considered as the first treatise of Speleology, is "*Mundus Subterranneus*" by Athanasius Kircher (1674).

Just at the same time when Kircher wrote his famous book another important scientist was active in speleology: Johann Weichard Valvasor, who travelled all over the classic karst area and systematically visited and described its caves. His book in four volumes "*Die Ehre des Hertzogsthums Krain*" (1689) has to be considered the first documentation of a true cave file and it is presently among the most rare books on speleology ever printed in the world.

Some of the first scientific investigations led to the elaboration of curious and incorrect theories, even if well accepted at that time. In the second half of the XVIIth Century a scientist put forth the idea that speleothems are true rock plants (Beaumont, 1676), the development of which is very similar to that of normal trees. The theory was later perfected in 1704 by J. P. Tourneford who wrote:

> "*... That certain rocks nourish themselves in the same way as plants. Perhaps they reproduce also in the same way..... that there are seeds which gradually swell up and develop the regular structure which is perhaps hidden beneath their surface... Thus the congelations grow up from seeds.*"

These are the reasons why in the XVIIIth Century some of the most common types of speleothems were often represented just as part of a tree: with stalactites as roots, stalagmites and columns as trunks, helictites as leaves or flowers (Fig. 6).

The XVIIIth Century and the start of cave tourism

Cave tourism started with King Tiglath Pileser in 1100 BC, and several visits to caves are variously reported since that time up to the XVIIth Century.

True organized cave tourism developed only in the XVIIIth Century when some caves become well known all over the world and therefore a tourist organisation grew around them.

The most renamed and worth of mention are:

- Postojna (Slovenia)
- Kungur (Russia) (Fig. 7)
- Antipatros (Greece)
- Staffa (Scotland)

These caves started to attract hundreds of visitors per year and many other cavities were therefore open for tourism also outside Europe: Mammoth Cave (Kentucky) was officially opened as a show-cave in 1816 but it has been shown as a tourist attraction some tens of years before (GURNEE, 1993).

Most of these early show caves are still important nowadays, being visited by several hundreds of thousand of visitors per year.

The success of cave tourism was also testified by the fact that, at the end of the XVIIIth and at the beginning of the XIXth Century, caving books were rather popular and became the tourist guides of the most renowned caves (LANG, 1806, HOHENWART, 1830, BULLIT, 1845).

The XIXth Century and the first true scientific researches in caves

In the second half of the XVIIIth Century, the fast evolution of research in many scientific fields inevitably improved the interest for caves and their environment. Fundamental books were printed in karst hydrogeology (VALLISNERI, 1717), cave morphology (CAPPELLERI, 1767) and mineralogy (ZIMMERMANN, 1790).

But it was during the XIXth Century that practically all the studies, which can be performed inside caves, started (CONFIGLIACHI, 1819). As a logical consequence of the development of several different "branches" in Speleology a first scientific treatise on cave and karst was printed by SCHMIDL (1854): all the aspects of caving, from biology to mineralogy, from cave exploration to mapping, etc are shortly described in this book.

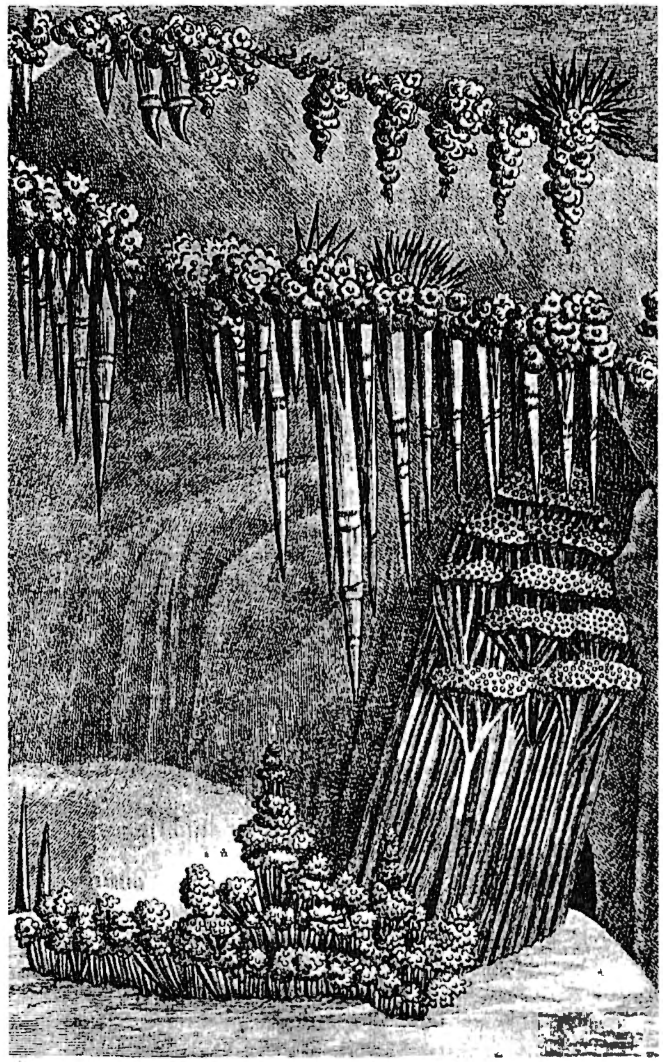


Fig. 6. Tournefort's theory forced some artists to represent speleothems as roots (stalactites), trees (stalagmites), flowers (coralloids), grass (helictites and crystals) (Antiparos Cave, Greece).
La théorie de Tournefort a inspiré de nombreux artistes à représenter les spéléothèmes comme des racines (stalactites), des arbres (stalagmites), des fleurs (coraloïdes), de l'herbe (helictites et cristaux) (Grotte d'Antiparos, Grèce).

Martel and the start of modern speleology

It is generally accepted that "modern speleology" started at the end of the XIXth Century thanks to the activity of the French caver Eduard Alfred Martel (1859–1938)

Even if other cavers, mainly from the "Classical Karst", were surely active before him (SHAW, 1993, SEZ. SPEL. CITTÀ DI CASTELLO, 1993, LAURETI, 2001), the reason why Martel has been correctly chosen as a symbol of the birth of "new speleology" is due to his popularisation of this activity. In his life

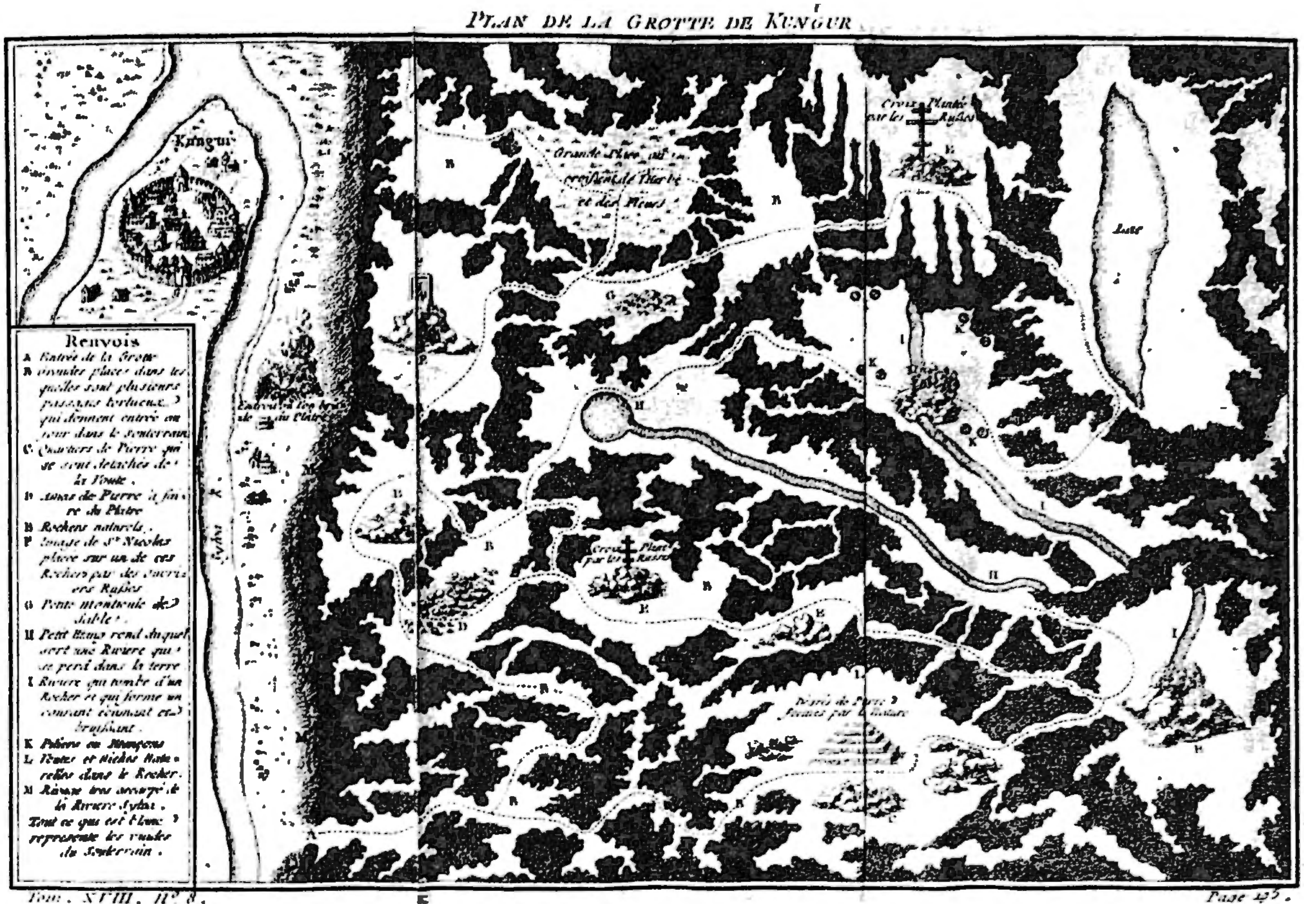


Fig. 7. Map of the Kungur gypsum cave open to tourism in the Ural Mts., Russia, in a copper engraving of the middle of the XVIII Century.
La carte de la grotte en gypse de Kungur ouverte pour le public dans les Monts Oural (Russie), dans une gravure en cuivre du XVIII^e siècle.

Fig. 8. Title page of "Les Abîmes" by E. A. Martel.
Page de couverture de «Les Abîmes» par E. A. Martel.

he explored caves all around the world and printed over 700 articles and over 20 books on caving topics (CHABERT & COURVAL, 1971), the most famous being "*Les Abîmes*" (1894) (Fig. 8), thus making speleological activities well known worldwide. Thanks to him, important journals dedicated to Speleology started to be printed, the most important of which was: "*Spelunca*" (1895) and a year later "*Mèmoires de la Société de Spéléologie*".

At the same time when Martel started going caving the first speleological societies were founded both on local and on national basis: the very first was the HöhlenKlub of Alppenzel in Switzerland which was founded in 1860 (BÄCHLER 1905), but lapsed three years later.

Most of these associations were founded by cavers working in the Classical Karst area: in 1873 the "*Abteilung für Grottenforschung*" in Trieste, in 1879 *Verein für Höhlenkunde* in Wien. But several Caving Clubs were also founded by different European nations as the *Yorshire Ramblers' Club* in 1892 (BELLHOUSE, 1899) and the Kyndwr Club in 1899 (BAKER, 1903) in England.

The oldest still active amongst these first speleological groups is presently the "*Circolo Speleologico Idrologico Friulano*" founded in Udine (Italy) in 1898 (ANON. 1898).

The complexity reached by caving activities at the end of the XIXth Century required the establishment of true caving organizations. Therefore between the end of the XIXth and in the first years of the XXth Century the first *National Speleological Societies* were organized in order to improve the cooperation between different caving clubs of the same countries: the first two were the *Société de Spéléologie*, created by Martel, in France in 1885 and the Società Speleologica founded in Italy in 1903 (ALZONA *et al.* 1903).

In the first decades of the XXth Century many of the european countries with well-developed speleological activities completed the national structure of their caving associations, which were often subdivided into three different levels: national, regional and local.

Another important evolution was represented by the organisation of regional and/or national speleological files and national speleological libraries in which all relevant information about the explored caves of a given area were collected and made accessible to the public at large.

The increased necessity of exchanging information between cavers led to the organisation of Speleological Congresses. Italy was the first country in which a National Speleological Congress was held in 1933 (CAI, 1933), followed by France in 1938 (SOC. SPÉL. DE FRANCE, 1939). Finally, the *First International Congress of Speleology* was organised in Paris 1953 with a participation of over 200 participants coming from 27 different countries of five continents.

Since then, an increasing number of speleological meetings, symposia, conferences, congresses were organised each year on a local, regional, national, and international basis: presently far over 200 of such reunions are scheduled yearly and their attendance ranges from a few tens to over 2000 cavers.

Speleology at the End of the Second Millennium

Speleology underwent a fast development in the second half of the XXth Century. Speleological activities started in many new countries and the number of caving clubs in the world rapidly exceeded the number of 1000.

The explorations

The explorations were pushed deeper and deeper into the earth (Fig. 9): the first –1000 has been achieved only in 1956 inside the Gouffre Berger (COURBON *et al.*, 1989) but in 2000 the caves deeper than 1 km were over 65 in 16 countries of 4 continents (ANON., 2000).

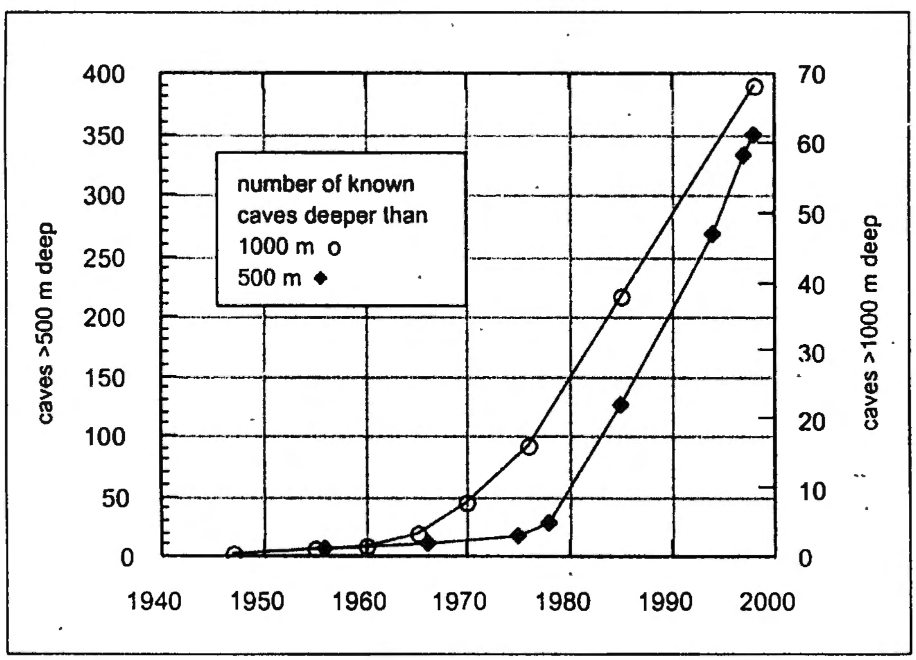


Fig. 9. Diagrammatic representation of the evolution in time of the exploration of caves deeper than 500 and 1000 meters.

Représentation schématique de l'évolution en temps des explorations des grottes avec des profondeurs de plus de 500 et, respectivement, 1000 m.

Speleological materials and techniques have greatly improved in the last tens of years of the Second Millennium: the introduction of the SRT about 40 years ago (Dobrilla, 1973) disclosed the underground world to practically all people interested to it, and the last diving technology allowed for fantastic explorations very deep into the saturated zone (Prosser & Grey, 1992).

Finally the cheap and easy travelling around the world allows the organization of hard speleological explorations in countries where caving activity was never performed before (Judson, 1973; Brook & Waltham, 1978; Badino *et al.*, 1999).

Simply, at the end of the Second Millennium no limits seem to exist for Explorative Speleology.

The Scientific Research

The most important speleogenetic mechanisms were understood (Klimchouk *et al.*, 2000), while in the last few tens of years caves proved to be the most powerful tools to perform research in a wide number of disciplines (Forti, 2000; 2002), the most important of which are listed in Table 1.

Since the last few tens of years, monographic volumes on most of these topics have been printed: "*Morfologia Carstică*" (Bleahu, 1974), "*The Science of Speleology*" (Ford & Cullingford, 1976), "*Morphogenetics of Karst Regions*" (Jakucs, 1977), "*Karst hydrology and physical speleology*" (Bögli, 1980), "*Paleokarst*" (James & Choquette, 1988), "*Encyclopaedia Biospeleologica*" (Juberthie & Decu, 1994), "*Cave Minerals of the World*" (Hill & Forti 1997).

Nevertheless most of the results in many of the scientific branches of speleology are scattered in hundreds of general and/or specialised journals which are rarely at easy disposal of the cavers. The reason for this situation is that important worldwide scientific speleological journals are still very rare ("*International Journal of Speleology*", "*Cave and Karst Science*", "*Theoretical and Applied Karstology*", "*Mèmoires de Biospéléologie*"); moreover, they have only a small circulation rarely exceeding 1000 copies, the single exception being the "*Journal of Cave and Karst Studies*", the former "*NSS Bulletin*", with over 5000 copies.

Table 1 - Main pure and applied sciences interested in cave environment (after Forti, 2000, modified).
Les principales sciences pures et applications liées au milieu souterrain (d'après Forti, 2000, modifié).

Discipline		Fields of interest
Archaeology		remains, graffiti, rock-paintings
Biology		adaptation strategies, microbiology, chemoautothropic environments
Physics		meteorology, climatology
Engineering		large voids, oil deposits, show caves
Medicine		speleotherapy, psychology, psychiatry
Geology	Geomorphology	karst, speleogenesis, paleoenvironmental reconstruction
	Geochemistry	stable isotopes, absolute dating
	Geophysics	terrestrial tides, seismology
	Hydrogeology	karst aquifers
	Mineralogy	cave minerals, low enthalpy processes
	Palaeontology	lairs, sedimentation traps
	Sedimentology	physic sediments, speleothems
	Stratigraphy	stratigraphic sequences
	Structural geology	structural elements, neotectonics
	Volcanology	lava flow morphologies, deep volcanic structure

Therefore it is still very difficult to get updated information in several branches of scientific speleology. Since 1970, the International Union of Speleology decided to print yearly a general bibliographic bulletin "*Speleological Abstracts*", in which all the publications related to any speleological field are reported; from 2002 this bulletin will be also available through the net.

But to know of the existence of a paper will be of little use if the possibility to obtain copies of it cannot be guaranteed. The scarcity of available issues for many of the caving journals and for most of the caving books makes it impossible to have them available at least in the National Speleological Libraries. For this reason the UIS set up a network of Documentation Centres (Table 2), covering all the main speleological areas of the world: upon request, they are ready to supply photocopies from the journals and/or books present in their library.

The Economic and Strategic Interests in Caves

In the last century, the social interest in cave environment grew dramatically both from the economic and strategic point of views.

The economic importance of caves derives from several activities that can be performed inside them; the most important of which are related to:

- Tourism
- Health care
- Agriculture
- Industry

After the Second World War, tourism related to show caves and natural parks in karst areas has grown and it is still growing

Table 2. The UIS Documentation Centres (UIS, 2000).
Les centres de documentation de l'UIS (UIS, 2000).

Country	Institution	Address
Argentina	Library "Dr Emilio Maury"	Grupo Espeleologico Argentino, Heredia 426 (C1427NF) Buenos Aires
Austria	Spelaögisches Documentationszentrum des Instituted für Höhlenforschung	c/o Naturhist. Museum Burgring 7 – A-1014 Wien
Belgium	Centre Documentation UBS/SSW	Maison de la Spéléologie, Rue Belvaux 93 – B-4030 Liege
France	Documentation Federation Française de Spéléologie	28 rue Delandine, F-69002 Lyon
Germany	Bibliothek des Verbandes des Deutschen Höhlen und Karstforscher	c/o G. Hoffman, Am Untersten Hammer 9, D-58644 Iserlhon
Japan	Natural Science Museum	c/o Dr Uéno, Hyakunin-cho 3-23-1, Shinjuku, Tokio 160
Great Britain	British Cave Research Association Library	c/o Roy Paulson, Holt House, Holt lane, Lea,Mattlock, Derbyshire DE4 5GQ
Italy	Centro Italiano di Documentazione Speleologica "Franco Anelli"	Istituto Italiano di Speleologia, Via Zamboni 67, I-40127 Bologna
Poland	Library of "Kras i speleologia"	Laboratory of Karst Environment, ul. Bedzinska 60, PL - 41-200 Sosnowiec
Portugal	Biblioteca Sociedade portuguesa de espeleologia	Rua Saraiva de Carvalho 233, P- 1350 Lisboa
Romania	Institutul de Speologie „Emil Racoviţă"	str. Frumoasă, 11, R-78114 Bucharest
Slovenia	Institut za raziskovanje kraza	Knjiznica, Titov trg 2, SV 66230 Postojna
Spain	Centre de Documentació espeleologica	Ap.C. 32110, E-08080 Barcelona 6
USA	National Speleological Society Library	1, Cave Avenue, Huntsville, Alabama 35810
Switzerland	Bibliothèque centrale Société Suisse de Spéléologie	Bibliothèque de la Ville, CH-2300 La Chaux-de-Fonds
Venezuela	Biblioteca Sociedad Venezolana de Espleleologia	Apartado 47.334 , Caracas 1041-1

Table 3. Evaluation of the economical importance of show caves in the world (after CIGNA *et al.*, 2000, modified).

Evaluation de l'importance économique des grottes touristiques dans le monde (d'après CIGNA et al., 2000 modifié).

Total number of show caves	~ 800
Number of "important" show caves (over 100,000 visitors/year)	~100
Total number of visitors/ year	~ 170,000,000
Money spent yearly for visiting show caves (€)	~1,700,000,000
People directly employed in show caves	~200,000-300,000
People, whose salary comes indirectly from show caves	~ 100,000,000

rapidly and currently represents a very important income in the budged of several countries. In Table 3 a rough evaluation of the present-day main parameters in cave tourism are presented but it must be emphasised that these figures must be at least doubled if Natural Parks with karst interest will also be considered.

The second activity of economic importance performed in caves is that related to health care: in the antiquity thermal caves have been used as *Thermae* (VERDE, 2000), but it was from the first half of the XXth Century onwards that thermal caves started to become important from the economic point of view (Fig. 10). In the second half of the last century the cold caves also started to be widely utilised for health care (*speleotherapy*) mainly in the countries of Eastern Europe (SANDRI, 1997): currently speleotherapy is normally used against several diseases like allergenic asthma, arthrosis, etc. (AA.VV., 1997).

Finally, caves are widely used for *mushrooms growing* and for some special *cheese production.*

Since the beginning of the human history caves have been, and still are, widely utilized as *strategic places* during wars. In the beginning they were mainly utilised as shelters for people and or strategic materials

But with the development of the war technics, caves were widely used also as *storage places of strategic materials* like fuel and ammunition, command headquarters, harbors and airports (Fig. 11).

Finally, starting with the Cuban revolution (NUÑEZ JIMENEZ, 1987), they become a privileged battlefield, as testified also by the recent war in Afganistan.

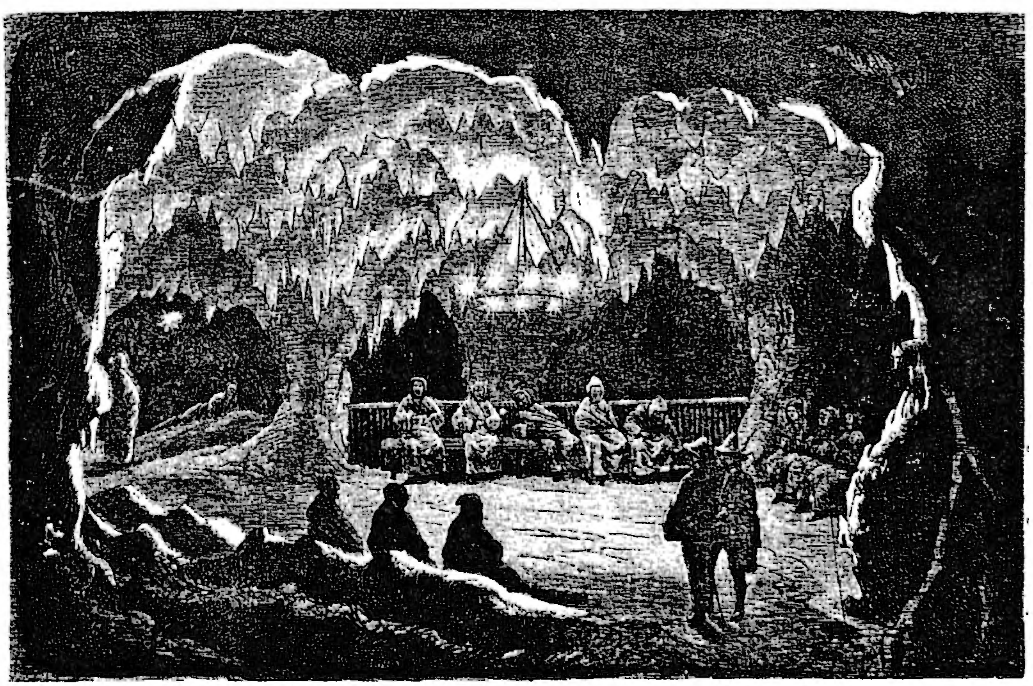


Fig. 10. Portion of the title page of the first guide of Giusti thermal cave, Italy, with an engraving of patients standing inside the cave (TURCHETTI, 1873).

Partie de la page de couverture du premier guide de la grotte thermale de Giusti, Italie, montrant les patients à l'intérieur de la grotte (TURCHETTI, 1873).

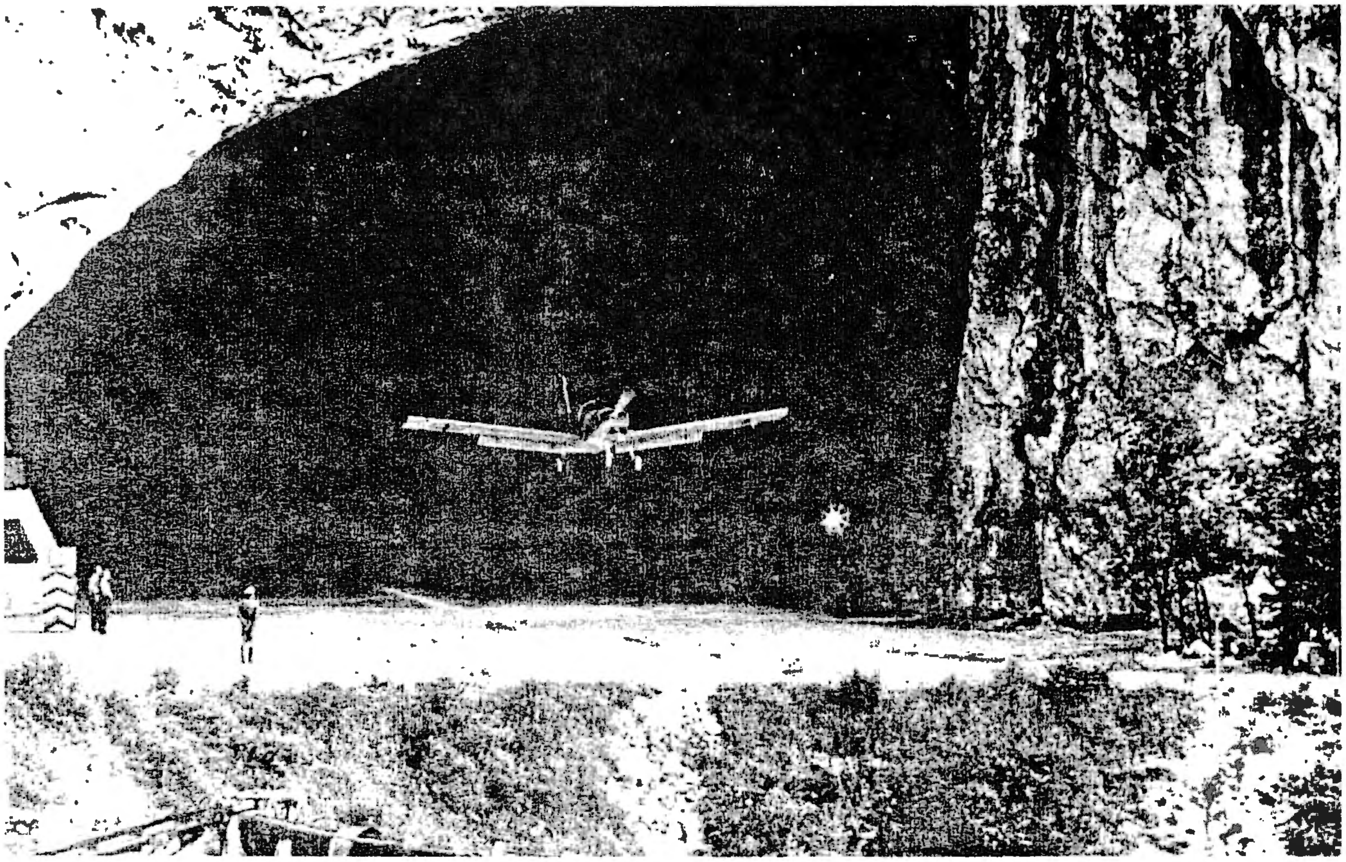


Fig. 11. An airplane taking off from the airport built up by German aviation in the Bedeilhac cave (Pyrenees) in 1944 (BERNADAC, 1975).
Avion décollant de l'aéroport construit par l'aviation allemande dans la grotte de Bedeilhac (Pyrénées) en 1944 (BERNADAC, 1975).

The National and International Speleological Organisations

Most of the National Speleological Organisations and the totality of International ones were founded after the Second World War.

Speleological Associations are presently active in over 100 countries of the world and in most of them national and/or regional structures have been established. The First International Congress of Speleology was held in Paris in 1953, while the U.I.S. ("Union Internationale de Spéléologie") was founded in Postojna in 1965 during the IVth International Congress (ANON., 1973).

Two Regional Speleological Federations exists: the FEALC (Federacion Espleologica de America Latina y del Caribe) founded in 1981 during the VIIIth International Speleological Congress in Bowling Green (URBANI, 1982), and FSCE (Speleological Federation of the European Community), established in 1990 during the XVIth Italian Congress of Speleology in Udine (CIRCOLO SPEL. IDROL. FRIULANO, 1993).

The UIS, which is recognized by the UNESCO as a non-governmental organisation, has actually 57 country members (BOSAK, 2002, *personal communication*) and its commissions cover most of the speleological activities around the world.

The UIS leadership is currently recognized worldwide being supported by the whole speleological community, although its real power is still scarce due to the difficulties to be really operative in a professional manner as it lacks a permanent structure.

The Challenges of the Third Millennium

The speleological challenges for the Third Millennium are many, and the most intriguing and/or important of them will be shortly outlined.

Explorations

Exploration shall be pushed forth to reach targets that would have been unbelievable until just a few years ago. Karst systems surely exceeding 2 km in depth exists in different areas of our planet, therefore the depth of 2000 m in a single cave will soon be reached and even surpassed: it is only a matter of time.

But length or depth records will not be the main challenge for caving explorers. There will be other boundaries to be surpassed in the future.

The systematic exploration of the frightening but fascinating world of the ice caves of Antarctica (Badino & Meneghel, 2001) will become reality in the next few tens of years.

Also the **exploration targets** will change dramatically in the next few centuries. It is currently well understood that our planet is not the only one in which caves developed: volcanic caves have already been detected on several planets of our solar system (Greeley, 1977; 1991; Licitra, 1999). These lava tubes (Fig. 12) may sometimes reach incredible lengths exceeding by far the longest caves on Earth. All these caves inside and outside the solar system are waiting to be explored and mapped by spaceman cavers.... And this is not science fiction...

It is quite sure that this explorations will happen in the near future not because of the scientific importance of such caves but due to the practical one: in fact they may be regarded as ideal places for the installation of the first settlements for space colonization.

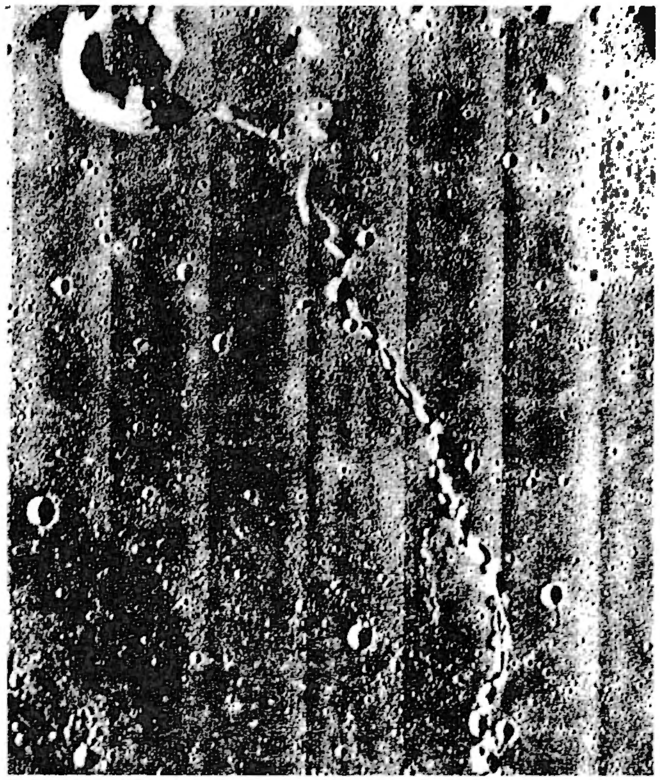


Fig. 12. Moon: collapses along a lava tube close to the border of the *Oceanus Procellarum*.

*Effondrements le long d'un tube de lave sur la lune proche de la bordure de l'*Oceanus Procellarum.

Pure and Applied Scientific Research

The importance of caves in pure and applied scientific research will largely improve in the Third Millennium.

The most important fields in pure research where it is reasonable to expect a noticeable increase of interest are:

- high-resolution paleoenvironmental reconstruction;
- microbiology
- low-enthalpy reactions
- special ecosystems

Caves are amongst the most durable geomorphic features and represent perfect sedimentological traps for physical and chemical deposits that may be kept untouched therein even over a very long span of time. In the last decade caves, and especially the hosted speleothems, yielded the best and powerful tools to reconstruct paleo-environments and paleo-climates of the Late Quaternary, sometimes allowing a resolution of up to one year or lower (Ford, 1997; Shopov, 1997, Antonioli *et al.* 2001). Moreover, speleothems proved to be extremely useful as natural recorders of strong earthquakes of the past, thus allowing a better definition of the seismic hazard (Forti, 1999; Quinif, 1998).

It is therefore reasonable to forecast for the Third Millennium a very fast increase of all those paleo-environmental and paleo-seismic analyses.

In the last few years, microbiology proved to be fundamental in caves: plenty of bacteria and other micro-organisms passively and/or actively interfere with the cave evolution, like those involved in the sulphur cycle (Fig. 13) (Forti, 2001).

The complex biochemical reactions involved in the development of different cave deposits, though still not completely understood, clearly bear an interest and importance far exceeding the simple speleogenetic one (Contos, 2001; Northup *et al.* 1997; Sasowsky & Palmer, 1994).

Normally they are low-enthalpy reactions and unraveling them is fundamental in order to improve our understanding of the natural mechanisms by which even ore bodies of economic interest may be formed and mobilized (Forti, 1989; 1996a). The study of biologically driven reactions is also fundamental to enhance our knowledge over peculiar environments like the chemoautotrophic ones, which characterise not only caves (Sârbu *et al.* 1996) but also some deep sea environments and it is obvious that such studies may be performed much more easily in caves (Forti *et al.*, 2002).

Caves' microbiology is presently not well known despite its great scientific interest. Thus it is reasonable to expect an increase in the co-operation between cave biologists and cave geochemists in the near future in order to obtain a fast improvement of the study of these phenomena.

The results of the applied research in caves will be even more important: in fact some of the most important challenges of

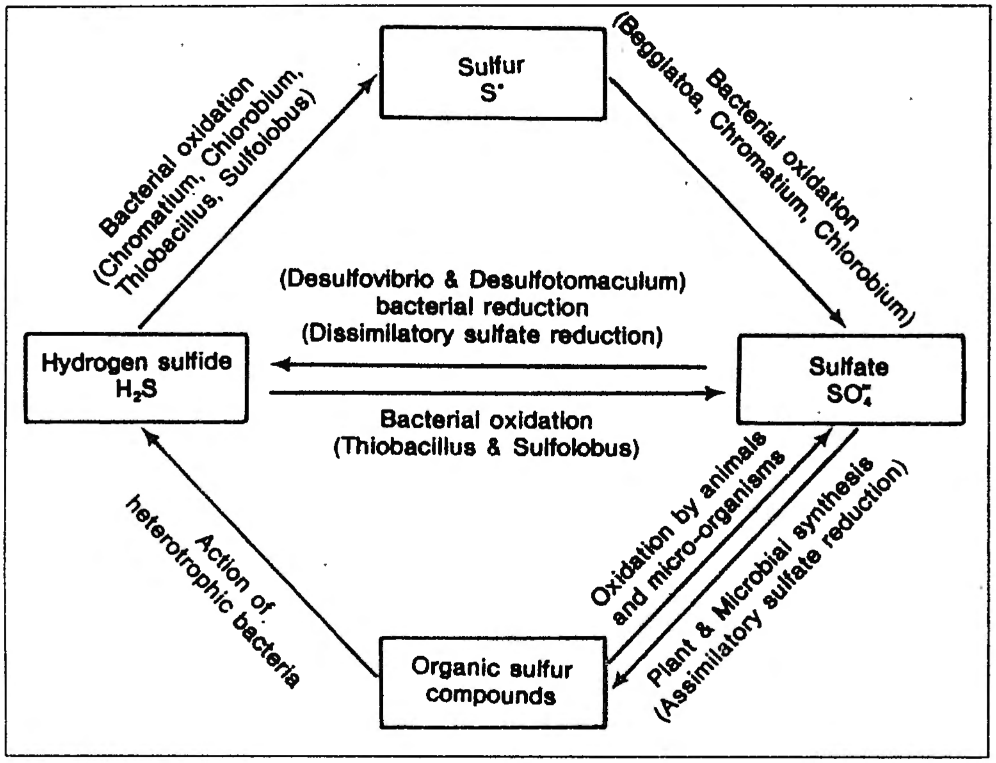


Fig. 13. The sulphur cycle (after Forti, 2001).

Le cycle du soufre (d'après Forti, 2001).

the whole humanity will probably be solved within karst environments. Among them two are worthwhile to be quoted:

- extensive search for new drinking water resources;
- new active principles in medicine.

The most relevant problem for future generations will surely be the drinking water supply. The pollution and the increase in demand are rapidly depleting all currently known sources of water. Karst aquifers started to be heavily utilized as a civil water supply in the last decades of the Second Millennium, but it is highly expected that in the near future the water hosted in karst areas will become if not the single, surely the most important among the relatively low-cost sources of drinking water (Fig. 14).

Caves should become extremely important sites for medical research. In fact even if it is still questionable the fact that caves could have been the "nursery" for new terrible diseases like Ebola (Fig. 15) and/or AIDS (Halliday, 1999), it has been definitely demonstrated that caves and their peculiar ecosystems may host specific and, in some cases, new viruses, bacteria and/or other micro-organisms.

The research started on this specific topic in the last couple of years in the United States (Bigelow, 1998) and it is just at the very beginning. The first achieved results suggest that they will be very fruitful: several hundreds of new micro-organisms and viruses have been observed in caves and some tens have been selected as potential "active vehicles" and they will be tested in the next tens of years.

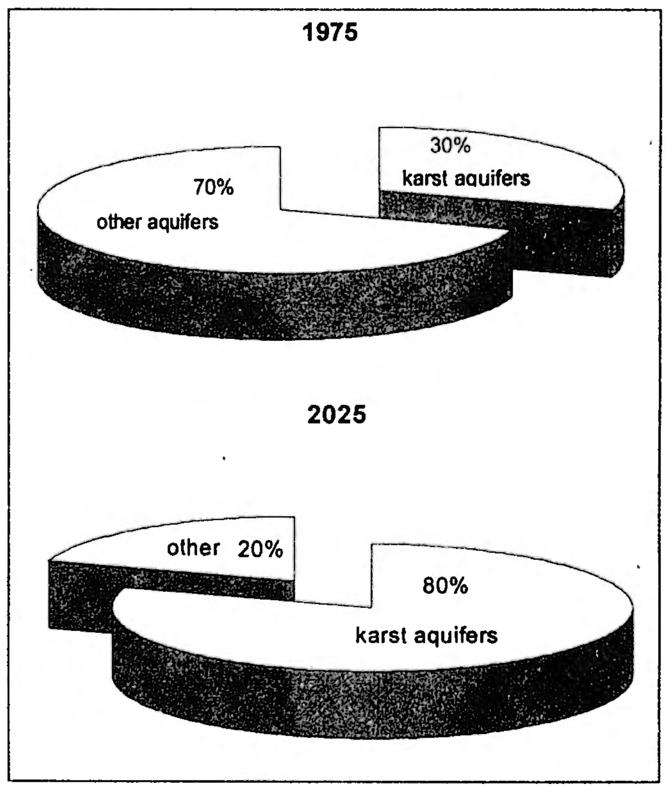


Fig. 14. Variation in civil water supply between 1975 and 2025 (FAO unpublished report).

Tendance d'évolution des sources d'eau potable entre 1975 et 2025 (d'après FAO, rapport non-publié).

Fig. 15. The author visiting Kitum cave (Mt. Elgon, Kenya), supposed to be the lair of Ebola virus.

L'auteur, visitant la grotte de Kitum (Mt. Elgon, Kenya) supposée d'être la tanière du virus d'Ebola.

But the most important problem that pure and applied scientific research will have to resolve even before improving its presence inside caves is *the preservation of cave environment.*

No real attention has been focused on the degradation of cave environment induced by scientific research: but often researchers do destructive sampling far over the real necessity of their studies. This happened because no real control over the behavior of scientists in a cave environment has been exercised until present. It is time to begin to enforce such a control...

Therefore the Third Millennium shall lead to a systematic decrease of destructive sampling in each of the speleological scientific fields.

Environmental Protection

Like the scientific ones, all other (social, economic, etc.) activities inside caves will experience a fast increase during the Third Millennium. Among them, tourism and other related activities shall expand greatly reaching new countries and areas, thus involving perhaps billions of peoples.

An obvious consequence of the increased human activities in cave and karst environment is the risk of a fast degradation of the related ecosystems.

Therefore the Third Millennium must be mainly dedicated to a strict control over different caving activities to ensure their sustainable development in time and the whole speleological community must cooperate in particular by means of:

- developing active protection of karst areas and caves;
- improving eco-compatible tourism;
- self limitation of some activities inside caves;
- strict control of the scientific activities therein.

The simplest and the easiest way to ensure protection from environmental risks is surely the creation of cave and/or karst parks and reserves.

But ruling the territory is normally a matter of Local and/or National Governments and therefore at local and national level the speleological associations must improve their voice at the political level.

In the same time, at the international level the UIS must cooperate with UNESCO in order to improve the number of karst and cave sites inserted among the World Heritages.

Anyway it is absolutely unrealistic to think of protecting more than 1–2% of the total karst patrimony of our planet in this way.

Development of Environmental Sustainable Tourism

Despite the opinion of most cavers and speleological associations it must be stressed that tourism does not automatically mean damaging of the cave environment. On the contrary, sometimes tourism transformation may be the unique chance to preserve some very fragile and precious environment (Forti, 1996b).

The present-day knowledge about cave environment, microclimate and ecosystem is complete enough to allow:

- the transformation of virtually any cave into a show-cave, maintaining unaltered its natural value;
- the choice of the best materials and ways to do it;
- the control of the tourists presence in such a way that none of the natural parameters of the cave will change in a permanent manner.

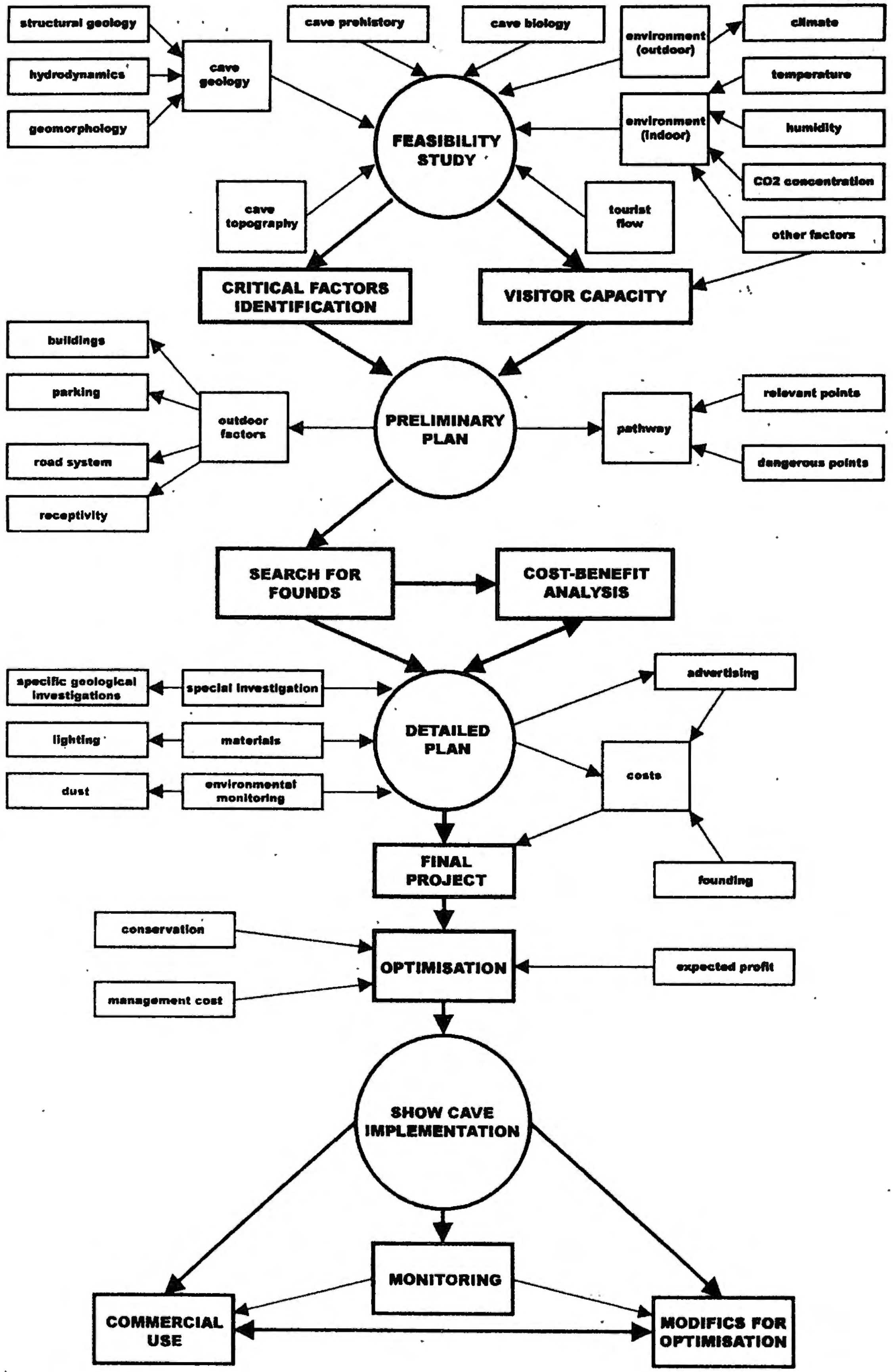


Fig. 16. Environmental impact assessment for the development and management of a show cave (after Cigna *et al.*, 2000, modified).
Evaluation de l'impact du développement et administration d'une grotte touristique sur le milieu (d'après Cigna et al., 2000, modifié).

This is only a matter of controls *before*, *during* and *after* the tourist development (CIGNA *et al.*, 2000; CIGNA & BURRI, 2001): in other words, a matter of correct management of a show cave (Fig. 16).

In the Third Millennium all caves opened to tourism must be monitored and must have a Technical Commission with the right to change the tourist flows on the basis of the achieved data; cave managers should understand that monitoring is not a simple cost, but instead a very productive investment.

The UIS and ISCA (International Show Cave Association) must co-operate in order to transform this statement into a common feeling in the near future. Anyway, from now on, *no cave without a monitoring network and a Technical Commission should be supported by any caver wherever in the world.*

Sustainable Criteria for Cave Exploration

Caves are very fragile environments and perhaps the single ones that are still partially unaltered in our world, consequently speleological explorations affect them greatly.

Until now most of the ecological concern was directed toward show caves, but in reality cave tourism affects far less than 0.1% of the whole subterrannean patrimony, while all other economic and/or strategic activities affect no more than another 0.1%.

It is obvious that speleological explorations affect a relevant fraction of 100%. The first exploration always causes a loss of naturality far more than any subsequent activities and it may damage the cave environment far more than a well organised tourist transformation. Further damages are brought about by any subsequent caving trips (BADINO, 2000; 2001).

It is the time for cavers to become aware of it and try to minimize their impact on the underground world by ruling self-limitation criteria in cave explorations.

As already verified in many of the most famous caving areas of our planet:

- *A limit for the frequentation of any cave must exist.*

  The guideline already available for show caves may be a reasonable starting point for the definition of the access criteria to a wild cave.

- *A limit must exist for cave modification during the exploration.*

  It is really unacceptable to have no limits (as currently) to enlarge entrances and/or passages, to destroy speleothems and physical infilling, to empty sumps, without any due care to cave microclimate, sediments, etc...

- *The impact on caves by improving the techniques and materials must be kept to a minimum.*

  Most of the cave damages during exploration or caving trips arise from the use of wrong technics and/or materials: all cavers must always be updated on them and those highly impacting discharged.

It is the time for the speleological community to discuss these topics on any level and to rule out consequently.

Final Remarks

The fast development of speleology in the last few decades clearly suggests that caving activity in the Third Millennium will surely experience an increase in any one of its fields. Extreme explorations will be performed not only on our planet; cave and karst tourism will rapidly expand reaching new countries on the five continents: several hundreds, if not thousands, of new show caves will be implemented to accomplish the request of billions of tourists.

Cave environments will become more and more important for exciting research in plenty of scientific fields, while the deep karsts will show their importance in terms of renewable resources (first of all for the drinking water supply) greatly enhanced.

Anyway, as a direct consequence of its development, speleology will also have to face several hard risks for caves and karst areas: first of all the possible unacceptable environmental alteration as a direct consequence of an excessive anthropic pressure over their fragile environment.

A definite limit for frequentation has to be fixed not only for show caves, but also for *any* of the natural cavities. Moreover the most impacting exploration activities and tools must be banned from caves: as in the case of carbide lighting, which may cause, and in reality causes, relevant damages to the cavern environment (burning and/or disfiguring speleothems, polluting the water, supplying heat to the environment) and may now be easily replaced by electric LED (BRUMMEL, 1999; CHAILLOUX, 1999).

Finally the unjustified *scientific oversampling*, a risk that has been underestimated until now if not completely neglected, must be strictly avoided. This problem already exists but the increase in scientific research in the near future will surely bring inside caves researchers who will not be completely aware of the problem or, even worse, be indifferent to cave environment protection.

To ensure the preservation of caves and karst for the future generations it is necessary that the speleological community will cause a voluntarily worldwide limit to the activities to be performed in caves and this should be the main role of the International Union of Speleology in the Third Millennium.

Something in this direction has already been done but much more still has to come: the UIS has the knowledge, the possibility, the authority and the right not only to control but also to rule these processes and all the national speleological association must co-operate with the UIS for the preservation of the cavern environment worldwide.

People and ideas are fundamental to reach this goal, but not enough: in fact the UIS needs much more money and tools to be successful in this endeavour.

But, first of all, the UIS must achieve effective power to establish the main rules on caving activities all over the world: to do this the full co-operation of all the national speleological associations is absolutely required. In fact it is time that national associations renounce some of their own rights in favour of the general interest of Speleology.

References

ALZONA, C., GORTANI, M., BARBIERI, C., & TREBBI, G. (1903) Società Speleologica costituita in Bologna il 18 marzo 1903. *Rivista It. Di Speleol.* 1, *1*, pp.1–4.

ANONIMOUS (1898) Le cercle spéléologique hydrologique d'Udine. *Spelunca Bull.*, 1, *2*, p. 47.

ANONIMOUS (1973) La fondation de l'Union Internationale de Speleologie. *Proc. 4th Intl. Congress of Spel., Yugoslavia 1965*, 1-2, pp. 36–40.

ANONIMOUS (2000) World's deepest caves. *The International Caver* 2000, pp. 80–81.

ANTONIOLI, F., SILENZI, S., & FRISIA, S. (2001) Tyrrhenian Holocene palaeoclimate trends from spelean serpulids. *Quaternary Science Reviews*. 20, *15*, pp. 1661–1670.

AA.VV. (1997) *Proc. Intl. Conf. "Protection and medical utilisation of karst environment" 3-5 June, Banska Bystrica*, 97 p.

AVICENNA (1929) *Avicennae de congelatione et conglutinatione lapidum being section of the " Kitâb al-Shifâ"* (Translated by HOLMYARD E.J. & MANDEVILLE D.C., *Eds.*), Paris, 86 p.

BÄCHLER, E. (1905) Beiträge zur Kenntniss der Höhlen des Säntisberges, *Jr. St. Gal. Naturw.* Ges. 1904, pp. 239–241.

BADINO, G. (2000) *L'attività speleologica e gli adattamenti turistici individuali delle grotte.* L'Aquila. (*in press*).

BADINO, G. (2001) Le terre della notte. *Geologia dell'Ambiente*, 3, pp. 44–48.

BADINO, G., BELLOTTI, A., BERNABEI, T., DE VIVO, T., DOMENICI, D., & GIULIVO, I. (1999) *Rio La Venta tesoro del Chiapas.* Padova, 320 p.

BADINO, G. & MENEGHEL, M. (2001) Caves in the glaciers of Terra Nova Bay (Victoria land, Antarctica). *Proc. 13th Intl. Spel. Congr. Brasilia*, 196/S1, p. 4.

BAKER, E. A. (1903) *Moors, crags & caves of the High Peak.* Manchester, 207 p.

BEAUMONT, J. (1676) Two letters concerning rockplants and their growth. *Philos. Trans. Royal Soc.* 11, *129*, pp. 732–742.

BELLHOUSE, H. H. (1899) The formation of the Yorkshire Rambler's Club. *Yorkshire Rambler's Club J.*, 1, pp. 3–12.

BERNADAC, C. (1975) *Le passé-montagne.* France-Empire, Paris, 192 p.

BIGELOW, J. (1998) Biomes: the promise of cave-dwelling microbes. *NSS News*, 56, *5*, p.145.

BLEAHU, M. (1974) *Morfologia carstică*. Ed. Stiinţifică, *Bucureşti*, 590 p.

BÖGLI, A. (1980) *Karst hydrology and Physical Speleology.* Springer, Berlin, 284 p.

BROOK, D. B. & WALTHAM, A. C. (1978) *Caves of Mulu.* London, 44 p.

BROUGHTON, P. L. (1972) Secondary mineralization in the cavern environment. *Stud. Speleol.*, 2, *5*, pp.191–207.

BRUMMEL, T. (1999) Revolution in lighting. *The Windy City Speleonews.*, 39, *5*, p. 68

BÜCHNER, B. (1535) *Wunderparliche Newe Zeitung so jetzt am tag Petri und Pauli im fünf und dreyssigisten Jahr.* 4 p.

BULLIT, A. C. (1845) *Rambles in the Mammuth Cave, during the year 1844.* Louisville, 101 p.

CAI (1933) *Atti del I Congresso Speleologico Nazionale*. Trieste, 254 p.

CAPPELLERI (1767) *Pilatis Montis Historia in Pago Lucernensi Helvetiae Siti.* Basilea, 188 p.

CHABERT, C. & COURVAL, M. DE (1971) *E.A. Martel 1859-1938 bibliographie.* Paris, 103 p.

CHAILLOUX, D. (1999) Action-light un éclairage à diode électroluminescente. *Spéléo*, 33, p. 30.

CIGNA, A. A. (1993) Speleology by Titus Lucretius Carus. *Proc. Int. Symp. "Protostoria della Speleologia", Città di Castello 13-15 Settembre 1991*, pp.17–24.

CIGNA, A. A. & BURRI, E., (2000) Development, management and economy of show caves. *Intl. J. Spel.*, 29B, *1/4*, pp. 1–27.

CIGNA, A., CUCCHI, F., & FORTI, P. (2000) Engineering problems in developing and managing show caves. Proc. Intl. Symp. Engineering Geology, Kathmandu, Nepal, *J. Nepal Geol. Soc.* 22, pp. 85–94.

Circolo Speleologico Idrologico Friulano (1993) Atti del XVI Congresso Nazionale di Speleologia. *Le Grotte d'Italia*, S.4, **15**, p.13.

Configliachi, P. (1819) *Monografia del Proteo Anguino di Laurenti*. Pavia, 120 p.

Contos, A. (2001) *Biomineralisation in Caves*. PhD Thesis, University of Sidney, 221 p.

Courbon, P., Chabert, C., Bosted, P., & Lindsley, K. (1989) *Atlas of the great caves of the world*. Cave Books, St. Louis , 370 p.

Dobrilla, J. C., Marbach, G., & Peigné, B., (1973) *Techniques de la Spéléologie Alpine*. Paris, 100 p.

Filodei de Homodeis, A. (1590) *Aetnae Topographia*. Perugia, 18 p.

Ford, D. C. (1997) Dating and Paleo-Environmental Studies of Speleothems. In: *Cave Minerals of the world*. (Hill, C. A. & Forti, P. *Eds.*) NSS, Huntsville, pp. 271–284.

Ford, T. D. & Cullingford, C. H. D. (1976) *The Science of Speleology*. London, 594 p.

Forti, P. (1983) I minerali di grotta. *Speleo*, **9**, pp. 9–24.

Forti, P. (1989) The role of sulfide-sulfate reactions in speleogenesis. *Xth Int. Spel Congr., Budapest*, **1**, pp. 71–73.

Forti, P. (1993) Breve nota a margine di un veloce viaggio in Iran (22-30 Ottobre). *Sottoterra*, **95**, pp. 21–23.

Forti, P. (1996a) Thermal Karst Systems. *Acta Carsologica*, **XXV**, pp. 99–117.

Forti, P. (1996b) Turisticizzazione e tutela dell'ambiente ipogeo: due aspetti non contrastanti. *Atti Int. Symp. "Grotte turistiche e monitoraggio ambientale", Fabrosa Soprana 1995*, pp. 49–56.

Forti, P. (1998) La storia delle concrezioni si allunga di 400 anni. *Speleologia*, **38**, p. 67.

Forti, P. (1999) Evidencias tectónicas y sísmicas a partir del estudio de espeleotemas: conocimiento actual y desarrollo futuro. *Intl. Symp. Cueva de Nerja*, pp. 19–33.

Forti, P. (2000) La speleologia: un potente strumento di indagine scientifica. *Geologia dell'Ambiente*, **3**, pp. 2–9.

Forti, P. (2001) Biogenic Speleothems: an overview. Abstract of Papers, *15th Int. Symp of Biospeleology, Intervales, Brazil*, pp. 3–6.

Forti, P. (2002) Motivi di interesse geologico delle grotte. *Convegno Massa-Carrara, Settembre 2001, in press*.

Forti, P., Galdenzi, S., & Sârbu, S. (2002) The hypogenic caves: a powerful tool for the study of seeps and their environmental effects. *Continental Shelf Research*. (*in press*).

Gill, D. (1991) Subterranean waterworks of biblical Jerusalem: adaptation of a karst system. *Science*, **2545037**, pp.1467–1471.

Greeley, R. (1977) Lava tubes on other planets. *Atti Seminario "Grotte Laviche", Catania 1975*, pp.181–191.

Greeley, R. (1991) Lava tubes in the Solar System. *Proc. 6th Int. Symp. On Vulcanospeleology, Hilo, Hawaii*, pp. 223–230.

Gurnee, R. (1993) A brief history of cave studies in the United States before 1887 (16th to the 19th century). *Proc. Int. Symp. "Protostoria della Speleologia", Città di Castello 13-15 Settembre 1991*, pp. 293–308.

Halliday, W. R. (1999) Overview of the 8th International Symposium on Vulcanospeleology. *Intl. J. Speleol.*, **27B**, *1/4*, pp. 9–10.

Herbinius, J. (1670) *Dissertationes de admirandis mundi cataractis supra et subterraneis*. Copenhagen, 267 p.

Hill, C. A. & Forti, P. (1997) *Cave Minerals of the World.*, NSS, Huntsville, 464 p.

Hohenwart, F. G., von (1830) *Adelsberger und Kronprinz Ferdinands-Grotte*. Wien, 16+10+14 p.

Huntignton, H., of (1853) *The chronicle...* (Forrester, T. *Trans. & Ed.*) London.

Kircher, A. (1674) *Mundus Subterraneus*. Amsterdam, 372 +516 p.

Klimchouk, A. B., Ford, D. C., Palmer, A. N., & Dreybrodt, W. (*Eds*) (2000) *Speleogenesis, evolution of karst aquifers*. NSS, Huntsville, 528 p.

Ko Hung (1946) Pao p'u Tzu (Book of the preservation-of-solidarity master). (Feifel, E. *Trans.*) *Monumenta Serica*, **11**.

Jakucs, L. (1977) *Morphogenetics of Karst Regions*. Bristol, 284 p.

James, N. P. & Choquette, P. W. (*Eds.*) (1988) *Paleokarst*. Springer, 416 p.

Juberthie, C. & Decu, V. (*Eds.*) (1994) *Encyclopaedia biospeologica*. **1**, Moulis-Bucarest, 834 p.

Judson, D. (1973) *Ghar Parau*. London, 216 p.

Lang (1806) *Gallerie der Enterirdischen Schopfungs-Wunder und des menschlichen kunstsleisses unter der erde*. Leipzig, 416 p.

Laureti, L. (2001) Storia della Speleologia. *SSI Quadrni didattici*, **11**, 40 p.

Licitra, G. (1999) *Grotte vulcaniche nel mondo .... ed oltre*. Centro Speleologico Etneo *"Dentro il Vulcano"*, pp. 47–56.

Martel, E. A. (1894) *Les Abîmes*. Paris, Delagrave, 578 p.

Northup, D. E., Reysenbach, A. L., & Pace, N. R. (1997) Microorganisms and speleothems. In: *Cave Minerals of the World* (Hill, C. A. & Forti P., *Eds.*), NSS, Huntsville, pp. 261–266.

Nuñez Jimenez, A. (1987) *Geografia y Espeleologia en Revolucion*. La Habana, 190 p.

Oppitz, D. (1929) Assyrerkönige als Höhlenforscher. *Mitt. Höhl.-u. Karstforsch.*, **2**, pp. 58–61.

Prosser, J. & Grey, H. V. (1992) *NSS Cave Diving Manual*. NSS, Huntsville, 378 p.

Quinif, Y. (*Ed.*) (1998) Karst & Tectonics. *Speleochronos*, hors serie, 199 p.

Sandri, B. (1997) Development of speleotherapy in Europe since the constitution of speleotherapy commission within the Union Internationale de Speleologie. *Proc. Intl. Conf. "Protection and medical utilisation of karst environment", Banska Bystrica*, pp. 62–64.

Sârbu, S. M., Kane, T. C., & Kinkle, B. K. (1996) A chemoautotrophically based groundwater ecosystem. *Science*, **272**, pp. 1953–1955.

Sasowsky, I. D. & Palmer, M. V. (1994) *Breakthroughs in Karst Geomicrobiology and Redox Geochemistry*. Symposium Abstract, Karst Waters Institute, 112 p.

Schmidl, A. (1854) *Die Grotte un Hohlen von Adelsber, Lueg, Planina and Laas*.

Sezione Speleologica „Città di Castello" (1993) *Protostoria della Speleologia*. Città di Castello, 352 p.

Shaw, T. D. (1992) *History of Cave Science*. Sydney Spel. Soc., 338 p.

Shopov, Y. Y. (1997) Luminescence of Cave Minerals. In: *Cave Minerals of the world*. (Hill C. A. & Forti, P., *Eds*), NSS, Huntswille, pp. 244–248.

Société Spéléologique de France (1939) *Actes du 1er Congrès National de Spéléologie*. Nîmes, 76 p.

Tankersley, K. B., Munson, C. A., Watson, P. J., Shafter, N. R., & Frushour, S. S. (1997) Archaeology and Speleothems. In: *Cave Minerals of the World* (Hill C. A. & Forti, P., *Eds*), NSS, Huntsville, pp. 266–270.

Tourneford, J. P. (1704) Description du labyrinthe du Candie, avec quelques observations sur l'accroissement et sur la génération des pierres. *Mem. R. Acad. Paris*, pp. 406–424.

Turchetti, O. (1873) *Guida dei bagni a vapore naturale della Grotta di Monsummano*. Loescher, Firenze, 94 p.

U.I.S. (2000) *BBS - Speleological Abstract*. Varese, p. 2.

Urbani, F. P. (1982) Speleological Association of Central, South America and Caribbean. *UIS Bulletin*, **1/2**, p. 13.

Vallisneri, A. (1726) *Lezione accademica intorno a l'origine delle fontane*. Venice, 408 p.

Valvasor, J. W. (1689) *Die Ehre des Hertzogthums Krain Lanbach*., 696+838+732+676 p.

Verde, G. (2000) *Il termalesimo di Sciacca dalla preistoria al XX secolo*. Sarcuto, Agrigento, 280 p.

Wright, R. V. (1971) *The Archaeology of the Gallus Site, Koonalda Cave*. Aust. Inst. Aboriginal Stud., Canberra, 133 p.

Zimmerman, M. (1790) *Voyage à la nitrière naturelle qui se trouve à Molfetta*. Venezia, 44 p.

received: 27 February 2002
revised: 26 July 2002
accepted: 30 July 2002

Theoretical and Applied Karstology, 15 (2002), pp. 27–34

TAK Articles

Unusual minerals related to phosphate deposits in Cioclovina Cave, Şureanu Mts. (Romania)

Bogdan P. Onac[1,2]*, Radu Breban[3], Joe Kearns[4], & Tudor Tămaş[1,2]

[1] *University of Cluj, Dept. of Mineralogy, Cluj-Napoca, Romania.*

[2] *"Emil Racoviţă" Institute of Speleology, Cluj Branch, Clinicilor 5, 3400 Cluj-Napoca, Romania.*

[3] *Speleoclub "Proteus", C.P. 633, 2750 Hunedoara, Romania.*

[4] *Materials Research Laboratory, The Pennsylvania State University, University Park PA, 16802, USA.*

Abstract

Cioclovina Cave hosted an extensive phosphate deposit estimated at over 50,000 m³. About 30,000 m³ were mined during the first half of the XXth Century and used as fertilizers. The mineralogy of this deposit is remarkable as it consists of several rare and/or unusual cave mineral species, mostly phosphates. Cioclovina Cave is the type locality for ardealite. Over 40 samples were analyzed by means of X-ray diffraction and fluorescence, scanning electron microscopy, optical observations on thin sections, and electron microprobe. Out of 26 minerals presented in this paper, 13 have not been previously documented from this cave (berlinite, burbankite, churchite, chlorellestadite, foggite, paratacamite, collinsite, monetite, fluorapatite, sampleite, romanechite, leucophosphite and todorokite). Furthermore, the first six minerals on this list were for the first time identified within the cave environment. At least one rare mineral species (berlinite or chlorellestadite) may have been produced by spontaneous combustion of bat guano, whereas the other ones formed within the sediment fill indicate reactions between phosphate-rich solutions and limestone bedrock, clays, sandstones or various trace elements. These reactions took place at different pH values producing specific minerals that may have environmental deposition significance.

Keywords: cave minerals, phosphates, guano combustion, Cioclovina Cave, Romania.

Quelques minéraux particuliers formés en relation avec les dépôts de phosphates de la Grotte de Cioclovina (Monts Şureanu, Roumanie)

Résumé

La grotte de Cioclovina abrite un dépôt massif de phosphates, dont le volume a été estimé à plus de 50.000 m³. Approximativement 30.000 m³ ont été exploités dans la première moitié du XXᵉ siècle et utilisés dans l'agriculture. La minéralogie de ce dépôt est remarquable du fait qu'il contient quelques espèces minérales rares et/ou particulières, la plupart des phosphates. La grotte de Cioclovina est la localité-type de l'ardéalite. Plus de 40 échantillons ont été analysés par diffraction de RX et fluorescence, au microscope électronique à balayage, par des observations optiques et microprobe électronique. Des 26 minéraux présentés dans le travail, 13 sont nouveaux pour cette grotte (le berlinite, le burbankite, le churchite, le chlorellestadite, le foggite, le paratacamite, le collinsite, le monetite, le fluorapatite, le sampleïte, le romanechite, le leucophosphite et le todorokite). En outre, les six premiers minéraux ont été identifiés pour la première fois dans le milieu souterrain. Au moins une des espèces minérales rares (le berlinite ou le chlorellestadite) pourrait être formée par la combustion spontanée du guano, tandis que les autres minéraux présents dans le sédiment suggèrent des réactions entre les solutions riches en phosphates, d'une part, et le calcaire des parois, l'argile, les grès ou divers éléments rares, d'autre part. Ces réactions ont eu lieu en diverses conditions de pH et ont produit des minéraux spécifiques, à signification environnementale.

Mots-clés: minéraux de grotte, phosphates, combustion du guano, Grotte de Cioclovina, Roumanie.

* corresponding author. *E-mail address*: bonac@bioge.ubbcluj.ro

Introduction

The phosphate deposit located within the Cioclovina Uscată Cave[1] (= Dry Cioclovina, hereafter called Cioclovina for simplicity) contains a fascinating assemblage of minerals that includes, apart from many rare phosphates, several carbonates, silicates, sulfates and hydroxide species. Most of the minerals identified within the phosphate deposit form nodules, crusts, bands of earthy-masses interbedded with sand, gravels, clays and concentric layers around weathered limestone blocks, volcanic, and metamorphic chunks. Only a few of the minerals form euhedral or subhedral crystals; all the others appear as earthy-masses.

Extensive investigations on the mineralogy of this cave occurred at the beginning of the XXth Century when over 30,000 m³ of phosphate sediments were mined out and used as fertilizers. Cioclovina Cave is the type locality for *ardealite*, $Ca_2(SO_4)(HPO_4) \cdot 4H_2O$, originally reported by Halla (1931) and fully described by Schadler (1932). Not until 1997 was the mineralogical interest in Cioclovina Cave rekindled when one of the authors (RB) began his graduate thesis. A few years later, Constantinescu *et al.* (1999) published a note on the presence of *crandallite*, $CaAl_3(PO_4)_2(OH)_5 \cdot H_2O$, incorporating some new data on the phosphate association. A recent extended abstract and a forthcoming paper include new mineralogical data on the bat guano deposit from Cioclovina and first mention the presence of *tinsleyite* $KAl_2(PO_4)_2(OH) \cdot 2H_2O$ and *carbonate-hydroxylapatite*, $Ca_5(PO_4,CO_3)_3(OH)$, (Dumitras & Marincea, 2000; Marincea *et al.*, 2002).

The aim of this preliminary report is to extend the previous mineralogical work carried out on Cioclovina Cave phosphate deposit, moreover, to present additional data and some comments on the most interesting mineral species. It must be stressed that the complex mineralogy of this cavern cannot be entirely presented in a single research paper.

Geological and speleological setting. Sample collection

The study area is situated in the upper part of the Luncanilor Valley, on the west-southwest side of the Şureanu Mountains (Fig. 1, inset). The basic stratigraphy around Cioclovina Cave consists of a thick carbonate sequence of Upper Jurassic (*Stramberg*-type facies) and Lower Cretaceous (*Urgonian* facies) ages. Underlying the carbonates are the gneisses of the Sebeş-Lotru Unit (Getic Nappe), and Permian to Lower Jurassic (Liasic) detrital deposits (Balintoni & Bucur, 2001; Stillă, 1981) (Fig. 1).

Cioclovina Cave (code 2063/8, Goran, 1982) develops in the Malm-Neocomian limestones and consists of a long fossil passage interrupted in the middle by a descending gallery and a 10 m deep pit that connects the upper level with the stream passage. Climbing a 30 m-long chimney, one can continue in the inactive passage. This level continues as well decorated passages and rooms (Fig. 2). The cave has been known since the late XIXth Century when scientists visited it to search for cave bear fossils and to investigate the extensive phosphate deposit. Much of the 15 to 20 m-thick phosphate deposit was mined out of the cave between 1912 and 1941. Nevertheless, in many parts of the cave one can still notice layers of phosphate sediments (5 to 6 m-thick) covered by flowstone in their upper part (Fig. 3).

Although the cave has a natural entrance, it is seldom used. A mining gallery dug during the course of guano-phosphate exploitation is the preferred entrance.

The relative humidity is between 75 and 95% throughout the sampled part of the cave, while the temperature remains constant year-round in the range of 8–9 °C. Variations, however, of both parameters occur in the sector where the man-made tunnel penetrates the cave.

Over 40 samples were collected from various settings along the main passage, between the natural entrance and the *Bivouac Room* (Fig. 2). These samples consist of crusts, nodules, aggregates of tiny crystals, and earthy-masses. In many of the occurrences the phosphate deposit actually represents phosphatized clay and residual or fluviatile silica-rich sediments. At other locations phosphate minerals precipitate at the locus of reaction with limestone, resulting in the metasomatic replacements taking the form of banded coatings. Except for the green-bluish nodules admixed with the pale-blue tiny crystals (sample #1323), all the other samples were hand-specimen-size pieces. To avoid hydration/dehydration or any other post-sampling process the samples were kept in air- and water-tight plastic bags.

Analytical methods

The mineralogy of phosphate deposits was studied using a combination of optical microscopy, X-ray diffraction (XRD), X-ray fluorescence (XRF), scanning electron microscopy (SEM) equipped with energy dispersive spectrometer (EDS), and electron microprobe analysis.

Polished thin sections were prepared from all hardrock samples, for studies using a NIKON Optiphot 2-POL petrographic microscope. The remaining material and the soft samples were crushed and ground. Powder splits were taken for the rest of the analyses.

XRD data were obtained using *Scintag Pad* V and *Philips* PW1800 diffractometers, both operating at 45 kV and 40 mA using Ni-filtered Cu Kα radiation. Silicon was added as an internal standard. The step-scan data were continuously collected over the range of 5 to 85° 2θ, using a step interval of 0.025° 2θ.

[1] Also known as Ciclovina Cave.

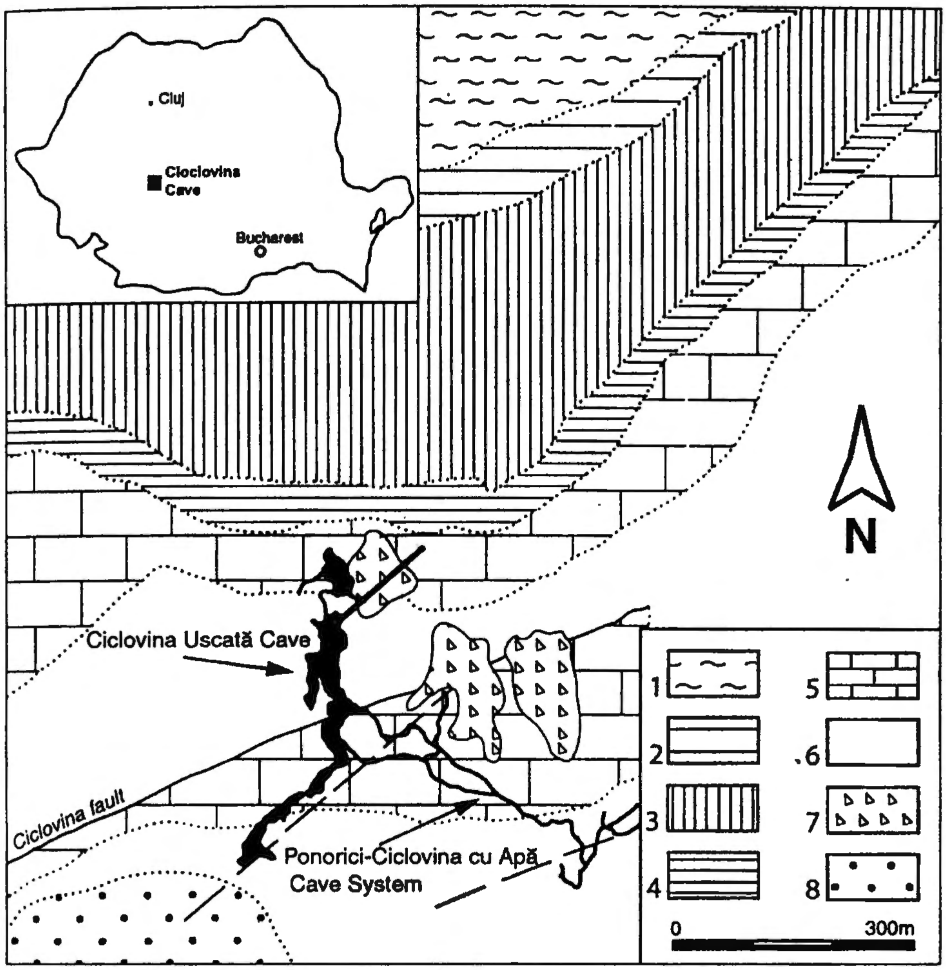


Fig. 1. Location of the study area and its geology. 1. schists and gneisses (Precambrian); 2. *Cioclovina Red Beds* (P_1); 3. conglomerates and sandstones (J_1); 4. limy sandstones (J_2); 5. cherty limestones (J_3); 6. reef limestones (K_1); 7. Quaternary loose sediments; 8. sandstones & marls (K_2) (after Stilla, 1981).

Situation de la zone étudiée et carte géologique. 1. schistes et gneiss (Precambrien); 2. Couches rouges de Cioclovina (P_1); 3. conglomérats et grès (J_1) 4. grès calcaires (J_2); 5. calcaires à cherts (J_3); 6. calcaires récifaux (K_1); 7. sédiments Quaternaires; 8. grès et marnes (K_2) (d'après Stilla, 1981).

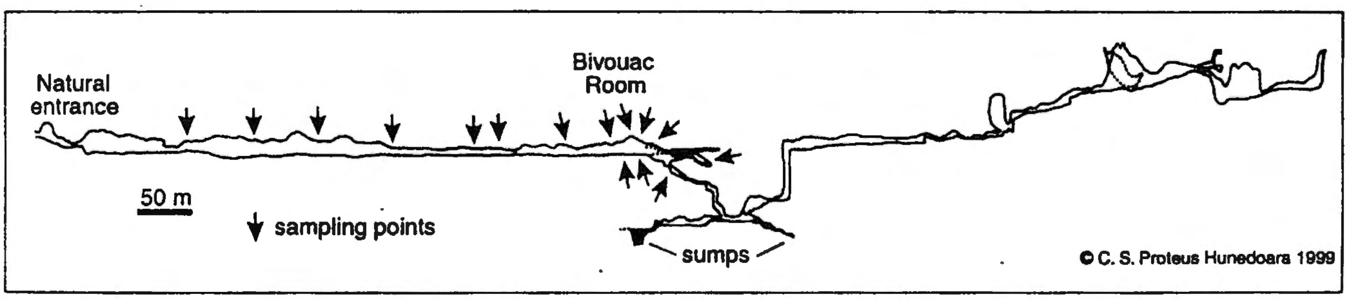


Fig. 2. Cross section through the Cioclovina Cave showing the location of sampling points.

Coupe transversale de la grotte de Cioclovina avec la localisation des points d'échantillonnage.

The bulk chemistry of most of the samples was determined by standard fused-button methods using a Spectro Analytical X-Lab 2000 XRF instrument. The elemental composition of selected samples was obtained using a JEOL JXA-6800 Superprobe operating at 20 kV accelerating voltage and 5 nA beam current.

For SEM observations and EDS spectra analysis, freshly fractured rock fragments, powder splits and crystal aggregates were gold-coated and inspected with a Hitachi 3500N electron microscope.

Results and discussions

Various authors (Schadler, 1929, 1932; Halla, 1931; Constantinescu *et al.*, 1999; Dumitraş & Marincea, 2000) have reported the presence of phosphate minerals such as ardealite, brushite, taranakite, crandallite, tinsleyite, and other non-phosphate cave minerals (e.g., calcite, gypsum, aragonite) in Cioclovina Cave. Therefore, only the more unusual or new cave-type minerals will be discussed here. A more detailed presentation of the formation of phosphate mineral assemblage in Cioclovina Cave, along with cave

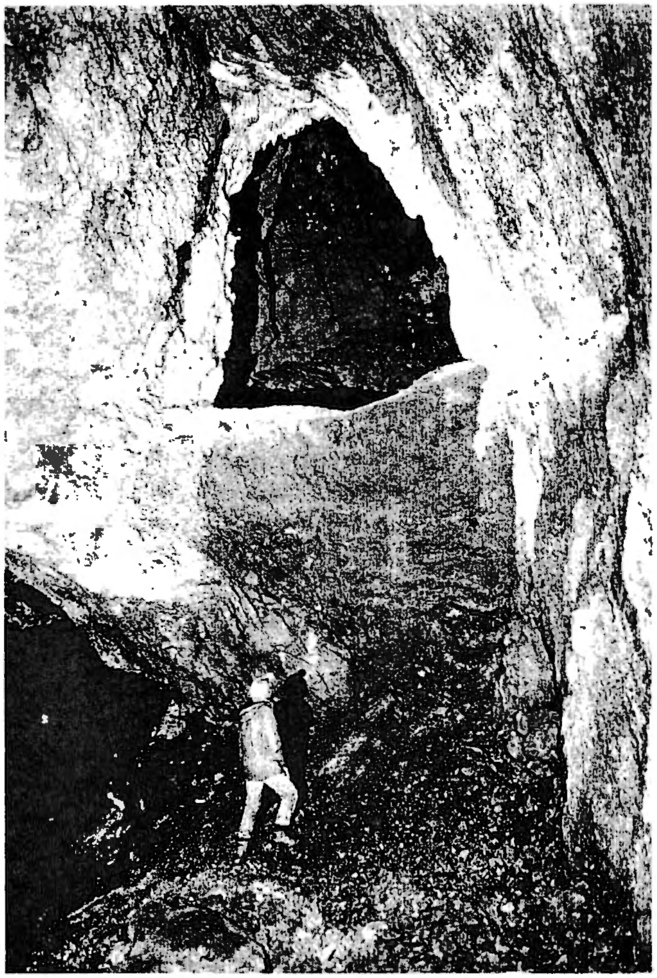


Fig. 3. Photograph showing the phosphate sediment infillings.
Photographie du dépôt de remplissage phosphatique.

environmental significance of this deposit will be the topic of forthcoming papers.

The cave minerals identified in Ciclovina Cave are listed in Table 1 and were assigned to six chemical classes. Although the title of this paper suggests only those minerals related to the phosphate deposits are examined, we also included a short presentation of the rare carbonates and two manganese oxides.

Carbonates

Ciclovina Cave contains a variety of speleothem types and subtypes (see Hill & Forti, 1997 for details) composed of calcite: soda straw, stalactites, stalagmites, columns, rimstone dams, flowstone, calcite rafts and corraloids. The dry conditions in some parts of the cave allow fast CO_2 evaporation allowing aragonite to precipitate from supersaturated solutions.

Burbankite, $(Ca,Na)_3(Sr,Ba,Ce)_3(CO_3)_5$ is a rare anhydrous carbonate that was identified by means of XRD and energy dispersive spectrometry (EDS) in a lacustrine-like sediment sequence near the Bivouac Room. It appears as a thin crust composed of sub-millimeter yellow grayish anhedral crystals. Burbankite was found in association with colorless or milky white needle-like brushite and gypsum crystals. The origin of burbankite is considered to be as follows: sodium is initially leached from the surrounding silicates, then transported into the cave by the underground stream. The alkali becomes balanced in solution by OH^- ions through hydrolysis and after reacting with carbon dioxide yields alkali carbonates solutions that precipitated burbankite under dry and poor or no drainage conditions.

Oxydes and hydroxides

Both **romanechite, $(Ba,H_2O)(Mn^{4+},Mn^{3+})_5O_{10}$** and **todorokite, $(Mn^{2+},Ca,Mg)Mn_3^{4+}O_7{\cdot}H_2O$**, have been found as millimeter-thick black coatings on cave walls and on, or between clasts in the fossil alluvial sequence in different parts of the cave. Identification relies on infrared spectroscopy (IR) and chemical analysis. The manganese in romanechite is not completely oxidized, as a result both Mn^{4+} and Mn^{3+} occur in the mineral structure. This admixture of romanechite and todorokite formed when reduced manganese (Mn^{2+}) travels in seeping water until an oxidizing environment (produced by guano) is encountered (White, 1997).

Halides

The only representative of this class is the **paratacamite, $Cu_2(OH)_3Cl$**. Presently, only its orthorhombic polymorph (atacamite) was identified in caves from Australia and South Africa (Hill & Forti, 1997). Paratacamite appears to be the thermodynamically stable phase at ambient temperature (Sharkey & Lewin, 1971; Pollard *et al.*, 1989). Although it has been reported as the end product of various oxidation and hydrolysis processes in oxidized zones of base metal ores in arid climates, it is certainly not confined only to such environments.

Paratacamite was found near the Bivouac Room as finely crystalline greenish nodules growing on and within brushite-rich sediments. In addition, it has been identified admixed with pale-blue sampleite on the surface of gypsum flowers. The XRD patterns of paratacamite are sharp (the strongest diffraction lines are 5.461Å (100), 2.752Å (55), and 2.266Å (45)) and in good agreement with the data recorded in ICDD file 25-1427 of paratacamite. The EDS spectrum obtained on different rhombohedral crystals of paratacamite is equally sharp, Cl and both $K\alpha_1$ and $L\beta_{3,4}$ lines of Cu being present. The mean analytical results (and ranges) for the electron-microprobe analyses of paratacamite nodules are: CuO 74.85% (73.5–76.1), Cl 16.15% (15.4–16.9), $(H_2O)_{calc}$ 13.6%, sum 104.6%, less O ≡ Cl 3.7, total 100.9 wt.%.

The deposition of paratacamite is attributed to the chemical reaction between chlorine and copper. The chlorine probably derived from both bat guano and percolating meteoric waters. The copper was supplied by the rocks above, which contain disseminated sulfides.

Table 1. Minerals identified in Cioclovina Cave – all minerals in bold are first time mentioned in this cave, whereas those in bold & italic were never documented from a cave environment worldwide (chemical formula according to MANDARINO, 1999).

Minéraux identifiés dans la grotte de Cioclovina — tous les minéraux dont le nome est écrit en caractères gras sont mentionnés pour la première fois dans cette grotte; ceux dont le nom est écrit en caractères gras et cursifs n'ont jamais été mentionnés nulle part au monde dans le milieu souterrain (formules chimiques d'après MANDARINO, 1999).

Chemical class	Minerals	Chemical Formula
Carbonates	Calcite	$CaCO_3$
	Aragonite	$CaCO_3$
	Burbankite ✓	$(Na,Ca)_3(Sr,Ba,Ce)_3(CO_3)_5$
Sulfates	Gypsum	$CaSO_4 2H_2O$
Silicates	Illite	$K_{0.65}Al_2[]Al_{0.65}Si_{3.35}O_{10}(OH)_2$
	Kaolinite	$Al_2Si_2O_5(OH)_4$
	Quartz	SiO_2
Oxides and hydroxides	Goethite	α-$Fe^{3+}O(OH)$
	Romanechite	$(Ba,H_2O)_2(Mn^{4+},Mn^{3+})_5O_{10}$
	Todorokite	$(Mn_2,Ca,Mg)Mn_3^{4+}O_7H_2O$
Halides	***Paratacamite***	$Cu_2(OH)_3Cl$
Phosphates	Ardealite	$Ca_2(SO_4)(HPO_4)4H_2O$ ✓
	Berlinite	$AlPO_4$ ✓
	Brushite	$CaHPO_4 2H_2O$ ✓
	Carbonate-hydroxylapatite	$Ca_5(PO_4,CO_3)_3(OH)$ ✓
	Chlorellestadite ✓	$Ca_5(SiO_4,PO_4,SO_4)_3(Cl,F)$
	Churchite ✓	$YPO_4 2H_2O$ ✓
	Collinsite	$Ca_2(Mg,Fe^{2+})(PO_4)_2 2H_2O$ ✓
	Crandallite	$CaAl_3(PO_4)_2(OH)_5H_2O$ ✓
	Fluorapatite	$Ca_5(PO_4)_3F$ ✓
	Foggite ✓	$CaAl(PO_4)(OH)_2H_2O$ ✓
	Hydroxylapatite	$Ca_5(PO_4)_3(OH)$ ✓
	Leucophosphite	$KFe_2^{3+}(PO_4)_2(OH)2H_2O$ ✓
	Monetite	$CaHPO_4$ ✓
	Sampleite ✓	$NaCaCu_5^{2+}(PO_4)_4Cl\ 5H_2O$ ✓
	Taranakite	$(K,NH_4)Al_3(PO_4)_3(OH)9H_2O$ ✓
	+Minyulite ✓	$KAl_2(PO_4)_2(OH)\text{-}2H_2O$

Phosphates

Our study identified 15 phosphate minerals, four having never been recorded in the cave environment (Table 1).

Berlinite, $AlPO_4$, is a rare aluminum phosphate that was found as sub-millimeter crystals along cracks in well-cemented clay or impregnating the body of this clay. X-ray diffractometry showed the crystals to be entirely composed of berlinite. The strongest diffraction lines are 3.367Å (100), 4.277Å (20), and 1.83Å (18) being very close to those obtained from Westanå (Sweden) and Katumba (Rwanda) specimens (GALLAGHER & GERARDS, 1963; STRUNZ, 1940). The X-ray diffraction data for the sample are given in Table 2. By using the *UnitCell* Program (HOLLAND & REDFERN, 1997), the lattice parameters of the berlinite were calculated (Table 2); the values compare well to those given on ICDD card no. 10-423 for synthetic berlinite.

To now, berlinite was found or synthesized only under hydrothermal conditions at temperatures exceeding 186 °C (MURAOKA & KIHARA, 1997; WISE & LOH, 1976). Below this temperature, *variscite* ($AlPO_4 \cdot 2H_2O$) is the thermodynamically stable mineral form. Therefore we believe variscite underwent a dehydration process due to relatively high temperature conditions caused by *in-situ* guano combustion that allowed its transformation into berlinite. The stability of the newly formed mineral under cave conditions needs further investigations to be fully understood.

The XRD of pale pinkish crusts deposited just below the limestone chunks that are buried in heavily compacted and transformed alluvial sediments near the Bivouac Room were revealed to be composed of ***chlorellestadite***, $Ca_5(SiO_4,PO_4,SO_4)_3(Cl,F)$. This unusual mineral is isostructural with the minerals of the apatite group (ROUSE & DUNN, 1982). It may have formed due to partial replacement of phosphate by silicate and sulfate according to

Table 2. Indexed powder pattern of berlinite and its unit cell parameters.

Indexation des raies de diffraction X du berlinite et les paramètres réticulaires.

d (Å)	I	hkl
4.277	20	100
3.989	4	101
3.619	2	003
3.367	100	102
2.471	7	110
2.303	7	104
2.255	8	112
2.140	13	200
1.991	5	202
1.830	18	114
1.682	5	204
1.666	1	210
1.615	2	106
1.551	10	212
1.461	2	116
1.425	1	300
1.391	5	214
1.381	7	302
1.294	3	215
1.262	2	304
1.234	4	220
1.205	2	222
$a = 4.94(4)$Å, $c = 10.87(1)$Å, $V = 230.1(2)$ Å^3		

the *ellestadite* scheme (McConnell, 1937; 1938) with the compensation of valence ($2PO_4^{3-}$ - SiO_4^{4-} + SO_4^{2-}) or during bat guano combustion when brushite, gypsum and silica might have been locally melted. Members of the ellestadite group were described elsewhere in the world and also derived from fire or thermal treatment of industrial waste (Sejkora *et al.*, 1999; Neubauer & Pöllmann, 1995). Discriminating between the two alternative genetic processes was, however, not possible at this stage of our investigations.

Collected from several locations around the Bivouac Room were aggregates and nodules composed of transparent needle-like crystals of brushite. Among these nodules matted white veins were observed. XRD revealed the material to be composed of **churchite, $YPO_4 \cdot 2H_2O$**, a rare-earth phosphate that contains minor amounts of La, Ce or Er. Churchite crystals under SEM appear lath-like or flattened on (010) (Fig. 4). As with the other phosphates, churchite derives its phosphorus from the abundant guano deposits whereas yttrium was probably leached from weathered schists.

Cioclovina Cave represents the third location ever to host **collinsite, $Ca_2(Mg,Fe^{2+})(PO_4)_2 \cdot 2H_2O$**. This rare cave mineral formed within a 4 to 5 cm polychrome, thick-sandwiched hydroxylapatite crust. Collinsite appears along the boundaries between different colored lamina, exfoliating as millimeter thin-walled balloons lining dissolution cavities. The mineral, identified by means of XRD, shows diffraction lines similar to those reported by Onac *et al.* (2001). Collinsite is believed to have precipitated from bat guano in damp, near-neutral pH environment.

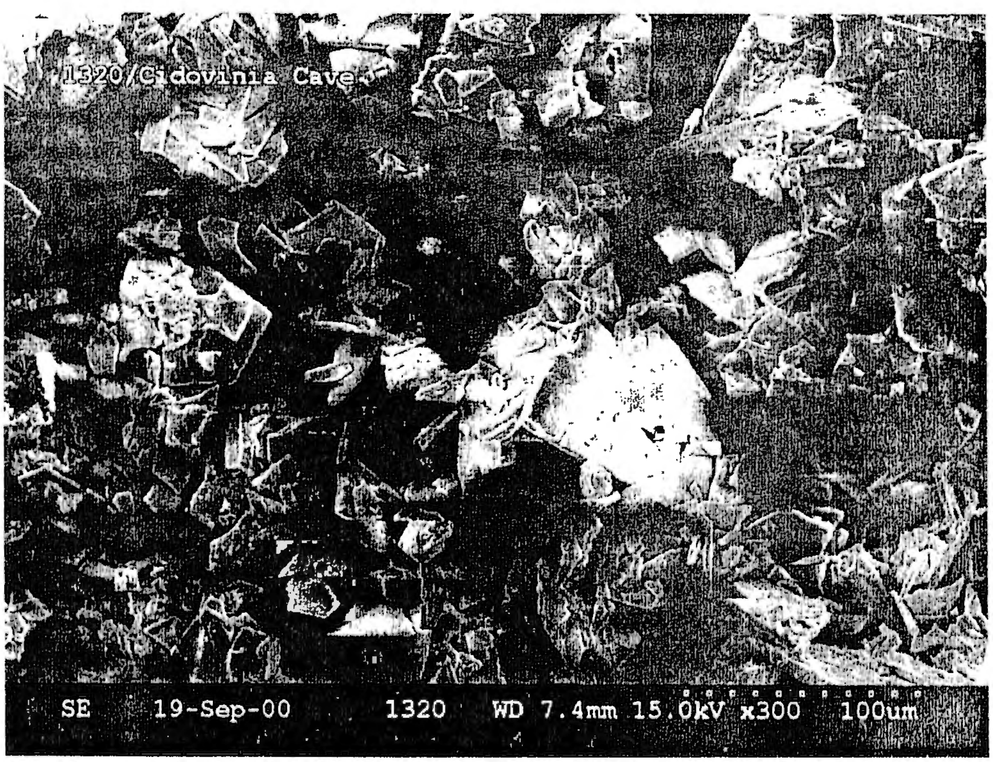


Fig. 4. SEM image of churchite crystals.

Image MEB des cristaux de churchite.

Fluorapatite, $Ca_5(PO_4)_3$, was identified by means of XRD and XRF in 3–5 mm thick multi-layered crusts in a narrow passage beyond the Bivouac Room. These crusts appear as patches varying in color from yellow-green to orange, to brown, and black. Under petrographic microscope, fluorapatite appears as colorless agate-like structure, being uniaxe (–). Depending on the degree of saturation of the seeping water and on pH (between 6 and 6.8), fluorapatite seems to represent an intermediate step in the development of hydroxylapatite (Hughes *et al.*, 1989; Hill & Forti, 1997).

Routine X-ray powder diffraction scans on black, earthy-mass aggregates collected from below brown-reddish crandallite-rich clays showed (apart from a few quartz lines) eleven poorly resolved reflections that fit the characteristic lines of **foggite, $CaAl(PO_4)(OH)_2 \cdot H_2O$.** Under SEM, foggite appears as bunched platy aggregates. Unfortunately, the fragility of the sample made it difficult to obtain an undamaged mount and hence charge-free SEM images. Certainly, a qualitative EDS or electron-microprobe analyses would confirm the presence of foggite in this cave. Considering, however, the location of our sample, one can consider foggite as a product of the partial decomposition of crandallite.

Leucophosphite, $KFe^{3+}(PO_4)_2(OH) \cdot 2H_2O$, forms thin pale yellowish-brown crusts no more than 1 mm thick within white taranakite veins (up to 15 mm thick) in a section below the Bivouac Room. This section has top clays intermixed with fine alluvial sediments. Leucophosphite has been identified by means of XRD. Unit-cell parameters based on ten least-square refinement of 31 XRD reflections were found to be a = 9.736±0.0426 Å, b = 9.6464±0.0457 Å, c = 9.7034±0.062 Å, and β = 102.72±0.11°, close to the ones recorded in the ICDD file 9-446. Tinsleyite, $KAl_2(PO_4)_2(OH)_4 \cdot 3H_2O$, the isostructural aluminum variety of leucophosphite, has been previously documented from another location in this cave by Marincea *et al.* (2002).

Monetite, $CaHPO_4$, was found in several locations throughout the cave along the artificial trail that cut the phosphate deposit. It occurs as white to white-yellowish friable material directly overlying the upper part of the limestone chunks that are buried in the phosphatic soil. All diffraction patterns exactly matched the standard monetite lines from ICDD file 9-80 and 9-80a. Cell dimensions were refined from the corrected d values using the *UnitCell* Program. The cell parameters are: a = 6.9047±0.006 Å, b = 8.576±0.008 Å, c = 6.6491±0.006 Å, α = 93.977±0.087°, β = 91.559±0.074°, and γ = 127.703±0.066°. Monetite is a dry and low pH environment indicator. Dehydration of brushite represents the most common pathway that leads to monetite.

Sampleite, $NaCaCu_5^{+2}(PO_4)_4Cl \cdot 5H_2O$, as mentioned above, was identified along with paratacamite growing on gypsum flowers within or on the upper part of brushite-rich sediments. The mineral is translucent and has a pale blue color and silky luster. It was studied by XRD. So far, no other investigation methods were applied to this mineral. Genetically, sampleite was deposited from the same solutions that precipitate paratacamite.

Conclusions

The diverse and interesting mineralogy of Cioclovina Cave is due to an unusual set of circumstances. First of all, it hosted an enormous amount of phosphate sediment as well as thousands of *Ursus spelaeus* (cave bear) remains within it. Combustion of guano has caused local transformations that may be responsible for the presence of at least two minerals formed herein. Nevertheless, unlike most limestone caves, Cioclovina is located adjacent to metamorphic and siliceous rock terrains. The sinking streams coming from these terrains carried significant quantities of allochtonous sediments that filled the cave passages during periodic flooding. The presence of various sulfides and other trace elements (Cu, Ce, Y) within the sediments and limestone bedrock contribute to an even more diverse mineralogy. Phosphate-rich solutions imbued the sediment column under various pH conditions causing clay, compact alluvial sediments, and limestone to be phosphatized to various degrees. This is how, many of the twenty-six minerals listed in Table 1, were precipitated solely in this highly peculiar phosphate environment of Cioclovina Cave.

Acknowledgments

We thank Dr. Jacques Martini for useful discussions on various aspects of the paper. We also acknowledge the support of the European Community *Access to Research Infrastructure* action of the *Improving Human Potential* Programme, contract HPRI-CT-1999-00008 awarded to Prof. B. J. Wood (EU Geochemical Facility, University of Bristol) that enabled us to perform the XRF and part of the XRD and electron microprobe analysis.

References

Balintoni, I. & Bucur, I. I. (2001) Short outlook on the structure of the South Carpathians. In: *Field trip guide, 4th Regional Meeting of IFAA* (Bucur, I. I., Filipescu, S., & Sasaran, E., *Eds.*), Presa Universitară Clujeană, Cluj, pp. 53–61.

Constantinescu, E., Marincea, S., & Crăciun, C. (1999) Crandallite in the phosphate association from Cioclovina cave, (Şureanu Mts., Romania). In: *Mineralogy in the system of the earth sciences* (Anastasiu, N. & Ilinca, G., *Eds.*), Imperial College Press, London, pp. 1–5.

Dumitraş, D. & Marincea, S. (2000) Phosphates in the bat guano deposit from the "Dry" Cioclovina Cave, Şureanu Mountains, Romania. *Rom. J. Mineral. Dep.*, **79**, *1*, pp. 43–45.

Gallagher, M. J. & Gerards, J. F. (1963) Berlinite from Rwanda. *Mineralogical Magazine*, **33**, pp. 613–615.

Goran, C. (1982) *Catalogul sistematic al peşterilor din România.* FRTA, CCSS, Bucureşti, 496 p.

Halla, F. (1931) Isomorphe Beziehungen und Doppelsalzbildung zwischen Gips und Brushit. *Z. Krist.*, **80**, pp. 349–352.

Hill, C. A. & Forti, P., *Eds.* (1997) *Cave minerals of the world* (2nd ed.), NSS, Huntsville, Alabama, 463 p.

HOLLAND, T. J. B. & REDFERN, S. A. T. (1997) Unit cell refinement from powder diffraction data: the use of regression diagnostics. *Mineral. Mag.*, **61**, pp. 65–77.

HUGHES, J.M., CAMERON, M., & CROWLEY, K. D. (1989) Structural variations in natural F, OH, and Cl apatites. *The American Mineralogist*, **74**, pp. 870–876.

MANDARINO, J. A. (1999) *Fleischer's Glossary of Mineral Species 1999*. The Mineralogical Record Inc., Tucson, Arizona, 225 p.

MARINCEA, S., DUMITRAS, D., & GIBERT, R. (2002) Tinsleyite in the "dry" Cioclovina Cave (Sureanu Mountains, Romania): the second occurrence. *Eur. J. Mineral.*, **14**, *1*, pp. 157–164.

MCCONNELL, D. (1937) The substitution of SiO_4- and SO_4-groups for PO_4-groups in the structure of apatite, ellestadite, the endmember. *The American Mineralogist*, **22**, pp. 997–986.

MCCONNELL, D. (1938) A structural investigation of the isomorphism of the apatite group. *The American Mineralogist*, **23**, pp. 1–19.

MURAOKA, Y. & KIHARA, K. (1997) The temperature dependence of the crystal structure of berlinite, a quartz-type form of $AlPO_4$. *Phys. Chem. Minerals*, **24**, pp. 243–253.

ONAC, B. P., MYLROIE, J. E., & WHITE, W. B. (2001) Mineralogy of cave deposits on San Salvador Island, Bahamas. *Carbonates and Evaporites*, **16**, *1*, pp. 8–16.

POLLARD, A. M., THOMAS, R. G., & WILLIAMS, P. A. (1989) Synthesis and stabilities of the basic copper(II) chlorides atacamite, paratacamite and botallackite. *Mineralogical Magazine*, **53**, pp. 557–563.

ROUSE, R. C. & DUNN, P. J. (1982) A contribution to the crystal chemistry of ellestadite and the silicate sulfate apatites. *The American Mineralogist*, **67**, pp. 90–96.

SCHADLER, J. (1929) Mineralogische-petrographische carakteristik der Phosphat ablagerung in der Cioclovina-Höhle bei Pui. *Publicaţiile Muzeului Hunedoara*, **5**.

SCHADLER, J. (1932) Ardealit, ein neues Mineral $CaHPO_4CaSO_4 + 4H_2O$. *Central-bl. Miner.* Abt. A., pp. 40–41.

SEJKORA, J., HOUZAR, S., & SREIN, V. (1999) Chlorine-rich hydroxylapatite from Zastavky near Brno. *Acta Musei Moraviae*, **84**, pp. 49–59.

SHARKEY, J. B. & LEWIN, S. Z. (1971) Conditions governing the formation of atacamite and paratacamite. *The American Mineralogist*, **56**, pp. 179–92.

STILLĂ, A. (1981) Géologie de la région de Haţeg-Cioclovina-Pui-Băniţa (Carpates Meridionales). *An. Inst. Geol. Geofiz.*, **66**, pp. 91–179.

STRUNZ, H. (1941) Isotypie von Berlinit mit Quartz. *Z. Kristallogr.*, **103**, pp. 228–229.

WHITE, W. B. (1997) Thermodynamic equilibrium, kinetics, activation barriers, and reaction mechanisms for chemical reactions in karst terrains. *Environmental Geology*, **30**, *1/2*, pp. 46–58.

WISE, W. S. & LOH, S. E. (1976) Equilibria and origin of minerals in the system Al_2O_3-$AlPO_4$-H_2O. *The American Mineralogist*, **61**, pp. 409–413.

received: 23 January 2002
revised: 30 July 2002
accepted: 30 July 2002

Theoretical and Applied Karstology, 15 (2002), pp. 35–41

X-ray powder data on some mineral species from Peştera Curată de la Nandru (Haţeg Basin, Romania)

Delia G. Dumitraş[1]*, Ştefan Marincea[1], Gabriel Diaconu[2], Ciprian Constantina[3], & Romeo Pavel[4]

[1]*Dept. of Mineralogy, Geological Institute of Romania, str. Caransebeş 1, 78344, Bucharest, Romania.*
[2]*"Emil Racoviţă" Institute of Speleology, str. Frumoasă 11, 78114 Bucharest, Romania*
[3]*Institute of Gemology, "Babeş-Bolyai" University, str. Avram Iancu 11, 3400, Cluj-Napoca, Romania.*
[4]*Museum of the Dacian and Roman Civilization, str. 1 Decembrie 39, Deva, 2700, Romania.*

Abstract

In the current contribution, we briefly characterize the main mineral species from the fossil bat-guano deposit in Peştera Curată de la Nandru cave, based on extensive X-ray powder diffraction study. The layered guano deposit inside the cave was well opened by recent archaeological works. Hydroxylapatite and brushite are the most common constituents; associated minerals are quartz, dolomite, calcite and clay minerals (illite and kaolinite). The mean cell parameters of hydroxylapatite, taken as weighed average of nine sets of values obtained by least-squares refinement of X-ray powder data, are a = 9.429(6) Å, c = 6.862(16) Å and V = 528.9(6) Å^3. These values account for the stoichiometry, as well, as in the case of brushite [a = 5.808(7) Å, b = 15.183(1) Å, c = 6.241(8) Å, β = 116.38(6) Å^3 for a representative sample]. Calcite [a = 4.980(2) Å, c = 17.033(7) Å, V = 365.8(1) Å^3] and dolomite [a = 4.807(9) Å, c = 16.062(6) Å, V = 321.4(1) Å^3] occur on diagenetic cracks that affect the deposit. Low (alpha) quartz with a = 4.920(3) Å, c = 5.406(4) Å and V = 113.3(1) Å^3, probably allogenic, and minor kaolinite and illite are admixed with the phosphates from the guano groundmass.

Key words: cave minerals, bat guano, X-ray powder data, hydroxylapatite, brushite, calcite, dolomite, quartz, Peştera Curată de la Nandru.

Données obtenues par diffration de rayons X en poudres sur quelques espèces minérales de la grotte «Peştera Curată de la Nandru» (Bassin de Haţeg, Roumanie)

Résumé

Dans cette étude, nous proposons d'offrir une caractérisation sommaire des principales espèces minérales trouvées dans le dépôt fossile de guano de chauve-souris de la grotte dite Peştera Curată de la Nandru, basée sur l'utilisation extensive de la diffraction de rayons X en poudres. Le dépôt de guano intercalé en couches dans les sédiments de cette grotte est rendu accessible par des travaux archéologiques récents. Les composantes les plus communes sont l'hydroxylapatite et la brushite; les minéraux associés sont le quartz, la dolomite, la calcite et des minéraux argileux (illite et kaolinite). Les paramètres réticulaires de l'hydroxylapatite, calculés sur 9 sets de données affinées extraites des diffractogrammes de rayons X en poudres, sont a = *9,429(6) Å,* c = *6,862(16) Å et* V = *528,9(6) Å^3. Ces valeurs indiquent la stoechiométrie du minéral aussi, comme dans le cas de la brushite* [a = *5,808(7) Å,* b = *15,183(1) Å,* c = *6,241(8) Å,* β = *116,38(6) Å^3 pour un échantillon représentatif*]. *La calcite* [a = *4,980(2) Å,* c = *17,033(7) Å,* V = *365,8(1) Å^3*] *et la dolomite* [a = *4,807(9) Å,* c = *16,062(6) Å,* V = *321,4(1) Å^3*] *ont été identifiées sur des fissures diagenétiques affectant le dépôt. Du quartz alpha avec* a = *4,920(3) Å,* c = *5,406(4) Å et* V = *113,3(1) Å^3, probablement allogénique, de l'illite et de la kaolinite sont mélangés avec les phosphates dans la masse de guano.*

Mots-clés: *minéraux de grottes, guano de chauve-souris, données de diffraction de rayons X en poudres, hydroxylapatite, brushite, calcite, dolomite, quartz, Peştera Curată de la Nandru.*

* corresponding author. *E-mail address*: delia@igr.ro

Introduction

Peştera Curată de la Nandru (= the Clean Cave from Nandru) (further on named the Nandru Cave for simplicity), has a certain notoriety because of the archaeological works that were carried out inside. Two levels of habitation, of Mousterian age, were described (CÂRCIUMARU, 1980). No mineralogical investigations of the cave were carried out so far.

The opportunity offered by the archaeological works and the accessibility of new material prompted us to initiate a brief mineralogical investigation of the fossil bat guano deposit from this cave. X-ray powder diffraction was used as principal analytical tool because of the frequent presence of admixtures and of the very fine-grained nature of the crystals.

Geological setting

Geographically, the cave is located in the Peştiş Valley, in the east-northeastern part of the village Peştişu Mic, about 6 km north from Hunedoara, the major town in the area. Geologically, the cave is located in a calcareous ridge built of Lower Carboniferous limestones of the Haţeg Basin (MUREŞAN *et al.*, 1980) (Fig. 1). The cave is very small, being composed of a principal chamber *c.* 9 m-long, continued by a short passage 6 m in length. A simplified sketch of the cave is given in Figure 2. Abundant alluvial deposits, consisting of silteous "*terra rosa*" with important clay participation may be observed on the floor of the cave.

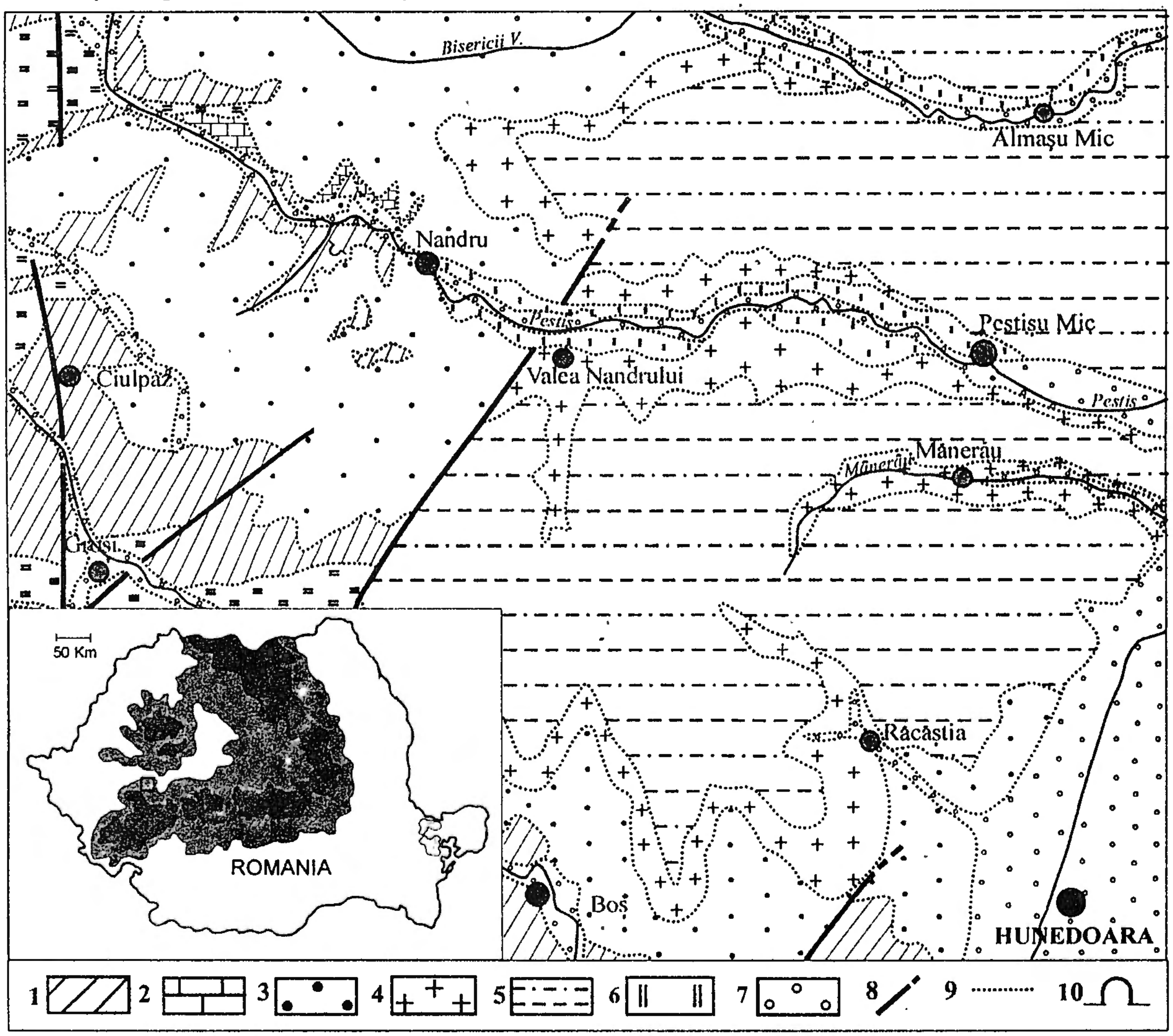


Fig. 1. Simplified geological map showing the location of the Nandru Cave (redrawn from MUREŞAN *et al.*, 1980). Key: 1. Lower Carboniferous (carbonaceous orthoquartzites, limestones, dolostones); 2. Cenomanian (ammonites- and gastropods-bearing calcareous sandstones); 3. Lower Miocene (gravels, sands, calcareous clays); 4. Lower Sarmatian (*Ostrea*-bearing limestones, cincrites); 5. Upper Sarmatian (sands, gravels, sandstones, clays); 6. Holocene deluvial deposits; 7. Holocene alluvia (sands, gravels, sandy clays); 8. fault; 9. geological limit; 10. Peştera Curată de la Nandru. Scale 1:50 000.

Carte géologique simplifiée avec la localisation de la grotte de Nandru (d'après MUREŞAN et al., 1980). Légende: 1. Carbonifère inférieur (orthoquartzites carbonatés, calcaires, dolomites); 2. Cénomanien (calcaires gréseux à ammonites et gastéropodes); 3. Miocène inférieur (graviers, sables, argiles calcaires); 4. Sarmatien inférieur (calcaires à Ostrea, cinérites); 5. Sarmatien supérieur (sables, graviers, grès, argiles); 6. Dépôts déluviaux Holocènes; 7. Dépôts alluviaux Holocènes (sables, graviers, argiles sableux); 8. faille; 9. limite géologique; 10. Peştera Curată de la Nandru. Echelle 1:50.000.

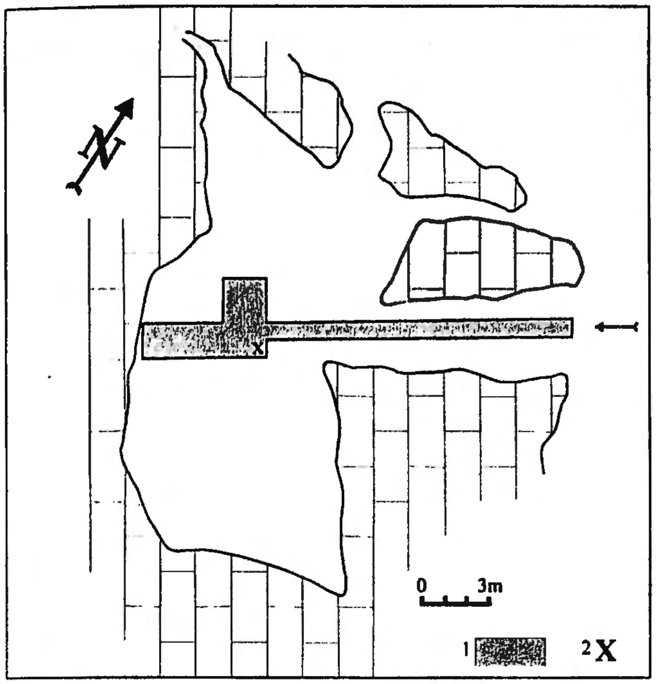


Fig. 2. Sketch of the Nandru Cave (redrawn from CÂRCIUMARU, 1980). Symbols in the legend represent: 1. archaeological works; 2. location of the samples.

Esquisse de la Grote de Nandru (d'après CÂRCIUMARU, 1980). Les symboles représentent: 1. fouilles; 2. point d'échantillonnage.

A pit approximately 3 m-long, 2.5 m-wide and 4 m-deep, dug during the archaeological investigations, is located in the central part of the main chamber. This pit opened a bat-guano layer about 1 m-thick. Textural particularities show that the guano was subject to a weak diagenesis; the deposit is granular and only slightly indurate. Our preliminary investigations showed, however, that the ammonium-bearing mineral species, characteristic for this kind of deposits, are lacking.

Some of the samples used for this investigation were collected from the dumps and walls of the archaeological works and particularly from the pit dump located at the center of the main chamber.

The phosphate-rich zones consist of 90–95 % hydroxylapatite + brushite, with minor amounts of quartz, dolomite, calcite and clay minerals (illite and kaolinite).

Analytical methods

X-ray powder diffraction (XRD) analysis was conducted using a Siemens D-5000 Kristalloflex automated diffractometer equipped with a graphite monochromator (Cu $K\alpha$ radiation, λ = 1.54056 Å). The apparatus was operated at a voltage of 40 kV, with a beam current of 30 mA. The data were collected from 5° to 90° 2θ, at 0.02° per second. Records were made with slit widths of 0.1°, 0.1°, 1 mm and 0.6 mm (for divergence, scatter, antidiffraction and receiving slits respectively). Synthetic fluorite (a = 5.4626 Å at 20° C) was used as an internal standard, and intensities were measured at peak maxima. Background was subtracted from raw intensity data interactively, using the computer program "Diffrac AT" in all the cases. The cell parameters were refined with the CELREF program (APPLEMAN & EVANS, 1973), as revised for microcomputer use by BENOIT (1987).

Freshly exposed surfaces of many aggregates were observed using a JEOL J.S.M.-840 scanning electron microscope set at 15 kV acceleration voltage and 10 nA beam current. Scanning electron microscopy - energy dispersion spectroscopy (SEM-EDS) analyses were performed using the same apparatus, equipped with a Tracor Northern TN-2000 system. Prior to the analysis, the samples were twice covered with gold.

Fluorescence tests were performed using a portable Vetter ultraviolet lamp, with 254 and 366 nm filters.

Description of the main mineral species

Hydroxylapatite

The color of the mineral varies from beige cream to light green, depending on the frequency of fluid and mineral inclusions (iron-bearing, as shown by SEM-EDS) and on the nature of the allocromatic pigment. In all cases, the mineral is transparent to translucent. The luster varies from vitreous (for bunches of crystals) to earthy (for masses) and somewhat pearly. The mineral does not effervesce when etched with HCl; no fluorescence was observed either under short- or long-wave ultraviolet radiation.

The SEM study shows that crystals of hydroxylapatite from Nandru are always disposed as compact radiating masses macroscopically perceived as nodules or small crusts. The individual crystals are usually tabular, with diameters of less than 15 µm and thickness of up to 1 µm (Fig. 3). The crystals are highly fractured, and weathering products (brushite, but also some gel-like, iron-bearing phases) may be observed within the fractures.

In all cases the specimens showed reasonable crystallinity. However, the lower crystallinity of some of the samples produces a broadening of the XRD peaks, and reflections such as (213) and (321) are difficult to resolve.

A problem occurred in the choice of the basic symmetry of the mineral, for a reasonable indexing of the observed diffraction patterns. The structure of hydroxylapatite is based on PO_4, $Ca(1)O_9$ and $Ca(2)O_5OH$ polyhedra, the hydroxyl groups being located in columns parallel to the c^* axis. The hydroxyl groups are too large to fit in the Ca triangles and are consequently displaced along c^* by 0.35 Å from the normal position in

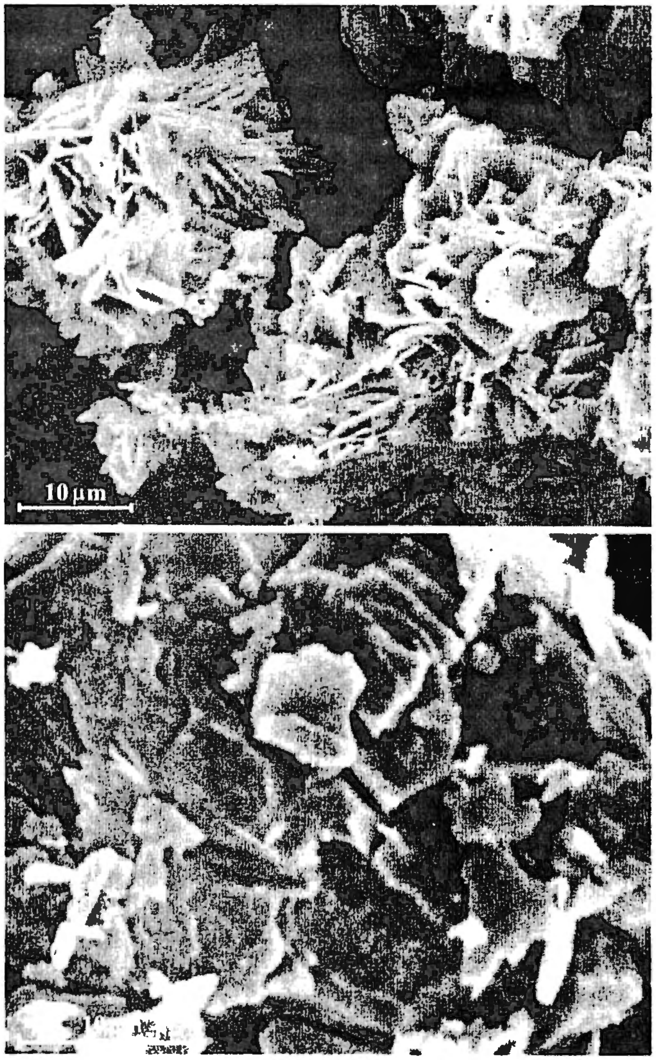


Fig. 3. SEM photomicrographs of typical hydroxylapatite aggregates.
Images MEB des agrégats typiques d'hydroxylapatite.

Table 1. Crystallographic parameters of hydroxylapatite samples from Nandru Cave.
Paramètres crystallographiques des échantillons d'hydroxylapatite de la grotte de Nandru.

Sample	a (Å)	c (Å)	V (Å³)	n[1]	N[2]
N 1 A	9.432(3)	6.863(3)	528.8(3)	3	53
N 1 B	9.426(3)	6.875(2)	529.1(3)	3	42
N 1 C	9.433(1)	6.822(2)	530.1(1)	10	32
N 3 A	9.435(4)	6.861(5)	528.9(5)	3	35
N 5 A	9.435(2)	6.866(2)	529.3(2)	4	56
N 6 A	9.430(3)	6.862(3)	528.5(3)	3	40
N 6 B	9.413(2)	6.879(2)	527.9(2)	8	36
N 6 C	9.428(1)	6.870(1)	528.8(1)	7	36
N 6 E	9.428(3)	6.868(5)	528.7(4)	3	25

1 = number of refinement cycles.
2 = number of reflections used for refinement (2θ = 10 - 85°).

fluorapatite (Kay *et al.*, 1964, Brunet *et al.*, 1999). This results in a monoclinic superstructure mentioned by Elliot *et al.* (1973) and in the lowering of the symmetry from hexagonal ($P6_3/m$) to monoclinic ($P2_1/b$). The difference between the unit-cell parameters *a* and *b* is however too small to be easily observed (according to Hughes *et al.*, 1989, *a* is with only 0.002 Å greater than *b*) and the β angle closely approximates 120 °C.

Consequently, within the resolution of the diffraction patterns performed during this study, the diffraction peaks corresponding to a hexagonal unit-cell were taken into consideration. Note that in all the diffractometric records the single peaks remain unsplit and the cell parameters were successfully and reliable refined based on hexagonal cells. In spite of the poor crystallinity of some of the samples, which resulted in reduced intensities of the main reflections and broadening of some others, indexing was always possible. The XRD patterns were indexed in analogy with PDF 86-1201. Sets of 25 to 56 reflections were used to refine the cell dimensions, which are summarized in Table 1. The full set of X-ray powder data is available from the corresponding author upon request.

The mean cell parameters resulted as weighed average of the values in Table 1 are $a = 9.429(6)$ Å, $c = 6.862(16)$ Å and $V = 528.9(6)$ Å³ (standard deviations, calculated as Std = σ_{n-1} are given in brackets). These values are consistent with the data obtained for the synthetic hydroxylapatite by Bigi *et al.* (1996) or Brunet *et al.* (1999): $a = 9.421(2)$ Å, $c = 6.882(2)$ Å and $V = 529.0(4)$ Å³. The differences between the cell parameters in Table 1 may reflect chemical variations [*i.e.*, the (F,Cl)-for-OH substitutions] and, within the limits of the error, are quite normal even for pure (synthetic) hydroxylapatite (e.g., Smith & Lehr, 1966).

Brushite

Brushite occurs as a snow-white powdery coating on hydroxylapatite or as nodular earthy masses (several mm to 0.5 cm in diameter) in the bat guano groundmass, which is composed principally by hydroxylapatite. Brushite from Nandru does not fluoresce under either short-wave (254 nm) or long-wave (366 nm) ultraviolet light.

The SEM study shows that the mineral occurs as irregular lining of some hydroxylapatite bunches of crystals, partial fillings of micro-veins or cracks affecting the hydroxylapatite mass, or, more frequently, as overgrowths of hydroxylapatite aggregates, in which the textural relationships clearly show that brushite postdates hydroxylapatite. The irregular aggregates of brushite are very fine grained. As may be observed in Fig. 4, the individual crystals are platy on (010), and may reach up to 10 μm across, no more than 5 μm wide and 1 μm thick. In habit they closely resemble synthetic brushite illustrated by Rinaudo *et al.* (1994) or Sivakumar *et al.* (1998), but no crystallographic forms may be distinguished.

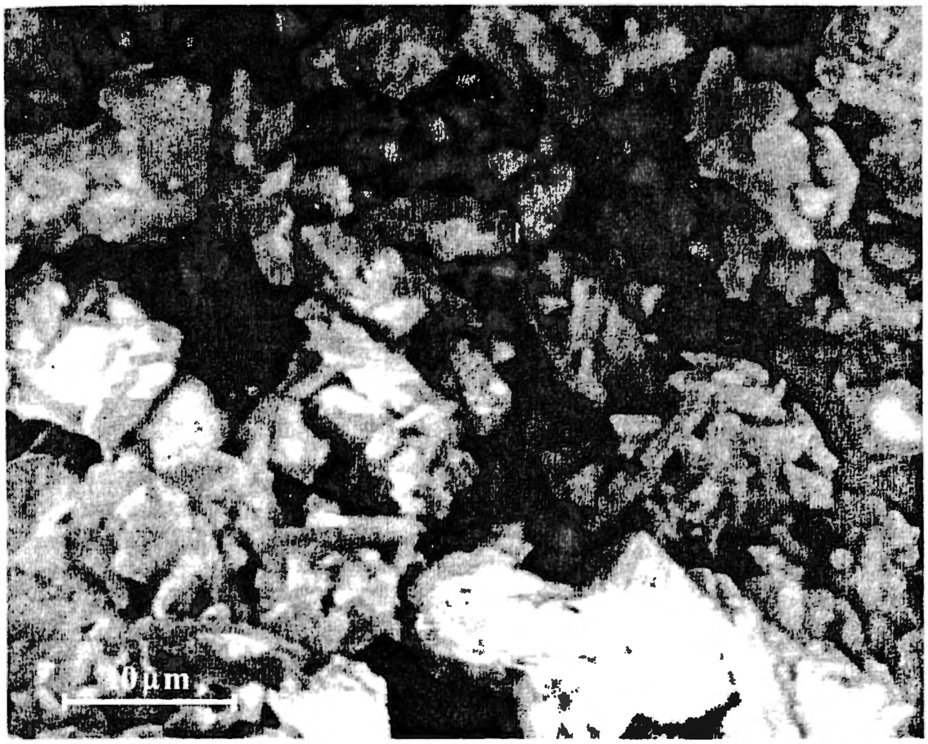


Fig. 4. SEM photomicrograph of a typical brushite aggregate.

Image MEB d'un agrégat typique de brushite.

Calculated and measured X-ray powder diffraction data for this mineral are given in Table 2. The lines were indexed in analogy with PDF 72-0713, which is reproduced for comparison in the table.

The cell parameters of the brushite samples from Nandru are close to those of synthetic brushite (a = 5.812(2) Å, β = 15.180(3) Å, c = 6.239(2) Å, b = 116.43(3) Å^3 according to Beevers, 1958 or Curry & Jones, 1971), indicating that their chemistry is reasonably close to the ideal composition.

Quartz

Quartz was identified in both phosphate- and carbonate-bearing samples from the guano deposit. Because of its small crystal size and dispersed nature, this mineral may be completely camouflaged in the phosphate matrix and therefore difficult to separate. The textural relationships alone failed to offer valuable criteria to discriminate between the authigenic and the allogenic nature of quartz. The lack of any associated Al- and K-bearing phosphate (e.g., taranakite, leucophosphite), prompted us, however, to consider the allogenic nature of this mineral species, because reactions involving clay minerals and H_3PO_4 normally produce authigenic quartz in excess (*see* Marincea *et al.*, 2002).

The X-ray powder patterns of both the handpicked separates and of the residua obtained after the selective dissolution of hydroxylapatite by HCl leaching indicate in all cases the presence of low (alpha) quartz. The cell parameters obtained by least-squares refinement of 25 XRD reflections obtained for a representative sample (N5A) are a=4.920(3) Å, c=5.406(4) Å and V= 113.3(1) Å^3. They are relatively close to those determined by Will *et al.* (1988) for the stoichiometric α-quartz [a = 4.91239(4) Å c = 5.40385(7) Å and V = 112.933 Å^3].

Dolomite

Dolomite was found sporadically in the bat-guano deposit from Nandru. The mineral occurs as massive, white-pinkish deposits on some diagenetic cracks affecting the guano mass. This textural particularity, as well as the availability of Mg^{2+} derived from the Sarmatian cinerites in the area (Mureşan *et al.*, 1980), suggest an authigenic, late diagenetic nature of this carbonate, which was probably deposited by direct precipitation from a Mg-rich "moonmilk". A mechanism of dissolution – recrystallization type may also be taken into consideration.

The cell parameters refined for a representative sample (N4) from 20 XRD reflections in the 2θ range between 10 and 88°, are a = 4.807(9) Å, c = 16.062(6) Å and V = 321.4(1) Å^3. Note that the a cell parameter closely match that found by Reeder (1983) for a nearby stoichiometric dolomite from Lake Arthur, United States [a = 4.8069(2) Å], whereas the value of c is greater than the value obtained by the quoted author for the same sample [c = 16.0034(6) Å], suggesting limited (Mn,Fe)-for-Mg substitutions.

Calcite

Calcite is scarce in the guano deposit from Nandru Cave, being common only in the sediments in vicinity. In the phosphate-bearing samples, the mineral occurs as milky-white, semitransparent, filling of late diagenetic veins. The cell parameters refined for a representative sample (N6) are a=4.980(2) Å, c= 17.033(7) Å and V=365.8(1) Å^3. They do not differ significantly from those

Table 2. X-ray powder diffraction data for selected samples of brushite from Nandru Cave[1].
Données des diffractions de rayons X en poudres pour des échantillons de brushite de la Grotte de Nandru.

Crt.	Sample N2A			Sample N3A			PDF 72-0713			(hkl)
no.	$d_{meas.}$(Å)	$d_{calc.}$(Å)	I/I_0	$d_{meas.}$(Å)	$d_{calc.}$(Å)	I/I_0	$d_{meas.}$(Å)	$d_{calc.}$(Å)[(2)]	I/I_0	
1	7.5631	7.5915	100	7.5249	7.5823	100	7.5900	7.5899	100	(020)
2	4.2301	4.2359	43	4.2192	4.2332	64	4.2371	4.2372	79	(12$\bar{1}$)
3	3.7899	3.7957	7	3.7847	3.7912	9	3.7950	3.7942	5	(040)
4	3.0429	3.0459	42	3.0384	3.0431	57	3.0460	3.0461	54	(14$\bar{1}$)
5	3.0429	3.0408	42	3.0384	3.0375	57	3.0460	3.0404*	54	(11$\bar{2}$)
6	2.9223	2.9257	1	2.9277	2.9234	5	2.9244	2.9240	35	(121)
7	2.8501	2.8517	4	2.8444	2.8517	4	2.8534	2.8533	6	(21$\bar{1}$)
8	2.6678	2.6684	1	—	—	—	2.6675	2.6675	2	(051)
9	2.6209	2.6227	18	2.6185	2.6203	25	2.6215	2.6223	32	(150)
10	2.6209	2.6232	18	2.6185	2.6198	25	2.6215	2.6213	32	(022)
11	2.5997	2.6017	13	2.5953	2.6016	11	2.6022	2.6020	20	(200)
12	2.2659	2.2672	2	—	—	—	2.2670	2.2670	3	(16$\bar{1}$)
13	2.1696	2.1705	7	2.1685	2.1680	12	2.1701	2.1702	12	(15$\bar{2}$)
14	2.1448	2.1460	8	2.1422	2.1451	14	2.1461	2.1460	11	(240)
15	2.0980	2.0985	2	2.0989	2.0974	8	2.0990	2.0990	4	(25$\bar{1}$)
16	2.0822	2.0836	4	—	—	—	2.0822	2.0820	6	(112)
17	2.0192	2.0196	1	2.0151	2.0188	5	2.0191	2.0189	2	(211)
18	1.9728	1.9736	1	1.9788	1.9719*	7	1.9738	1.9739	3	(21$\bar{3}$)
19	1.8979	1.8979	1	1.8950	1.8956	5	1.8975	1.8975	2	(080)
20	1.8755	1.8760	6	1.8750	1.8737	10	1.8752	1.8751	10	(062)
21	1.8565	1.8566	4	1.8545	1.8567	6	1.8575	1.8574	5	(32$\bar{1}$)
22	1.8147	1.8140	11	1.8116	1.8128	20	1.8139	1.8139	12	(260)
23	1.7969	1.7970	4	1.7949	1.7955	9	1.7972	1.7972	6	(26$\bar{2}$)
24	1.7788	1.7789	2	—	—	—	1.7787	1.7787	2	(18$\bar{1}$)
25	1.6154	1.6151	1	1.6161	1.6131	3	1.6146	1.6146	1	(091)
26	1.5632	1.5702	1	1.5680	1.5682	3	1.5696	1.5696	2	(082)
27	1.5520	1.5518	2	1.5514	1.5502	6	1.5516	1.5516	5	(20$\bar{4}$)
28	1.4352	1.4346	1	1.4392	1.4330*	3	1.4336	1.4335	3	(143)
29	1.3914	1.3912	1	—	—	—	1.3921	1.3921	1	(41$\bar{3}$)
30	1.3696	1.3694	2	1.3690	1.3679	7	1.3690	1.3690	3	(1.10.1)
31	1.3696	1.3671	2	1.3628	1.3653	3	1.3664	1.3664	2	(15$\bar{4}$)
32	1.3346	1.3400	1	1.3372	1.3384	3	1.3397	1.3397	2	(0.11.1)
33	1.3346	1.3341	1	1.3305	1.3326	3	1.3339	1.3339	1	(1.11.0)
34	1.3346	1.3341	1	1.3305	1.3326	3	1.3339	1.3337	1	(0.10.2)
35	1.3014	1.3009	1	1.3016	1.3008	2	1.3011	1.3010	2	(400)
36	1.2280	1.2281	1	—	—	—	1.2278	1.2279	1	(1.12.$\bar{1}$)
37	1.2169	1.2167	1	—	—	—	1.2162	1.2161	2	(282)
38	1.1529	1.1531	1	1.1521	1.1524	5	1.1523	1.1526	2	(352)
39	1.1529	1.1527	1	1.1521	1.1513	5	1.1523	1.1523	2	(0.12.2)
40	1.1036	1.1027	1	—	—	—	1.1033	1.1033	1	(54$\bar{3}$)
	a = 5.808(7) Å			a = 5.808(2) Å			a = 5.812(2) Å			
	b = 15.183(1) Å			b = 15.165(4) Å			b = 15.180(4) Å			
	c = 6.241(8) Å			c = 6.233(2) Å			c = 6.239(3) Å			
	β = 116.38(6)°			β = 116.39(2)°			β = 116.44(1)°			

[1] Monochromatized Cu K_α radiation, λ = 1.54056 Å, 2θ = 10–66°. Number of refining cycles: 8; 6; 3.
[2] As calculated by us, using the CELREF program (Appleman & Evans, 1973). Asterisk in $d_{calc.}$ column refers to reflections rejected during the refinement.

determined by Effenberger *et al.* (1981) for the synthetic calcite [$a = 4.9896(2)$ Å and $c = 17.0610(11)$ Å], which accounts for the stoichiometry.

Discussion and conclusions

The (hydroxylapatite + brushite) mineral association is one of the most common in the fossil bat-guano deposits from caves (*see* Hill & Forti, 1997, and referred works). Both minerals were formed by interaction between the bat guano and the phosphate-rich solutions derived from it and the calcareous basement or the "moonmilk" deposits. This suggested origin appears to be supported by the experimental work of Elliot *et al.* (1959) that showed that calcium phosphate precipitates from saturated phosphoric solutions as brushite up to pH 6.93 and as hydroxylapatite at higher pH levels. Variations in the acidity of the guano-derived solutions may be caused by the breakdown of calcium carbonate as a result of its interaction with the phosphoric acid in these solutions. One will note that in the bat-guano deposit from Nandru, hydroxylapatite always overcoats the carbonaceous ground, whereas brushite occurs distally, as crusts on hydroxylapatite. Calcite occurs in direct contact with brushite only in the fillings of the secondary cracks produced by the diagenetic desiccation of the guano deposit.

The persistence of unreacted illite and kaolinite inside the guano deposit shows, however, that the phosphoric solutions were not enough aggressive to decompose the clay minerals with formation of taranakite or leucophosphite + quartz, and places the lower pH limit at about 4.58 (the "pure brushite" limit found by Elliot *et al.*, 1959).

Acknowledgements

This research was partially funded by the Rhône-Alpes region, through a TEMPRA fellowship awarded to S.M. in 1999–2000. XRD patterns were recorded in the SPIN laboratory of École Nationale Supérieure des Mines de Saint-Etienne, whose staff is gently acknowledged. The study was also supported by a grant from the Romanian Ministry of Education and Research (program CERES, contract MEC-C 113/2001).

References

Appleman, D. E. & Evans, H. T., Jr. (1973) Indexing and least-squares refinement of powder diffraction data. *U.S. Geol. Surv., Comput. Contrib.*, **20**, (*NTIS Doc.* PB-216).

Beevers, C. A. (1958) The crystal structure of dicalcium phosphate dihydrate, $CaHPO_4 \cdot 2H_2O$. *Acta Cryst.*, **11**, pp. 273–277.

Benoit, P. H. (1987) Adaptation to microcomputer of the Appleman-Evans program for indexing and least-squares refinement of powder-diffraction data for unit-cell dimensions. *Am. Mineral.*, **72**, pp. 1018–1019.

Bigi, A., Falini, G., Foresti, E., Gazzano, M, Ripamonti, A., & Roveri, N. (1996) Rietveld structure refinements of calcium hydroxylapatite containing magnesium. *Acta Cryst.*, **B 52**, pp.87–92.

Brunet, F., Allan, D.R., Redfern, A.T.S., Angel R.J., Miletich, R., Reichmann, H.J., Sergent, J., & Hanfland, M. (1999) Compressibility and thermal expansivity of synthetic apatites, $Ca_5(PO_4)_3X$ with X = OH, F and Cl. *Eur. J. Mineral.*, **11**, pp. 1023–1035.

Cârciumaru, M. (1980) *Mediul geografic în Pleistocenul superior şi culturile paleolitice din România*. Ed. Academiei R.S.R, 268 p.

Curry, N.A. & Jones, D.W. (1971) Crystal structure of brushite, calcium hydrogen orthophosphate dihydrate: a neutron-diffraction investigation. *J. Chem. Soc., A*, pp. 3725–3729.

Effenberger, H., Mereiter, K., & Zemann, J. (1981) Crystal structure refinements of magnesite, calcite, rhodochrosite, siderite, smithsonite and dolomite, with discussion of some aspects of the stereochemistry of calcite-type carbonates. *Z. Kristallogr.*, **156**, pp. 233–243.

Elliot, J.S., Sharp, R.F., & Lewis, L. (1959) The effect of the molar Ca/P ratio upon the crystallization of brushite and apatite. *J. Phys. Chem.*, **63**, pp. 725–726.

Elliot, J. C., Mackie, P. E., & Young, R. A. (1973) Monoclinic hydroxylapatite. *Science*, **180**, pp. 1055–1057.

Hill, C. & Forti, P. (1997) *Cave minerals of the world. Second Edition*. Natl. Speleological Society, Hunstville, Alabama, 240 p.

Hughes, J. M., Cameron, M., & Crowley, K. D. (1989) Structural variations in natural F, OH and Cl apatites. *Am. Mineral.*, **74**, pp. 870–876.

Kay, M. I., Young, R. A., & Posner, A. S. (1964) Crystal structure of hydroxylapatite. *Nature*, **204**, pp. 1050–1052.

Marincea, Ş., Dumitraş, D., & Gibert, R. (2002) Tinsleyite in the "Dry" Cioclovina Cave (Sureanu Mountains, Romania): The second world occurrence. *Eur. J. Mineral.*, **14**, pp. 157–164.

Mureşan, M., Mureşan, G., Kräutner, H. G., Kräutner, F., Ţicleanu, N., Stancu, J., Popescu, A., & Popescu, G. (1980) Geological map of Romania, 1:50000. Explanatory note. *Hunedoara* sheet. Inst. Geol. Geof, Bucharest.

Reeder, R. J. (1983) Crystal chemistry of the rhombohedral carbonates. *Rev. Mineral.*, **11**, pp. 1–47.

Rinaudo, C., Lanfranco, A.M., & Franchini-Angela, M. (1994): The system $CaHPO_4 \cdot 2H_2O - CaSO_4 \cdot 2H_2O$: crystallizations from calcium phosphate solutions in the presence of SO_4^{2-}. *J. Cryst. Growth*, **142**, pp. 184–192.

Sivakumar, G.R., Girija, E.K., Narayana Kalkura, S., & Subramanian, C. (1998): Crystallization and characterization of calcium phosphates: brushite and monetite. *Cryst. Res. Technol.*, **33**, pp. 197–205.

Smith, J. P. & Lehr, J. R. (1966) An X-ray investigation of carbonate apatites. *J. Agr. Food Chem.*, **14**, pp. 342–349.

Will, G., Bellotto, M., Parish, W., & Hart, M. (1988) Crystal structures of quartz and magnesium germanate by profile analysis of synchrotron-radiation high-resolution powder data. *J. Appl. Cryst.*, **21**, pp. 182–191.

received: 4 April 2002
revised: 10 November 2002
accepted: 19 November 2002

Theoretical and Applied Karstology, 15 (2002), pp. 43-50

Karst of the ridge Dževrinska Greda: fluvial influences, caves, and groundwater circulation

Jelena Ćalić-Ljubojević[1,2]* & Vladimir Ljubojević[2]

[1] Geographic Institute "Jovan Cvijić" of the Serbian Academy of Sciences and Arts, Đure Jakšića 9, 11000 Belgrade, Serbia, Yugoslavia.

[2] Student Speleologic and Alpinistic Club (ASAK), Studentski trg 16, 11000 Belgrade, Serbia, Yugoslavia.

Abstract

Dževrinska Greda is an elongated and narrow ridge of Upper Jurassic limestone, situated next to the Danube Gorge (Iron Gates) in Eastern Serbia. It is uplifted along the conspicuous Dževrin Fault which extends further to the north, to the Mehedinți Plateau in Romania, and it is surrounded by non-carbonate rocks to the East (Cretaceous flysch and para-flysch) and to the West (Proterozoic and Paleozoic schists).
The relationships between non-carbonate and carbonate lithologies made this karst subject to strong influence of allogenic water input. Due to the small width of the ridge (max. 700 m, 250 m in average), fluvial influence is strong enough to penetrate to the opposite boundary of the limestone. Several separate input-output systems of karst groundwater were determined. Exposed limestone surface does not exceed 5 km², but 32 caves which altogether have more than 6500 m of passages were explored so far, indicating a significant karst development. The springs are mostly permanent, although relatively weak (up to 10 l/s), and show little seasonal variations. Three springs have elevated temperatures – from 17 to 19 °C. Characteristics of karst springs are the indication of retention capabilities of the karst aquifer as well as of a circulation of the groundwater at great depths. Deep circulation is mostly developed due to the favourable conditions along the regional dislocation – the Dževrin Fault.

Key words: contact karst, fluviokarst, warm karst springs, Carpatho-Balkanides.

Le karst de la crête Dževrinska Greda: influences fluviatiles, grottes et circulation souterraine

Résumé

Dževrinska Greda est une crête étroite et allongée formée sur les calcaires du Jurassique supérieur dans la Serbie de l'Est près du Danube, dans la zone des Portes de Fer. La crête est soulevée le long de la faille de Dževrin (prolongée vers le nord dans le Plateau de Mehedinți, en Roumanie) en direction N-S et entourée par des roches non-carbonatées à l'est (le flysch et para-flysch du Cretacé) et à l'ouest (des schistes cristallins protérozoïques et paléozoïques).
Le rapport entre les formations carbonatées et non-carbonatées a déterminé une importante influence de l'eau allogène sur ce karst. Comme la largeur de la crête est réduite (700 m au maximum, 250 m en moyenne), l'influence fluviatile est suffisamment importante pour que les rivières pénètrent les calcaires. Quelques systèmes de drainage distincts ont été mis en évidence. Quique la surface d'affleurement des calcaires ne dépasse pas 5 km², 32 grottes avec une longueur cumulée de plus de 6500 m ont été explorées jusqu'à présent, fait qui prouve un développement significatif du karst. La plupart des sources sont permanentes, même si leurs débits sont faibles (<10 l/s) et présentent des variations saisonnières peu importantes. Trois sources ont des températures élevées, entre 17 et 19 °C. Elles se caractérisent par une grande capacité de rétention de l'aquifère et démontrent une circulation profonde de l'eau souterraine. La circulation profonde est due essentiellement aux conditions favorables créées par la dislocation régionale de la faille de Dževrin.

Mots-clés: karst de contact, sources karstiques chaudes, Carpatho-Balkanides.

* corresponding author. *E-mail address*: jcal@sezampro.yu.

Location, Geological Surroundings and Evolution

The limestone ridge Dževrinska Greda is situated in Eastern Serbia and belongs to the Southern Carpathians. Further towards the south, there is the continuation to the westernmost part of Mt. Balkan, so one may also consider that Dževrinska Greda, as well as other mountains and ridges of Eastern Serbia, belongs to the Carpatho-Balkan mountain range.

Dževrinska Greda stretches in a N–S direction, over a length of 20 km, along the regional dislocation of **Dževrin Fault**. With its northernmost point, Dževrinska Greda reaches close to the Danube Gorge (the Iron Gates) and stretches further to the north, towards the Mehedinţi plateau in Romania (Fig. 1). One of the Romanian most famous cave systems, Topolniţa-Epuran, is situated in the portion of limestones which corresponds to those of the ridge Dževrinska Greda.

The ridge is situated within the system of great nappes of the Southern Carpathians. It is formed of limestones of Upper Jurassic age. On the west, Dževrin Fault makes its geological contact with the Proterozoic and Paleozoic schists (gneisses, micaschists, gneiss-micaschists, amphibolites). On the eastern side of the ridge, the limestones continue further to the east, but are covered with Cretaceous flysch-like sediments. The schists belong to the so-called *Getic Nappe* (and one sub-Getic Nappe), while the Cretaceous formations are partly autochtonous (lower beds, age Albian to Senonian), and partly belong to the *Severin Nappe* (Lower Cretaceous). All these geological units are present also on the other side of the Danube, in Romania. One may assume that the overthrust took place after the end of the Cretaceous, and that the faulting is a younger process since the nappes are disturbed by the faults as well (Fig. 2).

On the official geological map (Bogdanović *et al*, 1973), the conspicuous limestone peak of Dževrin is mapped as the northernmost point of the ridge (on the right bank of the Danube). However, recent detailed sedimentological surveys showed that the limestone of the peak Dževrin does not belong to the main ridge of Dževrinska Greda, but represents a separate olistholitic block (Grubić, 1992). This fact does not have direct consequences on the karst studies of Dževrinska Greda, but it is worth mentioning for a correct interpretation of large-scale structural and stratigraphic relations in the area.

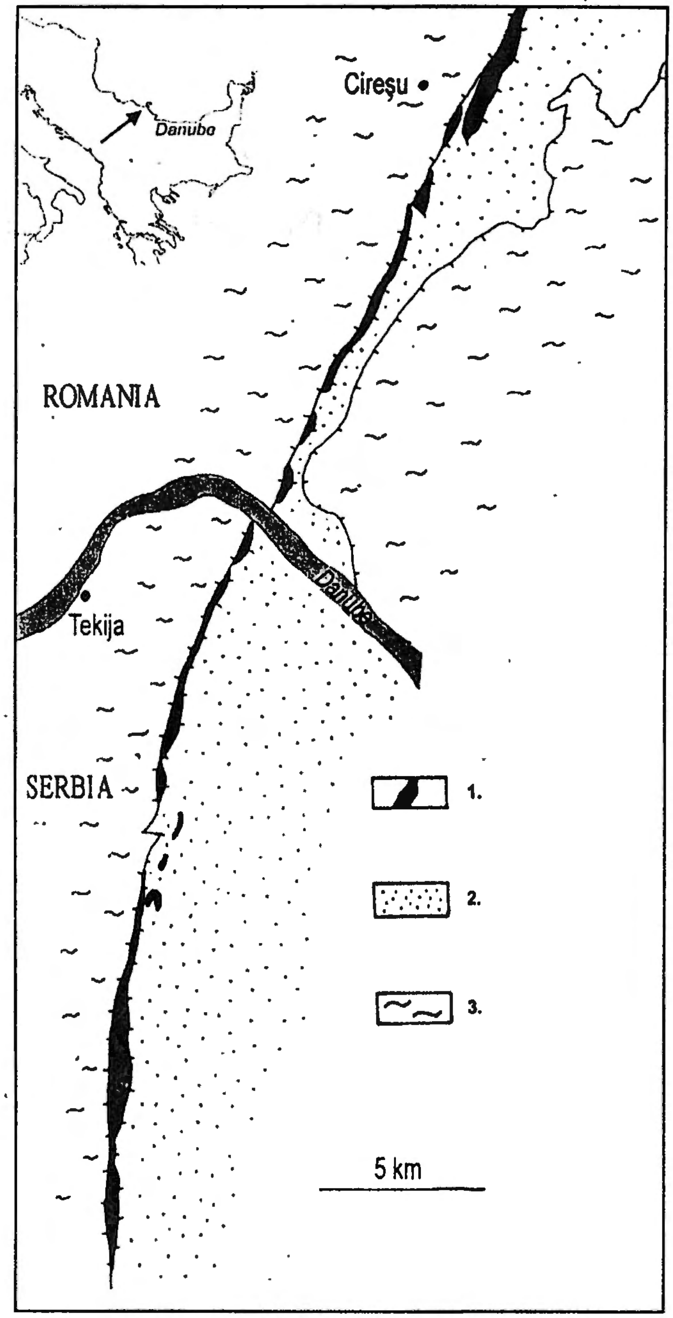


Fig. 1. Simplified geological map of the limestone ridge Dževrinska Greda (south of the Danube, Serbia) and Mehedinţi Plateau (north of the Danube, Romania). According to the national Geological Surveys, adapted. 1: Limestone ridges (Upper Jurassic/ Lower Cretaceous); 2: Cretaceous sediments (Autochtonous and Severin Nappe); 3: Proterozoic and Paleozoic schists (Getic and sub-Getic nappes).
Carte géologique simplifiée de la crête calcaire Dževrinska Greda (sud du Danube, Serbie) et du plateau de Mehedinţi (nord du Danube, Roumanie). D'après les cartes des services géologiques nationaux, adaptées. 1: crêtes calcaires (Jurassique supérieur/ Crétacé inférieur); 2: sédiments crétacés (Autochtone et Nappe de Severin); 3: schistes protérozoïques et paléozoïques (Nappes Gétiques et sous-Gétiques).

Surface Morphology and Karstic-Fluvial Interface

General inclination of the topographic surface is from west to east, and the river courses are mostly oriented in this way. The only exceptions are several weak sinking streams which are using short surfaces where flysch is inclined towards the limestone,

and three short gorges at the southern part of the ridge, which flow to the river system inclined towards the south. Four river systems of W–E orientation traverse the limestone ridge, and only the trunk streams managed to entrench into limestone and form through-gorges (Fig. 3).

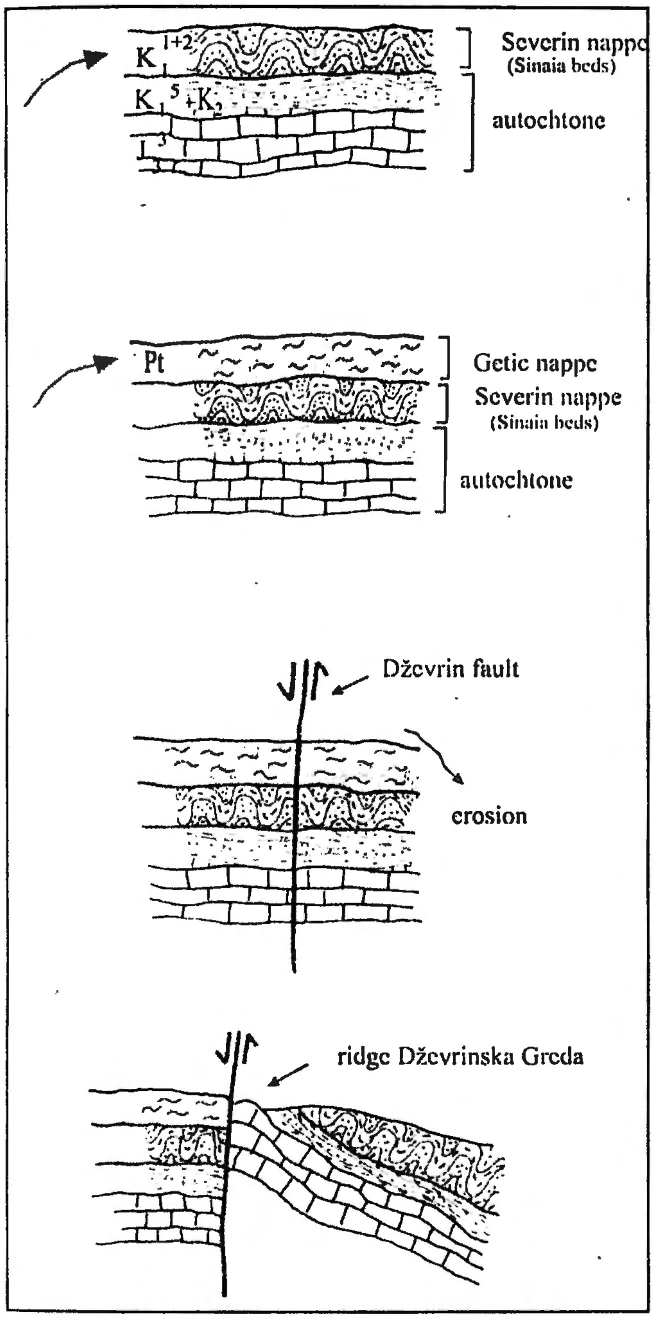


Fig. 2. Sketch of the general geological sequence of napping and faulting in the area of the Danube Gorge, and particularly Dževrinska Greda. View to the north.
Esquisse de l'évolution géologique des charriages et dislocations dans la zone du Défilé du Danube et particulièrement dans celle de Dževrinska Greda. Vue vers le nord.

Regarding the wider regional morphology, there are still disputes about the origin of the vast levelled surface with an average height of 400 m a.s.l., which is dissected by the above-mentioned streams. Is it a remnant of the Dacian Sea (abrasion terrace), or is its origin fluvio-denudational? There was no detailed research on this issue and for now, each option is hard to be completely argued. After the regression of the sea, the tectonic activity was too intense to allow the formation of such a large and flat fluvial levelled surfaces (a series of lower ones extends further to the east). On the other hand, it is as well hard to prove that the possible marine terrace (probably of Pliocene age) could have been preserved until nowadays.

The total surface of exposed limestones of Dževrinska Greda is relatively small – less than 5 km². The width of the ridge vary from several tens of metres to a maximum of 700 m (in the region of Drenjar Hills), with an average of about 250 m. Apart from the main ridge, limestones are also present as outcrops within the autochtonous Cretaceous formation on the east.

The presence of impervious terrains on both sides of the karst ridge gives to this area an attribute of contact karst and/or fluviokarst, with prominent allogenic influence. Two main types of contact are tectonic (on the west) and sedimentary (on the east). 'Reactions' of surface waters when they reach karst are various. The rivers are either 'stronger' than karst – they entrench and form through-gorges; or there is the typical karst case – streams sink and resurge after a certain portion of subterrannean flow (either partially traversable (caves) or not). This depends on several factors: first, tectonic pattern and previous development of karst conduits, which probably made some portions of limestone more 'attractive' to be attacked by surface waters; second, as this is the case of positive feedback effect, greater discharge of a river strengthens it to pass the limestone barrier. Some ofthe gorges may also have been formed by cave roof collapse, but there are no obvious evidences for this. Areas of fluvial influence from western and eastern side are overlapping, or the influence from the western side is so strong that it reaches the opposite boundary of karst.

Dževrinska Greda fits into the model of *stripe karst*, elaborated by Lauritzen (2001). It is a double-sided karst with a large allogenic perimeter relative to the area; more precisely, its length to average width ratio (γ) is 80. Dževrinska Greda has a contact which is by its characteristics closest to stripe karst contact type 1: sub-vertical unconfined; while caves are mostly of morphotype D *i.e.* extensive, linear drainage routes (*see* Figures 6 and 8).

Tectonic conditions

The dominant structural element of the area is Dževrin Fault. It has a complex kinematics (Fig. 4); one component of the movement is vertical (normal), with a sub-vertical fault plane (eastern block uplifted, as seen also in Fig. 2), while another component is of strike-slip character, which makes this fault

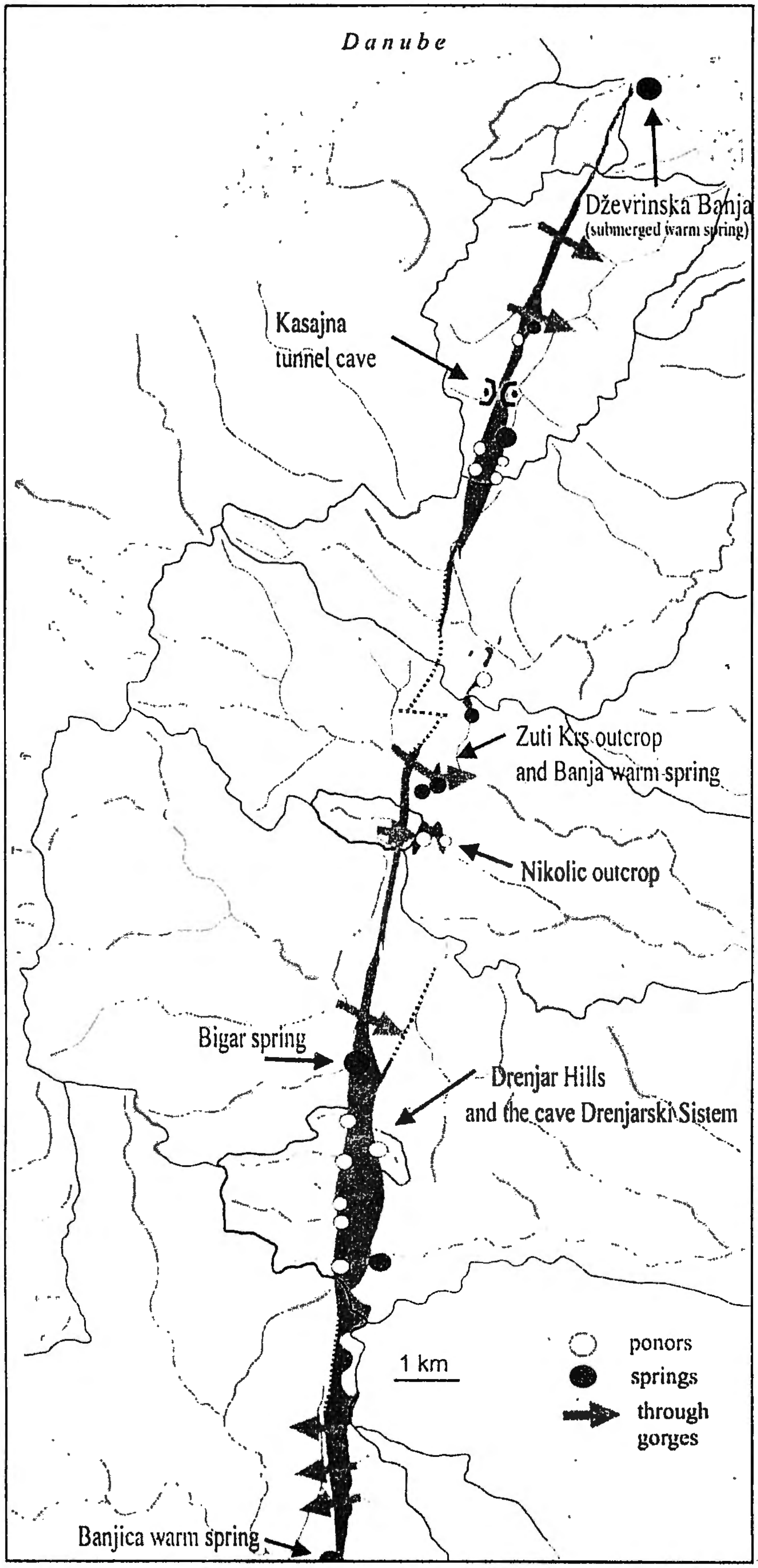


Fig. 3. Position of Dževrinska Greda in relation to the surface drainage network, and some of the typical contact karst features.
La position de Dževrinska Greda par rapport au réseau de drainage de surface et quelques éléments typiques du karst de contact.

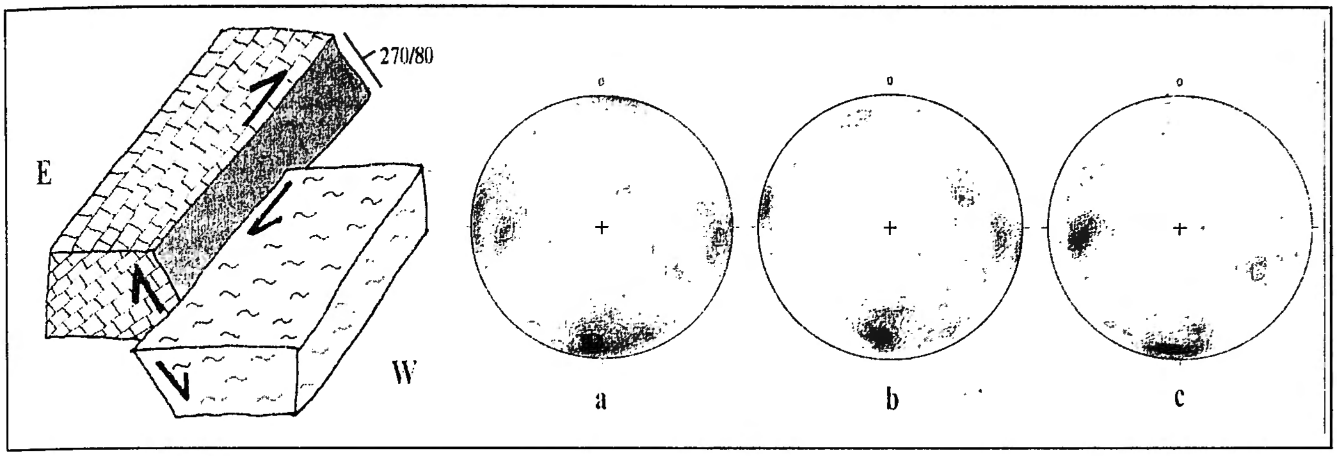


Fig. 4. Sketch of the kinematics of the Dževrin fault (on the left) and Schmidt's net projections of fracture planes along the limestone ridge (a: the whole ridge; b: the Drenjar Hills area; c: limestone outcrops to the east of the main ridge)

Esquisse de la cinématique de la faille de Dževrin (à gauche) et projections sur le réseau de Schmidt des plans de fracture le long de la crête calcaire (a: pour toute la crête; b: pour la zone des Collines de Drenjar; c: affleurements calcaires à l'est de la crête principale).

also dextral transcurrent (the eastern block moved towards the south). The opinion among Serbian geologists is that the vertical movements have stopped and that, currently, only the transcurrent movement is active (Grubić, 1992). The fault plane dips towards the west, but very prominent, even more numerous, are as well those fracture planes that dip towards the north, perpendicular to the main fault (see net projections in Fig. 4). However, caves are mostly developed paralelly to the fault strike (N–S), using tension joints of the vertical movement. Some passages are formed along tension joints of the transcurrent movement (striking approximately SW–NE).

Escarpments are visible in many places, but the central zones of the fault – crushed and broken (in the sense of Čar & Šebela, 2001) are missing from the surface, because they were eroded or are partially masked by screes; no tectonic breccia nor mylonite can be seen. Only the fissured zone remains visible (Fig. 5).

Water Input to Karst, Groundwater Directions, and Warm Springs

Three types of water input to karst are present: *allogenic streams* give concentrated input, *precipitation* gives a dispersed input, while *input from surrounding aquifers* is in small quantities at numerous places, mostly from the western fissured aquifer in the schists. Sinking streams are in most cases seasonal (with small catchment areas and greatly depending on rainfall), and have discharges of 0–20 l/s, while the important characteristic of all springs is that they are permanent and they do not exert typically karstic behaviour: the relation between minimal and maximal yields is never greater than approximately 1:10 and the reaction to drought is relatively smooth.

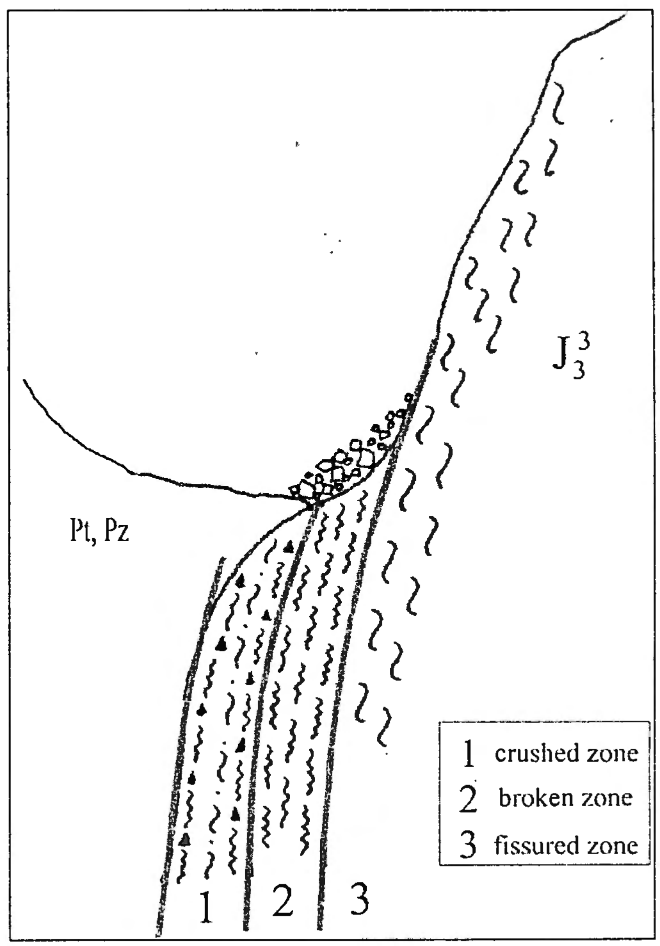


Fig. 5. Cross-section through the main fault zone of the Dževrin fault (according to the terminology of Čar & Šebela, 2001).

Coupe à travers la zone principale de fracture de la faille de Dževrin (d'après la terminologie de Čar & Šebela, 2001).

Considering that the precipitation in this area is relatively scarce (average 600–700 mm) and that the sinking streams seasonally dry out, permanent springs (although sometimes with flow rates of only about 0.5 l/s) prove that a supply from another aquifer (fissured schists) exists, and also that the karst aquifer is of considerable depth, with good retention capability.

The dominant direction of groundwater flow is from south to north, along the ridge, regardless of the W–E direction of the surface streams. However, due to the very small width of the limestone, there is no proven circulation through the whole ridge, but several input-output systems. Output points (springs) are usually in the gorges, and in all cases, further to the north, another system is present.

Only in a few cases groundwater directions are in accordance with surface streams — in the case of Mali Drenjar and Kašajna river; although it is quite disputable whether Kašajna waters, which occasionally flow through a short tunnel cave, can be regarded as groundwater at all.

One of the peculiar characteristics of the karst of Dževrinska Greda is the presence of three lukewarm springs, all of them with the temperatures 17–19 °C and followed by gases (mostly nitrogen, but also oxygen and CO_2). The northernmost spring Dževrinska Banja, which is now submerged by the Danube "Iron Gates" artificial lake, has a high content of NaCl (85 mg/l). The total mineralization in all warm springs is up to 530 mg/l (Filipović *et al.*, 1985). The southernmost point of Dževrinska Greda is also characterized by the presence of a warm spring — Banjica, with a discharge of about 3–5 l/s.

In-between these two locations, on *Žuti krš* limestone outcrop, is located the *Banja* warm spring, which has quite a complicated setting. There are actually three places of warm water outflow (on opposite sides of the river bed, and in the river bed itself), while in the very close vicinity there is a temporary cold water outflow from the cave *Velika Pećina*, and another cold spring just about 50 m upstream. The cave Velika Pećina is hydrologically connected with the cave *Nikolića Ponor*, situated in another limestone outcrop – Nikolić outcrop (see Fig. 1 and 3 for location of outcrops and Fig. 6 for cross-section). That connection was not proven by tracing, but it is rather obvious from the directions of cave passages, as well as from the presence of schist sand and pebbles in the cave Velika Pećina (the catchment area of Nikolića Ponor is built on schists).

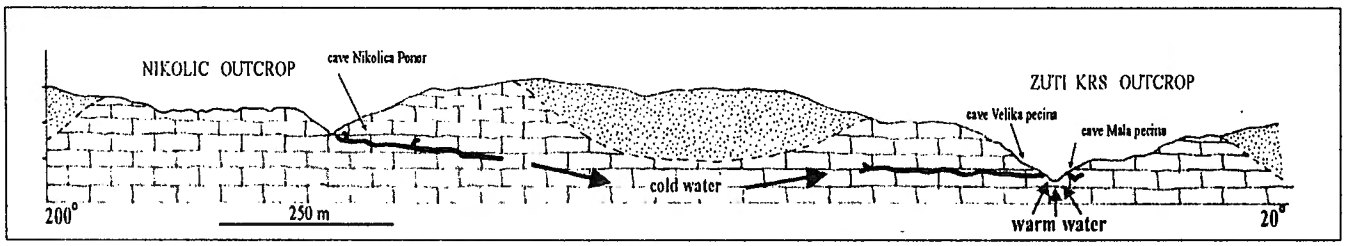


Fig. 6. Cross section through the limestone outcrops, along the direction 200°–20°, with indicated circulation of cold and warm groundwater.

Coupe transversale des affleurements calcaires le long de la direction 200°–20°, avec des indications sur la circulation des eaux souterraines froides et chaudes.

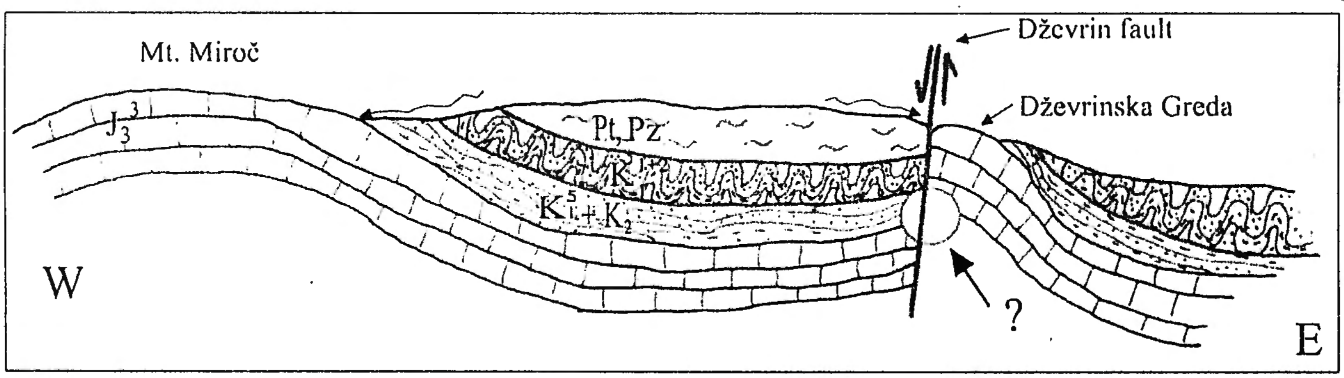


Fig. 7. Cross section through Mt. Miroč and the ridge Dževrinska Greda, with positions of Severin (K_1^{1-2}) and Getic (Pt, Pz) nappes. It is still not proven whether the limestones under the nappes are karstified and whether there is a connection between the limestone of Mt. Miroč and that of Dževrinska Greda. The sketch is not at scale.

Section à travers le Mont Miroč et la crête Dževrinska Greda avec les positions des nappes de Severin (K_1^{1-2}) et Gétique (Pt, Pz). On n'a pas encore prouvé si les calcaires en dessous de ces nappes sont ou non karstifiés et s'il existe une connexion entre les calcaires du Mont Miroč et ceux de la Dževrinska Greda. Echelle approximative.

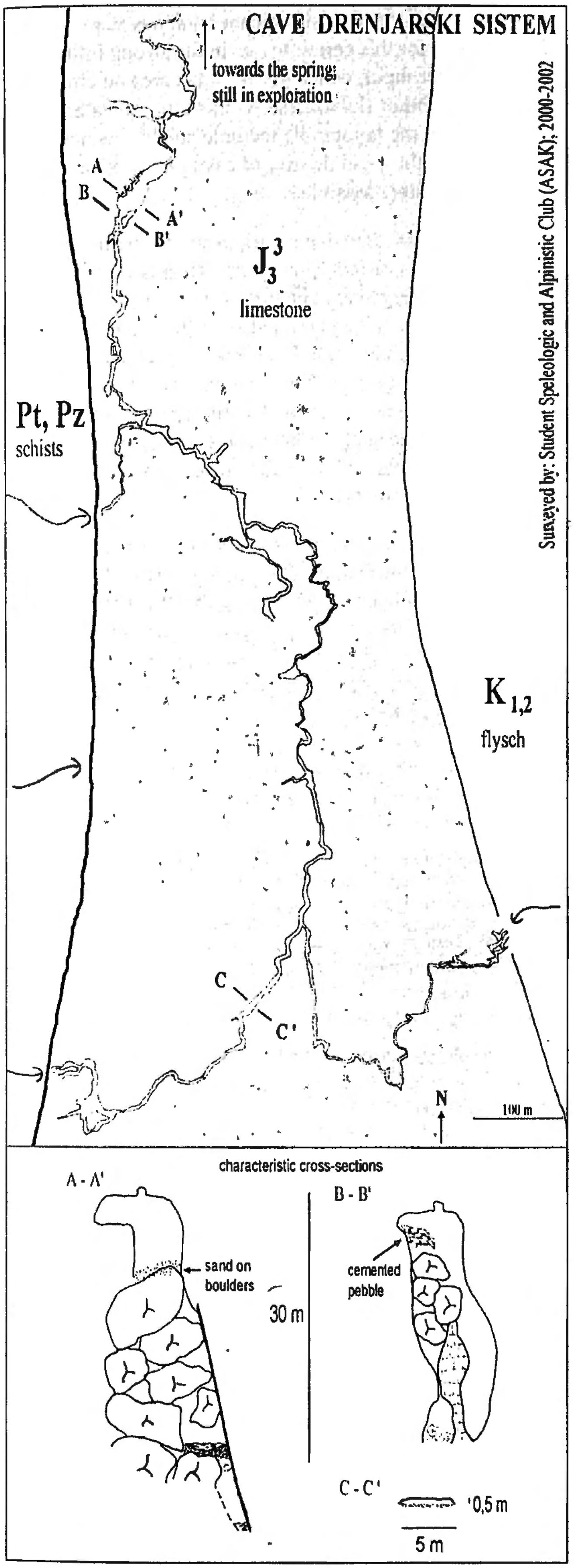


Fig. 8. Plan of the cave Drenjarski Sistem (3730 m) and typical cross-sections.
Plan de la grotte Drenjarski Sistem (3720 m) et sections transversales typiques.

Hydrogeologists consider that the warming of the water is caused by the deep circulation along the Dževrin Fault (due to thermic gradient), as well as by the presence of magmatic bodies. For example, 1.5 km east from the Banja spring, there is a dike of spilites which may act as a warming body for the groundwater (DRAGIŠIĆ *et al.*, 1988).

Karstification Extent

Considering the small limestone surface and the numerous types of water input, we can consider that karst is considerably developed on Dževrinska Greda. The density of surveyed cave passages is quite high taking into account the relatively small volume of rock. The presence of the regional fault enabled the deep circulation of the water, so although these parts are impenetrable, characteristics of these springs indicate the existence of conduits at greater depths.

Unfortunately, it is still unknown whether the limestones of Dževrinska Greda are currently in contact with the Mt.Miroč limestones, under the Getic and Severin nappes (Fig. 7). On the other side of the Danube, in Romania, it was proven by hydrodinamic studies (ROTARU *et al.*, 1995) and by water tracing (BANDRABUR *et al.*, 1999) that karstified limestones are continuous under the Getic Nappe, between Mehedinți Mts. and Mehedinți Plateau (karst of Mt. Miroč corresponds to the karst of Mehedinți Mts, while the karst of Dževrinska Greda corresponds to the karst of Mehedinți Plateau). However, such studies have not been carried out on the Serbian side. Among the reasons for this is the fact that sinking streams are quite weak, with small catchment areas, only seasonal activity, and very small flow rates, which make water tracing almost impossible.

The caves: positions, morphology, infills

The longest cave of the ridge Dževrinska Greda is the cave *Drenjarski Sistem*, with 3730 m of surveyed passages, and at least 500 m more to be surveyed, because intensive explorations are still in progress. Three ponors are connected and the main passage is heading towards the north, in the direction of Bigar spring (Fig. 8).

The underground morphology shows typical contact karst characteristics. Caves are considerably filled with sediments, mainly schists and quartz from the west, but also with components of flysch from the east. Usually numerous traces of sediment filling and washing out are visible in the passages. Pebbles are cemented even at great passage heights (see cross-sections in Fig. 8), while large portions of ceilings are paragenetically eroded. Apart from the influence of sediment infills, there are

also conspicuous traces of tectonic activity, which can all be seen on several typical cross sections from the Drenjarski Sistem.

We already mentioned that on several places surface rivers managed to entrench into the ridge, form through-gorges, and continue their surface flow. There are two cases of caves on opposite sides of a gorge (one of those in the Žuti Krš outcrop, see Fig. 6). The genesis of such caves is still not clearly understood. One of the possibilities is that these gorges are a younger feature that intersected the previously existing caves; while other options are either the formation of caves in accordance to river entrenchment, or even by backflooding of the river. Presently, these caves are out of permanent hydrological function; unfortunately, the scallops in them are insufficiently distinct to show the direction of the paleo-flow, while other possible evidence has not been found yet.

Concluding remarks

Taking into account the fact that the surface of exposed limestone on Dževrinska Greda is quite small (less than 5 km²), total length of all cave passages explored so far (more than 6500 m; when 32 caves are summed up) can be considered as one of the indicators of a significant karst development. One of the reasons for this certainly lies in the strong influence of allogenic water input, which gives to this area an attribute of contact karst and/or fluviokarst. As this kind of water input is combined with the favourable tectonic conditions next to the Dževrin Fault, the great density of cave passages per surface unit is quite comprehensible.

The behavior of the fluvial network in contact with the narrow limestone ridge is varied: some of the streams sink at the contact, while the larger of them entrench across the ridge. The dominant direction of karst groundwater flow is from the south towards the north, along the limestone belt. Due to the intensive tectonic activity, groundwater is capable of reaching considerable depths. The presence of warm springs and springs of stable discharge throughout the year, strongly points to deep groundwater circulation and to the presence of a karst aquifer with retention capability.

It is important to mention that the limestone belt continues to the other bank of the Danube (in Romania), stretching further in the Mehedinţi Plateau. Considering that the major geological conditions in this area are quite similar on both sides of the Danube, it can be expected that a more detailed comparison would perhaps give answers to some of the questions on the evolution of this karst area.

References

Bandrabur, G., Slăvoacă, D., Bandrabur, R., & Slăvoacă, R. (1999) Considérations hydrodynamiques sur le système karstique de Bârza (Monts et Plateau de Mehedinţi, Roumanie). *Theor. Appl. Karstology*, 11-12, pp. 133–138.

Bogdanović, P., Marković, V., Dragić, D., Rakić, M., Babović, M., Rajčević D., Popović, V., & Milojević, LJ. (1973) *Osnovna geološka karta SFRJ 1:100000, list Donji Milanovac*. Savezni geološki zavod, Beograd.

Čar, J. & Šebela, S. (2001) Kraške značilnosti narivnega stika apnenec-dolomit pri Predjami (Karst characteristics of thrust contact limestone-dolomite near Predjama). *Acta Carsologica*, 30, *2*, pp. 141–156.

Dragišić, V., Filipović, B., & Dimitrijević, N. (1988) Pojave termalnih voda na istočnim padinama Miroča. *Zapisnici Srpskog Geološkog Društva za 1985–1986*, Beograd, pp. 225–229

Filipović, B., Dimitrijević, N., & Dragišić, V. (1985) *Hidrogeološka studija pojava termalnih i termomineralnih voda na teritoriji SO Kladovo*. Faculty of Mining and Geology, Beograd, 47 p. (unpublished, *in Serbian*).

Grubić, A. (1992) Geološki profil Dževrinskog brda u SI Srbiji. *Ann. Geol. Penins. Balk.*, 56, *1*, pp. 17–35. (Geological section of Dževrin Hill in NE Serbia, *in Serbian*).

Lauritzen, S-E. (2001) Marble stripe karst of the Scandinavian Caledonides: an end-member in the contact karst spectrum. *Acta Carsologica*, 30, *2*, pp. 47–79.

Rotaru, A., Bulgăr, A., & Povară, I. (1995) L'étude hydrodynamique du système karstique de Motru Sec – Baia de Aramă (Roumanie). *Theor. Appl. Karstology*, 8, pp. 145–155.

received: 8 July 2002
revised: 30 October 2002
accepted: 02 November 2002

Theoretical and Applied Karstology, 15 (2002), pp. 51–59

Morphotectonic analysis in hydrogeological research of karst terrains. A case-study of SW Kučaj Massif, Eastern Serbia

Igor Jemcov*, Radmila Pavlović, & Zoran Stevanović

Faculty of Mining and Geology, Belgrade University, Djusina 7, 11000 Belgrade, Yugoslavia.

Abstract

The fracture structures are recognized as being among the principal factors of karst development by analyzing data obtained by remote sensing. Regional fractures were recognized through analysis of satellite imagery — scanograms, while the detailed fault pattern was obtained by stereoscopic analysis of aerial photographs. The method of quantitative geomorphologic analysis was used for the identification of neotectonically active structures. Neotectonic analysis was performed using a morphometric-statistical procedure — the calculation of topographic relief. As a new procedure, supplemental to fault pattern analysis, Digital Elevation Model (DEM) was applied.
Comparison of the results obtained by fault pattern analysis using remote sensing, quantitative geomorphologic analysis and digital elevation model with favored directions of karst groundwater flow, revealed a significant control of the position and function of the faults over karstification. General karst groundwater directions and drainage reorientation are mainly controlled by the morphotectonic evolution.

Key words: karstification, karst groundwater flow, remote sensing, Digital Elevation Model, neotectonic analysis.

L'analyse morphotectonique dans la recherche hydrogéologique des terrains karstiques. Etude de cas sur le sud-ouest du Massif de Kučaj, Serbie de l'Est

Résumé

En analysant les données obtenues par des photographies satellitaires, on a observé que les structures fracturales sont parmi les principaux facteurs qui favorisent le développement du karst. Les fractures régionales ont été reconnues sur des images satellitaires, tandis que le modèle structural de détail a été établi par analyse stéréoscopique des aérophotogrammes. Afin de mettre en évidence les structures actives au point de vue néotectonique, on a utilisé la méthode de l'analyse géomorphologique quantitative. Pour l'analyse néotectonique on a utilisé une procédure morphométrique et statistique, en calculant l'énergie de relief. En tant que nouvelle procédure complémentaire pour l'analyse du modèle structural, on a appliqué le modèle digital altitudinal («Digital Elevation Model» — DEM).
En comparant les résultats obtenus par l'analyse du modèle structural à l'aide des images satellitaires, l'analyse géomorphologique et le modèle digital altitudinal avec les directions préférentielles d'écoulement karstique, on a observé que la karstification est significativement influencée par la position et le fonctionnement des failles. Les directions générales d'écoulement souterrain et les captures karstiques sont contrôlées surtout par l'évolution morphotectonique.

Mots-clés: karstification, écoulements karstiques, analyse des photographies satellitaires, modèle digital altitudinal, analyse néotectonique.

* corresponding author. *E-mail address*: jemcov@ptt.yu

Introduction

Remote sensing and quantitative geomorphologic analysis are methods intensely used for hydrogeological investigations. The hydrogeology of South-Western Kučaj karst massif (Eastern Serbia) has been investigated by complex researches including the analysis of regional fault pattern on satellite images, the analysis of detailed structural fabric on aerial photograph, and neotectonic analysis based on topographic maps.

Studied area

The karst terrains of SW Kučaj, Eastern Serbia occupy two separate areas (Cvijić, 1893), with a total surface of about 320 km^2 (Fig. 1):

- the western karst zone — *Ravanica* zone (70 km^2)
- the eastern karst zone — *Kučaj* zone (250 km^2)

Significant lithostratigraphic differences between these two zones resulted from different paleogeographic evolution. Deposition of carbonate sediments in the western karst zone started during Lower and Middle Triassic, and ceased in the Upper Jurassic. In the eastern zone, the deposition of carbonate sediments commenced in the Upper Jurassic, and was completed at the end of the Lower Cretaceous.

In the discharge zone the ground waters are either gravitational or ascending, mainly depending on the base level of karstification. Six karst springs have been identified, with an average yield exceeding 100 l/s.

According to the results of a relatively small number of flow tracings, fictitious rates of groundwater flow range from 0.006 to 0.045 m/s, resulting in an average rate of 0.025 m/s (Stevanović & Dragišić, 1992). They also indicate a multidirectional circulation, and the occurrence of groundwater piracy between adjoining catchment areas.

Remote sensing

Besides lithology, the fault pattern is one of the principal factors that control the source, the circulation and the outlet of karst ground water. Consequently, analyses of regional and detailed fault patterns were accomplished by extensive use of remote sensing methods.

The main requirement for the application of remote sensing in geology and hydrogeology is the comparative analysis of images obtained using different sensors, in different spectral areas and at different scales of sensing (Pavlović & Krešić, 1990).

Data collection for the regional fault pattern was achieved using satellite images (Landsat missions 2 and 3, scale 1:500 000), analyzed by means of the logical comparative technique. The analysis was accomplished on images in different channels (Fig 2). Black & white contrast images were used, taken in green, red and related infrared spectral areas. The results obtained were correlated with the analytical results of color-composite images at the same scale. Faults, classified by significance in structural fabrics, were divided into two ranks (Stevanović *et al.*, 1996). The first one includes large features of regional importance – "preferential fault lines" (Pavlović, 1990). The other one includes faults of local significance, the ranking criteria being based on the scale of the investigated area. When an observed fracture was limited to the investigated area it was treated as a local one; if it extends outside the area's borders it was considered as having a regional significance.

Regional faults generally form two systems. One of them has a NW-SE strike (longitudinal structures), whereas the other is of NE-SW strike (transverse faults) (Fig. 3).

Undoubtedly, the widest application among remote sensing procedures in hydrogeology is the analysis of aerophotographs. Following the stereoscopic analysis of aerial photographs, on a scale of 1:50.000, the detailed fracture fabric of an investigated terrain can be determined. In general, the observed faults within a studied area show the same orientation as the regional fractures. Results of a statistical analysis of photogeologically determined faults, shows a maximum NW-SE orientation, similar to the orientation of lithostratigraphic units. Therefore, faults of NW-SE strike could be defined as longitudinal structures. Submaximum orientation shows faults of NE-SW orientation; these are transverse faults.

The Digital Elevation Model

The *Digital Elevation Model* (DEM), as a digital form of relief presentation has been used in the earth sciences for many decades. Originally only used as a convenient resource for visualization, DEMs are now a remarkable source for analysis and interpretation of geological data. In this study, DEM was applied for rupture pattern analysis, and for quantitative geomorphological analysis.

The DEM was also used as a helpful resource for 3D visualization of the landscape (Fig. 4). Three-dimensional landscape models provide a comprehensive view of geomorphologic features, as well as geological elements. Thereby, an improved and comprehensive view of geomorphologic features, different types of geological data, as well as a visualization of their mutual spatial relations, was achieved.

Application of the DEM in fault pattern analysis is based on the presence of a relief-shading model. The concept of fault pattern analysis rests upon simple following the lineaments with sharp morphologic reflection on surface. The advantage of using a shaded relief model as compared to aerial photos and satellite images is the absence of vegetation, cloudiness, different objects and other anthropic structures. Limitations in the application of the shaded relief model rupture pattern analysis were

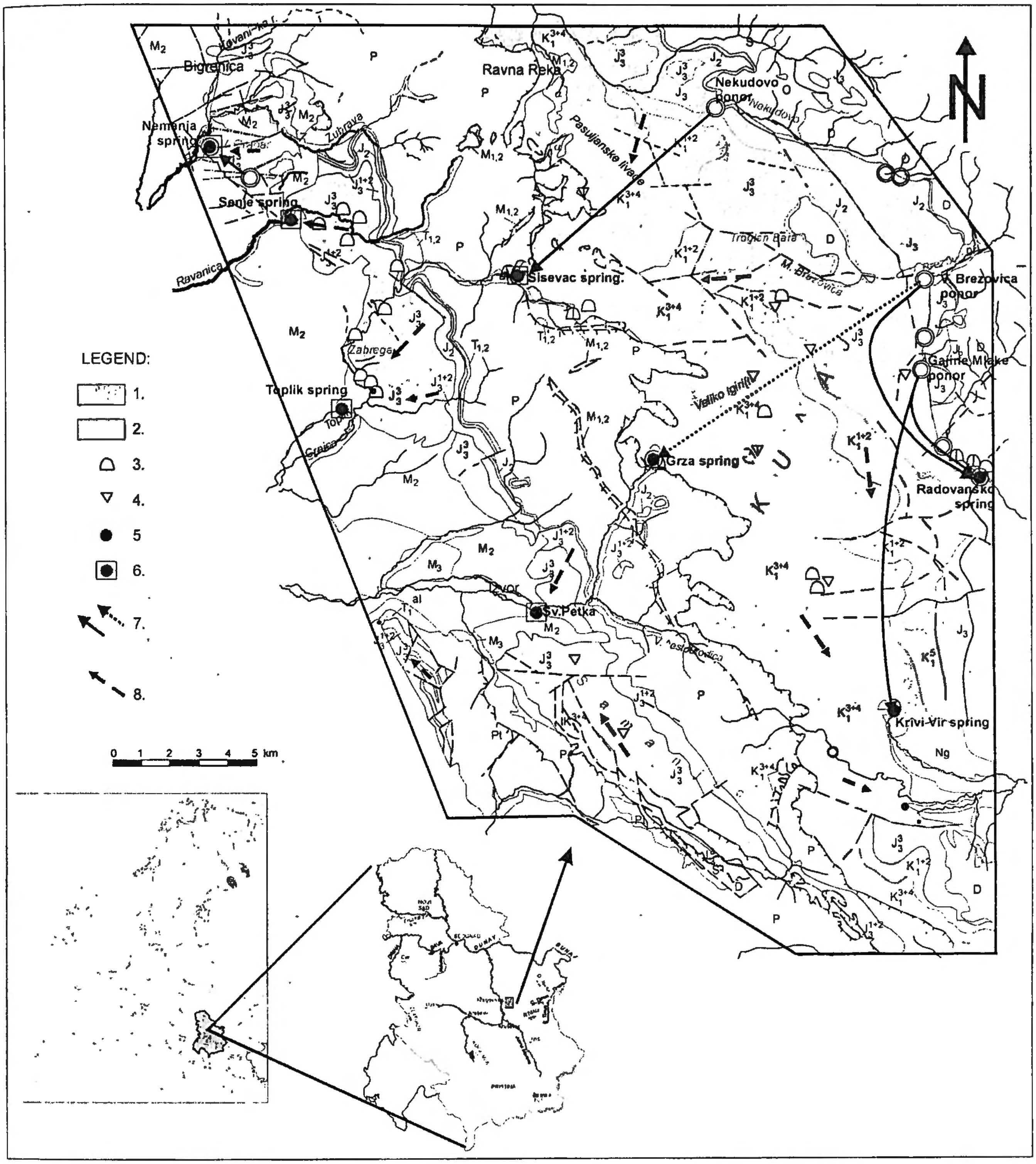


Fig. 1. The karst terrains of South-Western Kučaj Mts. (Eastern Serbia). 1. karst terrains; 2. non-karst terrains; 3. caves; 4. sinkholes; 5. karst spring (Qsr>100 l/s); 6. tapped karst spring (Qsr>100 l/s); 7. labeled underground drainage; 8. predicted drainage.

Les terrains karstiques du sud-ouest du Massif de Kučaj (Serbie de l'Est). 1. terrains karstiques; 2. terrains non-karstiques; 3. grottes; 4. dolines; 5. source karstique (Qsr >100 l/s); 6. source karstique captée (Qsr >100 l/s); 7. drainage souterrain démontré; 8. drainage souterrain supposé.

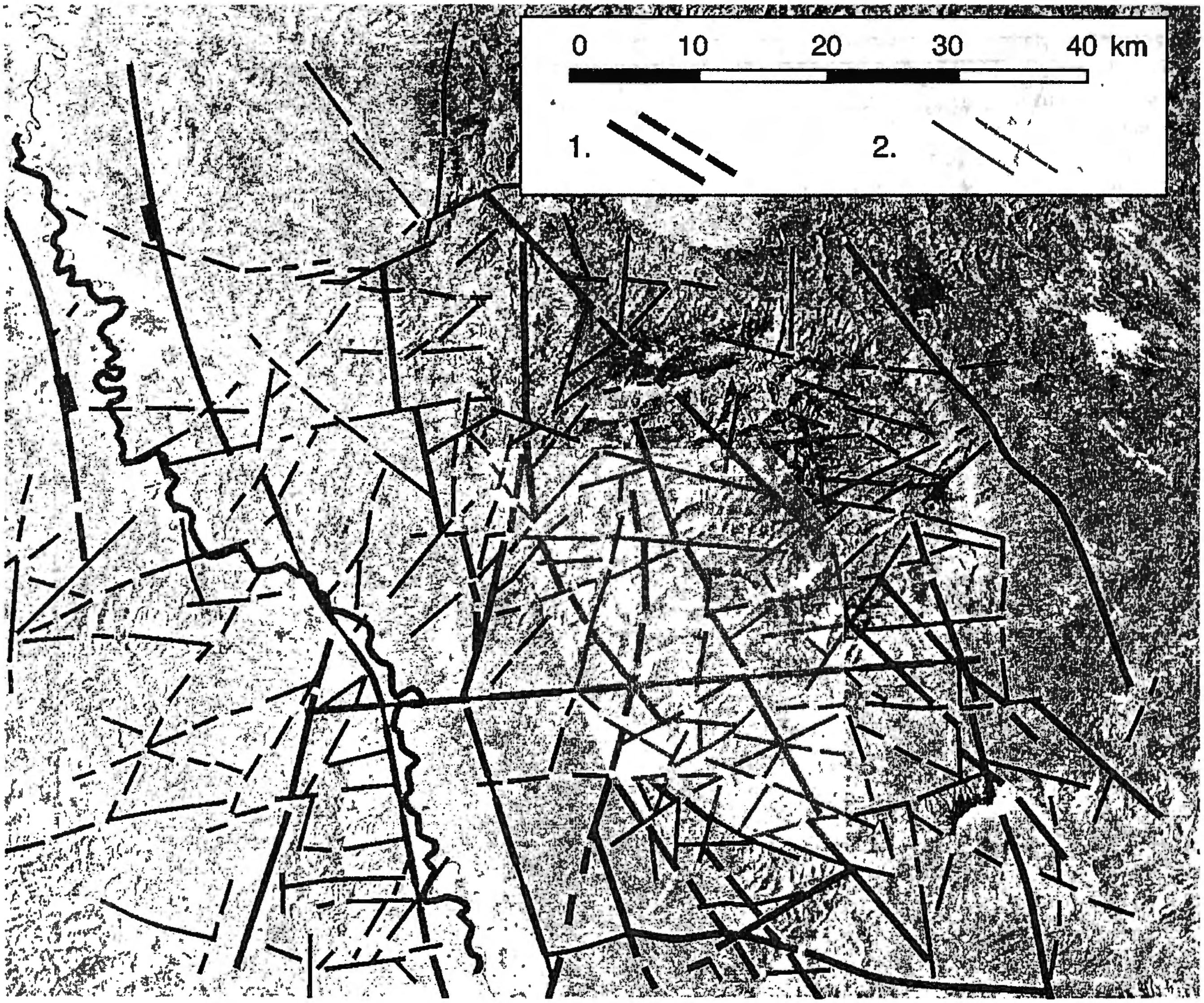


Fig. 2. Map of the regional fault pattern on the satellite image. Key: 1. regional faults, verified (solid lines) and supposed (dashed lines); 2 local faults, verified (solid lines) and supposed (dashed lines).

Le modèle structural régional superposé sur l'image satellitaire. Légende: 1. failles régionales, confirmées (lignes continues) et supposées (lignes interrompues); 2. failles locales, confirmées (lignes continues) et supposées (lignes interrompues).

resolved by parallel analysis of multiple generated models with varying position of the simulating lighting source. Data acquired as a result of shaded relief model analysis highly correlates with the results of the analysis and interpretation of fault patterns on satellite images and aerial photos.

By merging satellite imagery with the shaded relief model, the plausibility of analysis has been improved substantially, providing considerable additional information.

The DEM as a digital form of relief presentation contains all the essential numeric information of the terrain (x, y, z), required for morphometric analysis. The application of the methods of quantitative geomorphologic analysis is greatly simplified by

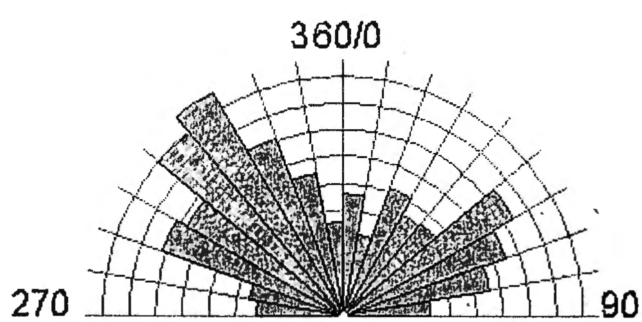


Fig. 3. Orientations of photo-geologicaly determined faults.

Oriéntations des failles déterminées par des moyens photo-géologiques.

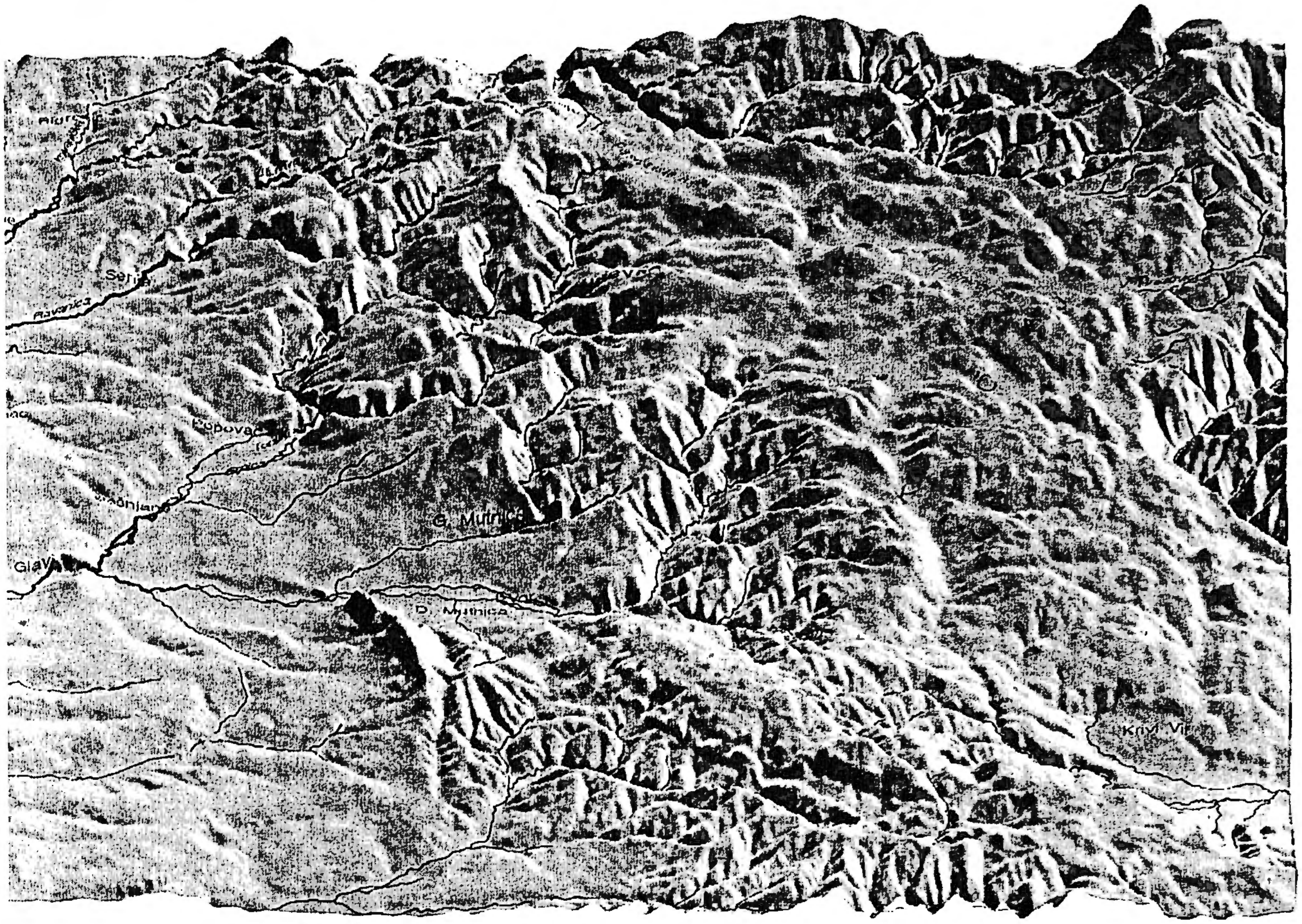


Fig. 4. The 3D model of the investigated area. *Modèle tridimensionnel de la zone étudiée.*

automated extraction of requisite data from digitally recorded data. Errors which were previously common, such as those ocurring during the retrieval of data from topographic maps, are now completely excluded (Marković *et al.*, 1996).

Quantitative geomorphologic analysis

The fault pattern comprises all fractures, irrespective to their size, genesis, time of origin or movement intensity. Nevertheless, fault chronology (the time of activation and the duration of its activity) directly affect the development of karst processes. Considering their influence over hydrogeological characteristics, recently active fractures have the highest significance. These are the fractures formed in recent geological history, or pre-Neogene faults that were repeatedly activated during the recent geologic periods.

The method of quantitative geomorphologic analysis was used in order to define the youngest tectonic activity, *i.e.* to determine the neotectonic zones, the general movements of tectonic blocks, as well as to establish the direction and intensity of motion of particular blocks. This is in fact a morphometric-statistical procedure, carried out by analysis of topographic maps and DEM.

The procedure of topographic relief analysis (Penck, 1924; Marković *et al.*, 1996) was applied in the study of the South-Western Kucaj karst massif.

The *topographic relief* represents the potential energy defined as a result of height differences within measured equal unit fields. Data obtained by systematic measurement of potential energy allow the construction of a map with contour lines. Contour lines represent anomalies with respect to the reference level (mean value of the whole measured data set).

The interpretation of map anomalies of topografic relief is simple. In general terms positive values of energy of relief anomalies, *i.e.* reinforced erosion correspond to the areas of neotectonic uplifting. Conversely, negative values mean reinforced accumulation by subsidence of corresponding blocks (Fig. 5A). Furthermore, contour lines, their orientation and gradient define neotectonic structures and boundaries between

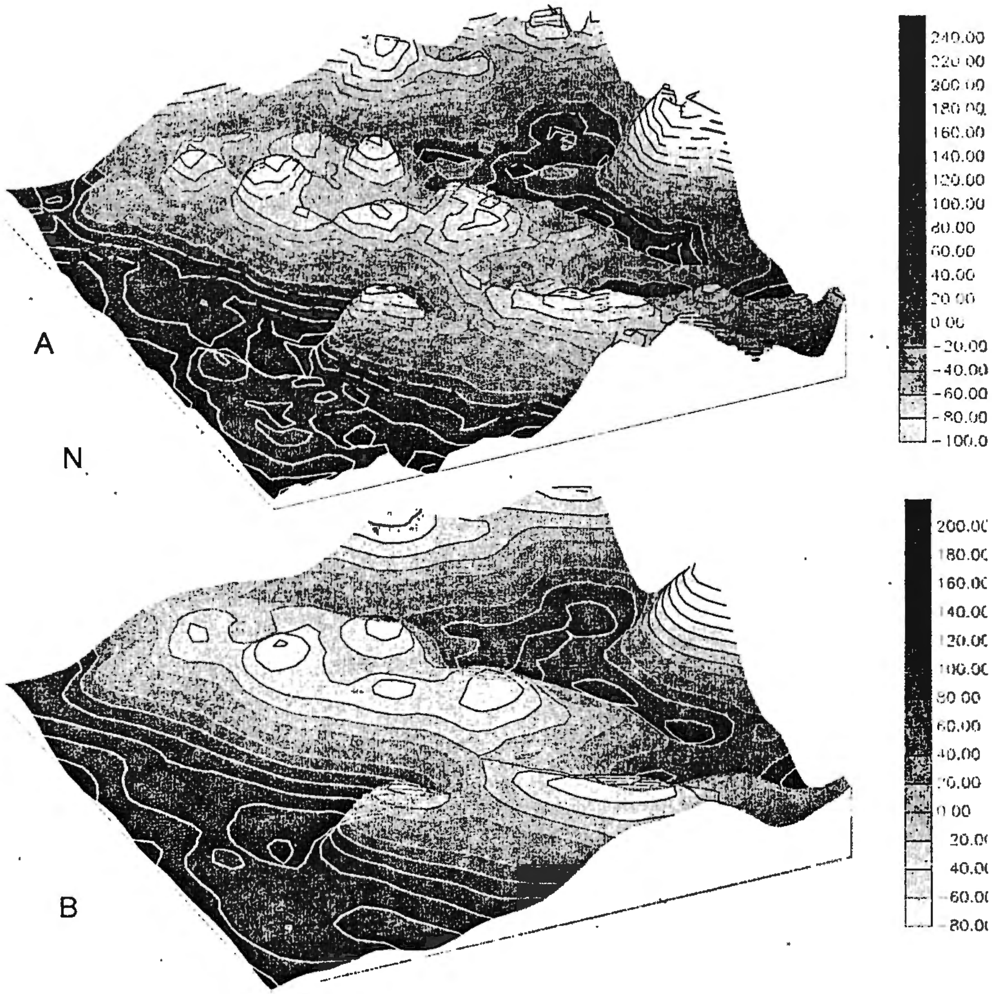


Fig. 5. A. Blockdiagram showing the topographic relief;
B. Anomalies of first trend of the topographic relief.
A. Représentation tridimensionnelle de l'énergie de relief;
B. Anomalies du premier ordre de l'énergie de relief.

blocks with different signs and intensities of movement. The correlation between a geological map and a contour map of topographic relief anomalies is needed in order to increase the objectivity of interpreted data (Marković *et al.*, 1996).

In order to focus on the regional influence of the youngest tectonic activity over the landscape shaping, the effects of exogenous forces, lithological structure and terrain structure have to be removed. This is accomplished by smoothing the surface of the topographic relief model. Smoothing may be seen as a generalization which emphasizes the general trend of the structures presented as contour lines. Smoothing is performed mathematically-statistically, by using the "moving average" method.

Positive values of anomalies represent a relative neotectonic uplift, while negative values correlate to areas of relative neotectonic subsidence. A change of the anomaly sign corresponds to neotectonically active structures - high gradient of contour lines. Values of isolines of the first trend of the topographic relief are proportional, but not equivalent with the movement values. They only show relative relationships between blocks and indicate the sign of movement along neotectonic structures.

The interpretation of neotectonic activities of the studied area based on the analysis of the map of first trend of topographic relief anomalies, shows differential vertical block movements (Fig. 5B).

Interpretation of neotectonic activities greatly correlates with the fracture structure as determined by the analysis of satellite and aerial photos. A high degree of correspondence was determined on a detailed fault pattern map between neotectonic structures and the location of regionally important fractures.

Influence of morphotectonic evolution on flow directions and redistribution of karst groundwater

The recent fault pattern is the result of repeated tectonic movements, and many of the identified faults are still active. The locations of main karst springs are controlled by regional faults. Large karst springs - Crnica spring, Toplik spring, Radovansko spring, St. Petka spring, with average yields exceeding 100 l/s emerge along zones crossing longitudinal and transverse faults.

The directions of karst groundwater flow are controlled by the geological structure, karstification level and local hydrogeological conditions. They are mostly determined by the evolution of karst processes. Tectonics and limestone structure are the principal factors of karstification and groundwater circulation.

The first stage, which has the strongest influence on subsequent groundwater circulation, is certainly the uplifting and the formation of karst massifs (western part of Kučaj anticline). Longitudinal faults of NW-SE strike (e.g. Senje-Kepoljin, Kučaj, Samanjac) have established the general directions of groundwater movement towards the regional base-level.

In the following stage of karstification, periclinal inclination of the terrain, the disposition of impermeable rocks and transverse faults of NE-SW orientation controlled the paleo-hydrographic pattern and defined the position of erosion base-level. At this stage fluvial processes are dominant. Although initially the massif was built of intensely fissured carbonate sediments, due to the immaturity of the joint systems, the dissolution effect of the water was limited. Most of the water still flowed as surface streams, creating fluvial landscape features.

In the subsequent stages of evolution, karstification becomes a dominant process as compared to fluvial erosion. Due to epirogenic movements and faster incision of the main drains at the rim, the erosion base-level was lowered. Stream flows, weakened by the karstification processes, were not able to downcut further and remain overhanged. Further on, the river network continues to degrade and the groundwater levels were lowering. In this phase, the karstification progresses along the directions of the original paleo-flows, mostly defined by transverse faults. This assumption is suggested by the fact that cave passages coincide with the transverse faults orientation (NE-SW)(Fig. 6); passages oriented along longitudinal faults are almost completely missing, especially in the eastern karst belt. Fluvio-karstic processes continue their local development in the western karst belt, where a narrow area of carbonate deposits is criss-crossed by transverse fractures. This resulted in deep incision of bigger streams (Ravanica, Crnica, Grza).

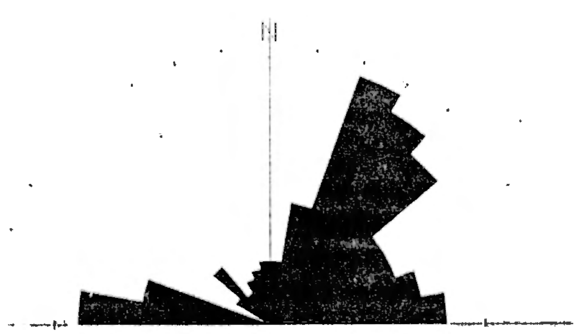


Fig. 6. Main orientation of passages in caves from Kučaj Massif. *Orientations préférentielles des galeries des grottes du Massif de Kučaj.*

The lowering of karstification processes can be easily traced by following the hypsometry of the cavities; the highest objects are hydrogeologically inactive, while the lowest ones are temporarily or perennial active (Ravanicka cave, Nemanja 2, Grza, Sisevac cave, etc.)

The recent stage of karstification processes (including the present time) is characterized by the rearrangement of the drainages between some of the adjoining areas, as a result of differential block movement along neotectonic zones. The rearrangement of karst groundwater flows follows the regional erosion base-level, with the abandonment of local erosion base-levels and creation of smaller catchment areas. Groundwater piracy is characteristic for this phase (Fig. 7).

In the eastern karst belt, the reorientation of the groundwater was determined by dye tracing of the Velika Brezovica ponor. Waters originating in the Grza catchment area were re-directed towards the Radovansko spring. Re-direction of the karst groundwater flow towards the Radovansko spring was a consequence of the relative lowering of the central block (A) with respect to the side-blocks (B and C). Another typical example of groundwater piracy is the re-direction of the karst groundwater flow from the Resavica catchment area towards the Crnica spring as a consequence of intensely rising of the north block (E).

In the western karst belt, piracy is not characteristic due to the deep incision of surface streams along transverse faults. Only one case of piracy was detected by dye tracing of Pirivoje ponor (Ravanica catchment area); this is due to a relative lowering of the northern (D) block with respect to the southern one (B).

Conclusions

From the regional structural analysis, cave orientation and main drainage zones, appears that the position and mutual relationships of longitudinal and transverse fault-structures plays an important role in the formation of preferential directions of karst groundwater movement in different phases of karstification. In

Fig. 6. General directions of karst groundwater and fault pattern on the shaded relief model. Key: 1. regional faults (verified and supposed); 2. local faults (verified and supposed); 3. neotectonically active zone; 4. karst spring; 5. swallet; 6. underground drainage verified connection; 7. predicted groundwater flow direction.

Directions générales de l'écoulement karstique et modèle structural superposés sur le modèle du relief. Légende: 1. failles régionales (confirmées et supposées); 2. Failles locales (confirmées et supposées); 3. zones actives au point de vue néotectonique; 4. source karstique; 5. perte; 6. drainage souterrain démontré; 7. direction supposée d'écoulement souterrain.

the last development phase, neotectonically active fractures are especially important. Comparison of the studied underground water movement directions and neotectonically active zones in the eastern karst belt of SW Kučaj massif, revealed that longitudinal faults have had an important role in the establishment of the direction of karst drainages, and that the main drainage elements of karst groundwaters are connected to neotectonically active zones – Nemanja spring, Krivi Vir spring, Radovansko spring, Izvor spring and Toplik spring.

References

Cvijić, J. (1893) Geographical investigation in Kucaj area in Easter Serbia. *Geol. Anal. of Balkan Peninsula*, V. Belgrade (*in Serbian*).

Krešić, N. & Pavlović R. (1990) Remote sensing as a method for determining of directions of karst groundwater flow. *Nas Krs*, **28-29**, pp. 21–34.

Marković, M., Pavlović, R., & Ćupković, T. (1996) Quantitative geomorphological analysis; a direction of further development of geomorphology. *Collection of the papers of Geographic Institute "Jovan Cvijic" - Serb. Acad. of Science and Arts*, **46**, pp. 107–119 (*in Serbian*).

Pavlović, R., & Krešić, N. (1990) Remote sensing in hydrogeological research of eastern Serbia karst. *Intl. Symposium of Remote Sensing and Water Resources, Enshede, Netherlands.*

Pavlović, R. (1990) *Complex relief analysis as method of geological investigation.* PhD. Thesis, Faculty of Min. and Geology, Belgrade University, Belgrade. (*in Serbian*).

Penck, W. (1924) *Die Morphologishe Analyse.* J. Engelhorn. Stuttgart.

Stevanović, Z. & Dragišić, V. (1992) Directions of circulation of karst ground waters in the Carpatho-Balkanides, Serbia. In: *Tracer Hydrology* (Hötzl, H & Werner *Eds.*) Balkema, Rotterdam, pp. 291–295.

Stevanović, Z., Marković, M., Pavlović, R., Jemcov, I., Dragišić, V., & Čupković, T. (1996) Correlation Between Regional Fault Pattern and Karst water Flow Directions Based on Examples from Eastern Serbia (Yugoslavia). *Theor. Appl. Karstology*, **9**, pp. 149–154.

received: 22 July 2000
revised: 17 November 2002
accepted: 29 November 2002

Theoretical and Applied Karstology, 15 (2002), pp. 61–72

Environmental isotopes studies and the hydrogeological model of South Dobrogea (Romania)

Augustin Țenu*, **Florin Davidescu, Răzvan Petreş, & Lăcrămioara Coarnă**

National Institute of Meteorology and Hydrology, Sos. Bucureşti-Ploieşti 97, 71552 Bucharest, Romania.

Abstract

Due to its natural and anthropic features, South Dobrogea (Romania) is a very interesting area from a hydrogeological point of view. In the region there are two superposed calcareous aquifers — the upper aquifer (Sarmatian) and the lower aquifer (Barremian–Jurassic) — which form the so-called "karstic system" of a strategic importance. Isotopic monitoring (^{3}H, ^{14}C, ^{13}C, D, ^{18}O) was performed over the last 25 years by an integrated research of all natural types of waters, in order to improve the knowledge of hydrogeological parameters and of the regional pattern flow. The main isotopic characteristics of meteoric and surface waters are briefly described in the paper. Within the karstic system, our study focused on the lower aquifer for which an up-to-date regional model was carried out by correlating all hydrodynamic and isotopic information. The main isotopic features can be synthesized as follows: the recharge area is located mainly in the Pre-Balkan Platform (Bulgaria); the main groundwater flow direction is east-northeast, towards Lake Siutghiol and the flow velocities, at regional scale, vary from 100 m/year for the secondary groundwater flow to 500–1,800 m/year for the main one.

Key words: karstic aquifers, isotopes, monitoring, conceptual model.

Etudes des isotopes environnementaux et le modèle hydrogéologique de la Dobrogea du Sud (Roumanie)

Résumé

Grâce à ses caractéristiques naturelles et anthropiques, la Dobrogea du Sud (Roumanie) est une région très intéressante au point de vue hydrogéologique. Dans cette région il y a deux aquifères calcaires superposés — l'aquifère supérieur (Sarmatien) et l'aquifère inférieur (Barremien–Jurassique) — qui forment le «système karstique» ayant une importance stratégique. Le monitorage isotopique (^{3}H, ^{14}C, ^{13}C, D, ^{18}O) a été effectué au cours des 25 dernières années pour tous les types d'eaux naturelles, afin d'une meilleure connaissance des paramètres hydrogéologiques et d'élaborer un modèle régional de l'écoulement souterrain. Les principales caractéristiques des eaux de surface et des précipitations y sont brièvement décrites. Pour le système karstique, notre étude a été focalisée sur l'aquifère inférieur, pour lequel on a réalisé un modèle fondé sur toutes les informations hydrodynamiques et isotopiques. Les principales caractéristiques isotopiques peuvent être synthétisées ainsi: l'aire d'alimentation de l'aquifère est localisée dans la Plate-forme Pré-Balkanique (Bulgarie); la direction principale de l'écoulement souterrain est E-NE, vers le lac de Siutghiol et les vitesses d'écoulement varient entre 100 m/an pour l'écoulement secondaire et 500–1800 m/an pour l'écoulement principal.

Mots-clés: aquifères karstiques, isotopes, monitoring, modèle.

* corresponding author. *E-mail address*: isotopes@fx.ro.

Introduction

South Dobrogea is a region that hosts a karstic system of strategic importance for Romania. Until 1973, the classical hydrogeological prospection has not been able to yield a definitive picture of the groundwater pattern.

A preliminary survey (ŢENU, 1973) using D/H ratio measurements provided promising results. Consequently, an isotopic and geochemical regional survey program started.

Beginning with 1982, a sampling network (Fig. 1), including not only the groundwater but all the water types of the hydrological cycle, was maintained unchanged and all environmental isotope analyses were performed: tritium (^{3}H), radiocarbon (^{14}C), carbon 13 (^{13}C), oxygen 18 (^{18}O) and deuterium (D). Additionally, in 1994, $\delta^{18}O$ and $\delta^{15}N$ in NO_3^- measurements have been carried out as well.

This isotopic database covers about a quarter of a century and, currently includes more than 2500 analyses.

Regional framework

South Dobrogea is located in the southeastern part of Romania, on the Black Sea shore, at about 44° northern latitude and 28° eastern longitude. This region covers a surface of about 4800 km² and its altitude is generally below 100 m; it is characterized by an annual mean temperature of 11.2 °C and a variable amount of rainfall (380–500 mm/year). The permanent streams are lacking and the runoff is the scarcest of the country: 0.2–0.6 l/s per km² (6–19 mm/year). Several lakes are situated along the Danube River or the Black Sea shore.

The karstic system of South Dobrogea is formed by two superposed aquifers, separated by a discontinuous acviclude:

- *the upper aquifer*, is developed within a calcareous Sarmatian (Late Miocene) plate which is over 10 m-thick especially in the southeastern part of the region;
- *the lower aquifer* — very important from the economic point of view — underlies most of South Dobrogea, in a unitary, karstified, limestone and dolomitic complex of Jurassic and Barremian (Early Cretaceous) age.

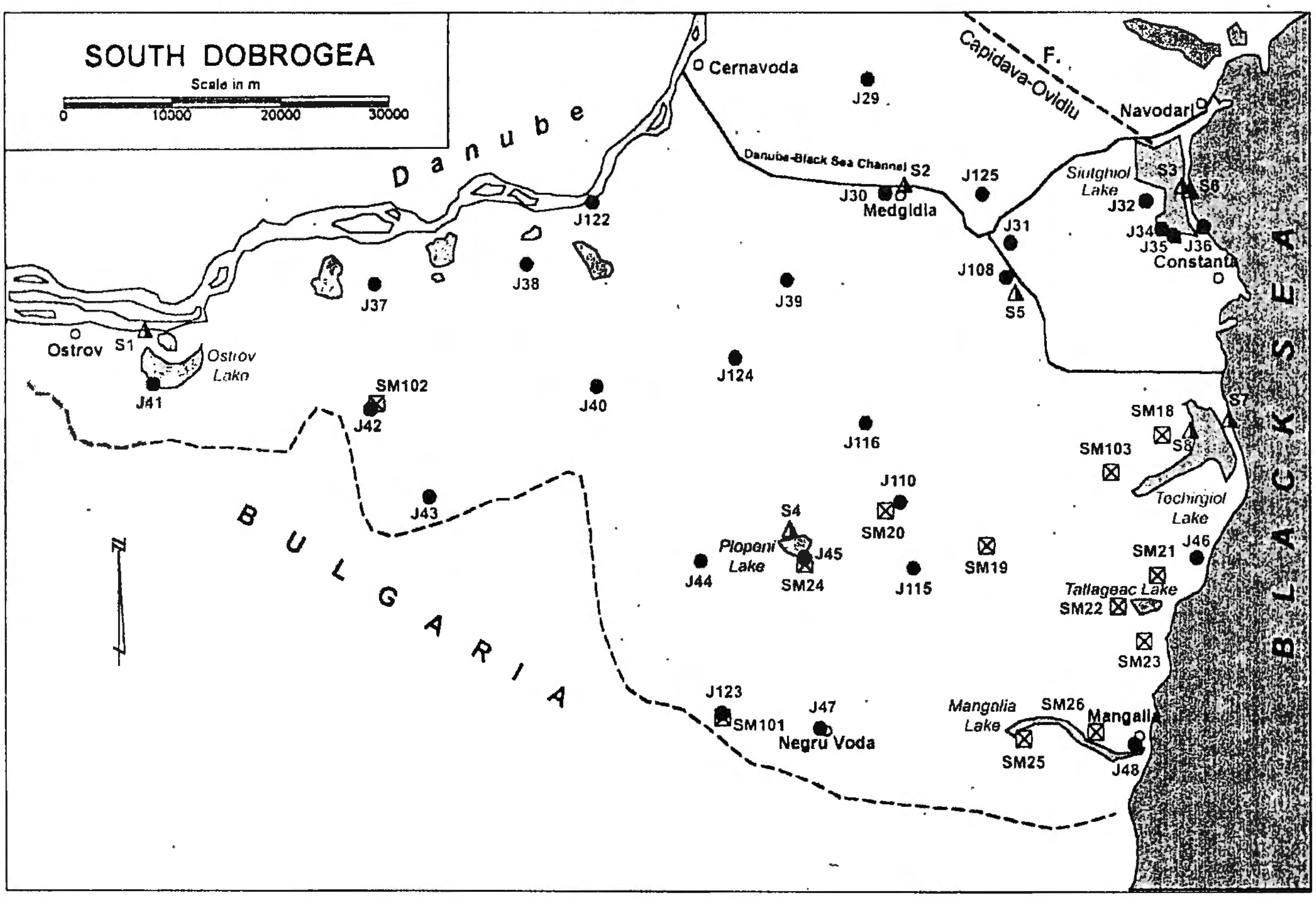


Fig 1. The geochemical sampling network. Key: Triangles-Surface water; Squares-Upper aquifer; Circles-Lower aquifer.
Le réseau d'échantillonnage géochimique. Légende: triangles – eaux de surface; carrés – aquifère supérieur; cercles – aquifère inférieur.

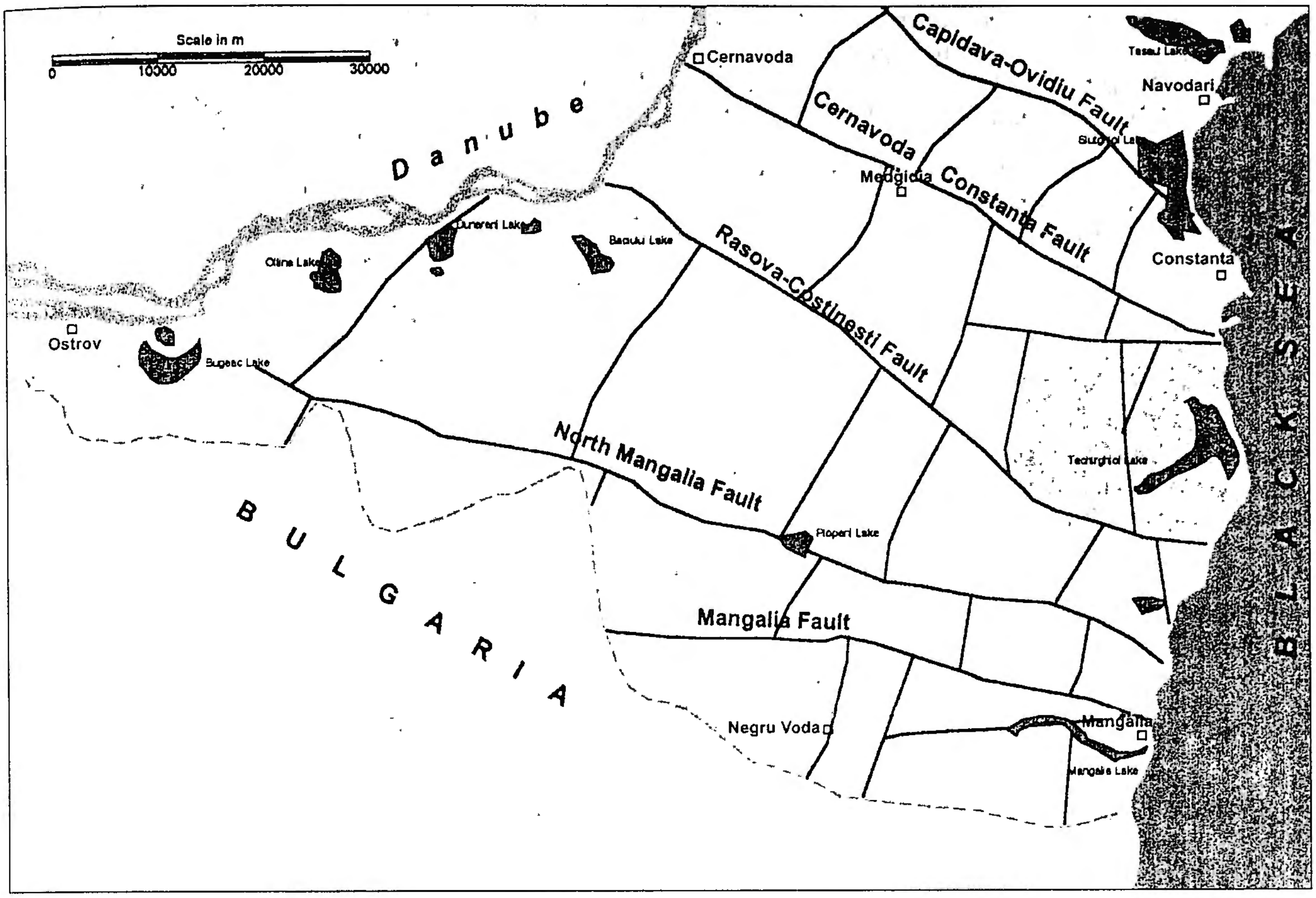


Fig. 2. Structural map of South Dobrogea. *Carte structurale de la Dobrogea du Sud.*

The thickness of the lower aquifer complex is about 1000 m in the southwestern part of South Dobrogea but decreases to about 400 m towards the east and especially in the northeast (Siutghiol Lake area).

This complex descends from the South towards the North and Northeast and it is affected by two main fault systems NNE–SSW and WNW–ESE oriented, respectively (Fig. 2). The last fault system includes the great overthrust fault *Capidava-Ovidiu* that represents the northeastern geological boundary of South Dobrogea; this is the youngest fault and has a major hydrogeological significance.

Experimental procedures and isotopic expression units

In order to measure the stable isotopes – oxygen-18 (^{18}O), deuterium (D or ^{2}H) and carbon-13 (^{13}C) the water samples were treated as follows:

- ^{18}O isotopic analyses were carried out by equilibrating CO_2 with the water at 25 °C;
- deuterium isotopic measurements were made by reduction of water to hydrogen by metallic uranium at 600 °C;
- for the carbon isotopic ratios the barium carbonate was treated with phosphoric acid and the carbonate samples were previously roasted at about 450 °C in a helium steam.

The oxygen, hydrogen and carbon isotopic compositions are given in the δ notation in ‰ vs. SMOW (Standard Mean Ocean Water) for $\delta^{18}O$ and δD, and in ‰ vs. PDB-1 (Pee-Dee-Belemnite) standard for $\delta^{13}C$.

VG Micromass 602 C double collector and *Varian Mat 250* mass spectrometers were used for the isotopic measurements. The accuracy of oxygen and carbon isotopic analyses is ± 0.1‰ and ±1 ‰ for the hydrogen ones.

The measurements of tritium (T or ^{3}H) in natural waters imply a previous enrichment technique; in our laboratory, the fractionated electrolytic process was used. Counting of the ^{3}H activities was achieved by the liquid scintillation technique; we successively used a *Packard 3320* and a *Beckman 5801* spectrometer.

The tritium concentrations are expressed as "tritium units" (1 TU = 0.11983 Bq/l) corresponding to a concentration of one tritium atom per 10^{18} atoms of hydrogen.

Using these preparation and measurement techniques, a minimum 5 TU detection limit and a ±10 % global accuracy are obtained in our laboratory; for the sample of 1996 a detection limit below 1 TU was reached at Thonon laboratory (France).

The radiocarbon measurements included the precipitation as $BaCO_3$ of carbonate and bicarbonate dissolved in about 200 l of water. The $BaCO_3$ obtained was converted into benzene according to the following reactive steps:

$$BaCO_3 \xrightarrow{H^+} CO_2 \xrightarrow{Li(600°C)} Li_2C_2$$
$$Li_2C_2 \xrightarrow{H_2O} C_2H_2 \xrightarrow{Pericatal.} C_6H_6$$

The benzene obtained was counted on the same liquid scintillation spectrometer like the one used for tritium activities. The radiocarbon activity is expressed as pMC (percent of modern carbon) and the significance limit is usually 2 pMC. The activity of 1 pMC represents the activity equal to 95 % of that of NBS (National Bureau of Standards) oxalic acid (1 pMC = 13.585 dpm/g C_{total}).

Isotopic Analyses Results

An integrative insight over the entire isotopic distribution contents for all water types at regional scale as average values is presented in Table 1. One may notice the good individualization of each water type.

Meteoric and surface waters

Meteoric water was sampled at Constanța meteorological station during the period 1980–1989.

Tritium was measured within this entire interval. Figure 3 shows the evolution of ^3H concentration as monthly values (inset) and annual weighted averages; the annual values of Vienna and Bucharest stations were added only for an easy comparison. At Constanța station a normal annual distribution of concentrations according to seasonality may be noticed; also, for all stations there is a decreasing trend and a very good correlation to the experimental curves, which may be a consequence of the same continental conditions.

Table 1. Comparative average isotopic composition of the main water types in South Dobrogea: May 1986.
Composition isotopique moyenne comparative des principaux types d'eaux dans la Dobrogea du Sud en mai 1986.

Water type	N*	^3H (TU)	δD (‰)	$\delta^{18}O$ (‰)	^{14}C (pMC)	$\delta^{13}C$ (‰)
Meteoric water	1	31	–59.1	–9.0	—	—
Danube River	3	38	–64.8	–10.1	—	—
Black Sea	2	28	–23.0	–3.6	—	—
Upper aquifer	12	15	–66.1	–10.0	43.2	–10.6
Lower aquifer	27	<5	–78.0	–11.1	18.4	–7.8

* number of sampled points.

For stable isotopes, D and ^{18}O, 40 monthly samples were collected between 1983 and 1987. The regression line (Fig. 4), defined by the equation $\delta D = 7.12 \times \delta^{18}O + 1.98$ is very similar to the meteoric waters line (MWL) ($R^2 = 0.92$). Also, we calculated the useful input-function as follows: $\delta D = -74.6‰$ and $\delta^{18}O = -11‰$.

Surface waters include different natural water bodies (Danube River, Black Sea, salt- and fresh-water lakes) as well as a regional network of irrigation or transport channels.

Since these waters partially constitute the recharge, they were systematically sampled, with the same annual frequency as the groundwater. Table 2 includes the results for 1974, 1986 and 1996, and Figure 5 shows the δD–$\delta^{18}O$ diagram for the results obtained in 1986. It may be noticed that the stable isotope concentrations cover, at a regional scale and at the same moment, a great range of values ($\delta^{18}O = -2.8$ to -10.9 ‰ and $\delta D = -20.0$ to -68.8 ‰) reflecting the different water types. Surprisingly, for the same water body, during the 1974–1996 period, only small changes were recorded, the most important being the progressive enrichment of Lake Siutghiol that we consider to be a consequence of the draught installed over the last 30 years.

The relationship for all surface waters ($\delta D = 6.5 \times \delta^{18}O - 4.5$) is very similar to the MWL ($R^2 = 0.92$), but our experimental points are grouped into two areas: one for the waters from the Danube and all the channels and another, with less negative values, for the waters from littoral lakes and the Black Sea.

Karstic aquifers

The karstic waters, especially the lower aquifer, have been the targets of our isotopic research in the last 25 years. From the entire period, we selected three moments: 1974, 1986, and 1996, as being representative from the hydrogeological point of view and better illustrated by isotopic analyses.

The upper aquifer

The sampling of the upper aquifer began only in 1985 in a permanent network, consisting of twelve water-sampling points (boreholes, wells, and springs). Table 3 shows the results for the moments 1986 and 1996.

The zonal distributions of $\delta^{18}O$ and of radiocarbon are in agreement with the regional piezometric pattern (Fig. 6) showing gradients towards the Black Sea.

Figure 5 shows the correlation δD–$\delta^{18}O$ for the upper aquifer in 1986 and its equation: $\delta D = 9.6 \times \delta^{18}O + 18.9$; $R^2 = 0.4$. It may be noticed that the contents of stable isotopes are placed,

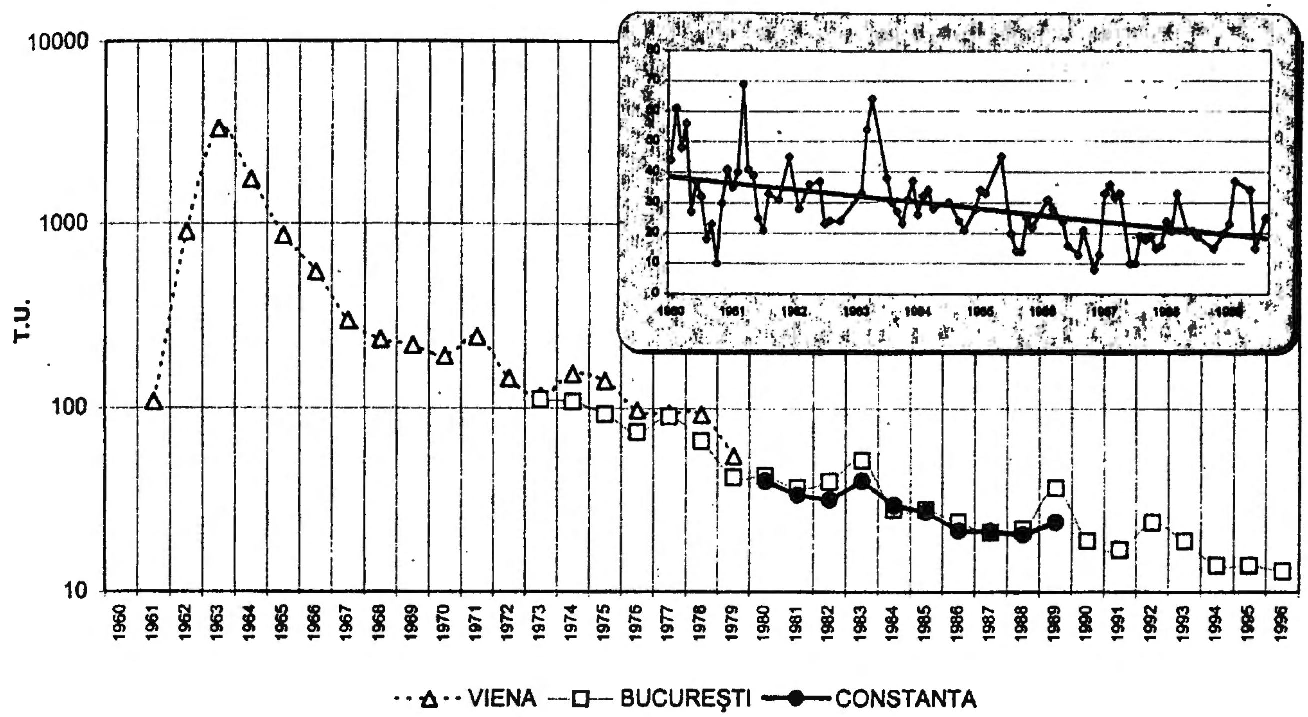


Fig. 3. Annual averages of monthly weighted tritium contents of meteoric waters in Vienna, Bucharest and Constanţa (Dobrogea, Romania) in the 1960–1996 interval (Inset: evolution of monthly values in Constanţa, 1980–1989).
Evolution des valeurs moyennes annuelles pondérées en tritium des eaux de précipitation collectées à Vienne, Bucarest et Constanţa dans l'intervalle 1960–1996 (En médaillon: évolution des valeurs mensuelles à Constanţa, 1980–1989).

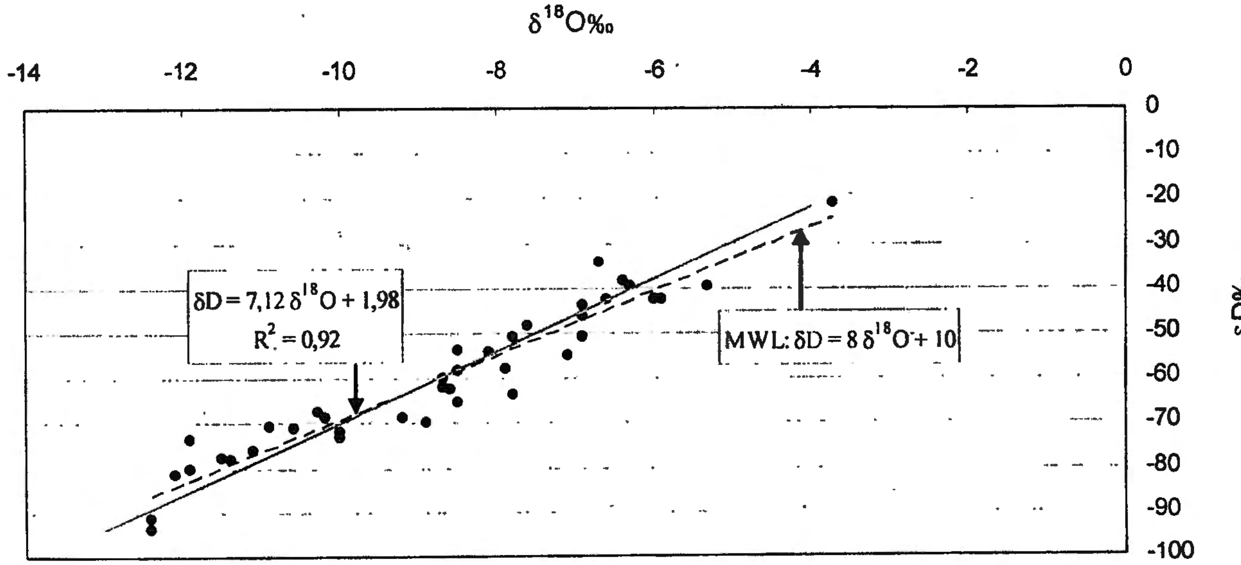


Fig. 4. δD–δ[18]O diagram for the monthly meteoric water in Constanţa (1983–1987).
Diagramme de corrélation δD – δ[18]O pour les eaux météoriques mensuelles, à la station de Constanţa (1983–1987).

Table 2. Isotopic results for the surface waters.
Résultats des déterminations isotopiques dans les eaux de surface.

Sampling point	1974 T (TU)	1974 $\delta^{18}O$ (‰)	1974 δD (‰)	1986 T (TU)	1986 $\delta^{18}O$ (‰)	1986 δD (‰)	1996 T (TU)	1996 $\delta^{18}O$ (‰)	1996 δD (‰)
S1/Danube at Cernavodă	112.3	−10.8	−59.8	41	−10.1	−68.8	14	−10.9	−58.2
S2/Danube–Black Sea Channel at Medgidia	98.7			35	−10.1	−68.0	13	−10.7	−61.1
S3/Lake Siutghiol at Mamaia Resort	90.1	−5.9	−43.3	28	−4.3	−37.8	17	−4.1	−29.6
S4/Lake Plopeni at Negreşti				30	−3.7	−34.0	11	−7.3	
S5/Danube–Black Sea Channel at Basarabi				24	−9.0	−64.8	18	−10.4	
S6/Black Sea at Mamaia Resort	43.9	−5.4	−31.8	28	−4.1	−26.1		−4.3	
S7/Black Sea at Eforie Nord Resort	35.5	−4.1	−21.6	27	−3.1	−20.0	17	−2.8	
S8/Lake Techirghiol at wharf				24	−3.2	−23.6	14		

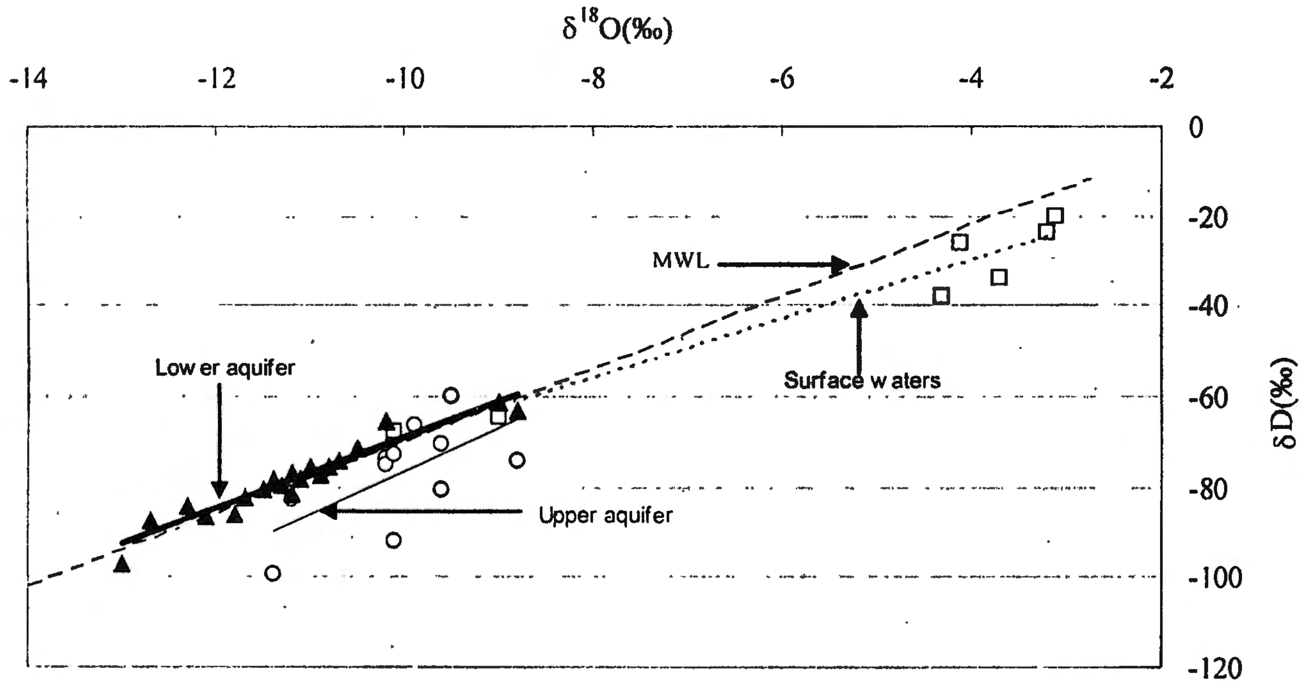


Fig. 5. δD-$\delta^{18}O$ diagram for the surface waters and groundwaters in 1986.
Key: 1. Diamonds: Surface waters: $\delta D = 6.5 \times \delta^{18}O - 4.5$, $R^2 = 0.96$; 2. Squares: the upper aquifer: $\delta D = 9.6 \times \delta^{18}O + 18.9$, $R^2 = 0.40$; 3. Triangles: the lower aquifer: $\delta D = 7.9 \times \delta^{18}O + 9.9$, $R^2 = 0.93$; MWL: Meteoric Water Line.

Diagramme de corrélation $\delta D - \delta^{18}O$ pour les eaux de surface et les eaux souterraines, en 1986. Légende: 1. Eaux de surface: $\delta D = 6.5 \times \delta^{18}O - 4.5$, $R^2 = 0.96$; 2. Aquifère supérieur: $\delta D = 9.6 \times \delta^{18}O + 18.9$, $R^2 = 0.40$; 3. Aquifère inférieur: $\delta D = 7.9 \times \delta^{18}O + 9.9$, $R^2 = 0.93$; MWL: droite générale de corrélation des précipitations mondiales.

Table 3. Isotopic results for the upper aquifer. *Résultats des déterminations isotopiques pour l'aquifère supérieur.*

No	Sampling point	1986 T (TU)	1986 ^{14}C (pMC)	1986 $\delta^{13}C$ (‰)	1986 $\delta^{18}O$ (‰)	1986 δD (‰)	1996 T (TU)	1996 ^{14}C (pMC)	1996 $\delta^{13}C$ (‰)	1996 $\delta^{18}O$ (‰)	1996 δD (‰)
1	SM18/Techirghiol–P11	8	15.7	−9.3	−10.2	−73.8	<2.4			−10.2	−97.7
2	SM19/Amzacea–P2	<5	52.4	−9.2	−10.2	−75.2	6.0			−9.9	−66.5
3	SM20/Credinţa–P1	33	85.7	−9.7	−9.5	−60.2	12.3	79.9	−10.5	−9.4	−68.1
4	SM21/Costineşti–P6	<5	19.0	−10.6	−11.2	−82.9	7.0			−11.4	−75.2
5	SM22/Dulceşti–F CAP	8	30.6	−10.4	−8.8	−74.2	11.0			−9.9	−66.8
6	SM23/Tatlageac–P3	7	17.3	−11.0	−10.1	−92.2	9.0			−10.1	−73.6
7	SM24/Chirnogeni–FCAP	10			−9.6	−80.4	7.0			−10.0	−72.3
8	SM25/Albeşti–P5	25	30.6	−10.6	−9.6	−70.5	12.0			−10.0	−70.4
9	SM26/Mangalia–P3				−11.4	−99.3	6.0			−10.5	−75.8
10	SM101/Cerchezu–well						15.1	90.7	−12.7	−9.5	
11	SM102/Băneasa–spring	9	55.7	−8.8	−10.1	−72.8					
12	SM103/Moviliţa–well	41	81.6	−10.9	−9.9	−66.5					

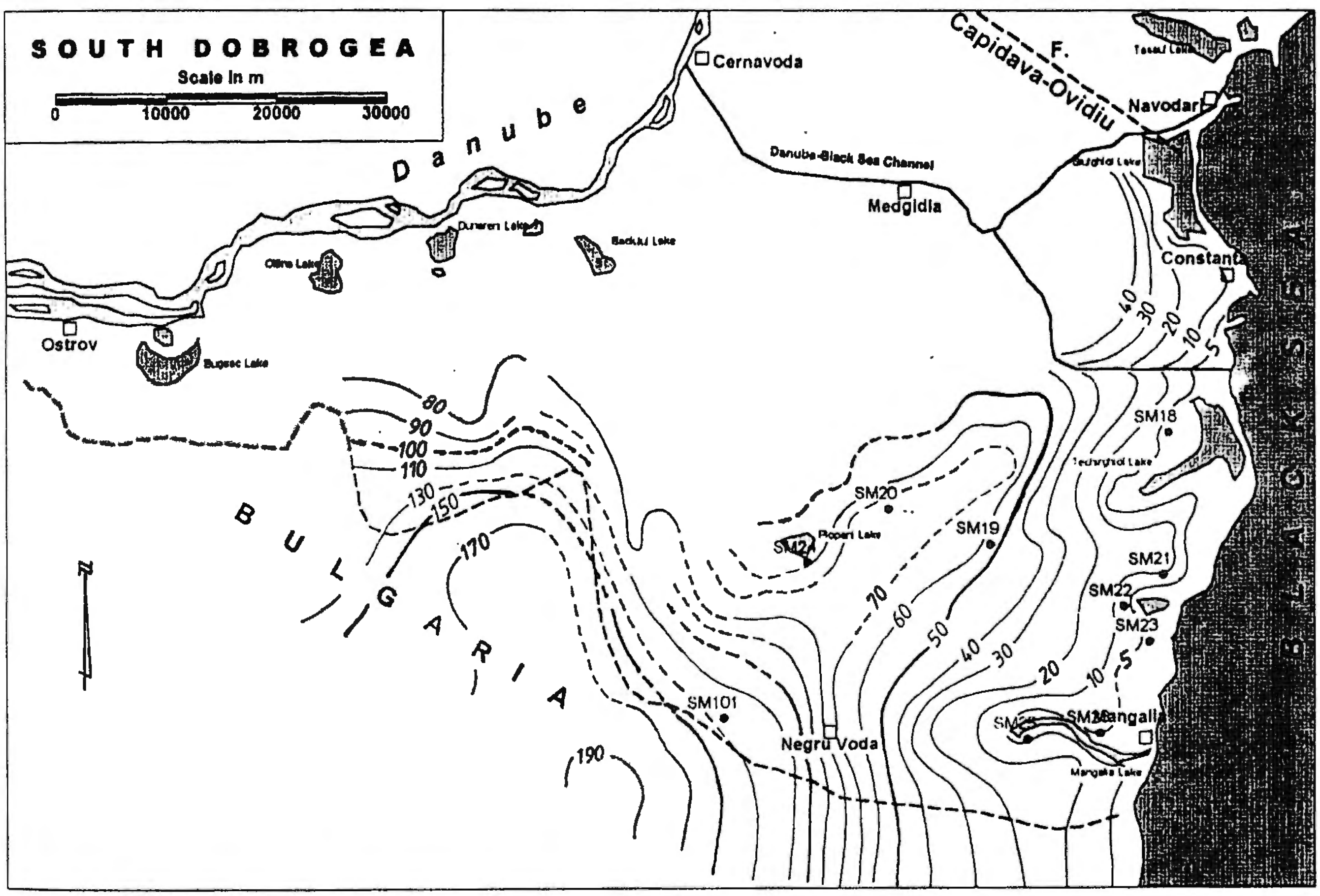


Fig. 6. Piezometric map of the upper aquifer—1986 (beyond the Romanian border, after PULIDO-BOSCH *et al.*, 1997).
Carte piézométrique de l'aquifère supérieur en 1986 (au-delà de la frontière roumaine, d'après PULIDO-BOSCH et al., 1997).

with a great dispersion, between those of the Danube and those of the lower aquifer. This dispersion is probably the consequence of two factors acting especially along the Black Sea littoral: the partially evaporated surface waters and the deeper ascending groundwater.

The lower aquifer

The study of the environmental isotopes of this aquifer began in 1974 with a few points (ŢENU *et al.*, 1975) and has yielded a first regional image of the isotopic distribution and, consequently, of the pattern flow (Fig. 7).

This regional pattern flow was confirmed later (Fig. 8), despite the fact that the piezometric surface has changed during the last 30 years (ŢENU *et al.*, 2001).

After 1982, 27 wells were selected as a permanent network for geochemical and isotopic sampling. Table 4 shows the isotopic results obtained at the three mentioned characteristic moments and Table 5 summarizes the same results but only for the three boundary areas of the aquifer.

Concerning the tritium, it may be noticed that significant concentrations were measured only for some wells situated next to the Bulgarian border, in the southwestern part of the South Dobrogea – named "recharge (SE Ostrov) area" in Table 5 - and in the East Medgidia bifurcation zone of the Danube-Black Sea Channel. Besides the information about the placement of the main intake area, these tritium values prove a good isolation over the entire area against external influences except for the east Medgidia area where there is a minor descending recharge (Fig. 9).

The ranges of stable isotopes D and ^{18}O are, more or less, the same as for other freshwaters in the region but the average values are more negative. The equation of their correlation, $\delta D = 7.9 \times \delta^{18}O + 9.9$), is practically the same as that of the MWL ($R^2 = 0.93$) (Figure 5).

The zonal distributions of the stable isotopes values were found almost unchanged within the entire research period. This stability is proved moreover by the high correlation coefficient of the $\delta^{18}O$ values ($R^2 > 0.82$) measured during a four years interval, at the same laboratory and locations. The most positive concentrations, close to the actual "input function", were registered in the southwestern part of the region, and the most negative ones along the southern Black Sea littoral. The low concentrations measured in 1974 emphasize a permanent contribution of the deeper groundwater, and therefore the great importance of tectonics in the upward leakage, especially in the Mangalia–Lake Techirghiol area.

The progressive increase of this contribution after 1974, emphasized by a decrease in contents, seems to prove that, during the last 25 years, there was a continuous overdraught which has unbalanced the natural equilibrium of the two recharge components.

For the radiocarbon in Table 4, we preferred its expression as pMC. The variation of measured ^{14}C activities for the same point is generally small excepting some areas (e.g. Lake Mangalia), where the recharge conditions have changed during the last 25 years. Therefore, all isoline maps drawn for the 1974, 1986 and 1996 (Fig. 8) moments show the same main features: a central SW–NE stripe with higher concentrations, limited by two areas in which the water shows a progressive aging towards Lake Mangalia and Cernavodă town.

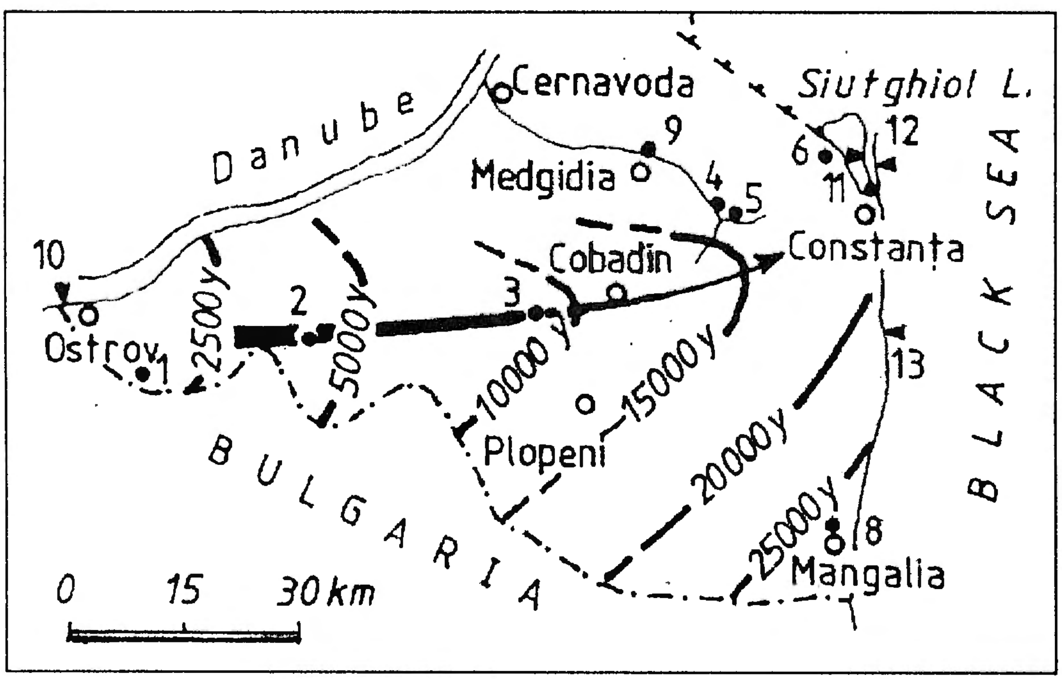


Fig. 7. Zonal distribution of ^{14}C ages for lower aquifer — 1974.
Distribution des âges ^{14}C pour l'aquifère inférieur en 1974.

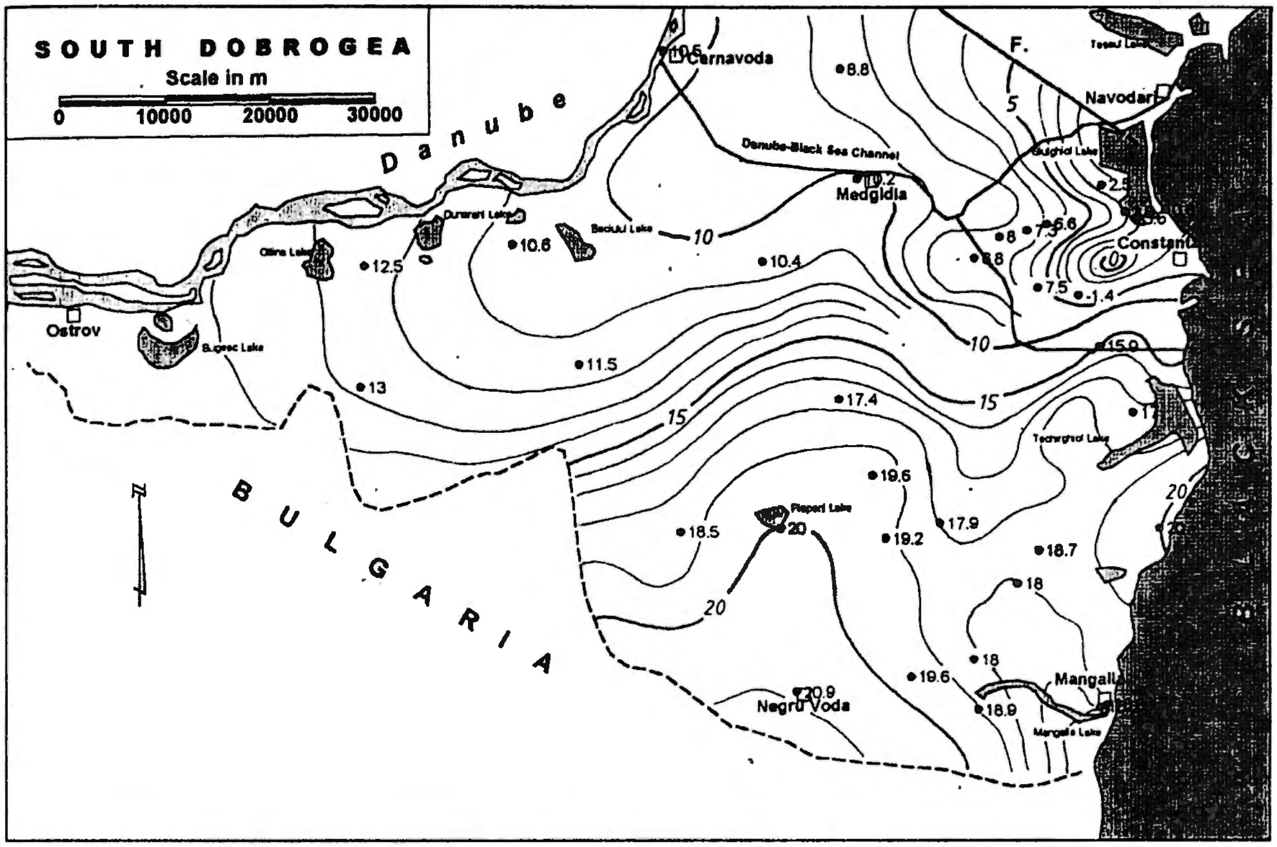


Fig. 8. Piezometric map of the lower aquifer — 1996. *Carte piézométrique de l'aquifère inférieur — 1996.*

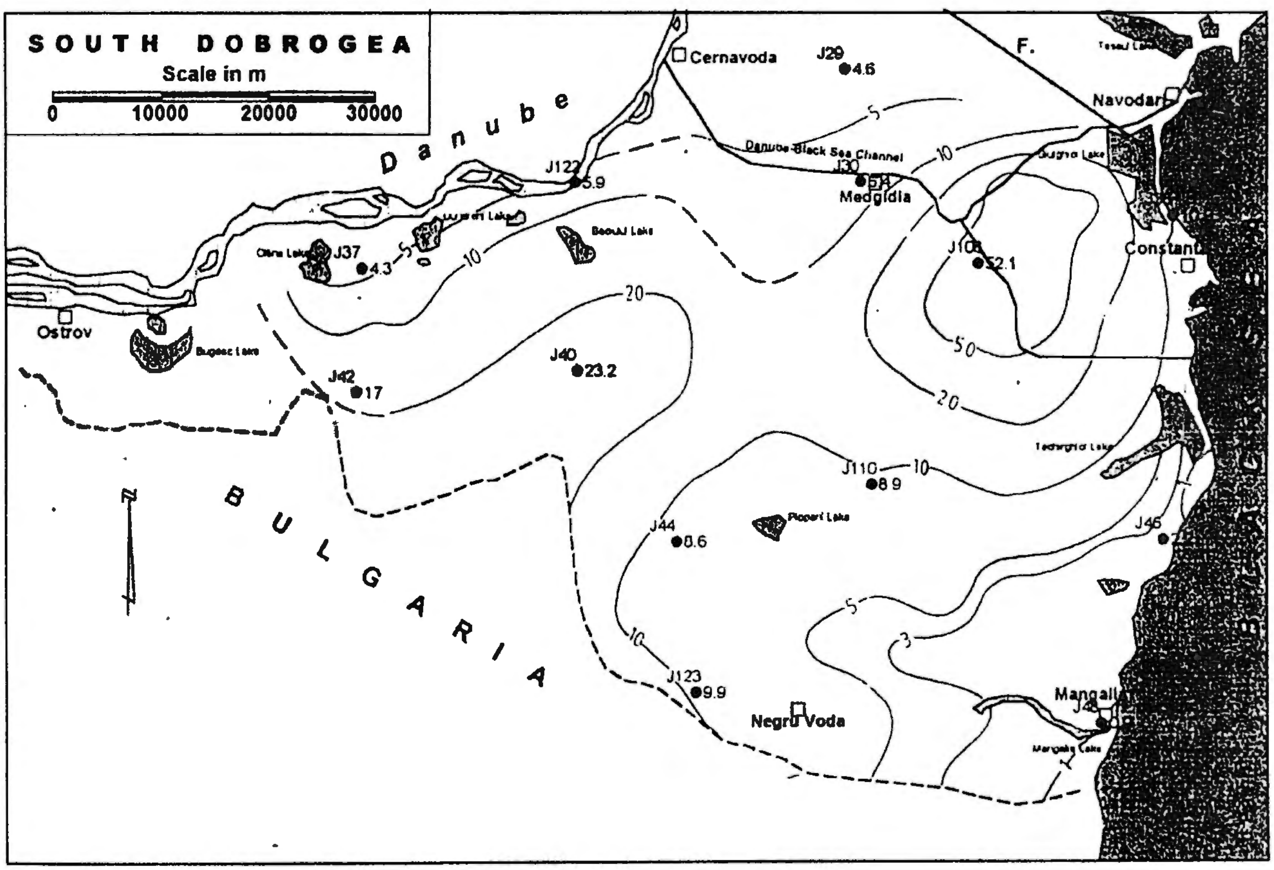


Fig. 9. ^{14}C (pMC) isoline map of the lower aquifer — 1996. *Carte des isolignes ^{14}C (pMC) pour l'aquifère inférieur—1996.*

Table 4. Isotopic results for the lower aquifer.
Déterminations isotopiques pour l'aquifère inférieur.

No.	Sampling point	1974 T (TU)	1974 ^{14}C (pMC)	1974 $\delta^{13}C$ (‰)	1974 $\delta^{18}O$ (‰)	1974 δD (‰)	1986 T (TU)	1986 ^{14}C (pMC)	1986 $\delta^{13}C$ (‰)	1986 $\delta^{18}O$ (‰)	1986 δD (‰)	1996 T (TU)	1996 ^{14}C (pMC)	1996 $\delta^{13}C$ (‰)	1996 $\delta^{18}O$ (‰)	1996 δD (‰)
1	J29/Tortomanu–F 5044						<5	5.7	−7.4	−11.7	−82.6	<0.8	4.6	−7.0	−12.2	−82.9
2	J30/Medgidia–F 5091				−11.6	−68.3	<5	7.8	−7.7	−11.3	−79.7	0.9	6.4	−6.9	−12.0	−77.7
3	J31/Poarta Alba–F 5036						<5	13.8	−7.7	−10.9	−77.4				−12.1	−83.5
4	J32/Constanţa–P7						11			−10.5	−71.6				−10.3	−73.9
5	J34/Constanţa–P10		8.2	−6.7	−12.5	−77.2	<5			−10.7	−74.2				−11.8	−83.5
6	J35/Constanţa–P1						<5	9.9	−8.1	−11.0	−75.5				−12.1	–
7	J36/Mamaia–F IMH		10.4	−7.7	−12.5	−78.8	<5	9.9	−8.0	−11.2	−77.0	<0.8	10.9	−8.2	−12.2	−86.7
8	J37/Oltina–F 5048						<5	3.8	−7.0	−11.0	−75.8	1.1	4.3	−6.8	−11.7	–
9	J38/Alimanu–F Vinalc.						<5	11.1	−7.4	−10.2	−65.7				−10.9	−76.8
10	J39/Peştera–F 5046						<5	10.6	−8.1	−11.5	−80.5				–	−88.7
11	J40/Adamclisi–F 5063						<5	22.9	−8.9	−11.2	−81.7	1.5	23.2	−8.8	−11.9	−85.5
12	J41/Gârliţa–F		82.9	−9.2	−11.0	−64.6	11	79.0	−9.4	−8.8	−63.3				−10.7	−72.0
13	J42/Băneasa–F 5062		54.8	−7.7	−11.2	−70.3	<5	17.5	−8.0	−9.0	−61.3	0.8	17.0	−8.9	−10.5	−73.9
14	J43/Dobromiru Deal–Spring						7	35.9	−8.2	−10.5	−71.6				−10.7	−70.7
15	J44/Independenţa–F 5064						<5	7.1	−8.8	−10.8	−75.8	<1	8.6	−9.3	−11.4	−76.8
16	J45/Plopeni–F 5074						<5	82.7	−10.2	−11.4	−78.3				−11.6	−82.6
17	J46/Costineşti–F 5068						<5	4.0	−1.4	−12.7	−87.7	<0.8	2.2	−6.7	−13.0	−96.4
18	J47/Negru Vodă–F 5065						<5	4.1	−7.9	−12.3	−84.1				−11.1	
19	J48/Mangalia–F 5082		4.1	−7.3	−12.8	−78.2	<5	2.9	−7.3	−12.1	−86.4	<0.8	0.9	−0.3	−13.1	−94.4
20	J108/Poarta Albă–F 5042							34.6				14.3	52.1	−8.9	−10.7	
21	J110/Ciobaniţa–F 5054											0.9	8.9	−8.4	−12.0	
22	J115/G–ral Scărişoranu–F 5066							7.9	−8.1	−11.8	−85.9					
23	J116/Cobadin–F 5067							9.5	−8.7	−13.0	−97.0					
24	J122/Rasova–2H											<0.8	5.9	−6.6	−11.4	
25	J123/Cerchezu–F 2											<0.8	9.9	−7.8	−11.6	
26	J124/Petreni–F CAP		33.5	−7.9	−11.3	−73.2										
27	J125/Castelu–F 5053							6.5	−7.2	−11.1	−78.3					

Table 5. Time evolution of isotopic results for three characteristic areas of the lower aquifer.
Évolution dans le temps des résultats isotopiques pour trois zones caractéristiques de l'aquifère inférieur.

Year	Recharge area (SE Ostrov) ^{3}H (TU)	δD (‰)	$\delta^{18}O$ (‰)	^{14}C (pMC)	$\delta^{13}C$ (‰)	Main discharge area (Lake Siutghiol) ^{3}H (TU)	δD (‰)	$\delta^{18}O$ (‰)	^{14}C (pMC)	$\delta^{13}C$ (‰)	Discharge area (Lake Mangalia) ^{3}H (TU)	δD (‰)	$\delta^{18}O$ (‰)	^{14}C (pMC)	$\delta^{13}C$ (‰)
1974		−64.6	−11.0	82.9	−9.2		−78.8	−12.5	10.4	−7.7		−78.2	−12.8	4.1	−7.3
1986	11	−63.3	−10.8	79.0	−9.4	<5	−77.0	−11.2	9.9	−8.0	<5	−86.4	−12.1	2.9	−7.3
1996	6	−72.0	−10.7			<1	−86.7	−12.2	10.9	−8.2	<1	−94.4	−13.1	0.9	−0.3

For the first two stages, 1974 (ŢENU *et al.*, 1975) and 1986 (ŢENU *et al.*, 1987), our results — as well as the total radiocarbon data existing in the hydrogeological literature — were expressed as radiometric ages and they have been corrected only for A_0', the initial ^{14}C concentration.

These "uncorrected" or "partially corrected" values led to an overestimation of the groundwater ages and implicitly to the underestimation of the flow velocities. A "complete ^{14}C correction" by evaluating a total retardation factor such as for the isotopic exchange reactions during the underground movement of the water as well as for the delay caused by the diffusion exchange between the fissures and matrix, was carried out for South Dobrogea by ŢENU & DAVIDESCU (1996).

The actual velocities obtained in this way: 500 to 1,800 m/year for the central stripe, and only less than 100 m/year in the Lake Mangalia area, differ up to two orders of magnitude from the values previously obtained. Despite the fact that few hydraulic flow directions were found ("no radiocarbon flow direction"), these values are in agreement with the velocities hydraulically calculated suggesting that they are close to the "true values".

The regional conceptual model for the lower aquifer can be synthesized by some main isotopic features as follows (Fig. 10):

- **recharge area:** mainly in the Pre-Balkan Platform (Bulgaria);

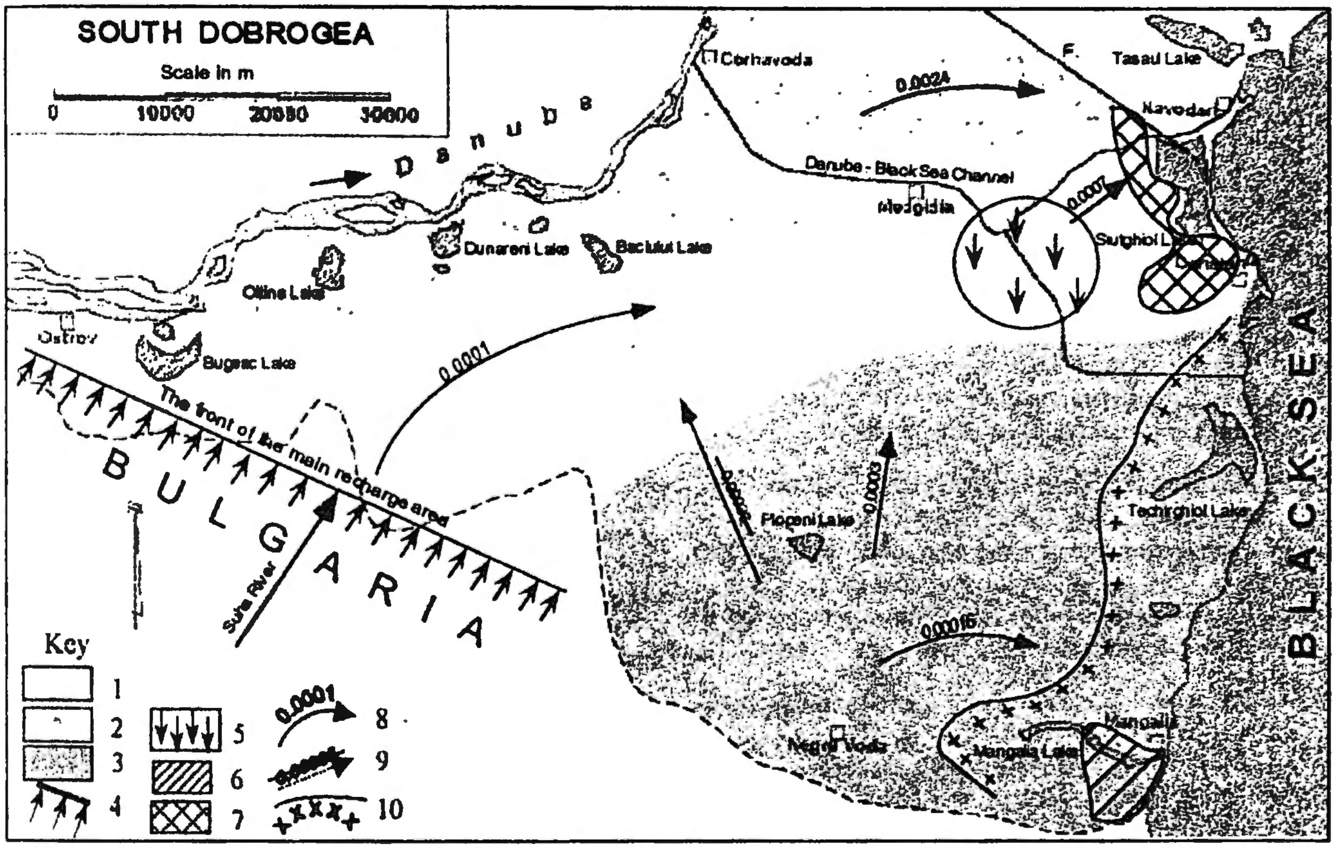


Fig. 10. Hydrogeological conceptual model of the lower aquifer, updated for 1996. Key: *Aquifer type*: 1. Shallow groundwater (^{14}C = 20–50 pMC, ^{3}H = 0.8–14.3 TU); 2. Partially confined aquifer (locally covered by the Lower Cretaceous acvitard: ^{14}C = 5–10 pMC, ^{3}H = < 0.8–1,1 TU); 3. Confined aquifer covered by the intermediate complex acvitard: ^{14}C = 1–10 pMC, ^{3}H = < 0.8 TU); *Recharge*: 4. The front of the main recharge area; 5. Adventive recharge (by surface water) area; *Drainage:* 6. Natural drainage area (Np below + 17 m); 7. Major (natural and anthropic conditioned) discharge area (Np below + 2m); *Groundwater hydraulics:* 8. Flow direction of groundwater, confirmed by isotopic means and the value of hydraulic gradient; 9. Flow direction of groundwater, suggested by underground hydraulic information but non-confirmed by radiocarbon; 10. Zero line of the area having the piezometric head above the upper aquifer (up to 15 m).

Modèle hydrogéologique conceptuel de l'aquifère inférieur, actualisé pour l'année 1996. Légende: Types de nappes: *1. Nappe libre (^{14}C = 20–50 pMC, ^{3}H = 0,8–14,3 TU); 2. Nappe partiellement captive (couverte localement par l'aquitard du Crétacé inférieur: ^{14}C= 5–10 pMC, ^{3}H = < 0,8–1,1 TU); 3. Nappe captive (couverte par le complexe aquitard intermédiaire; ^{14}C = 1–10 pMC, ^{3}H = < 0,8 TU);* Recharge: *4. Front principal de recharge; 5. Aire de recharge adventive par des eaux de surface;* Drainage: *6. Aire de drainage naturel (Np au dessous de + 17 m); 7. Aire majeure de drainage naturel et artificiel (Np au dessous de + 2m);* Hydraulique souterraine: *8. Direction d'écoulement des eaux à travers l'aquifère, confirmé isotopiquement et la valeur du gradient hydraulique; 9. Direction d'écoulement des eaux à travers l'aquifère, déduite hydrauliquement mais infirmé par radiocarbone; 10. Ligne zéro pour l'aire ayant des niveaux piézométriques plus élevés (jusqu'à 15 m) que l'aquifère supérieur.*

- **recharge water**: precipitation, runoff, small rivers and probably from the Danube;
- **groundwater flow**: the main direction is east-northeast, towards Lake Siutghiol and the secondary is southeastward, towards Lake Mangalia;
- **other inputs**: upward leakage in the Lake Techirghiol –Lake Mangalia area and a minor descending recharge in East Medgidia area;
- **flow velocities**: 500-1,800 m/year on the main groundwater flow and up to 100 m/year on the secondary one.

Conclusions

The long term isotopic survey of the waters from South Dobrogea allowed the achievement of a comprehensive isotopic database, as well as an integrative insight over all water types and their relationships. Special attention was given to the karstic system, including their hydrodynamic parameters and the assessment of vulnerability, the most important being the lower aquifer for which an improved model was achieved.

For the meteoric waters, both the tritium mean monthly concentrations and the D and ^{18}O concentrations were determined, through multiannual analyses. The isotopic mark was identified at Constanţa station. They were used in studying the inter-relations of these waters with the surface waters (especially littoral lakes) or the groundwater in the region.

For the surface waters, the environmental isotopes (^{3}H, D and ^{18}O) were analyzed. An important characteristic feature of the region is the great range of values for stable isotopes: $\delta^{18}O$ vary from −2.8 to −10.9 ‰ and δD from −20.0 to −68.8 ‰, a consequence of the very different genetic types of water (the Danube, the Black Sea, lakes).

Besides the great utility of these data in establishing the groundwater recharge model, the enrichment in D and ^{18}O of Lake Siutghiol points out the regional draught that extended over the last 30 years.

For the upper aquifer, the tests started in 1985 and have been performed up to present-day covering all the range of environmental isotopes. The zonal isotopic distributions are in agreement with the regional piezometric pattern, showing gradients towards the Black Sea.

For the lower aquifer, the tritium measurements have proved, that the recharge area of the aquifer is located in the southeast of Ostrov area and, generally, it is well protected from external influences.

Both spatial distribution and the correlative relation of the stable isotopes agree with the results of ^{3}H measurements concerning the recharge area. At the same time, they have pointed out the contribution of the deeper groundwater and therefore the great importance of tectonics in the upward leakage, especially in the Mangalia – Techirghiol area. At a regional level, the distribution of stable isotopes values was found almost unchanged during the entire research period.

For radiocarbon, the variation of measured ^{14}C activities at the same points was generally small, except for the Lake Mangalia area; here the variations were assigned to both tectonic reasons and to the continuous local overdraught which has unbalanced the natural equilibrium of the two recharge components. All ^{14}C-isolines regional maps show the same main features: a central SW–NE stripe with higher concentrations, limited by two areas in which the water shows a progressive ageing towards Lake Mangalia and Medgidia town, respectively.

The regional model based on the isotope studies can be thus synthesized by the existence of a Pre-Balkan Platform recharge area, a groundwater flow direction mainly oriented towards the Siutghiol Lake and a flow velocity of 500–1,800 m/year.

References

Pulido-Bosch, A., Machkova, M., López-Chicano, M., Calvache, M.L., Dimitrov, D., Calaforra, J.M., Velikov, V., & Pentchev, P. (1997) Hydrogeology of the upper aquifer, Dobrich region, northeastern Bulgaria. *Hydrogeology Journal*, **5**, pp.75–85.

Ţenu, A. (1973) Exemples d'application des isotopes du milieu dans l'hydrogéologie roumaine. *Meteorology and Hydrology*, **2**, pp. 21–31.

Ţenu, A. & Davidescu, F. (1996) Some considerations about radiocarbon method in carbonate fissured aquifers. *Acta Geologica Hungarica, (39 Supplementum) Isotope Workshop III, Budapest*, pp. 186–190.

Ţenu, A., Noto, P., Cortecci, G., & Nuti, S. (1975) Environmental isotopic study of the Barremian-Jurassic aquifer in South Dobrogea (Romania). *J. of Hydrology*, **26**, pp. 185–198.

Ţenu, A., Davidescu, F., & Slăvescu, A. (1987) Recherches isotopiques sur les eaux des formations calcaires dans la Dobroudja Méridionale (Roumanie). *Isotopes Techniques in Water Resources Development, Proc. of IAEA Intern. Symp.*, Vienna, pp. 439–443.

Ţenu, A., Davidescu, F., Petreş, R., & Stănescu, G. (2001) Variation des ressources souterraine du Dobrogea du Sud (Roumanie), effet conjugué des causes climatiques et anthropiques. *Regional Management of Water Resources, Proc. of symp. Sixth IAHS, Maastricht*, **268**, pp. 131–137.

received: 5 July 2002
revised: 18 October 2002
accepted: 13 November 2002

Theoretical and Applied Karstology, 15 (2002), pp. 73–91

Biokarst on a tropical carbonate island: Guam, Mariana Islands

Danko Taboroši *

Laboratory of Geoecology, School of Environmental Earth Science, Hokkaido University, N-10, W-5, Sapporo, 060-080 Hokkaido, Japan.

Abstract

"Biokarst" refers to erosional and depositional karst features formed by direct biologic action. However, since no distinct karst landform is produced exclusively by biologic action, most features known as biokarst are actually products of both biotic and abiotic processes operating concurrently in intricate interrelationships. Although biokarst landforms are often regarded as features of local interest and limited significance, the effects of living organisms on karst geomorphology are profound on an ecosystem scale, and are widespread, diverse and of fundamental importance. This is especially true in tropical and coastal environments, where the biologic influence on karst is so common and intense that it makes the distinction between "biokarst" and "non-biokarst" thoroughly impracticable. A survey of karst on Guam has confirmed that nearly all of the small- and medium-scale karst features documented on the island are affected by biota, and bear characteristics of what has been termed biokarst.

Keywords: biokarst, phytokarst, carbonate island, Guam.

Biokarst dans une île tropicale calcaire: le Guam, archipel des Mariannes

Résumé

Le terme «biokarst» se réfère aux formations karstiques d'érosion et de dépôt formées par action biologique directe. Pourtant, comme il n'existe aucun phénomène karstique produit exclusivement par action biologique, la plupart des formes connues comme «biokarst» sont en réalité des produits des processus biotiques et abiotiques qui agissent de concert. Bien que les formations biokarstiques soient considérées souvent comme ayant des significations et des intérêts limités, les effets que les êtres vivants ont sur la géomorphologie du karst à l'échelle de l'écosystème sont profonds: en même temps, ils sont divers, généraux, et ont une importance fondamentale. Ces considérations sont valables surtout dans les zones tropicales et côtières, où l'influence biologique sur le karst est si commune et intense, qu'elle rend impossible toute distinction entre «biokarst» et «non-biokarst». Un examen du karst de Guam a confirmé que presque toutes les formes karstiques de dimensions petites ou moyennes sont affectées biologiquement et qu'elles gardent l'empreinte de ce qu'on a appelé «biokarst».

Mots-clés: biokarst, phytokarst, île calcaire, Guam.

Introduction

The term "biokarst" refers to erosional and depositional karst features produced by direct biologic action (Viles, 1984). The precursory term "phytokarst" was coined by Folk *et al.* (1973) to refer to extremely jaggedly dissected limestone pinnacles in the Cayman Islands. They recognized that the pinnacles were covered by a coating of filamentous cyanobacteria and proposed that algal boring was responsible for the observed geomorphology. The term phytokarst was later applied by other researchers to a variety of dissimilar features in which biologic action was suspected. Bull & Laverty (1982) tried to organize all biologically mediated karst features under the term phytokarst, which they redefined as *sensu lato*, and grouped them into *biolithogenic*, *destructive* (erosional), *physical* (tectonic), and *constructive* (depositional) types. The term phytokarst was later replaced by biokarst (Schneider & Torunski, 1983) to recognize the involvement of organisms other than plants.

* corresponding author. *E-mail address*: danko@ees.hokudai.ac.jp

The organisms whose effects on limestone have been studied include bacteria (e.g., Smyck & Drzal, 1964; Sand *et al.*, 1991; Castanier *et al.*, 1999), cyanobacteria (e.g., Viles, 1987; Merz, 1992; Schneider & Le Campion Alsumard, 1999), fungi (e.g., De la Torre *et al.*, 1993), algae (e.g., Kobluk & Risk, 1977), lichens (e.g., Acsaso *et al.*, 1982; Chen *et al.*, 2000), plants (e.g., Herwitz, 1993; Wall & Wilford, 1966), terrestrial and freshwater invertebrates (e.g., Stanton, 1984; Drysdale, 1998), marine invertebrates (e.g., Schneider & Torunski, 1983; Trudgill, 1987; Albergaria Moreira, 1996), and vertebrates (e.g., Hooper, 1958; Miller, 1990; Butler, 1995). A similarly wide range of processes (depositional, diagenetic, and erosional) and karst phenomena is affected by biota. This includes travertine (e.g., Casanova, 1981; Bayari *et al.*, 1994; Drysdale, 1999), calcrete (e.g., Khadkikar *et al.*, 2000; Alonso *et al.*, 1998; Klappa, 1979), beachrock (e.g., Webb *et al.*, 1999), karst breccia (Jones & Kahle, 1985), desert stromatolites (e.g., Krumbein & Gielf, 1979), tufa (e.g., Ford, 1989; Pentecost, 1985), speleothems (e.g., Barton *et al.*, 2001; Went, 1969; reviewed in Forti, 2001), cave wall deposits (e.g., Cañveras *et al.*, 2001), moonmilk and related features (e.g., Northup & Lavoie, 2001; Jones, 2001; Caumartin & Renault, 1958), limestone pavement (e.g., Jones, 1965; Verrecchia, 1990), coastal karrenfelds (e.g., Folk *et al.*, 1973), solution runnels (Fiol *et al.*, 1996), solution basins (e.g., Moses & Smith, 1993), smooth surfaces and pits (e.g., Danin, 1983), karst pinnacles (e.g., Zhang & Bao, 1994), shafts (e.g., Tricart & DaSilva, 1960), soil pipes (e.g., Walsh & Morawiecka-Zacharz, 2001), etc.

Such an incredible diversity of organisms, processes, and landforms involved clearly indicates the high incidence and complexity of biologic influences on karst geomorphology. This is, perhaps, nowhere as clear as it is in tropical and coastal settings, where nearly all karst features are profoundly affected by biologic processes. The purpose of this paper is to illustrate the widespread influence of biota on karst geomorphology in tropical and coastal environments by providing examples from Guam. A survey of exokarst features on the island has revealed that nearly all small- and medium-scale features documented are affected by biologic processes, and bear characteristics of what has been termed "biokarst".

Nonetheless, landforms commonly referred to as biokarst are also profoundly affected by inorganic processes. Biologic action, however intense, is typically just one of the factors involved in shaping a particular geomorphic feature, and organic processes operate concurrently in intricate interrelationships with various inorganic processes to produce any given landform. In the most thorough review of the subject, Viles (1988) states that no one distinctive landform can be related directly to biologic action, and that biologic and inorganic processes interact and occasionally outweigh each other. To support and illustrate this statement by examples from Guam is the second aim of this paper, which reviews various biokarst features and discusses both biologic as well as inorganic processes associated with them.

Finally, the observations presented contribute new data to knowledge of the global distribution of various karst phenomena.

Study area

Guam, the largest (549 km^2) and southernmost of the Mariana Islands (Fig. 1), is elongate in shape, 48 km long, and 6–19 km wide. It is divided into two parts by the Pago-Adelup Fault: *southern Guam*, a rugged volcanic highland with several limestone outliers; and *northern Guam*, an undulating limestone plateau fringed by precipitous coastal cliffs, locally fronted by a narrow coastal plain. In northern Guam, Late Miocene volcanic basement units are overlain by detrital Mio-Pliocene Barrigada Limestone. It extends to the surface in the interior of northern Guam, but elsewhere grades laterally and upwards into the Plio-Pleistocene Mariana Limestone, a reef and lagoonal deposit dominating the northern plateau and east coast of southern Guam. In southern Guam, volcanic units dominate much of the terrain, and are locally overlain by Miocene Bonya and Alifan limestone outliers. The principal geologic reference for Guam is still the USGS report by Tracey *et al.* (1964), which includes a 1:50 000 scale geologic map.

Karst features of Guam can be grouped into three broad categories: *surface features* (the epikarst, closed contour depressions, and features related to surface flow), *caves* (pit caves, stream caves, and flank margin caves), and the *discharge features* (coastal and submarine springs and seeps). In northern Guam, the karst is typical of carbonate island karst (Mylroie & Carew, 1997), whereas the karst of the southern highlands resembles that of the tropical continental settings. A comprehensive inventory of the karst features of Guam was carried out by Taboroši (2000). Mylroie *et al.* (2001) amended this work by describing the karst geology of Guam in terms of the Carbonate Island Karst Model (CIKM), a general model of carbonate island karst (Mylroie & Vacher, 1999).

The climate of Guam is tropical wet/dry, with an equable mean annual temperature of 27 °C. January through May is the dry season, broken by occasional showers. The wet season lasts from July to November, during which heavy rains and tropical storms are common. The mean annual precipitation averages 215–250 cm/year (Lander, 1994). Northern Guam has no perennial streams and its vegetation is dominated by a thick shrub jungle in the undeveloped portions of the plateau and limestone forests in the coastal plains. The rugged uplifted volcanic highlands of southern Guam are dominated by deeply incised river valleys and grassland vegetation, with shrub vegetation associated with limestone outliers.

Biokarst Features on Guam

Karst features known to be biologically produced, mediated, or influenced encompass nearly all of the small- and medium-scale exokarst features on Guam. They occur in a wide range of environments, including coastal (reefs, intertidal benches

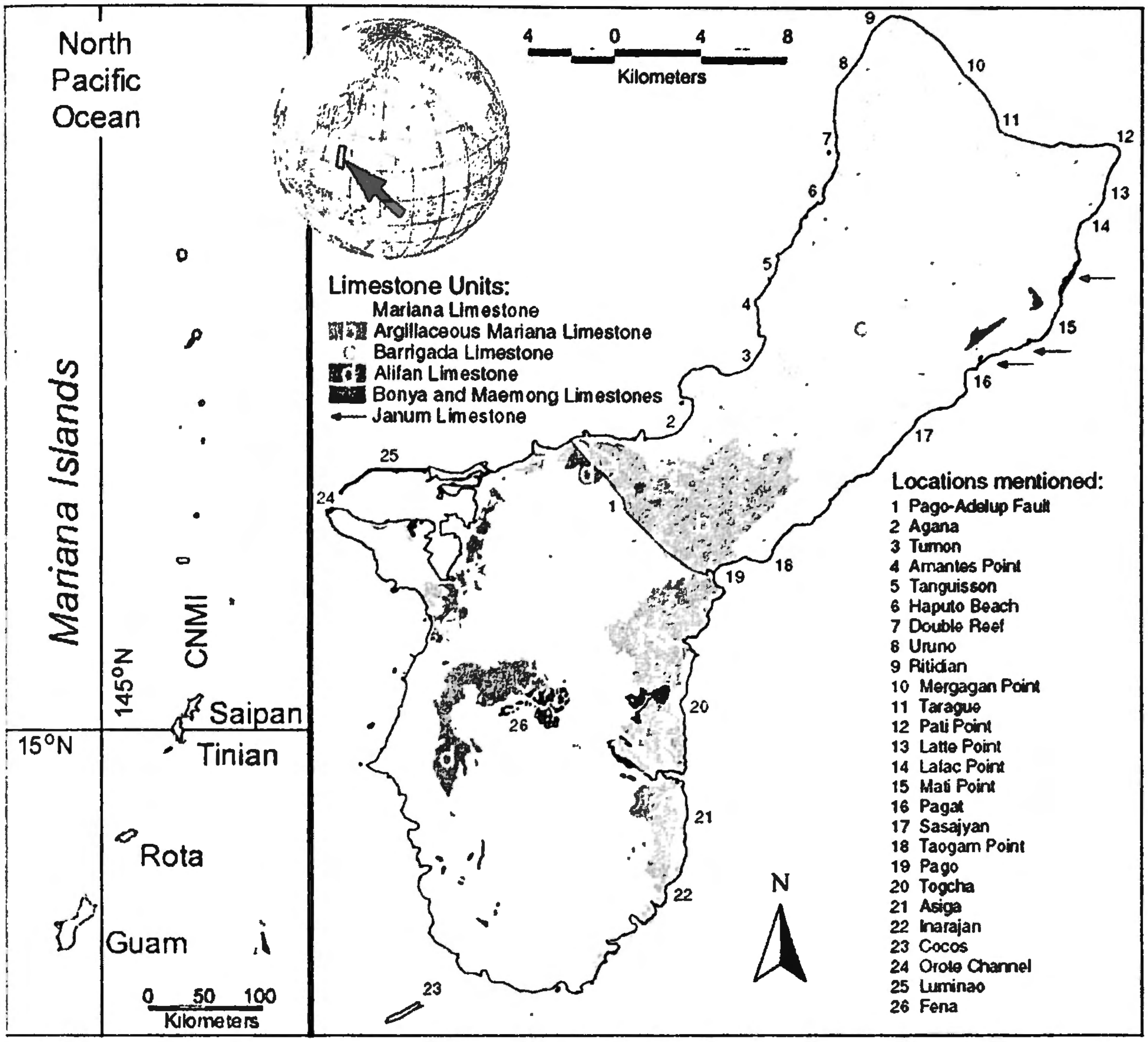


Fig. 1. Location of Guam, with a simplified geologic map showing locales mentioned in text.
Situation du Guam et carte géologique simplifiée, avec les localités citées dans le texte.

and terraces, marine notches, beachrock, etc.), epikarstic (karren, solution pans and pits, soil pipes, etc.), and hypogean (caves and cave deposits) (Fig. 2). The following discussion includes several landforms that are not intrinsically karst, such as coral and algal reefs and beachrock deposits, but which become thoroughly karstified and form an integral part of karst systems on carbonate islands. Although not karst features *per se*, they may be considered biokarst, as the latter is not limited to disolutional features but also includes depositional and biolithogenic structures.

Reefs

Coral and algal reefs are not karst features but bioconstructed deposits. Nevertheless, they have been referred to as examples of depositional biokarst (Viles, 1984) and are included in this discussion because of the important role they play on tropical carbonate islands. They are not only found on most such islands, but also represent their principal builders. The entire northern half of Guam is an uplifted Plio-Pleistocene reef, whereas the southern half contains several smaller uplifted Plio-Pleistocene and Miocene reefs. Modern fringing reefs almost entirely surround Guam, being absent only in those parts of the northeastern coast dominated by sheer cliffs. The reefs range in width from narrow benches spanning a few meters across, to broad reef flats that are up to 800 m wide. The largest reef flats have developed within the coastal embayments of Agana, Tumon, Tanguisson, Tarague, Pago, and Togcha. In addition to fringing reefs, there are two barrier reefs on Guam: Cocos, which fully encloses a large lagoon (7.5 km^2); and Luminao, which partially encloses a smaller one. The geomorphology of modern reefs on Guam has been discussed by Easton *et al.* (1978), Randall & Holloman (1974), and Randall & Siegrist (1988). Riding (2002) has provided a review and classification of organic reefs in general.

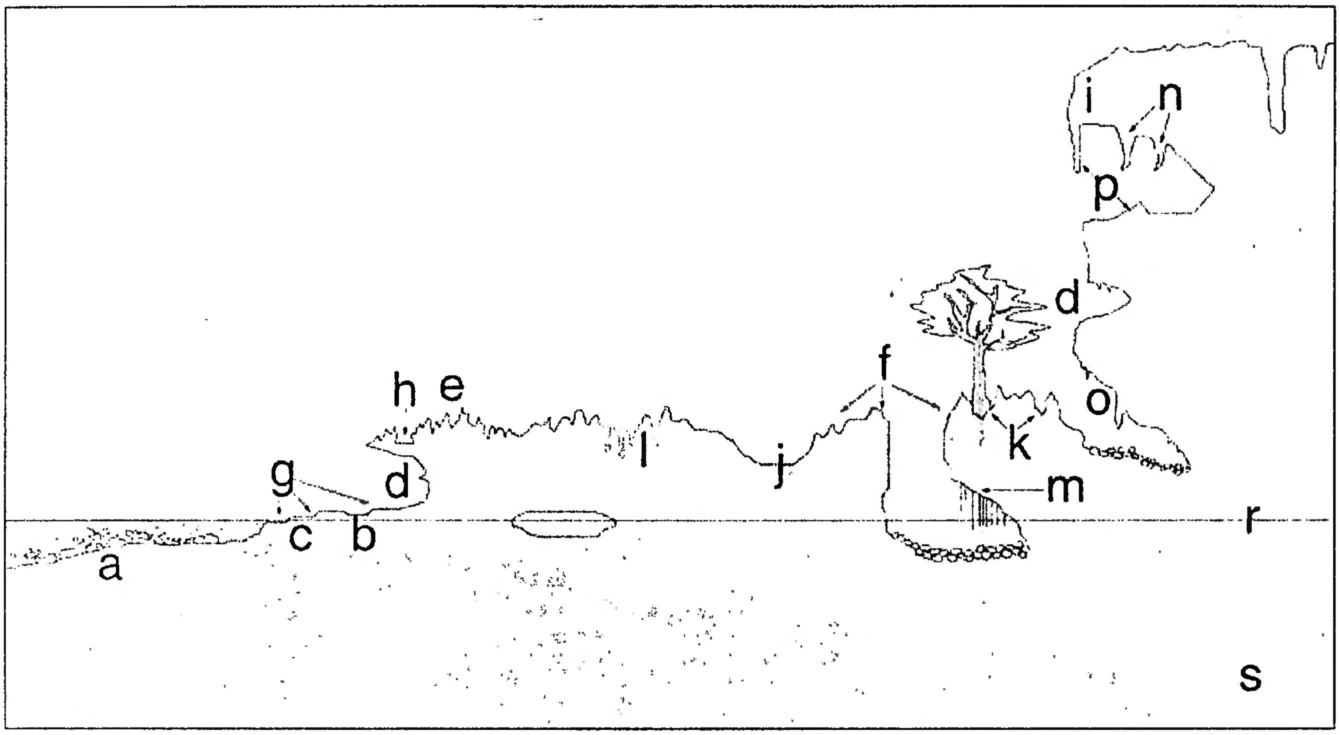


Fig. 2. Bioconstructed landforms and biologically produced, or influenced karst features on Guam: a. fringing reef; b. intertidal bench; c. rimmed terraces; d. marine notches; e. champignon surfaces and karrenfelds; f. karren; g. bioerosional karren; h. solution pans; i. case hardening on cliff faces; j. calcrete; k. solution pits; l. soil pipes; m. root holes; n. tufaceous stalactites; o. "directed phytokarst"; p. moonmilk; r, s. oxidation of organic materials accumulated at the freshwater lens pycnoclines enhances dissolution; not shown are beachrock, root grooves, rhizoliths, and freshwater tufa..

Formes de relief bioconstruites et formes karstiques produites ou influencées biologiquement de Guam: a. récif; b. plage intertidale; c. terrasses «en gours»; d. encoches marines; e. surfaces «en champignon» et table de lapiés; f. lapiés; g. lapiés de bio-érosion; h. kamenitza; i. encroûtement de surface sur abrupt calcaire; j. caliche; k. puits de dissolution; l. crypto-karst; m. trous de racines; n. stalactites tufières; o. «phytokarst directionnel»; p. mondmilch; r, s. l'oxydation de la matière organique accumulée au contact entre l'eau douce et l'eau saline augmente la dissolution; les cannelures de racines, les rhysolithes et le tuf calcaire d'eau douce ne sont pas représentés dans la figure.

Intertidal benches and rimmed terraces

In addition to coral reefs, there are other types of bioconstructional activity taking place along the rocky carbonate coastlines of tropical islands, particularly in the intertidal and shallow subtidal zones (Spencer & Viles, 2002). Some of the resultant structures are known as intertidal benches, surf benches, cornices, and trottoirs (Focke, 1978) and are constructed by coralline algae, vermetid molluscs and serpulid worms (Dalongeville, 1995). On Guam, such benches are found along nearly the entire rocky limestone coastline of the island. They are situated just below the mean sea level, separate the coastal cliffs from the deep water or fringing coral reefs, and range in width from less than a meter to over 20 m wide. Very narrow benches are found in areas sheltered by fringing reefs and are interpreted as portions of bedrock left by the retrogression of associated marine notches. The wider benches are found in areas where the absence of fringing reefs has resulted in vigorous surf action at the shore, and are thought to be bioconstructed by coralline algae and vermetid molluscs. Guam's intertidal benches can be followed along the coast for many kilometers and are locally interrupted by sea caves, large fractures, coves and sandy beaches. They are generally flat-floored, but locally contain numerous potholes, primary "reef caves", and blowholes spouting seawater pushed in by waves. In areas of particularly energetic surf, the algal and vermetid bioconstructions are locally discontinuous with the coastal cliffs, forming small platforms up to 15 meters away from the coast, in addition to the coastal bench.

Intertidal benches are commonly separated by networks of algal and vermetid rims into individual shallow basins filled by seawater, intermittently pushed in by waves. The basins are generally a few meters across and up to 20 cm deep, and are set apart by rims of comparable height and width. They can be quite spectacular, and the largest basins can reach up to 10 m across and 2 m deep, surrounded by taller rims up to 50 cm wide. The basins are commonly arranged in a step-like pattern, forming series of pools, bounded on one side by the wall of the next higher rimmed basin and elsewhere by a low rim or coastal cliff. The top pool in each series is generally located near the highest point that can be reached by waves or sea spray on a relatively calm day, allowing seawater pushed in by waves to cascade over the rims from one pool to another. Such

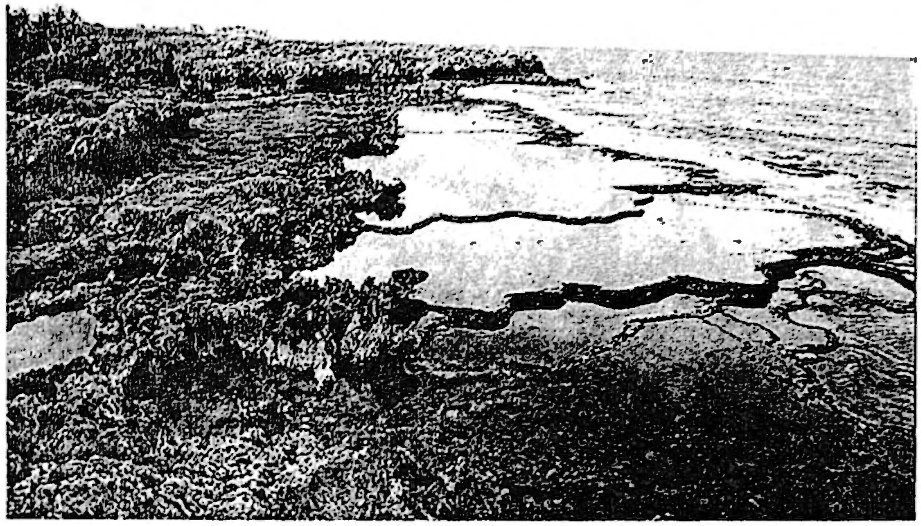


Fig. 3. Rimmed terraces on the intertidal bench in Inarajan.

Terrasses «en gours» sur la plage intertidale de Inarajan.

pools have been termed rimmed terraces (EMERY, 1962) and are reminiscent of geyserite terraces. Their origin is debatable. In addition to bioconstruction by algae, a combination of other processes is probably involved, including bioerosion, dissolution by agitated seawater, and physical abrasion. The best examples of rimmed terraces on Guam are found between Haputo Beach and Double Reef, between Lafac Point and Latte Point, and in Inarajan (Fig. 3); while Pati Point exhibits unusual paleo-rimmed terraces. Although located in the supratidal zone, about two meters above mean sea level and splashed by extremely vigorous wave action, the rims of the Pati Point terraces are inexplicably devoid of living algae and are heavily dissected by dissolution. Similar extremely dissected rims have been observed on Tinian, an island north of Guam, where they are also highly localized and found only in areas of most extreme surf.

Marine notches

Marine notches are cut into the bedrock of rocky coasts and extend parallel to the sea level. They form best in limestone, but are locally present in non-limestone coastlines as well, indicating that they are not exclusively karst features. On Guam, marine notches are found in most of the coastal limestone cliffs (Fig. 4), and were first described by STEARNS (1941). The notches associated with the modern sea level extend along the entire rocky shoreline of Guam. Their profile is generally semicircular, about 2 m in vertical and horizontal dimensions, although variable widths and irregular profiles are also common. The notches tend to have inclined floors leading upward from the intertidal algal benches and inclined or flat roofs. Apices are locally present in the back walls, roughly half way between the roofs and the notch floors. In limestone blocks discontinuous with the coast, the circumferential marine notch at sea level results in a mushroom or pedestal rock form. The best examples of such features are found in Orote Channel and the Tanguisson and Haputo areas. Notches above the modern sea level are associated with paleoshorelines (DICKINSON, 2000) and are preserved only locally, the best examples being found in the cliffs at Amantes, Mergagan, Latte, and Mati points.

The development of marine notches is commonly dominated by bioerosion (PIRAZZOLI, 1996). The organisms thought to be instrumental in the development of marine notches on Guam include limpets (e.g. *Patelloida chamorrorum*), chitons (e.g. *Acanthopleura gemmata*), and boring barnacles (*Lithothrya* sp.) (G. Paulay, pers. comm.). In addition to the abrasive action of marine invertebrates, the notches are also shaped by physical abrasion and chemical and biologic dissolution (PIRAZZOLI, 1986; RUST & KERSHAW, 2000), the proportional effect of each component varying with local conjuncture (TRUDGILL, 1983; KERSHAW & GUO, 2001). Whereas the end-members of biogenetic *vs.* non-biogenetic coastlines are morphologically recognizable (FISCHER, 1990), coastlines are generally altered by both groups of processes acting in complex relationships (SPENCER & VILES, 2002).

Important new observations from Guam and other islands indicate that a notch can occur in coastal cliffs completely unrelated to coastal erosion, biologic or otherwise. Voids that develop in the mixing zone along the discharge boundary of a karst aquifer groundwater lens are often breached by cliff retreat and can produce scars remarkably similar to marine notches (MYLROIE & CAREW, 1991).

Champignon surfaces and karrenfelds

Exposed surfaces of Plio-Pleistocene Mariana Limestone are dominated by spectacularly chaotic and extremely rough karren, which consist of densely packed cm-scale irregular

Fig. 4. Marine notches in the coastal cliff at Taogam Point.
Encoches marines creusées dans la falaise de Taogam Point.

solution pits, separated by ridges and sharp tips in the nodal points. On Guam, they exist in a variety of forms, from the most extremely jagged pits and points and even completely penetrating holes in the coastal areas (Fig. 5a), to somewhat more rounded inland forms, having a more subdued relief but similar overall appearance (Fig. 5b). There is variation in color as well: the most extremely eroded coastal surfaces are black or dark gray, whereas those inland are light gray to white. The intensity of color is thought to reflect the amount of organic coating by endolithic and epilithic organisms (JONES, 1989). Perhaps the most remarkable feature of this type of karren is the apparent continuum of form across a range of scales, from millimeters to meters. In an almost fractal-like pattern, the mm-scale and cm-scale points and pits appear to be repeated on a larger scale and cover extensive areas, creating extremely rough karrenfelds of amazingly jagged pinnacles and irregular pits among them (Fig. 6).

Despite being the predominant karren assemblage on young reef limestones, there is no precise terminology associated with this morphology. Its most intensely corroded variant is reported from many tropical limestone coasts and is commonly referred to as phytokarst (FOLK *et al.*, 1973). Other terms used include champignon surface (STODDART *et al.*, 1971), lacework morphology and sponge-work morphology (BULL & LAVERTY, 1982), and coastal karren (MYLROIE & CAREW, 1995). All of these are more appropriate than the term phytokarst, since they do not invoke a specific genetic mechanism. Considered one of the most variable and least understood karren types, its appearance is thought to be largely influenced by endolithic and epilithic organisms (JONES, 1989), but their impact on the topography has never been convincingly demonstrated (VILES, 2001). Nevertheless, the term "phytokarst" is used for both cm-scale sculpturing, as well as the similarly jagged m-scale karrenfeld landscapes. Despite the semblance of form across a range of scales, the processes involved in shaping these features are thought to be scale-dependent (VILES, 2001), albeit poorly known. Whereas the impact of endolithic microorganisms on rock morphology may be considerable at small scales, the large scale pinnacle morphology is probably the result of differential erosion due to meter-scale heterogeneities, such as variations in mineralogy and cementation (TRUDGILL, 1976) and structural weaknesses (VILES & SPENCER, 1986). In addition to biologic erosion and dissolution, the mechanisms contributing to geomorphology probably include physico-chemical dissolution, wave action, wetting and drying, and salt weathering and hydration (FORD & WILLIAMS, 1989). The relative contribution of each process to the overall morphology most likely varies with local conditions.

Observations on Guam indicate that this type of topography, although most characteristic at the coast, is also found in inland areas, with some minor differences. On the cm-scale, the inland features are less extremely sculpted; their points are less sharp; pits are shallower; completely penetrating holes are less common; and the pinnacles commonly terminate in jagged knife-edge forms, instead of the sharp points typical to the coast. Rudimentary rillenkarren are present in inland areas, indicating an increased relative contribution of gravity flow to the overall form. On the meter-scale, the inland topography is generally reduced; the pinnacles are lower; the pits among them are partially filled with soil and support vegetation; and the shallow flat-bottomed solution pans, common among the coastal pinnacles, are not found. Despite these differences, the continuum between coastal and inland pinnacle forms is quite clear, and their overall appearance is very similar.

Karren

Karren features on Guam belong to two broad categories: those found on young reef limestones, and those found on diagenetically mature re-crystallized limestones. The former are highly irregular and jagged, and are comprised of densely packed solution pits and points. Showing little or no hydrodynamic control, this type of karren appears to be a subdued variety of the previously discussed champignon surfaces (STODDART *et al.*, 1971); therefore, biologic activity is probably highly significant to its development. Conversely, the karren that developed in the massive, re-crystallized limestone

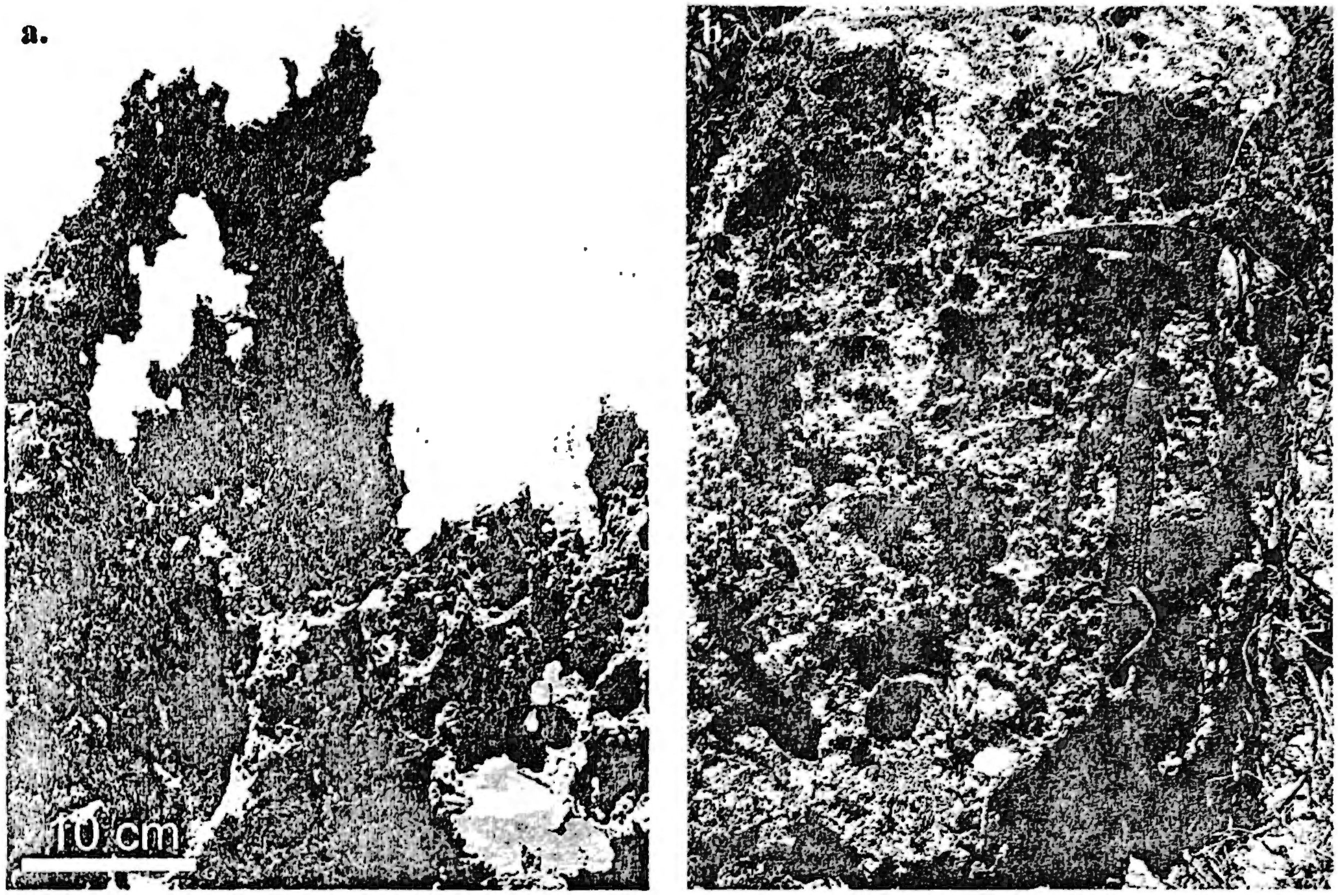


Fig. 5. Irregular and jagged karren features: a) extremely dissolved coastal type, north of Haputo Beach; b) inland type, Double Reef.
Lapiés irréguliers et ruiniformes: a. type côtier fortement dissous, nord de Haputo Beach; b. type d'intérieur, Double Reef.

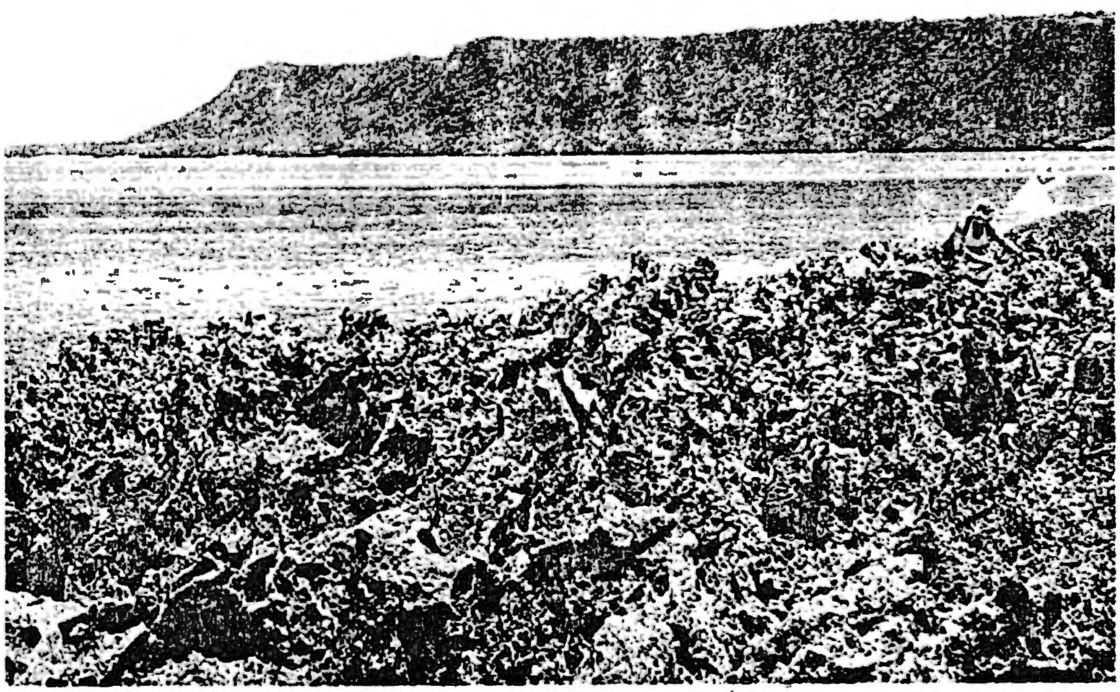


Fig. 6. Pit and pinnacle karrenfeld on the coast south of Haputo Beach (note person for scale).
Lapiaz à pinacles sur la côte sud de Haputo Beach (à noter le personnage pour l'échelle).

outcrops in southern Guam are more regular; and although polygenetic forms are present, the dominant features are solution runnels and other gravity controlled karren. However, even such classic karst features as solution runnels, generally thought to form by chemical dissolutional processes, have recently been associated, on a fundamental level, with biocorrosion by algae (Fiol *et al.*, 1996).

Bioerosional karren

Karren features found in the subtidal, intertidal, and supratidal zones of limestone coasts are distinct from the rainfall solution karren of inland sites, as well as the irregular champignon surfaces or phytokarst of Folk *et al.* (1973). These features are produced largely by bioerosion (typically grazing or boring by marine invertebrates) and occur in an astonishing variety, matching the diversity of marine bioeroders. In some cases, the grazing scars and boreholes of individual organisms are recognizable (Schneider & Torunski. 1983). On Guam, the coastal microrelief is extremely variable and chaotic, with various bioerosional scars overprinting each other. Some basic types can be recognized, and roughly correspond to supratidal, intertidal, and subtidal zones. In certain sheltered coastal sites, such as the walls of sea caves, unusual bioerosional scars similar to *Lithophaga* boreholes are found conspicuously oriented along consistent axes (Fig. 7).

Solution pans

Solution pans (Fig. 8) are small, flat-bottomed basins found in karst areas worldwide. They are influenced by inorganic processes such as wetting and drying and salt crystallization, but

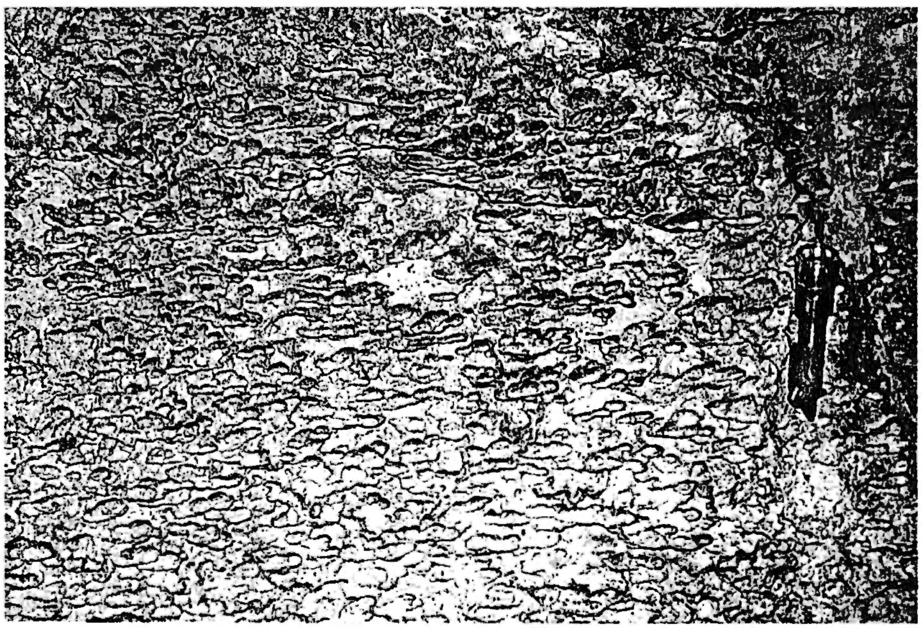


Fig. 7. Oriented bioerosional karren in the walls of a coastal cave in Tinian, an island north of Guam (flashlight for scale is 12 cm long).

Lapiés de bio-érosion sur les parois d'une grotte côtière à Tinian, île située au nord du Guam (la lanterne qui sert d'échelle a une longueur de 12 cm).

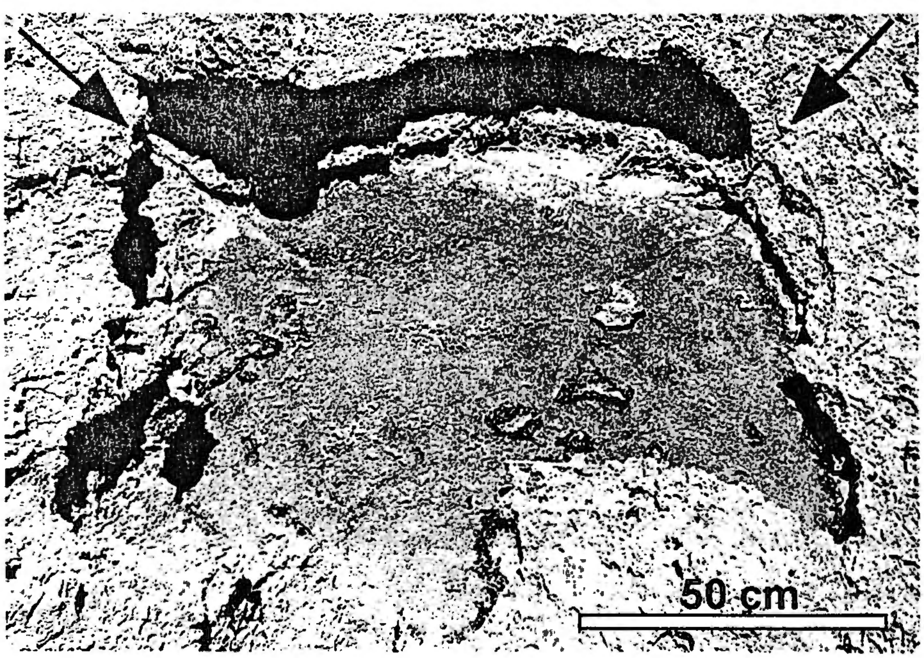


Fig. 8. Coastal solution pan in Sasajyan. Note the intersecting joints marked by arrows.

Kamenitza à Sasajyan. A noter l'intersection des fissures indiquées par les flèches.

the crucial factor in their development is thought to be dissolution by stagnant water, made corrosive by CO_2 from accumulated plant debris (White, 1988). More direct biologic action, such as mechanical removal of rock fragments by lichens, has also been suggested (Moses & Smith, 1993). Solution pans typically form on rock pavements and lightly vegetated or bare rock areas (Ford & Williams, 1989). On Guam they are only found nestled among the coastal karst pinnacles, and are curiously absent in the rest of the island.

The solution pans examined on Guam have flat and smooth floors, indicating the absence of bioerosion and abrasion. Many of them exhibit structural control and commonly develop at the intersections of joints or along a single joint, in which case they are elongate. They have overhanging margins and are rarely associated with overflow, or either inlet or outlet channels. If active, they may contain accumulated rainfall, evaporating seawater of various chlorinities, or sea salt crystals. Whereas the deepening of some supratidal pools is thought to be a direct result of differential bioerosion (Schneider & Torunski, 1983), the fact that their remarkably flat floors are covered by pervasive organic veneers seems to indicate that biologically mediated dissolution is instrumental. Although warm stagnant seawater is incapable of dissolving limestone, it is conceivable that there is a thin layer of undersaturated water, which is in contact with both the organic layer and the bedrock.

Beachrock

Beachrock is lithified beach sand dipping gently toward the sea (Bernier & Dalongeville, 1996). It is most commonly found in the intertidal zone of tropical and subtropical coasts. On Guam, it occurs locally on all beaches along the northwest and north coast of the island, the most extensive deposits being located at Tanguisson, Uruno, and Ritidian. The beachrock typically dips seaward, following the unlithified beach surface, and its composition reflects that of the surrounding calcareous sand. On some beaches, such as Tanguisson, the beachrock is conglomeratic and contains coral rubble and other fossils surrounded by a matrix of sand-sized calcareous grains. The surface texture of the beachrock on Guam is highly variable, and ranges from flat, smooth algae-covered surfaces to the rough, jagged surfaces pockmarked by characteristic karren, presumably reflecting the relative age of the deposits.

A number of hypotheses have been set forth to explain the precipitation of beachrock-forming cements. They involve both physiochemical processes, such as the evaporation of seawater, the mixing of freshwater and seawater (Moore, 1973), or CO_2 de-gassing due to groundwater discharge, wave agitation, and/or increasing temperature (Gischler & Lomando, 1997); as well as biologic processes, such as the uptake of photosynthetic CO_2 by intertidal microflora (Merz, 1992) and/or the increases in pH associated with heterotrophic microbes (Webb *et al.*, 1999). An interplay of concurrent inorganic and biologic precipitation was suggested by Krumbein (1979).

Case-hardened surfaces and calcrete

Biologic influences on the deposition and consolidation of limestone have been recognized in the formation of case-hardened surfaces, calcretes, tufas, travertines, oncolites, stromatolites, and speleothems (Viles, 1988). The exact role of organisms, however, is often insufficiently known, but most likely varies from insignificant to dominant.

Case-hardening, first recognized in the Caribbean, is the phenomenon of strengthening rocks via vadose diagenesis, and is thought to be assisted by blue-green algae, bacteria, and other organisms. Viles (1988) found case-hardened surfaces on Aldabra Atoll coinciding with the presence of endolithic, epilithic, and chasmolithic microflora. Case-hardening is an important phenomenon on emergent coral reefs, where primary pores within the coral-algal framework become infilled by precipitated calcite, thus making the rock in the vadose zone less permeable. On Guam, such infilling of primary voids by calcite is easily observed in quarry walls and road cuts where the exposed surfaces are commonly case-hardened. This phenomenon has also been noticed in thin sections from drilling cores (Jenson & Siegrist, 1994).

Calcrete occurs in areas where evaporation exceeds precipitation. It involves the chemical precipitation of $CaCO_3$, binding soil, alluvium, or weathered rock by carbonate-rich waters (Goudie, 1983); however, biologic action can also be instrumental (Klappa, 1979; Verrecchia, 1990). On Guam, calcrete can be found locally inside flat-floored sinkholes. Such sinkholes commonly act as sediment traps, and their flat floors can indicate a thick layer of sediment infilling (White, 1988). Analysis of rock samples from a sinkhole in Tarague area, northern Guam, revealed them to be calcrete floatstones containing coral and mollusc fragments, cemented in a calcified paleosol matrix.

Solution pits

Solution pits are round-bottomed cavities, normally up to a meter in diameter. They are thought to be one of the most widespread forms of karren (Ford & Williams, 1989). Biologic activity is commonly associated with pit development, particularly on a small scale. Danin (1983) suggested that cm-scale hemispherical pits in limestone are directly caused by euendolithic cyanobacteria. Comparable features coated by a black organic layer, presumably cyanobacteria, have been documented on walls in the twilight zone of coastal caves on Guam. On a larger scale, biologic processes are generally not thought to be instrumental in the development of solution pits, but they are known to accelerate the pit deepening. Organic processes in the soil, accumulating in or surrounding the pits, can make deepening extremely rapid. Sweeting (1966) reported the dissolution of 3-5 cm deep pits within ten years by water enriched by organic acids. Longman & Brownlee (1980) suggested that vegetation plays an important role in the development of pits and pinnacles in Palawan (Philippines), and indicated that the decay of organic matter

accumulated in depressions as small as trittkarren facilitates the dissolution process, producing pits and even sinkholes. Plant root action has also been suggested as a contributing factor to the development of pits in limestone (TRICART & DASILVA, 1960).

On Guam, solution pits are found in all exposed limestones. They are somewhat rare in finer grained units such as foraminiferal limestones, and are most common in reef limestones, whose heterogeneity is probably favorable to their initiation. The pits are found in the highest densities within the jagged pinnacle karrenfelds and limestone forests. In limestone forests, the pits are partially filled with soil and decaying organic materials, enabling them to support dense vegetation, including large trees commonly rooted inside them.

Soil pipes

Soil pipes are subrosional soil or sediment-filled cylindrical pits in the epikarst. They are a common feature on Guam, usually up to 0.5 m wide and 3-4 m deep, and can be observed in high densities in quarry walls and road cuts. Soil pipe casts of lithified paleosol are also common on the island.

Soil pipes develop by the dissolution of limestone below the soil cover and are thought to form along structurally determined zones. There is evidence, however, that the initiation of soil piping is determined by chemistry and the variable permeability of rocks, rather than by structural controls (WALSH & MORAWIECKA-ZACHARZ, 2001), and this appears to be the case with very heterogeneous rocks such as the young reef limestone of carbonate islands. Organic deposits, such as guano, also promote soil pipe development in raised reef limestone (JENNINGS, 1985). Following the initiation of soil pipes,

Fig. 9. Root grooves on the surface of a collapsed boulder, Tarague.
Cannelures de racines sur la surface d'un bloc, à Tarague.

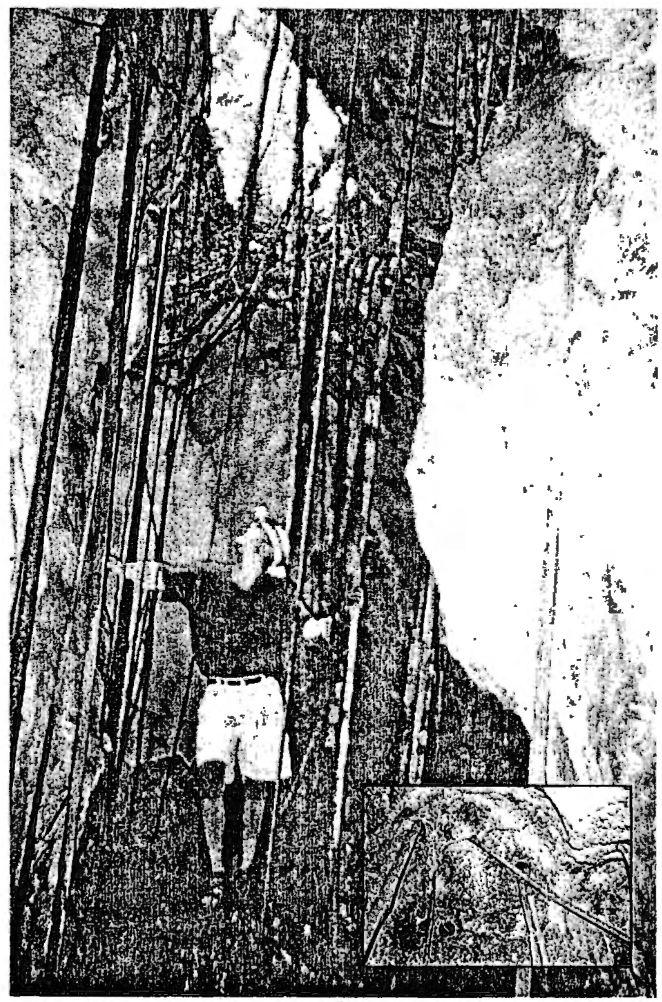


Fig. 10. Cave entrance concealed by numerous banyan tree roots, Nimitz Hill. Inset: root holes close-up (lens cap is 55 mm in diameter).

Entrée d'une grotte masquée par de nombreuses racines de banians à Nimitz Hill. En bas: détail des trous de racines (le couvercle de l'objectif a un diamètre de 55 mm).

organic processes are instrumental in their continued development. Soil pipes are enlarged by percolating meteoric water acidified by biogenic CO_2 in the soil. Some authors have hypothesized that soil pipes are a direct result of dissolution by acidified water concentrated around tree roots (Brink & Partridge, 1980; Walsh & Morawiecka-Zacharz, 2001).

Root karst

In addition to soil pipes, a variety of small-scale karst features, both erosional (Wall & Wilford, 1966) and accretional (Wilford & Wall, 1965) are thought to form by plant root action. Bull & Laverty (1982) discuss those features as types of physical phytokarst and propose the term rhizokarst, and Klappa (1980) provides a review. On Guam, at least three types of small-scale features appear to be produced directly by plant roots.

Root grooves (Wall & Wilford, 1966) have been documented on the freshly exposed surface of a single collapsed boulder in Tarague. They appear as an irregular ramifying network of hemispherical grooves (Fig. 9).

Root holes are made in limestone rocks by roots of trees. The best examples on Guam are associated with the banyan trees (*Ficus prolixa*) that commonly grow around the entrances of caves (Fig. 10). The roots completely penetrate the cave roof, emerging from widened holes in the rock (Fig. 10, inset), and reach the cave floors by growing considerable distances through the open air of the cave. Upon reaching the floor, they grow into the soil, anchoring the tree and tightening the subaerially exposed portion of the root until it becomes completely straight and firm. The roots are typically several centimeters in diameter, and probably cause the widening of holes in the bedrock in which they grow, indirectly by acidifying the rain water flowing down the roots, or directly by the pressure they exert on the host rock as they grow. Some cave entrances are almost entirely concealed by dense curtains consisting of hundreds of banyan tree roots.

Rhizoliths, most likely root tubules (Klappa, 1980), have also been documented in the reef limestones on Guam. Found standing in the centers of small pits (of primary or solutional origin), these features are tufaceous stalks, up to 7 cm tall (Fig. 11). The base of the stalks, at the bottom of the pits, is weak enough to be broken by hand. There are partially infilled holes, a few millimeters in diameter, running the length of the stalks.

Freshwater tufas

Freshwater tufas, travertines, stromatolites, and similar deposits can be precipitated by waters supersaturated with respect to calcium carbonate. $CaCO_3$ can be precipitated indirectly by the removal of CO_2 by cyanobacterial and algal photosynthesis (Casanova, 1981), or directly by organisms (Chafetz & Folk, 1984). The role and contribution of biota to the individual processes is subject to debate. Some studies suggest that the influence of biota on sedimentation is less than is generally thought (Pentecost, 1985) or even negative, because of bioerosion (Schneider, 1977). Biologically produced freshwater deposits are typically not found on small carbonate islands, since such islands usually lack surface waters in karst areas. In Guam, however, in the cockpit karst terrain in central southern Guam, several carbonate-rich streams emerge from caves and flow moderate distances as surface streams over the alluvium-covered carbonate units. In those environments, minor tufa and travertine deposits are associated with cascades and small waterfalls, and are shaped as laminar tapered domes, reflecting the trajectories of cascading water.

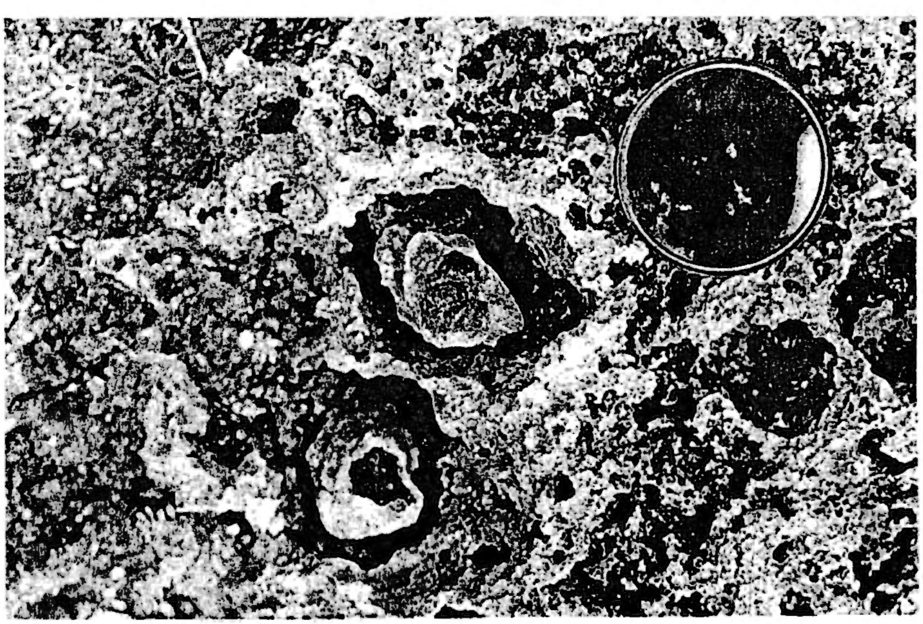


Fig. 11. Tufaceous stalks (root accretion features), Double Reef. The filter is 55 mm in diameter.

Tiges tufières (formation d'accrétion autour des racines), Double Reef. Le filtre a un diamètre de 55 mm.

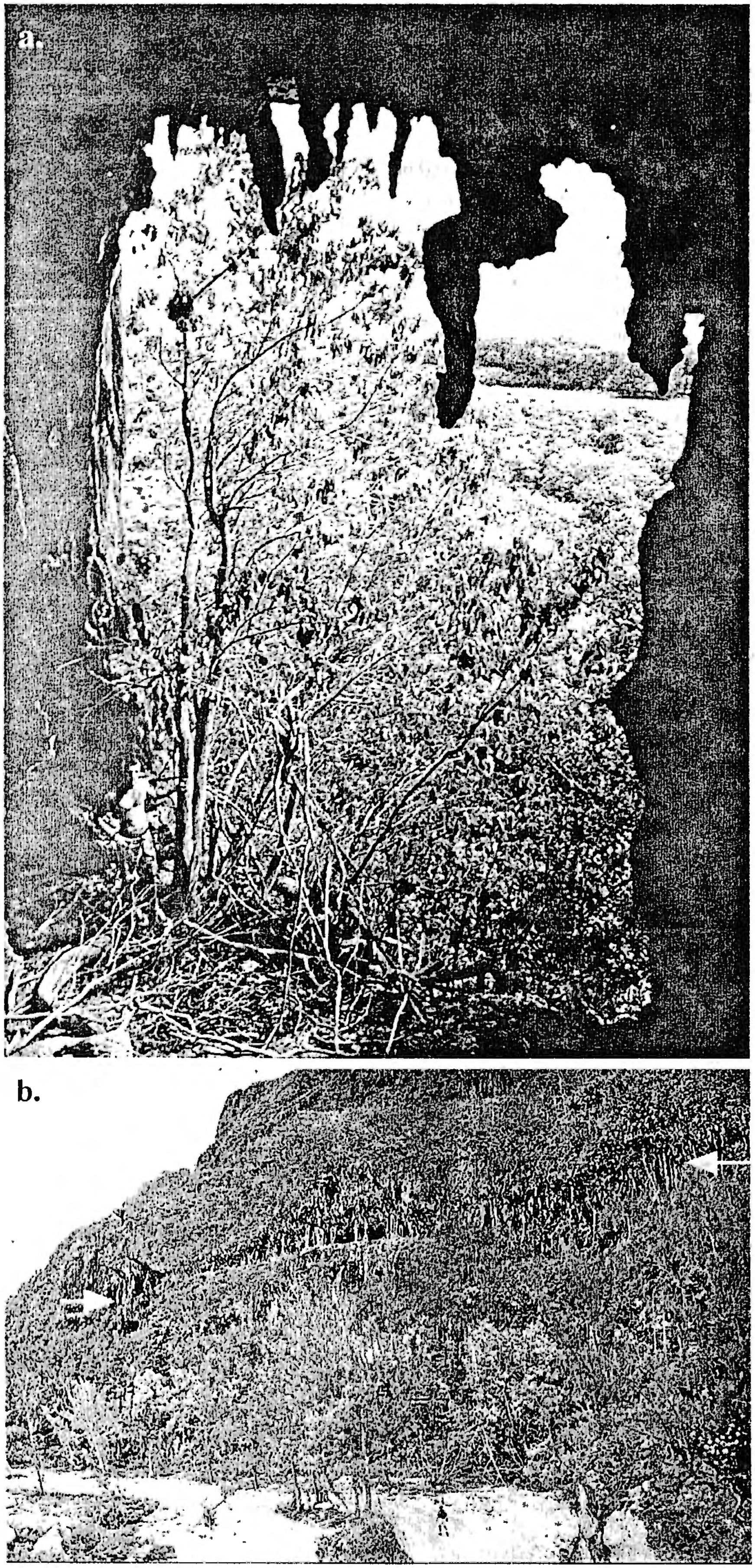


Fig. 12. Tufaceous stalactites in cliff face settings. a. breached flank margin cave, Ritidian. The largest stalactite is 2 meters long (note person for scale, lower left); b. horizontal notch containing numerous tufaceous stalactites, Tarague (note person for scale, at the bottom, off center).

Stalactites tufières en falaise. a. grotte de type brèche de bord de flanc, à Ritidian. La stalactite la plus grande a une longueur de 2 m (à noter le personnage d'en bas, à gauche, pour l'échelle); b. encoche horizontale contenant de nombreuses stalactites tufières, à Tarague (à noter le personnage d'en bas pour l'échelle).

Subaerial tufas (tufaceous stalactites)

Stalactites made of tufa-like deposits are fairly common in the humid tropics and many are reported from cave entrances. They have not been subject to detailed studies and their formation mechanisms are poorly known, but the activity of cyanobacteria, algae, and mosses is often suggested. BULL & LAVERTY (1982) classified these features as depositional phytokarst and called them non-vertical stalactites. VILES & GOUDIE (1990) refer to the terms "*aussen Stalactiten*" and "*Stalactitenvorhang*" from German literature on tropical tower and cone karst. Terms applied to analogous features include cave karst stromatolites and heliotropic speleothems (FUXING & JIANHUA, 1993), phototropic phytospeleothems and phytoerratics (LICHON, 1992), subaerial stromatolites (COX *et al.*, 1989) and stromatolitic stalagmites (JAMES *et al.*, 1994).

On Guam, tufaceous stalactites, which can be thick and massive, are ubiquitous in cliff-side entrances of breached flank margin caves (Fig. 12a), and may also be found in horizontal notches on coastal cliffs (Fig. 12b). Unlike normal cave stalactites, the growth axis of tufaceous stalactites is not always vertical. Their leaning can be a result of preferential deposition by bacteria or algae on the side facing the light, as suggested by BULL & LAVERTY (1982); but groups of stalactites leaning in conflicting directions, and specimens exhibiting curved shapes, appear to indicate more complex growth histories.

Tufaceous stalactites, typically lacking the crystalline luster of normal cave speleothems, are lightweight, porous, and friable, and feel powdery or earthy. They can be easily broken by hand, revealing white chalky interiors, homogeneous from the periphery to the core, and generally deposited in concentric layers (Fig. 13). Somewhat harder micritic stalactites, similar to those described from the Cayman Islands by JONES & MOTYKA (1987), have also been documented. They appear to be transitional forms between tufaceous and normal cave speleothems, since they commonly contain sparry calcite in addition to chalky and microcrystalline fabrics. X-ray diffraction (XRD) analyses of selected samples from Guam have indicated that they are uniformly composed of low-Mg calcite.

Fig. 13. A tufaceous stalactite from Ritidian. The scale is in centimeters.
Stalactite tufière de Ritidian. Echelle en centimètres.

The origin of tufaceous stalactites is poorly known. Although the most likely mode of deposition is the cyanobacterially-assisted growth of subaerial tufa in cave entrances, the decay of cave (normal) speleothems, when exposed to open atmosphere by cliff-retreat, can also be a factor. Understanding the origin of tufaceous stalactites in coastal cliffs is crucial to karst studies on carbonate islands, because it makes possible the easy distinction between notch-like breached flank margin caves and marine notches (MYLROIE & CAREW, 1997; CARNEY *et al.*, 1997). The two commonly appear similar, but whereas both are associated with former sea levels, only the flank margin caves are related to freshwater discharge and may provide clues about the paleodynamics of the freshwater lens. Until recently, the presence of extensive speleothem deposits in the cliff-side voids was considered the key factor in distinguishing breached caves from marine notches; but the discovery of massive tufaceous stalactites, apparently growing in open atmosphere conditions has blurred that distinction.

"Directed phytokarst"

Unusual small-scale, light-oriented features are sometimes reported from the twilight zones of tropical caves. Apparently biologically produced erosional forms, they have been termed photokarren by WALTHAM & BROOK (1980) and "directed phytokarst" by BULL & LAVERTY (1982), based on examples from insular Malaysia. Morphologically similar features have been documented on Guam, where they grow on the sides of tufaceous speleothems in certain cave entrances. They appear to be composed of calcified algal filaments, up to 5 mm in length, intertwined and grouped in clusters pointing toward the light (Fig. 14). Although superficially comparable to erosional forms termed photokarren and "directed phytokarst", the structures observed on Guam are clearly depositional. As such, they represent unique and, to the best of my knowledge, previously unreported karst features. No specific term is being proposed yet as these features are currently under active study.

Moonmilk

Moonmilk, considered a speleothem, has been described as "soft, plastic and pasty" when wet and "crumbly and powdery" when dry (HILL & FORTI, 1997). It is a microcrystalline aggregate, containing calcite and other minerals. It is thought to be precipitated inorganically (BORSATO *et al.*, 2000), as well as biologically (NORTHUP & LAVOIE, 2001) by bacterial action

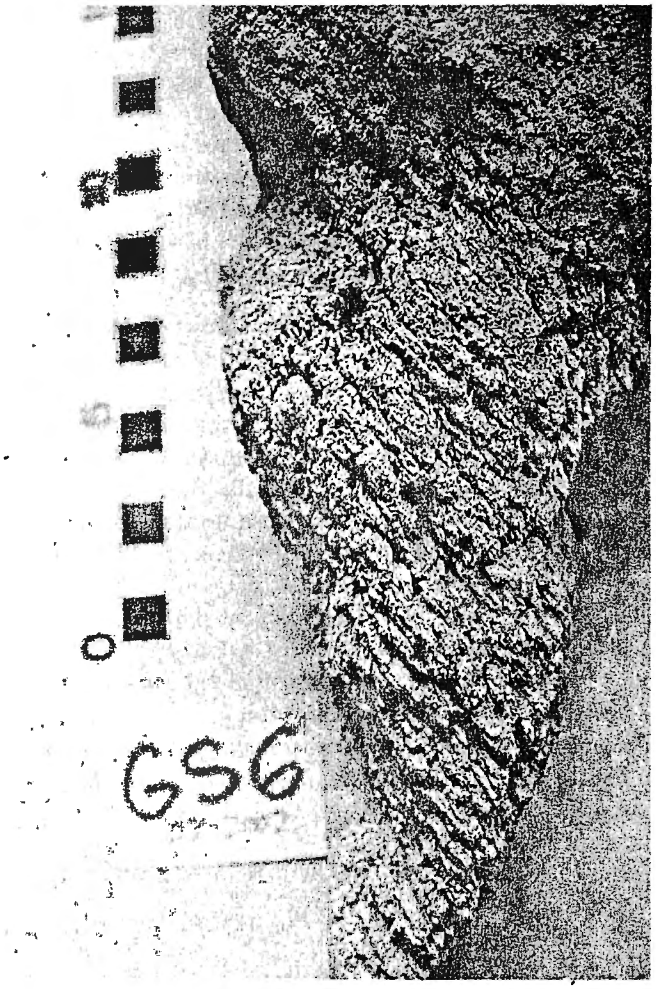


Fig. 14. Light oriented thread-like depositional features on the surface of a tufaceous stalactite, Ritidian. The scale is in centimeters.

Structures filamenteuses faiblement orientées, déposées sur la surface d'une stalactite tufière de Ritidian. Echelle en centimètres.

Fig. 15. Organic coating (scratched by hand), covering a stalagmite in a breached flank margin cave in Ritidian. Color of the coating is purple, with green and ochre patches.

Pellicule organique (grattée à la main) couvrant une stalagmite d'une grotte de type brèche de bord de flanc de Ritidian. La pellicule est de couleur pourpre, avec des taches vertes et ocres.

(DANIELLI & EDINGTON, 1983) and fungal action (PHILLIPS & SELF, 1987), both intra- and extra-cellularly (GRADZINSKI *et al.*, 1997). Moonmilk can also form by speleothem decay (HILL & FORTI, 1997). BULL & LAVERTY (1982), therefore, classify it as both a constructive (depositional) and a destructive (erosional) form of phytokarst.

On Guam, moonmilk-like loose powders and wet pasty substances and biomats are found commonly on speleothems and cave walls and can be up to several millimeters thick. They are typically purple, green, and gray (Fig. 15) and are present only in cave areas where light penetrates. The best developed ones are found in breached flank margin caves, which are exposed to light and outside atmosphere by cliff retreat or roof collapse. They are also found periodically submerged in caves having freshwater pools, such as Marbo Cave, where they cover the walls in the range of tidal fluctuations. Similar biomats, reported from Mexican cenotes, are thought to be products of photosynthetic purple bacteria (GARY, 2002).

Conclusions

Karst features that are thought to be directly related to organic processes have been termed phytokarst (BULL & LAVERTY, 1982) or biokarst (SCHNEIDER & TORUNSKI, 1983; VILES, 1984). They have largely been regarded as features of local interest and of limited significance (VILES, 1988). Whereas this may be the case with certain individual organisms and unusual small-scale features, the effects of living organisms on karst geomorphology are profound on an ecosystem scale, and they are widespread, intense, diverse and of fundamental importance. As a rising number of karst features are recognized as biokarst, the roles of biota in processes beyond the small-scale phenomena are becoming the focus of important studies. Organisms are now considered instrumental in rock surface weathering (VILES, 1995) and speleogenesis (SASOWSKY & PALMER, 1994; MARTIN *et al.*, 2002). The evolution of entire karst landscapes is thought to be biologically controlled through the interrelationships of

Table 1. Karst features of Guam and the most important biologic and inorganic processes thought to be associated with them. References are given in text.

Formations karstiques de Guam et les plus importants processus biologiques et inorganique qui paraissent y être associés. Voir le texte pour les références bibliographiques.

Karst features	Influences on observed geomorphology	
	Biologic	Inorganic
Coral reefs	Bioconstruction by corals, coralline algae; Bioerosion	Wave action; freshwater discharge; topography
Intertidal benches and rimmed terraces	Bioconstruction by coralline algae, vermetid mollusks; Bioerosion	Dissolution by wave agitated seawater; abrasion by rocks
Marine notches	Bioerosion (bioabrasion by grazers, biocorrosion by endoliths)	Dissolution by wave agitated seawater; mechanical abrasion
Champignon surfaces and pinnacles	Bioerosion (biocorrosion by endoliths and epiliths)	Dissolution; wetting and drying; salt weathering and hydration
Karren	Biologic weathering, dissolution by water enriched by organic CO_2	Physico-chemical dissolution by precipitated meteoric water
Bioerosional karren	Bioerosion (bioabrasion by grazers, biocorrosion by endoliths)	
Solution pans	Dissolution by organically acidified water; mechanical action of lichens	Physico-chemical dissolution by accumulated meteoric water
Beachrock	Influence of intertidal microflora and heterotrophs on pH and CO_2 levels	CO_2 degassing due to evaporation, wave action, groundwater discharge
Case-hardening and calcrete	Direct and indirect precipitation of calcite by bacteria, algae, lichens...	Physico-chemical precipitation of calcite from carbonate-rich waters
Solution pits	Biocorrosion; dissolution by organic acids in water; root action	Physico-chemical dissolution by percolating meteoric water
Soil pipes	Dissolution by organically acidified water; root action	Physico-chemical dissolution by percolating meteoric water
Root grooves and root holes	Dissolution by organic acids from plants; mechanical action of roots	
Rhizoliths	Binding effect of plant roots	
Freshwater tufa deposits	Indirect precipitation by autotrophs (CO_2 removal); Direct precipitation	Physico-chemical precipitation by carbonate-rich waters
Tufaceous stalactites	Indirect precipitation by autotrophs (CO_2 removal); Direct precipitation	Physico-chemical precipitation by dripping supersaturated water
"Directed phytokarst"	Direct or indirect precipitation or corrosion by autotrophs	
Moonmilk	Microbial precipitation; microbial corrosion	Physico-chemical precipitation; corrosion
Caves	Organically produced acids drive dissolution, other processes	Inorganic dissolution, collapse

vegetative cover, erosion, and dissolution rates (Hupp *et al.*, 1995), and some authors have suggested that the process of karstification is essentially of biogenic character (Barany-Kevei, 1992). Biologic influence is being demonstrated in an increasing variety of karst features, and even such quintessential abiotic and hydrodynamically controlled forms as rillenkarren have recently been linked, on a fundamental level, to biologic processes (Fiol *et al.*, 1996).

All this is perhaps nowhere as obvious as it is in tropical and coastal settings, where the distinction between "biokarst" and "non-biokarst" becomes thoroughly impracticable, as nearly all karst features are affected by biologic processes, in addition to the inorganic ones (Table 1). This survey of karst on Guam has revealed that practically all small- and medium-scale exokarst features documented on the island are biologically mediated and bear characteristics of what is known as "biokarst". The biologic influences on karst actually extend even further. On tropical carbonate islands, even the formation of large caves is thought to be greatly dependant on organic processes. Some of the most common island caves, known as flank margin caves (Mylroie & Carew, 1990), have

developed in improbably short time spans if the only mechanism invoked is inorganic dissolution (Sanford & Konikow, 1989). Their speleogenesis is largely a result of enhanced dissolution through oxidation of organic materials transported by vadose water from the epikarst and accumulated at the pycnoclines in the freshwater lens (Mylroie & Balcerzak, 1992). All this indicates that, in tropical and coastal environments, the biologically influenced karst features are not small-scale peculiarities, but actually encompass most of, if not all karst phenomena.

Acknowledgments

The research reported here is part of a project funded by the U.S. Geological Survey, Water Resources Division, through the Water Resources Research Institute, Regional Competitive Award Program, award no. 1434-HQ-96-GR-02665. Initial work was also supported by the Guam Hydrologic Survey Program of the Water and Environmental Research Institute of the Western Pacific, University of Guam, which was initiated by the 24th Guam Legislature. The author is grateful to Dr. John Jenson, Dr. John Mylroie, and David Vann for invaluable support in the field, to Dr. David J. Lowe for an exceptionally thorough review and indispensable observations, and to Dr. John Mylroie and Dr. Paul Williams for important critical comments. Guidance and support of Dr. Kazuomi Hirakawa are also greatly appreciated.

References

Acsaso, C., Galvin, J., & Rodriguez-Pascual, C. (1982) The weathering of calcareous rocks by lichens. *Pedobiologia*, **24**, pp. 219–229.

Albergaria Moreira, M.E.S. (1996) Bio-erosional features in beach-rock reefs at coasts of Mozambique and Brazil. *Z. für Geomorphologie Supplementband*, **102**, pp. 151–168.

Alonso, Z.A.M., Silva, P.G., Goy, J.L., & Zazo, C. (1998) Fan-surface dynamics and biogenic calcrete development: interactions during ultimate phases of fan evolution in the semiarid SE Spain (Murcia). *Geomorphology*, **24**, *2–3*, pp. 147–167.

Barany-Kevei, I. (1992) Les facteurs écologiques dans la formation du karst. In: *Karst et évolutions climatiques* (Salomon, J.N. & Maire, R., *Eds.*). Presses Universitaires de Bordeaux, Bordeaux, pp. 51–59.

Barton, H.A., Spear, J.R., & Pace, N. R. (2001) Microbial Life in the Underworld: Biogenicity in Secondary Mineral Formations. *Geomicrobiology Journal*, **18**, *3*, pp. 359–368.

Bayari, C.S., Kurttas, T., & Temel, A. (1994) Hydrogeology, hydrogeochemistry, and geochemistry of the biogenic travertines in the lower Zamanti Basin (eastern Taurids-Turkey). *Cave and Karst Science*, **21**, *1*, p. 5.

Bernier, P. & Dalongeville, R. (1996) Mediterranean coastal changes recorded in beach-rock cementation. *Z. für Geomorphologie Supplementband*, **102**, pp. 185–198.

Borsato, A., Frisia, S., Jones, B., & Van Der Borg, K. (2000) Calcite moonmilk: crystal morphology and environment of formation in caves in the Italian Alps. *J. Sedimentary Research*, **70**, *5*, pp. 1171–1182.

Brink, A.B.A. & Partridge, T.C. (1980) The nature and genesis of solution cavities (Makondos) in Transvaal cave breccias. *Palaeontol. Afr.*, **23**, pp. 47–49.

Bull, P.A. & Laverty, M. (1982) Observations on phytokarst. *Z. für Geomorphologie*, **26**, pp. 437–457.

Butler, D.R. (1995) *Zoogeomorphology*. Cambridge University Press, Cambridge and New York, 231 p.

Cañveras, J.C., Sanchez-Moral, S., Sloer, V., & Saiz-Jimenez, C. (2001) Microorganisms and microbially induced fabrics in cave walls. *Geomicrobiology Journal*, **18**, *3*, pp. 223–240.

Carney, S.M., Mylroie, J.E., & Carew, J.L. (1997) Bioerosion notches versus flank margin caves; viability as paleo sea level indicators. *J. of Cave and Karst Studies*, **59**, *3*, p. 169.

Casanova, J. (1981) Morphologie et biolithogenèse des barrages de travertines. *Bull. de l'Association de Géographie Française*, **479–480**, pp. 192–193.

Castanier, S., Le Métayer-Levrel, G., & Perthuisot, J.-P. (1999) Ca-carbonates precipitation and limestone genesis — the microbiogeologist point of view. *Sedimentary Geology*, **126**, *1-4*, pp. 9–23.

Caumartin, V. & Renault, P. (1958) La corrosion biochimique dans un réseau karstique et la genèse du mondmilch. *Notes biospél.*, **13**, pp. 87–109.

Chafetz, H.S. & Folk, R.L. (1984) Travertines: Depositional morphology and the bacterially controlled constituents. *J. Sedimentary Petrology*, **54**, pp. 289–316.

Chen, J., Blume, H.-P., & Beyerm, L. (2000) Weathering of rocks induced by lichen colonization – a review. *Catena*, **39**, *2*, pp. 121–146.

Cox, G., James, J.M., Leggett, K.E.A., & Osborne, R.A.L. (1989) Cyanobacterially deposited speleothems: subaerial stromatolites. *Geomicrobiology Journal*, **7**, pp. 245–252.

Dalongeville, R. (1995) Le rôle des organismes constructeurs dans la morphologie des littoraux de la Mer Méditerranée: algues calcaires et vermetidés. *Norois*, **4**, pp. 73–88.

Danielli, H.M.C. & Edington, M.A. (1983) Bacterial calcification in limestone caves. *Geomicrobiological Journal*, **3**, pp. 1–16.

Danin, A. (1983) Distribution of cyanobacteria and lichens on hillsides of the Negev Highlands and their impact on biogenic weathering. *Z. für Geomorphologie*, **27**, *4*, pp. 423–444.

De la Torre, M.A., Gomez Alarcon, G., Vizcaiño, C., & Garcia, M. T. (1993) Biochemical mechanisms of stone alteration carried out by filamentous fungi living in monuments. *Biogeochemistry*, **19**, pp. 129–147.

Dickinson, W. R. (2000) Hydro-isostatic and tectonic influences on emergent Holocene paleoshorelines in the Mariana Islands, Western Pacific Ocean. *J. of Coastal Research*, **16**, *3*, pp. 735–746.

Drysdale, R.N. (1998) Aquatic insect larvae as geomorphic agents in travertine-building: a case study from the Barkly karst, Australia. *Geografia Fisica e Dinamica Quaternaria, Suppl.*, **3**, pp. 53–59.

Drysdale, R.N. (1999) The sedimentological significance of hydropsychid caddis-fly larvae (Order: Trichoptera) in a travertine-depositing stream: Louie Creek, northwestern Queensland. *J. of Sedimentary Research* (Section A), **69**, *1*, pp. 145–150.

Easton, W.H., Ku, T.L., & Randall, R. H. (1978) Recent reefs and shorelines on Guam. *Micronesica*, **14**, *1*, pp. 1–11.

Emery, K. O. (1962) *Marine Geology of Guam*. 403-B, U.S. Geological Survey Professional Paper, U.S Government Printing Office, Washington, D.C., 76 p.

Fiol, L.I., Fornós, J.J., & Ginés, A. (1996) Effects of biokarstic processes on the development of solutional rillenkarren in limestone rocks. *Earth Surface Proc. and Landforms*, **21**, *5*, pp. 447–452.

Fischer, R. (1990) Biogenetic and nonbiogenetically determined morphologies on the Costa Rican coast. *Z. für Geomorphologie*, **34**, *3*, pp. 313–321.

Focke, J.W. (1978) Limestone cliff morphology on Curaçno (Netherlands Antilles), with special attention to the origin of notches and vermetid/coralline algal surf benches ('cornices', 'trottoirs'). *Z. für Geomorphologie*, **2**, pp. 329–349.

Folk, R.L., Roberts, H.H. & Moore, C.H. (1973) Black phytokarst from Hell, Cayman Islands, British West Indies. *Geological Society of America Bull.*, **84**, pp. 2351–2360.

Ford, D.C. & Williams, P.W. (1989) *Karst geomorphology and hydrology*. Unwin Hyman, Winchester, Massachusetts, 320 p.

Ford, T. D. (1989) Tufa – The Whole Dam Story. *Cave Science*, **16**, *2*, pp. 39–50.

Forti, P. (2001) Biogenic speleothems: an overview. *Intl. J. Speleol.*, **30A**, *1*, pp. 39–56.

Fuxing, W. & Jianhua, C. (1993) Karst cave stromatolites. In: *Geology, Climate, Hydrology and Karst Formation: IGCP 299 Newsletter* (Shengyou, X. & Daoxian, Y., *Eds.*), The Institute of Karst Geology, Guilin, China, 79 p.

Gary, M. (2002) Understanding Zacatón: Exploration and initial interpretation of the world's deepest known phreatic sinkhole and related karst features, southern Tamaulipas, Mexico. In: *Hydrogeology and Biology of Post-Paleozoic Carbonate Aquifers, Symp. Proc.: Gainesville, FL* (Martin, J.B., Wicks, C.M., & Sasowsky, I.D., *Eds.*), Karst Waters Institute, Gainesville, Florida, pp. 141–145.

Gischler, E. & Lomando, A.J. (1997) Holocene cemented beach deposits in Belize. *Sediment. Geol.*, **110**, pp. 277–297.

Goudie, A.S. (1983) Calcrete. In: *Chemical Sediments and Geomorphology: Precipitates and Residua in the Near-Surface Environment* (Goudie, A.S. & Pye, K., *Eds.*), Academic Press, London, pp. 93–131.

Gradzinski, M., Szulc, J., & Smyk, B. (1997) Microbial agents of moonmilk calcification. In: *Proc. 12th Intl. Congress of Speleology, La Chaux-de-Fonds, Switzerland* (Jeannin, P.Y., *Ed.*), pp. 275–278.

Herwitz, S.R. (1993) Stemflow influences on the formation of solution pipes in Bermuda aeolianite. *Geomorphology*, **6**, pp. 253–271.

Hill, C.A. & Forti, P., *Eds.* (1997) *Cave minerals of the world*. National Speleological Society, Huntsville, Alabama, 238 p.

Hooper, J.H.D. (1958) Bat erosion as a factor in cave formation. *Nature*, **182**, p. 1464.

Hupp, C.R., Osterkamp, W.R., & Howard, A.D., *Eds.* (1995) Biogeomorphology, terrestrial and freshwater systems. *Geomorphology Special Issue*, **13**, *1–4*, pp. 1–347.

James, M.J., Patsalides, E., & Cox, G. (1994) Amino Acid Composition of Stromatolitic Stalagmites. *Geomicrobiology Journal*, **12**, pp. 183–194.

Jennings, J.N. (1985) *Karst geomorphology*. Basil Blackwell, Oxford and New York, 293 p.

Jenson, J.W. & Siegrist, H.G., Jr. (1994) Bedrock hydrogeologic features influencing internal transfer in the Northern Guam Lens Aquifer System. *Eos Transactions*, **75**, *43*, p. 257.

Jones, B. (1989) The role of microorganisms in phytokarst development on dolostones and limestones, Grand Cayman, British West Indies. *Canadian Journal of Earth Science*, **26**, pp. 2204–2213.

Jones, B. (2001) Microbial activity in caves—A geological perspective. *Geomicrobiology Journal*, **18**, *3*, pp. 345–357.

Jones, B. & Kahle, C.F. (1985) Lichen and algae; agents of biodiagenesis in karst breccia from Grand Cayman Island. *Bull. of Canadian Petroleum Geology*, **33**, *4*, pp. 446–461.

Jones, B. & Motyka, A. (1987) Biogenic structures and micrite in stalactites from Grand Cayman Island, British West Indies. *Canadian J. of Earth Sciences*, **24**, pp. 1402–1411.

Jones, R.J. (1965) Aspects of the biological weathering of limestone pavements. *Proc., Geologists' Association*, **76**, pp. 421–433.

Kershaw, S. & Guo, L. (2001) Marine notches in coastal cliffs: indicators of relative sea-level change, Perachora Peninsula, central Greece. *Marine Geology*, **179**, pp. 213–228.

Khadkikar, A.S., Chamyal, L.S., & Ramesh, R. (2000) The character and genesis of calcrete in Late Quaternary alluvial deposits, Gujarat, western India, and its bearing on the interpretation of ancient climates. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **162**, *3–4*, pp. 239–261.

Klappa, C.F. (1979) Lichen stromatolites: Criterion for subaerial exposure and a mechanism for the formation of laminar calcretes (caliche). *J. of Sedimentary Petrology*, **49**, pp. 387–400.

Klappa, C.F. (1980) Rhizoliths in terrestrial carbonates: classification, recognition, genesis and significance. *Sedimentology*, **27**, pp. 613–629.

Kobluk, D.R. & Risk, M.J. (1977) Rate and nature of infestation of a carbonate substratum by a boring alga. *J. of Experimental Marine Biology and Ecology*, **27**, pp. 107–115.

Krumbein, W.E. (1979) Photolithotrophic and chemoorganotrophic activity of bacteria and algae as related to beachrock formation and degradation (Gulf of Aqaba, Sinai). *Geomicrobiology Journal*, **1**, pp. 134–203.

Krumbein, W.E. & Giele, G (1979) Calcification in a coccoid cyanobacterium associated with the formation of desert stromatolites. *Sedimentology*, **26**, pp. 593–604.

Lander, M.A. (1994) Meteorological factors associated with drought on Guam. *Water and Energy Research Institute of the Western Pacific.* University of Guam, Technical Report No. 75.

Lichon, M.J. (1992) The phototropic phytospeleothems of Moss Palace, Mole Creek, Tasmania. *Helictite*, **30**, *1*, pp. 8–10.

Longman, M.W. & Brownlee, D.N. (1980) Characteristics of karst topography, Palawan, Philippines. *Z. für Geomorphologie*, **24**, *3*, pp. 299–317.

Martin, J.B., Wicks, C.M., & Sasowsky, I.D., *Eds.* (2002) Hydrogeology and Biology of Post-Paleozoic Carbonate Aquifers, *Proc. Symp. „Karst Frontiers: Florida and Related Environments".* Karst Waters Institute, Gainesville, FL, 212 p.

Merz, M.U. (1992) The biology of carbonate precipitation by cyanobacteria. *Facies*, **26**, pp. 81–101.

Miller, T.E. (1990) Bellholes; biogenic (bat) erosion features in tropical caves. *Geo* (11th Friends of Karst meeting; program and abstracts, National Speleological Society), **17**, *2–3*, p. 76.

Moore, C.H., Jr. (1973) Intertidal carbonate cementation, Grand Cayman, West Indies. *J. Sediment. Petrol.*, **43**, pp. 591–602.

Moses, C.A. & Smith, B.J. (1993) A note on the role of the lichen *Collema auriforma* in solution basin development on a carboniferous limestone substrate. *Earth Surf. Process. Landforms*, **18**, pp. 363–368.

Mylroie, J.E. & Balcerzak, W.J. (1992) Interaction of microbiology and karst processes in Quaternary carbonate island aquifers. In: *Proceedings of the First International Conference on Ground Water Ecology* (Stanford, J.A. & Simons, J.J., *Eds.*), American Water Resources Association, Bethesda, MD, pp. 37–46.

Mylroie, J.E. & Carew, J.L. (1990) The flank margin model for dissolution cave development in carbonate platforms. *Earth Surface Processes and Landforms*, **15**, pp. 413–424.

Mylroie, J.E. & Carew, J.L. (1991) Erosional notches in Bahamian Carbonates: bioerosion or groundwater dissolution? In: *Proc. Fifth Symposium on Geology of the Bahamas*, Bahamian Field Station, Port Charlotte, Florida, pp. 85–90.

Mylroie, J.E. & Carew, J.L. (1995) Chapter 3: Karst development on carbonate islands. In: *Unconformities and Porosity in Carbonate Strata* (Budd, D.A., Harris, P.M., & Saller, A, *Eds.*), 63, Am. Ass. of Petroleum Geologists, pp. 55–76.

Mylroie, J.E. & Carew, J.L. (1997) Land use and carbonate island karst. In: *The Engineering Geology and Hydrogeology of Karst Terranes* (Beck, B. F., & Stephenson, J.B., *Eds.*), Balkema, Rotterdam, pp. 3–12.

Mylroie, J.E., Jenson, J.W., Taboroši, D., Jocson, J.M.U., Vann, D.T., & Wexel, C. (2001) Karst features of Guam in terms of a general model of carbonate island karst. *J. of Cave and Karst Studies*, 63, *1*, pp. 9–22.

Mylroie, J.E. & Vacher, H.L. (1999) A conceptual view of carbonate island karst. In: *Karst Modeling, Symposium Proceedings: Charlottesville, VA* (Palmer, A.N., Palmer, N.V., & Sasowsky, I.D., *Eds.*), pp. 48–58.

Northup, D.E. & Lavoie, K.H. (2001) Geomicrobiology of Caves: A Review. *Geomicrobiology Journal*, **18**, *3*, pp. 199–222.

Pentecost, A. (1985) Association of cyanobacteria with tufa deposits: Identity, enumeration and nature of the sheath material revealed by histochemistry. *Geomicrobiological Journal*, **4**, pp. 285–298.

Phillips, S.E. & Self, P.G (1987) Morphology, crystallography and origin of needle-fibre calcite in Quaternary pedogenic calcretes of South Australia. *Australian Journal of Soil Research*, **25**, *1*, pp. 429–444.

Pirazzoli, P.A. (1986) Marine Notches. In: *Sea-level Research: a Manual for the Collection and Evaluation of Data* (van de Plassche, O., *Ed.*), Geo Books, Norwich, UK, pp. 361–400.

Pirazzoli, P.A. (1996) *Sea-Level Changes in the Last 20,000 Years.* Wiley, New York, 211 p.

Randall, R.H. & Holloman, J. (1974) Coastal survey of Guam. *Marine Laboratory, University of Guam*, Technical Report **14**, 404 p.

Randall, R.H. & Siegrist, H.G., Jr. (1988) Geomorphology of the fringing reefs of northern Guam in response to Holocene sea level changes. In: *Proc. 6th International Coral Reef Symposium, Australia*, 3, pp. 473–477.

Riding, R. (2002) Structure and composition of organic reefs and carbonate mud mounds: concepts and categories. *Earth-Science Reviews*, **58**, pp. 163–231.

Rust, D. & Kershaw, S. (2000) Holocene tectonic uplift patterns in northeastern Sicily: evidence from marine notches in coastal outcrops. *Marine Geology*, **167**, *1–2*, pp. 105–126.

Sand, W., Ahlers, B., & Bock, E. (1991) The impact of microorganisms – especially nitric acid-producing bacteria – on the deterioration of natural stones. In: *Science, Technology and European Cultural Heritage* (Baer, N.S., Sabbioni, C., & Sors, A.I., *Eds.*), Butterworth-Heinemann, Oxford, pp. 481–484.

Sanford, W.E. & Konikow, L.F. (1989) Porosity development in coastal carbonate aquifers. *Geology*, **17**, pp. 249–252.

Sasowsky, I.D. & Palmer, M.V., *Eds.* (1994) *Breakthroughs in Karst Geomicrobiology and Redox Geochemistry.* Karst Waters Institute, Colorado Springs, CO, 111 p.

Schneider, J. (1977) Carbonate construction and decomposition by epilithic and endolithic microorganisms in salt- and fresh-water. In: *Fossil algae* (Flugel, E., *Ed.*), Springer-Verlag, Berlin, pp. 248–260.

Schneider, J. & Le Campion Alsumard, T. (1999) Construction and destruction of carbonates by marine and freshwater cyanobacteria. *European Journal of Phycology*, **34**, pp. 417–426.

Schneider, J. & Torunski, H. (1983) Biokarst on limestone coasts, morphogenesis and sediment production. *Marine Ecology*, **4**, pp. 45–63.

Smyck, B. & Drzal, M. (1964) Untersuchungen uber den Einfluss von Mikroorganismen auf das Phanomen der Karstbildung. *Erdkunde*, **18**, pp. 102–113.

Spencer, T. & Viles, H.A. (2002) Bioconstruction, bioerosion and disturbance on tropical coasts: coral reefs and rocky limestone shores. *Geomorphology*, (*in press*).

STANTON, W.I. (1984) Snail holes in Mendip limestones. *Proceedings, Bristol Naturalists' Society*, **44**, pp. 15–18.

STEARNS, H.T. (1941) Shore benches on north Pacific islands. *Geological Society of America Bulletin*, **52**, pp. 773–780.

STODDART, D.R., TAYLOR, J.D., FARROW, G.R., & FOSBERG, F.R. (1971) The geomorphology of Aldabra. In: *A discussion on the results of the Royal Society Expedition to Aldabra, 1967–1968*. (WESTOLL, T.S. & STODDART, D.R., *Eds.*), Phil. Trans. Roy. Soc. London, pp. 31–65.

SWEETING, M.M. (1966) The weathering of limestones (with particular reference to the Carboniferous limestones of Northern England). In: *Essays in Geomorphology* (DURY, G.H., *Ed.*), Heinemann, London, pp. 177–210.

TABOROŠI, D. (2000) *Karst features on Guam*. MSc. Thesis, Water and Environmental Research Institute of the Western Pacific, University of Guam, 324 p.

TRACEY, J.I., JR., SCHLANGER, S.O., STARK, J.T., DOAN, D.B., & MAY, H.G. (1964) *General Geology of Guam*. US Geological Survey Professional Paper 403-A, US Government Printing Office, Washington, DC, 104 p.

TRICART, J. & DASILVA, T.C. (1960) Un example d'évolution karstique en milieu tropical sec: le morne de Bon Jesus de Lapa (Bahia, Bresil). *Z. für Geomorphologie*, **4**, pp. 29–42.

TRUDGILL, S.T. (1976) The subaerial and subsoil erosion of limestones on Aldabra Atoll, Indian Ocean. *Z. für Geomorphologie Supplementband*, **26**, pp. 201–210.

TRUDGILL, S.T. (1983) Measurement of rates of erosion of reefs and reef limestones. In: *Perspective on Coral Reefs* (BARNES, D.J., *Ed.*), Austral. Inst. Mar. Sci. Contrib., **20**, pp. 256–262.

TRUDGILL, S.T. (1987) Bioerosion of intertidal limestone, Co. Clare, Eire - 3: Zonation, process and form. *Marine Geology*, **74**, pp. 111–121.

VERRECCHIA, E.P. (1990) Litho-diagenetic implications of the calcium-oxalate-carbonate biogeochemical cycle in semiarid calcretes, Nazareth, Israel. *Geomicrobiology Journal*, **8**, pp. 87–99.

VILES, H.A. (1984) Biokarst: review and prospect. *Progress in Physical Geography*, **8**, pp. 523–542.

VILES, H.A. (1987) Blue-green algae and terrestrial limestone weathering on Aldabra Atoll: an SEM and light microscope study. *Earth Surface Processes and Landforms*, **12**, pp. 319–330.

VILES, H.A. (1988) Organisms and karst geomorphology. In: *Biogeomorphology* (VILES, H.A., *Ed.*), Basil Blackwell Ltd., New York, pp. 319–350.

VILES, H.A. (1995) Ecological perspectives on rock surface weathering: Towards a conceptual model. *Geomorphology*, **13**, pp. 21–35.

VILES, H.A. (2001) Scale issues in weathering studies. *Geomorphology*, **41**, pp. 63–72.

VILES, H.A. & GOUDIE, A.S. (1990) Tufas, travertines and allied carbonate deposits. *Progress in Physical Geography*, **14**, pp. 19–41.

VILES, H.A. & SPENCER, T. (1986) 'Phytokarst,' blue-green algae and limestone weathering. In: *New directions in Karst* (PATERSON, K. & SWEETING, M.M., *Eds.*), GeoBooks, Norwich, pp. 115–140.

WALL, J.R.D. & WILFORD, G.E. (1966) Two small scale solution features of limestone outcrops in Sarawak, Malaysia. *Z. für Geomorphologie*, **10**, pp. 91–94.

WALSH, P. & MORAWIECKA-ZACHARZ, I. (2001) A dissolution pipe palaeokarst of mid-Pleistocene age preserved in Miocene limestones near Staszów, Poland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **174**, *4*, pp. 327–350.

WALTHAM, A.C. & BROOK, D.B. (1980) Cave development in the Melinau limestone of the Gunung Mulu National Park. *J. Geogr.*, **146**, pp. 258–266.

WEBB, G.E., JELL, J.S., & BAKER, J.C. (1999) Cryptic intertidal microbialites in beachrock, Heron Island, Great Barrier Reef: implications for the origin of microcrystalline beachrock cement. *Sedimentary Geology*, **126**, pp. 317–334.

WENT, F.W. (1969) Fungi associated with stalactite growth. *Science*, **16**, pp. 385–386.

WHITE, W.B. (1988) *Geomorphology and hydrology of karst terrains*. Oxford Press, New York, 464 p.

WILFORD, G.E. & WALL, J.R.D. (1965) Karst topography in Sarawak. *Journal of Tropical Geography*, **21**, pp. 44–70.

ZHANG, J. & BAO, H. (1994) On modern biokarst erosion on Yongan stone pinnacles, Fujian province. *Mountain Research*, **12**, *3*, pp. 136–144.

received: 5 September 2002
revised: 17 November 2002
accepted: 29 November 2002

Theoretical and Applied Karstology, 15 (2002), pp. 93–99

The Quaternary morphogenesis of the Lagoa Santa tropical karst, Minas Gerais State, SE Brazil

Heinz Charles Kohler[1]* & Joachim Karfunkel[2]

[1]*Pontifícia Universidade Católica de Minas Gerais, Av. Dom José Gaspar, 500, Coração Eucarístico, 30535-610, Horizonte, Brazil.*
[2]*Departamento de Geologia, Universidade Federal de Minas Gerais, Campus Pampulha, Av. Antônio Carlos 6627, 31270-901 Belo Horizonte, Brazil.*

Abstract

The tropical karst of the Lagoa Santa region, north of Belo Horizonte, in South-Eastern Brazil was studied, in order to describe the Quaternary morphogenesis and to elucidate the morphodynamic evolution of this area. The karst developed over an interfluvial block, at altitudes between 650 and 850 m above sea level. Structural alignments, consequence of the Brasilian geotectonic cycle, were reactivated through the Cenozoic. These alignments, together with climate oscillations through time, control the main trends of the karst scenario and allow the authors to postulate a morphogenetic history from Tertiary through Holocene.

Key words: geomorphology, tropical karst, Precambrian carbonates, lithostratigraphy, karst morphogenesis, Quaternary climate fluctuation.

La morphogenèse quaternaire du karst tropical de Lagoa Santa, Minas Gerais, sud-est du Brésil

Résumé

Le karst tropical de la région de Lagoa Santa situé au nord de Belo Horizonte, dans le sud-est du Brésil, a été étudié dans le but de décrire sa morphogenèse quaternaire et d'élucider l'évolution morphodynamique de cette zone. Ce karst s'est développé sur un bloc interfluvial, à 650–850 m d'altitude. Les alignements structuraux formés dans le cycle géotectonique brésilien ont été réactivés durant le Néozoïque. Ces alignements, ainsi que les oscillations climatiques, ont contrôlé les principales caractéristiques du paysage karstique et permettent une reconstitution de l'histoire morpho-génétique depuis le Tertiaire et jusqu'au Holocène.

Mots-clés: géomorphologie, karst tropical, carbonates précambriens, lithostratigraphie, morphogenèse karstique, variations climatiques quaternaires.

Introduction

The tropical karst region of Lagoa Santa is located approximately 30 km north of Belo Horizonte, the capital of Minas Gerais state. The karst region is situated on a mountain plateau in the northeastern part of Lagoa Santa urban area, developed over an interfluvial block at altitudes between 650 and 850 m above sea level (Fig. 1). To date, it is the oldest karst area studied in Brazil, comprising karstological, paleontological, archaeological and speleological interests. This karst is outstanding due to its extension, economical, and ecological importance.

The *Rio das Velhas* is the main river that drains the region of Lagoa Santa. It is situated at the eastern side of the karstic block and represents the base-level (650 m) of the karst aquifer. With a flow rate of 200 000 m^3/sec it is also one of the largest tributaries of the *São Francisco* River. Towards the south and the west the block is bordered by the smaller stream

* corresponding author. *E-mail address*: charleskohler@uol.com.br

Ribeirão da Mata, whereas the *Serra de Santa Helena* marks its northern border. The whole block is tilted towards the east. Consequently the superficial drainage follows this direction (e.g. Samambaia, Mocambo, Bebida creeks), with a flow rate around 10 m^3/sec. AULER (1994) has measured in the Mocambo basin flow rates of 1.55 m^3/sec during the dry season (October, 1993) and 2.8 m^3/sec in the rainy season (February, 1994), with temperatures varying between 21.9 °C (July) and 23.9 °C (February). Amounts of dissolved calcium carbonate for these creeks are, according to KOHLER (1989), between 127 and 165 ppm, whereas the pH-values oscillate between 7.2 and 7.8.

The climate recorded during the 1970 decade (COPAER, 1980), showed an average pluviometric index of 1,381 mm, with a daily maximum of 162 mm and totaling 105 rainy days/year. January and August were the most rainy and driest months, respectively, however only 20% of rains have had durations of more than four hours. The average annual temperature was 20.8 °C with an average maxima and minima of 27.2 °C and 15.4 °C, respectively.

The natural vegetation on top and around the karst terrain is represented by deciduous and semi-deciduous forests, while hydrophile and hygrophile vegetation predominate in permanent and temporary lagoons. In places with a covered karst a mosaic-like *cerrado* (savana-like vegetation) is ubiquitous. Geologically the region belongs to the southern portion of the São Francisco Craton, composed of low grade metamorphic pelites and calcitic/siliceous limestones of Precambrian age (Upper Proterozoic).

The aim of the present study is to analyze morphologically and morphogenetically the features of the exokarst scenery, in order to elucidate the morphodynamic evolution of the area.

Geologic settings

The major geotectonic feature in central-eastern Brazil is represented by the São Francisco Craton (ALMEIDA *et al.*, 1977) with its adjoining fold belts, belonging to the Mantiqueira Province (SCHOBBENHAUS *et al.*, 1984). Initial deposition of the Proterozoic in this area of Brazil, is related to an extensive platform, which has been stabilized during the end of the Trans-amazonic cycle (~ 2 Ga). This platform have suffered taphrogenesis due to crustal extension around 1.8 Ga ago. The crustal rifting processes gave rise to an intense acid to intermediate volcanism, dated in the Atlantic shield (e.g. Espinhaço) between 1770–1710 Ma (U/Pb).

Between 1000 and 900 Ma (KARFUNKEL & HOPPE, 1988; PEDROSA-SOARES *et al.*, 2000) the craton went through important upheaval movements, with dramatic climate changes, leading to a continental glaciation: the *São Francisco Glaciation* (KARFUNKEL *et al.*, 2000). Much evidence of this period has been described from the Upper Proterozoic fold belts around the craton during the last 30 years (e.g. KARFUNKEL & KARFUNKEL, 1977; HETTICH, 1977; KARFUNKEL & HOPPE, 1988). Negative diastrophic crustal movements of the cratonic area (~ 750 Ma) resulted in a new climatic change and the formation of a large epicratonic sea, in which the psamo-pelitic-carbonatic sediments of the Bambuí Group were deposited. The last large geotectonic cycle in central-eastern Brazil, the *Brasiliano* cycle (~ 650–550 Ma) affected the Proterozoic units in the Atlantic Shield by tectonic and metamorphic changes, mainly at craton borders and in the fold belts. Sediments of the Bambuí Group suffered such processes at the southeastern part of the craton (e.g. the Lagoa Santa region), whereas sediments from central parts of the epicratonic Bambuí-sea show little tectonic and metamorphic changes.

Stratigraphic subdivisions in the Lagoa Santa region, at the south-eastern border of the São Francisco Craton, are based on pioneering works of BRANCO & COSTA (1961), BARBOSA (1965) and BRAUN (1968). Many difficulties occured in establishing a stratigraphic subdivision valid for the whole area; they were mainly caused by facies interfingering in a large region with heterogeneous depositional conditions. Therefore, in the present paper, we use the modified subdivision suggested by SCHÖLL (1972), DARDENNE (1978), GROSSI SAD & QUADE (1985), and TULLER *et al.* (1992). According to DARDENNE (1978) the Bambuí Group shows at its basal part a paraconglomerate (*Carancas Formation*), covered by a carbonate-mudstone sequence (*Sete Lagoas*, *Santa Helena* and *Lagoa do Jacaré* formations). The Carancas Formation is not an equivalent of the older glacial deposits of the São Francisco Glaciation; this formation rather represents subaquatic, reworking levels and aquatic detritus flux formed in paleodepressions of the cratonic basement, then covered by uniform marine sequences.

GROSSI SAD & QUADE (1985) established three formations in the Lagoa Santa region: *Vespasiano*, *Sete Lagoas* and *Santa Helena*. The first is composed of the Carancas Formation, occurring very locally as relicts and of the Pedro Leopoldo facies of SCHÖLL (1972), designated by TULLER *et al.* (1992) as the Lagoa Santa Member. All these terms and names show clearly, that there is only partial agreement between the authors, concerning the nomenclature in the Bambuí sequence. The carbonatic rocks in the Lagoa Santa region, which underwent low-grade metamorphism, are subhorizontal or slightly tilted (5–10° E). Two litho-types can be distinguished: (i) *siliceous limestone* at the base, with 75–90% $CaCO_3$, <7% SiO_2 and 0.5–3% MgO, and (ii) *calcitic limestone* at the top, with 94–99% $CaCO_3$, <6% SiO_2 and <1% MgO (A. Campos, *pers. comm.*).

The carbonatic sequence (Sete Lagoas Formation), with a thickness of about 200 m is overlain by the metapelites of the Serra de Santa Helena-Formation. This economically important calcitic limestone is gray to black and includes as accessory minerals quartz, feldspar, muscovite, chlorite, apatite and fluorite (SCHÖLL, 1972; TULLER *et al.*, 1992). Main structural elements are oriented in NE/SW and NW/SE directions. They can be

traced easily on airborne images and photographs by doline (sinkhole) alignments, or by straight, narrow streams, creeks and caverns (KOHLER, 1989).

The karst

The exokarst scenery of the Lagoa Santa region is characterized by closed depressions (e.g. dolines, uvalas, poljes), that transform in temporary lagoons (Fig. 1) when the karst aquifer level emerges as a consequence of the reloading during maximum rainfall periods (summer). Thus it can be classified as a typical ***karst of intermittent lagoons***.

The geologic map (1:500 000) displays the Lagoa Santa karst region as an enclosed window incised in the Precambrian metapelites. Outstanding is a narrow mountain range, with a NW–SE direction, representing a remnant of the "*Sul Americana*" surface (KING, 1956), as well as the anomalous course of the Córrego da Mata (Mata creek), flowing to the south, in contrast with the general direction of the hydrographic network.

Analyzing the region on a larger scale (1:50 000), four geomorphologic compartments have been identified (from SW towards the NE):

(i) a topographically higher area, up to 850 m at the Serra do Ferradores (covered karst with remnant lateritic detritus, covered by allochtonous soils), containing a fluviokarst with blind valleys and dolines (Palmeira-Mocambo);

(ii) a semicircular belt comprising dolines and uvalas (extending from Confins to Macambeiro);

(iii) a lower elevation plateau containing a complex system of asymmetric dolines of different ages, aligned along ancient, Precambrian structural trends (NW-SE and NE-SW), expressed by straight segments of abrupt walls.

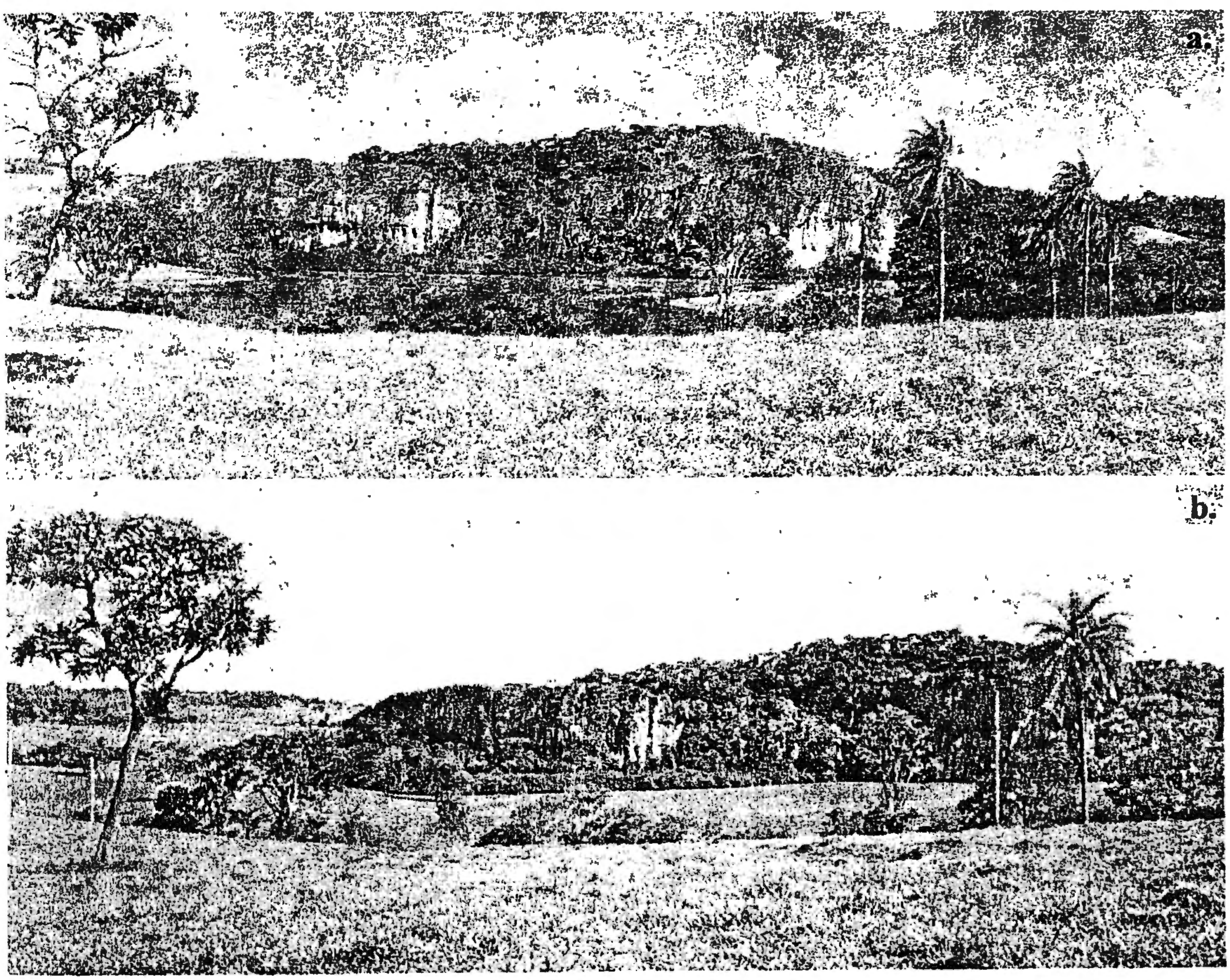


Fig. 1. View of the Cerca Grande massif during the (a) summer, and (b) winter.
Vue du massif de Cerca Grande durant l'été (a) et l'hiver (b).

The different ages are marked by twin-dolines inside a larger, older doline. This compartment incorporates the Samambaia, Macacos, Baú and Cerca Grande massifs;

(iv) the lowermost compartment at approximately 650 m with many poljes and ponors, is situated next to the main river, the Rio das Velhas.

At a scale of 1:1 000 horizontal and vertical karren (*Schichtenkarren* and *Rund-Rillenkarren*, respectively) at the walls of the massifs can be seen (Fig. 2). As a consequence of dissolution dynamics by pluvial water, the karren occur in a major concentration on the upper portion of the high walls (>20 m) together with some oblique joints.

The morphogenetic features have been imposed by sedimentary facies, hence mineralogically the depressions (e.g. dolines, uvalas) represent areas of calcitic limestones, while topographic positive relief areas (e.g. humes, towers) are composed of siliceous carbonate rocks. Cavern systems (endokarst) develop at the bottom of the walls near the actual doline and ponor level. Several chambers are coated with speleothems that can fill, in some cases, ancient conduits. Under the stalagmitic floor remains of extinct mega-fauna have been discovered.

Karst morphogenesis

The karstic landscape of the Lagoa Santa region developed mainly during the Quaternary; however its origin is remote and probably related to the breakdown of Gondwana during the Late Jurassic - Early Cretaceous, when extensional crustal dynamics gave rise to the opening of the South Atlantic (Mesozoic reactivation according to ALMEIDA, 1977).

On top of the later formed Sul Americana continental platform the drainage system had been reorganized and the actual Rio São Francisco basin formed. This basin formed mainly on outcrops of Upper Proterozoic metasediments of the Bambuí Group.

After a long period of apparent stability, probably during Mid Tertiary, a large surface (etchplain), the Sul Americana Surface ("*master surface*" of KING, 1956), was formed at an actual topographic level of approximately 850 m, was formed. A thick red lateritic soil developed as the consequence of a hot and humid climate.

Within carbonate units under the pelites of the Bambuí Group (< 830 m actual topography) the endokarst developed a cave system filled by karst water. Evidence points towards corrosion conduits that formed under hydraulic pressure. According to BÖGLI (1978) endokarstic corrosion processes start when the water reaches the soluble rock.

Analysis of the present-day Lagoa Santa drainage system (Fig. 3) points towards an important anomaly. The general trend of the hydrographic system with its largest river, the Rio das

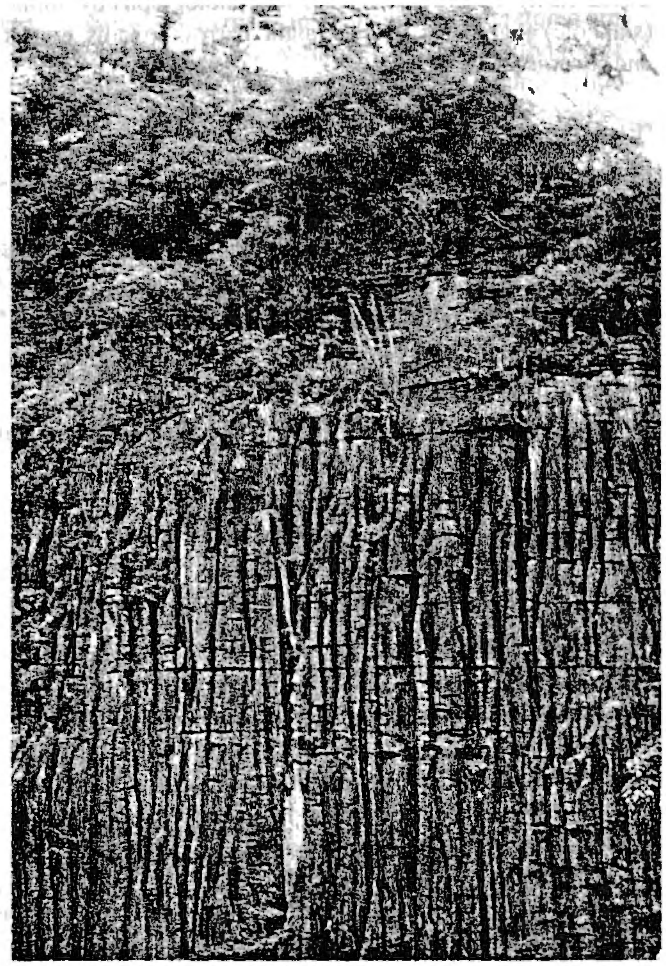
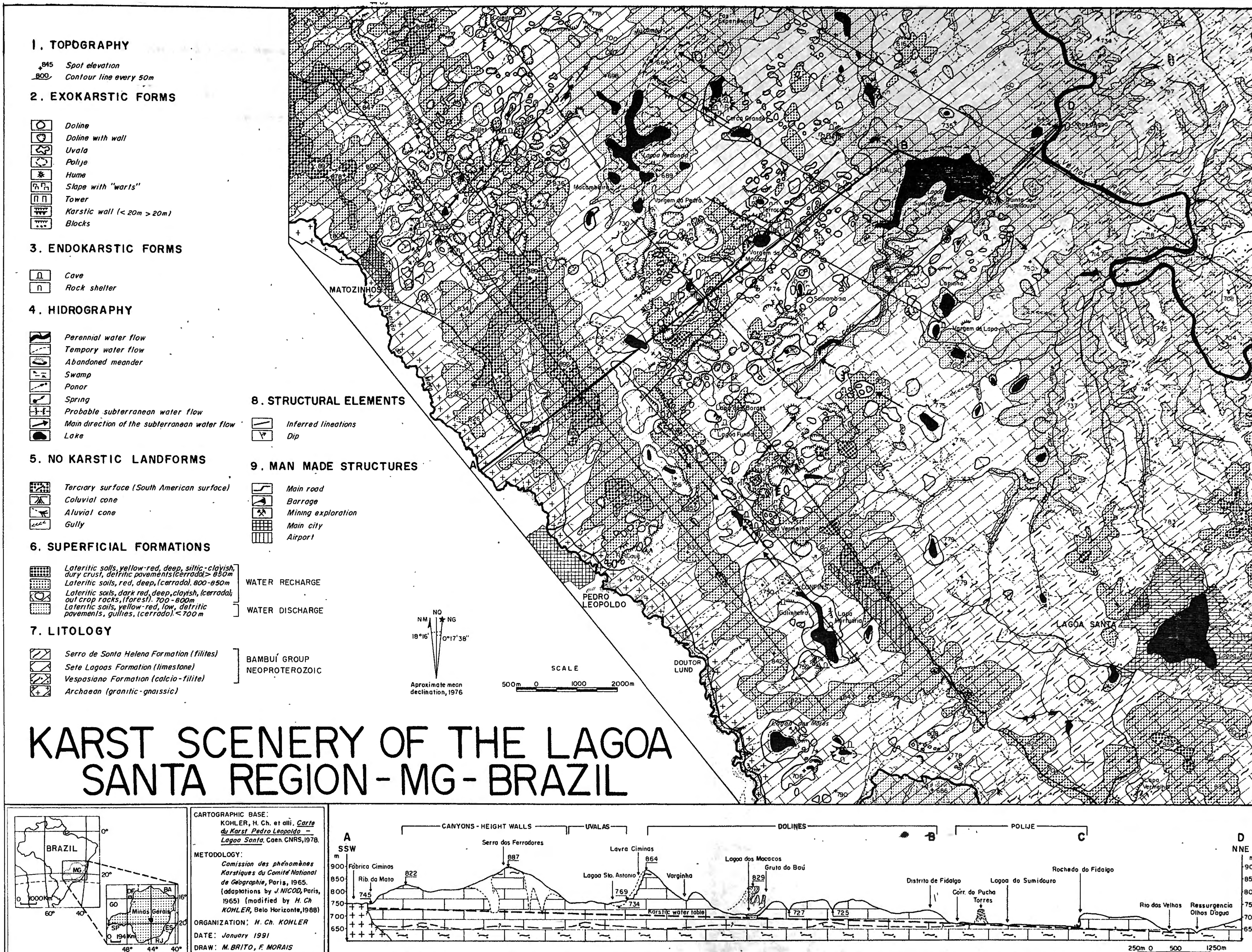


Fig. 2. Schichtkarren and Rund-Rillenkarren at the wall of the Baú massif. The cactus (mandacarú) is a reminiscent of a dry savanna climate.
Schichtkarren et Rund-Rillenkarren sur la parois du massif de Baú. Le cactus (mandacarú) est un relique du climat de savane sec.

Velhas and its tributaries, is northwards. Solely one of its tributary, the Ribeirão da Mata (Mata Creek) flows in an almost opposite direction, towards the southeast. This anomaly suggests that the Rio das Velhas once occupied the actual course of the Ribeirão da Mata, flowing at that time in a northwestern direction. Geomorphic evidence supporting this hypothesis are:

- anomalous hydrographic flow of the Ribeirão da Mata;
- the width of over 100 m of the Ribeirão da Mata (bed) is incompatible with its present flow rate;
- the Rio das Velhas shows, after its confluence with Ribeirão da Mata, an undulatory course with many rapids and waterfalls;
- gravel of fluvial origin at 850–900 m;
- Quaternary terraces;

KARST SCENERY OF THE LAGOA SANTA REGION - MG - BRAZIL



- fluvial gravels inside the endokarst;
- occurrence of fluvial gold, similar to that which occur in the Rio das Velhas terraces, inside the endokarst. The origin of the gold can be attributed only to the gold deposits derived from the Quadrilátero Ferrifero;
- the surface is tilted in a southeastern direction, while the strata dip towards the northeast;
- regional evidence for neotectonic processes.

According to VON RICHTHOFEN (1886) the age of a river is contemporaneous with the massif which accommodates its springs and tributaries. The Rio das Velhas originates in the Serra de Ouro Preto and reaches the locality of the Ribeirão da Mata in the Lagoa Santa region, only after passing through several sectors of the Quadrilátero Ferrifero (Iron Quadrangle). As a consequence of a long period of morphostructural evolution of this massif, the Rio das Velhas has been dislocated. Its actual bed, due to superimposition, lies inside old structural alignments (VON FREYBERG, 1932).

The Rio Paraopeba, a tributary of the large São Francisco River, located upstream to the confluence of the latter with the Rio das Velhas, passes the extension of the Serra do Curral (northeast of the Quadrilátero Ferrifero) and the Fecho do Funil in a narrow and straight, ravine-like course, without waterfalls and chutes. The only apparent anomalous behavior displays the Rio das Velhas, that shows, after its confluence with the Ribeirão da Mata, juvenile features, with dozens of waterfalls and rapids, down to the São Francisco River at Barra do Suaçuí.

During the Pleistocene, when the denudation cycles of the Rio das Velhas dissected the Sul Americana surface, this river deposited gravel, found today at topographic levels of 850–900 m on top of the carbonates and metapelites. During this period the Rio das Velhas, after passing the Serra do Curral, continued towards northwest, along the structural alignment between the basement and the rocks of the Bambuí Group — a course that is currently occupied by the Ribeirão da Mata bed. When the dissection reached the limestone level, today at 820 m, it turned into a karstic river. The passage of the Rio das Velhas through the Lagoa Santa endokarst is shown by the presence of well rounded gravels of quartz and quartzite inside cavern speleothems of the Poços region in Matozinhos (KOHLER *et al.*, 1976). Connections with the Paraopeba basin can be observed in the Sete Lagoas area, in the Gruta Rei do Mato (Rei do Mato cave), situated on the actual water-divide between Velhas and Paraopeba rivers. PAULA COUTO (1975) affirms the probable existence of "*a very good synchronization between the fossil mammal fauna in the caverns of Minas Gerais and São Paulo and the Ludiense Argentino of Upper Pleistocene age*". This affirmation translates in time the beginning of the incision and the consequent denudation of the interfluvial block towards the Mid Pleistocene. In the Upper Pleistocene the denudation and corrosion processes have already open the caverns, which were subsequently occupied by the Ludinense fauna. It is important to remember that the European quaternarists have established a magnetic inversion and the beginning of an important glaciation during the Mid Pleistocene, at approximately 700 ka BP.

The evolution of this karst region can be explained simply, if we admit a much higher flow rate at that time, than that of today, which is around 10 m^3/sec. This would satisfactory explain the paleokarst processes that were responsible for the configuration of the actual landscape.

In short, it can be postulated, that the Rio das Velhas, after crossing the Quadrilatero Ferrifero, sought to adapt its course to the easier passage towards the north. Its course passed the lithological contact basement/Bambuí and reached the karstic region in the vicinity of Matozinhos, entering into the underground.

The Rio das Velhas, allochtone to the karst, transports its water at 200 m^3/sec through a labyrinth of endokarstic channels. Along its route it floods the caves and deposits clay and gravels; in addition it corrodes the walls of conduits, widens passages and removes calcium carbonate. These widened conduits and passages can form collapse dolines, creating a fluviokarst scenario. Archaeologists (e.g. PROUS, 1978) describe the clay as "reddish". In the reddish clay beneath the stalagmitic level, fossil bones have been discovered. Gravel was found cemented in the roof of passages (e.g. at Balet and Curral de Pedras). Finally the watercourse reappears as a tributary of the Rio Paraopeba. The lack of bauxite in karst can be explained by its age (~700 ka BP), although the overlying lithology is composed of rocks rich in aluminium phyllosilicates.

Concluding remarks

Structural alignments, consequence of the Brasiliano cycle, that were reactivated during Cenozoic time, control the main trends of the karstic landscape of the Lagoa Santa region. The superimposed effects of tectonics and climate over the carbonatic lithologies through time, left evidence that allowed the reconstruction of its structural history.

The morphogenetic events in a preliminary chronological approximation can be described, according to KOHLER & PILÓ (1991) in the following way:

- **Tertiary** — the interfluvial block was peneplaned by the Sul Americana surface during a warm/humid climate. Thick laterite soils were developed;
- **Pliocene/Pleistocene** — dissection of the Sul Americana surface due to different Velhas cycles. Alternating climate between cold/dry and warm/humid;

- **Mid Pleistocene — the denudation cycle Velhas has reached the carbonatic rocks level creating the upper passages of the endokarst. Alternating climates have triggered a superficial karstification;**

- **Late Pleistocene — (>22 ka BP) strong incision of the topography. Formation of built-in surfaces with doline levels between 10 and 12 m above the actual level during a warm/humid climate.**
  The maximum corrosion was recorded between 13 and 22 ka BP and speleothems were precipitated into the cave passages during a cold/dry climate.

- **Holocene — maximum incision during climatic crises between 3000 and 5000 years BP. Periodic inundation of plains and formation of dolines and uvalas.**

Thus the successive karstic features are not interpreted as the result of single cyclic events, but rather as the consequence of complex Quaternary climatic oscillations which favored changes of the flow rates and chemical characteristics of the waters.

The scenario of the karstic phenomena over the interfluvial block Ribeirão da Mata - Rio das Velhas represents a remarkable example of initiation, genesis and dynamics of an intertropical karst - a true case-study for interfluvial surfaces from other regions.

Acknowledgements

This study was partly supported by the Conselho Nacional de desenvolvimento Científico e Tecnológico (CNPq), as well as by the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG). We thank D.B. Hoover for reviewing the final manuscript.

References

Almeida, F. F. M., de (1977) O Cráton do São Francisco. *Rev. Bras. Geoc.*, 7, 4, pp. 349–364.

Auler, A. (1994) *Hydrological and Hydrochemical characterization of the Matozinhos - Pedro Leopoldo karst, Brazil*. MSc. Thesis, Dept. Geography and Geology, Western Kentucky Univ., Bowling Green, 110 p. (*unpublished*).

Barbosa, O. (1965) Série Bambuí. Simp. das formações Eo-Paleozóicas do Brazil. *XIX Congr. Bras. Geol.*, SBG, Rio de Janeiro, Brazil.

Bögli, A. (1978) *Karsthydrographie und physische speleologie*. Springer, Berlin, 279 p.

Branco, J. J. R. & Costa, M. T. (1961) Roteiro para excursão Belo Horizonte - Brasilia. *Contribuição ao 14. Congr. Bras. Geol. Publ.*, 15, UFMG, Belo Horizonte, 25 p.

Braun, O. P. G. (1968) Contribuição à estratigrafia do Grupo Bambuí. *Anais 22. Congr. Bras. Geol.*, Belo Horizonte, pp.155–166.

Copaer, B.H. (1980) *A construção do aeroporto e a proteção do meio ambiente e os valores culturais*. Belo Horizonte (Brazil), Ministério da Aeronaútica, 288 p.

Dardenne, M.A. (1978) Síntese sobre a estratigrafia do Grupo Bambuí no Brasil central. *Anais 30. Congr. Bras. Geol.*, 2, SBG., Recife, pp. 597–610.

Freyberg, b., von (1932) Ergebnisse geologischer Forschungen in Minas Gerais, Brasilien. *N. Jb. Min. Geol. Palaeont.*, Sonderbd. 2, Stuttgart, 403 p.

Grossi Sad, J. H. & Quade, H. (1985) Revisão estratigráfica do Grupo Bambuí (Bloco Oriental) em Minas Gerais. *Anais do III Simp. de Geol. De Minas Gerais*, Belo Horizonte, pp.68–83.

Hettich, M. (1977) A glaciação Proterozóica no centro-norte de Minas Gerais. *Rev. Bras. Geoc.*, 7, pp. 87–101.

Karfunkel, B. & Karfunkel, J. (1977) Fazielle Entwicklung der mittleren Espinhaço-Zone mit besonderer Berücksichtigung des Tillit-Problems (Minas Gerais, Brasilien). *Geol. Jb.*, 24, pp. 3–91.

Karfunkel, J. & Hoppe, A. (1988) Late Proterozoic glaciation in central-eastern Brazil: synthesis and model. *Paleogeogr., Paleoclimat., Paleoecol.*, 65, pp. 1–21.

Karfunkel, J., Dupont, H., Hoppe, A., Schobbenhaus, C., Noce, C. M., & Peregovich, B. (2000) The Neoproterozoic São Francisco Glaciation in Central-Eastern Brazil. In: *17. Geowissenschaftliches Lateinamerika Kolloquium*, 18, pp. 44.1–44.5.

King, L. C. (1956) A Geomorfologia do Brasil Oriental. *Ver. Bras. Geogr.*, 18, pp. 147–265.

Kohler, H.C. (1989) *Geologia cárstica na região de Lagoa Santa.*, PhD Thesis, Univ. of São Paulo, São Paulo. 113 p. (*unpublished*).

Kohler, H.C. & Piló, L.B. (1991) The Quaternary chronology of the morphogenetic events in the karstic region of Lagoa Santa. In: *INQUA Congress, 13, Beijing, 1991. Abstracts*.1, p.168.

Kohler, H.C., Queiroz Neto, J.P., Coltrinari, L., Ferreira, R. P. D., Stanowski, S. M., Cançado, A. M., Gomes, D., & Macieira, F. L. (1976) Os diferentes níveis de seixos nas "formações superficiais" da região de Lagoa Santa. *Anais do XXIX Congr. Bras. Geol.*, 1, pp. 343–347.

Paula Couto, C. (1975) Mamíferos fósseis do quaternário do sudeste brasileiro. In: *Internat. Symp. On the Quaternary. Bol. Paranaense de Geociências* (Bigarella, J. J. & Becker, R.D. *Eds.*), 33, Curitiba, pp. 89–132.

Pedrosa-Soares, A. C., Cordani, U.G., & Nutman, A. (2000) Constraining the age of Neoproterozoic glaciation in eastern Brazil: First U-Pb (SHRIMP) data of detrital zircons. *Rev. Bras. Geoc.*, 30, pp. 058–061.

PROUS, A. (1978) Breve histórico das pesquisas sobre o homem na região de Lagoa Santa/Minas Gerais. *Inst. De Geogr., USP, Colóquio Interdisciplinar Franco - Brasileiro*, 2, São Paulo, pp. 21–27.

RICHTHOFEN, F., VON (1886) *Führer für Forschungsreisende. Anleitung zu Beobachtungen über Gegenstände der physischer Geographie und Geologie*. Oppenheimer, Berlin. 734 p.

SCHOBBENHAUS, C., CAMPOS, D. A., DERZE, G. R., & ASMUS, H. E. (1984) *Geologia do Brasil*. MME/DNPM, Brasilia, 501 p.

SCHÖLL, W. U. (1972) Der südwestliche Randbereich der Espinhaço-Zone, Minas Gerais, Brasilien. *Geol. Rdsch.*, **61**, pp. 201–216.

TULLER, M. P., RIBEIRO, J. H., & DANDERFEER, A. (1992) *Mapeamento geológico da área do Projeto VIDA*. CPRM, Belo Horizonte.

received: 6 August 2002
revised: 18 November 2002
accepted: 18 November 2002

Theoretical and Applied Karstology, 15 (2002), pp. 101–110

Small mammals of the cave sites in the Baikalian region

Margarita Erbajeva*, **Fedora Khenzykhenova, & Nadja Alexeeva**

Geological Institute, Siberian Branch, Russian Academy of Sciences, 6a Sahianova Str., 670047 Ulan-Ude, Russia.

Abstract

This paper deals with the small mammal assemblages from the cave sites of the Baikalian region. In the region there are more than 300 caves and shelters (Filippov, 1993a, 1993b), some of which contain numerous small mammal fossils. The oldest fauna is the Middle Miocene from Aya cave containing *Eurolagus*, *Heterosminthus* and *Gobicricetodon*. In other caves, more than 30 taxa of insectivores, lagomorphs and rodents were discovered, mainly of Late Pleistocene and Holocene age. Most of the small mammals belong to modern species, which inhabit the region nowadays; however, specimens of *Lagurus lagurus* and *Dicrostonyx* sp., whose area of distribution lies outside of the region currently, were also found.

Key words: Mammalia, rodents, lagomorphs, caves, Baikalian region, Prebaikalia, Transbaikalia, Miocene, Late Pleistocene, Holocene.

Les micromammifères des sites spéléiques de la région Baïkalienne

Résumé

Dans ce travail on fait une présentation des associations de micromammifères des grottes de la région Baïkaliene. Il y a ici plus de 300 grottes et abris-sous-roche (Filippov, 1993a; 1993b), dont quelques-uns contiennent de nombreux restes fossiles de micromammifères. La faune la plus ancienne est d'âge Miocène moyen, provient de la grotte d'Aya et inclut Eurolagus, Heterosminthus *et* Gobicricetodon. *Dans d'autres grottes, plus de 30 taxons d'insectivores, lagomorphes et rongeurs ont été découverts, la plupart étant d'âge Pléistocène supérieur et Holocène. La majorité des micromammifères sont des espèces récentes, qui peuvent être trouvées actuellement dans la région, mais des exemplaires de* Lagurus lagurus *et* Dicrostonyx sp., *dont l'aire de distribution est maintenant plus restreinte ont été également identifiés.*

Mots-clés: Mammalia, rongeurs, lagomorphes, grottes, région Baïkaliene, Prebaïkalia, Transbaïkalia, Miocène, Pléistocène supérieur, Holocène.

Introduction

The Baikalian region is located in the center of Asia. The territory stretches from South to North between 47° and 58°N; from West to East it extends between 102° and 114°E (Fig. 1). It is situated on south-eastern borderland of the Siberian Platform, one of the stable blocks of the Asiatic continent and a part of the Central-Asian folded belt formed during the long geological evolution of Paleoasian ocean. The region is spread within the Central-Asian mountain belt and it is characterized by the alternation of large, tectonically determined relief forms. The studied area includes the territory of south Eastern Siberia - Prebaikalia and Western Transbaikalia which has more than 70 recorded caves and shelters, the most of them being karst caves, distributed unevenly across the territory in a variety of climate, geologic, physiographic, and hydrologic regimes. Their classification was provided by Filippov (1993a, 1993b).

Systematic studies of the caves had been carried out at the end of XIXth and beginning of the XXth Century. Geologists P. Kropotkin and I. Tschersky and archaeologists B. Petri, G. Debets, G. Vologodskyi and others were the early investigators that reported the first data on the caves from the western shore of Lake Baikal. Around the 80's of the last century detailed, multidisciplinary studies of the most caves of the Prebaikalian National Park, located on the western coast

* corresponding author. *E-mail address*: erbajeva@gin.bsc.buryatia.ru.

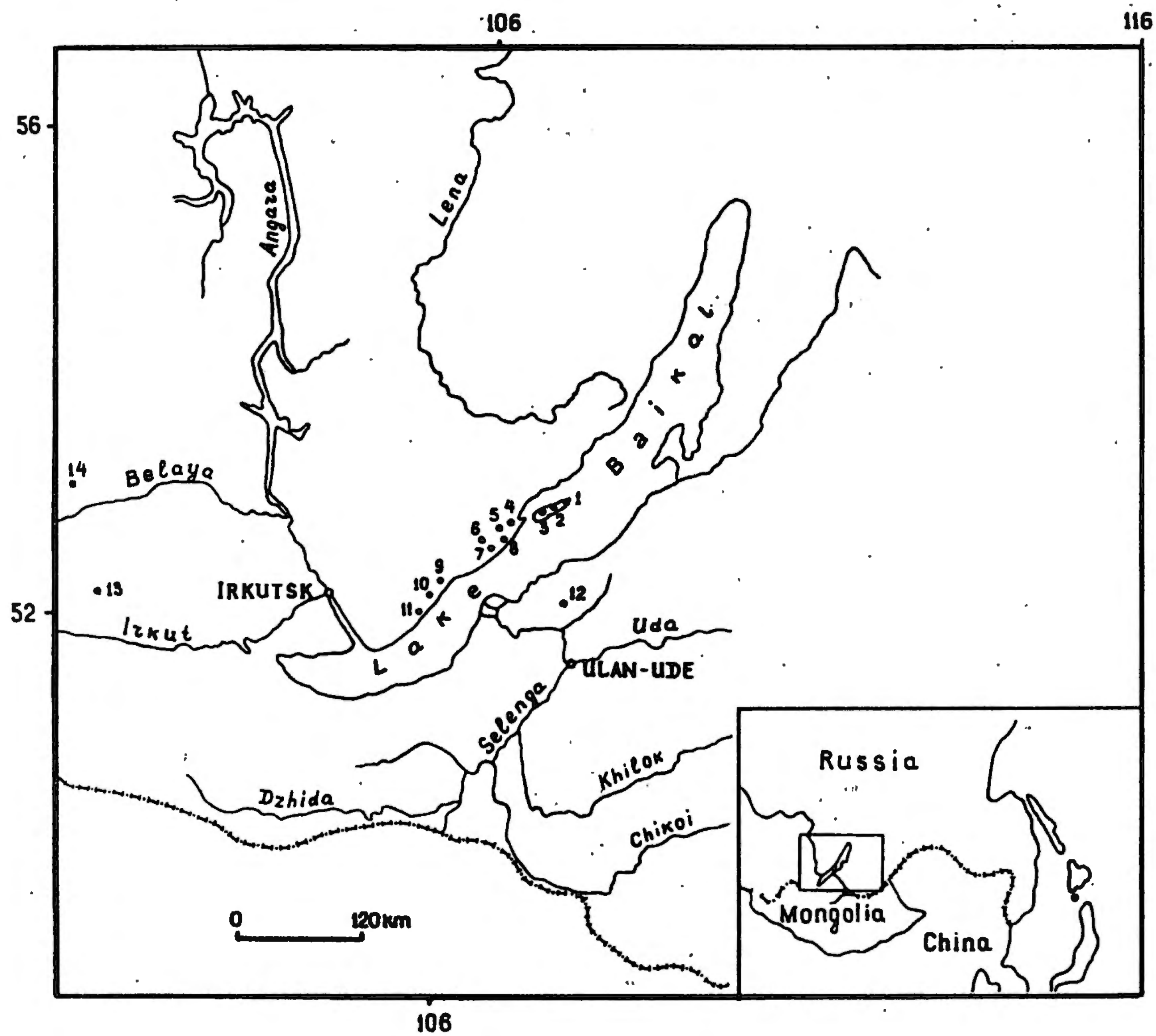


Fig. 1. Sketch map of the Baikalian region showing the location of cave sites. *Carte de la région Baïkalienne avec la situation des sites étudiées.*
1. Uzurskaya; 2. Shamanskaya; 3. Boro Khukhan; 4. Khurganskaya; 5. Tonta; 6. Bolshaya Baidinskaya; 7. Sluchainaya; 8. Aya; 9. Kurtun 1; 10. Kurtinskaya; 11. Kadilinskaya; 12. Kalcitovaya; 13. Brekchievaya; 14. Unylskaya.

of Lake Baikal were provided by different specialists – speleologists, geologists, paleontologists, biologists, climatologists, archaeologists etc. (Goryunova *et al.*, 1996). At that time many fossil-bearing caves were discovered in the region and the first remains of small mammal were obtained here. The fossil remains are not well preserved, there are some fragments of lower jaw and maxilla with different numbers of teeth or without teeth. The main materials consist of isolated teeth and fragments of the postcranial skeleton. Probably they originate from owl pellets; some of these may come from animals which died in the cave itself. As usually, the bone deposits of most caves are subject of the activities of predators, either animals or birds, or both. The faunal data have provided significant information on biotic and climatic changes that have occurred in the area from the late Pleistocene to the present. Studied fossils were collected mainly by the geologist and speleologist Dr. A Filippov and his colleagues, and in part by F. Khenzykhenova.

All small mammal materials (rodents and lagomorphs) are stored at the Geological Institute in Ulan-Ude.

Caves and small mammals assemblages

The paper deals with the small mammalian faunas of some caves located on Olkhon Island (sites Uzurskaya, Shamanskaya, Boro Khukhan) and on the west coast of lake Baikal, mainly in its mid and southern part (Khurganskaya, Tonta, Bol'shaya Baidinskaya, Sluchainaya, Aya, Kurtun-1,

Kurtinskaya, Kadilinskaya), as well as Brekchievaya and Unylskaya in the Sayan region and the only one cave in Transbaikalia (Kalcitovaya) (Fig.1).

The oldest site with small mammal faunas is the unique Miocene cave **Aya** in Eastern Siberia. It is situated on the Priolkhon Plateau, more than 200 m above of Lake Baikal surface in the Aya Bay, over 30 km southwest of Olkon Island. It is a phreatic cave developed in graphite marbles of Upper Archean–Early Proterozoic age. The length and depth of this cave are 550 m and 40 m, respectively. At this site eight layers of Late Cenozoic deposits were described by Erbajeva & Filippov (1997).

The uppermost two layers are Late Pleistocene in age (based on the analysis of sediments and faunas); the later include fishes, amphibians, bats and rodents (*Microtus* sp.). In the next, Middle Pliocene, redeposited dark-brown soil, containing grit and rock debris grouting with black loam cement, remains of fishes, bats and undetermined small mammals were collected. Abundant fossils, including turtles, amphibians, birds, fishes and mammals were found in layers 4, 5 and 6 (Filippov *et al.*, 2000).

The small mammal fauna is not numerous and it includes: *Eurolagus* cf. *fontannesi* (Deperet, 1887), *Heterosminthus erbajevae* Lopatin, 2001, *Gobicricetodon* sp. nov. Sen & Erbajeva (*in press*), Insectivora gen. indet. In this fauna lagomorphs are a dominant group. In the lowermost three layers (7 and 8) no fossil remains were found.

The next group of caves are known on Olkhon Island: **Uzurskaya, Shamanskaya** and **Boro Khukhan**. The first is located on the north-eastern part of the island, near the village of Uzur. The cave is developed also in graphite marbles of Archean-Early Proterozoic age. Its length, width and depth are 5 × 1.5 × 2 m, respectively and it is filled with grey sandy loam 30 cm-thick. The next small mammals recognized here were: *Lepus* sp., *Ochotona* cf. *hyperborea* Pall., *Spermophilus* sp., *Cricetulus* sp., *Alticola* sp., *Lagurus lagurus* Pall. The fauna includes both forest and steppe inhabitants. However, it is characterized by the predominance of the steppe inhabitants among which *Lagurus lagurus* was the most abundant form (more than 50% of the total population).

The sites Shamanskaya and Boro Khukhan are located in the middle area of Olkhon Island. Fossil-bearing layers are rather deep in the first cave (around 1.1 m) and shallow at the second site (0.2 m). Their faunas are similar and include common taxa: *Lepus timidus* L., *Spermophilus undulatus* Pall., *Cricetulus barabensis* Pall., *Clethrionomys* cf. *rutilus* Pall., *Alticola* sp., *Microtus oeconomus* Pall., *Microtus* cf. *fortis* Buechner. They belong to modern species that inhabit the region at the present time. However fauna of Shamanskaya cave, in addition to the above-mentioned taxa, contains *Clethrionomys rufocanus* Sundevall and *Lagurus lagurus* Pall. The latter species does not exist in the recent fauna of the region.

Small mammal associations of these two sites and quantitative ratio of taxa show that open landscapes were distributed rather widely; however forest biotopes were dominant.

The other group of studied caves are located mainly on the western coast of Lake Baikal, along Primorskyi Mountain, while one cave, **Kalcitovaya**, is located on the eastern coast of Lake Baikal, in the Transbaikal area. They are all developed as well in graphite marbles of Archean-Early Proterozoic age. Two caves **(Unylskaya and Brekchievaya)** are situated in East Sayan mountainous region.

Fossil remains from these caves were collected from different layers reffered to the Late Pleistocene and Holocene but we shall mainly discuss the Late Pleistocene small mammals.

The number of fossil remains in each cave differs very much. Huge number of specimens (more than 900 specimens from three layers) were collected in **Kurtun-1** site; around 500 specimens in both **Kurtinskaya** (two layers) **and Tonta** (five layers) caves, 25 — in **Bol'shaya Baidinskaya**, 42 — in **Sluchainaya**, 70 — in **Khurganskaya** (two layers) and others (Filippov *et al.*, 1995). All these caves contain faunas of similar taxa. The list of the small mammal species is given in Table 1.

The species composition of the faunas show, that all these caves contain mainly recent taxa that inhabit Prebaikalia nowadays except for *Lagurus lagurus* and *Dicrostonyx* sp. During the late Pleistocene and early Holocene, *Lagurus lagurus* was widely distributed in the Baikalian region, its area of distribution extending to the south-east of Eastern Transbaikalia. The nearest modern area of distribution of this species is Mongolia in the south and the steppes of Khakasia and Kazakhstan in the west (Gromov & Erbajeva, 1995). Next species, the arctic lemming *Dicrostonyx torquatus* Pall. may be found in Eurasia, at the present time, only within the tundra and the northern forest tundra zone (Gromov & Erbajeva, 1995). In total, the faunas of these caves demonstrate that in the region a mosaic-type landscape have existed, including forest, tundra-steppes, steppes, meadows and river valleys. The forest inhabitants (*Lepus timidus*, *Ochotona hyperborea*, *Pteromys volans*, *Sciurus vulgaris*, *Tamias sibiricus*, *Clethrionomys rutilus*, *C. rufocanus*, *Alticola argentatus*, *Lemmus* sp., *Myopus schisticolor*, *Micromys minutus* and others) were predominant groups in the fauna of that time. The typical steppe dwellers such as *Lagurus lagurus* and *Microtus gregalis*, inhabitants of the dry meadows — *Spermophilus undulatus*, *Cricetulus* sp., *Microtus arvalis*, *M. maximoviczi* and moist meadows (*Microtus oeconomus*) had a rather sporadic distribution.

The analysis of species composition of the sites Kurtun-1, Brekchievaya and Unylskaya has revealed that the small mammal faunas was a disharmonious one, including both tundra and steppe dwellers — *Dicrostonyx* and *Lagurus*, the animals which inhabit at present time quite different natural zones. The disharmonious faunas were widely distributed

Table 1. The list of the small mammals from different caves of the Baikalian region.

La liste des différents micromammifères des grottes de la région Baïkalienne.

* Caves/*Grottes*: 4: Khurganskaya; 5: Tonta; 6: Bol'shaya Baidinskaya; 7: Sluchainaya; 9: Kurtun-1; 10: Kurtinskaya; 11: Kadilinskaya; 12: Kalcitovaya; 13: Brekchievaya.

No.	Species	4*	5	6	7	9	10	11	12	13	14
	Insectivora										
1.	*Sorex* sp.	+		+		+	+	+	+	+	
	Lagomorpha										
2.	*Lepus timidus* L.			+	+	+		+	+		
3.	*Lepus* sp.		+	+		+		+		+	
4.	*Ochotona hyperborea* PALLAS	+		sp	+	+	+	sp	sp	sp	+
	Rodentia										
5.	*Pteromys volans* L.					+			+		
6.	*Sciurus vulgaris* L.	+				+			+		
7.	*Tamias sibiricus* (LAXMANN)	+	+			+	+		+		+
8.	*Spermophilus undulatus* PALLAS	+	+		sp	+	+				+
9.	*Marmota* sp.					+					
10.	*Cricetulus* sp.	+	+		+	+			+	+	
11.	*Alticola argentatus* (SEVERTZOV)		+			+					
12.	*Alticola* sp.		+	+	+	+	+	+	+		+
13.	*Clethrionomys rutilus* PALLAS	+	+	+		+	+	+	+	+	+
14.	*Clethrionomys rufocanus* SUNDEV.	+	+	+	+	+	+	+	+	+	+
15.	*Clethrionomys* sp.		+	+		+		+			
16.	*Dicrostonyx* sp.					+				+	+
17.	*Lagurus lagurus* PALLAS					+					+
18.	*Arvicola terrestris* L.	+	+			+	+			+	
19.	*Microtus oeconomus* PALLAS	+	+	+		+	+	+	+	+	+
20.	*Microtus fortis* BUECHNER		cf	+		cf		+		cf	
21.	*Microtus arvalis* PALLAS					cf	+			+	
22.	*Microtus gregalis* PALLAS	+	+	+		+	+	+		+	+
23.	*Microtus maximoviczi* SCHRENK								+		
24.	*Microtus* sp.	+	+								
25.	*Lemmus* sp			+				+			+
26.	*Myopus schisticolor* (LILLIJEBORG)								+	+	
27.	*Myopus* sp.		+			+	+				
28.	*Apodemus* sp.					+					
29.	*Mus* sp.			+				+	+		
30.	*Micromys* cf. *minutus* (PALLAS)		+	+		+					

during the Pleistocene cold period in the Northern Eurasia from the Western Europe to the Prebaikalia.

In contrast to Prebaiakalia in the Transbaikal area, at that time a vast territory was occupied by dry cold steppes with arid climate where *Lasiopodomys brandti*, *Ochotona daurica*, *Lagurus lagurus*, *Marmota sibirica*, *Allactaga sibirica* were the dominant groups among the small mammals. No fossils of collared lemmings were found here ever.

Short review of some taxa from caves

Among small mammals collected in the caves of the Baikalian region around 30 taxa are established (Table 1); one form is reffered to insectivores, three — to lagomorphs and other 26 taxa belong to the rodents. Of the rodents, the most abundant and characteristic forms are *Clethrionomys rutilus*, *C. rufocanus* and *Myopus schisticolor*, as well as *Alticola* and different species of the genus *Microtus*. They all currently exist in modern fauna of the region. The most important and significant elements of the cave faunas are *Dicrostonyx* and *Lagurus* which are not present any more in the region.

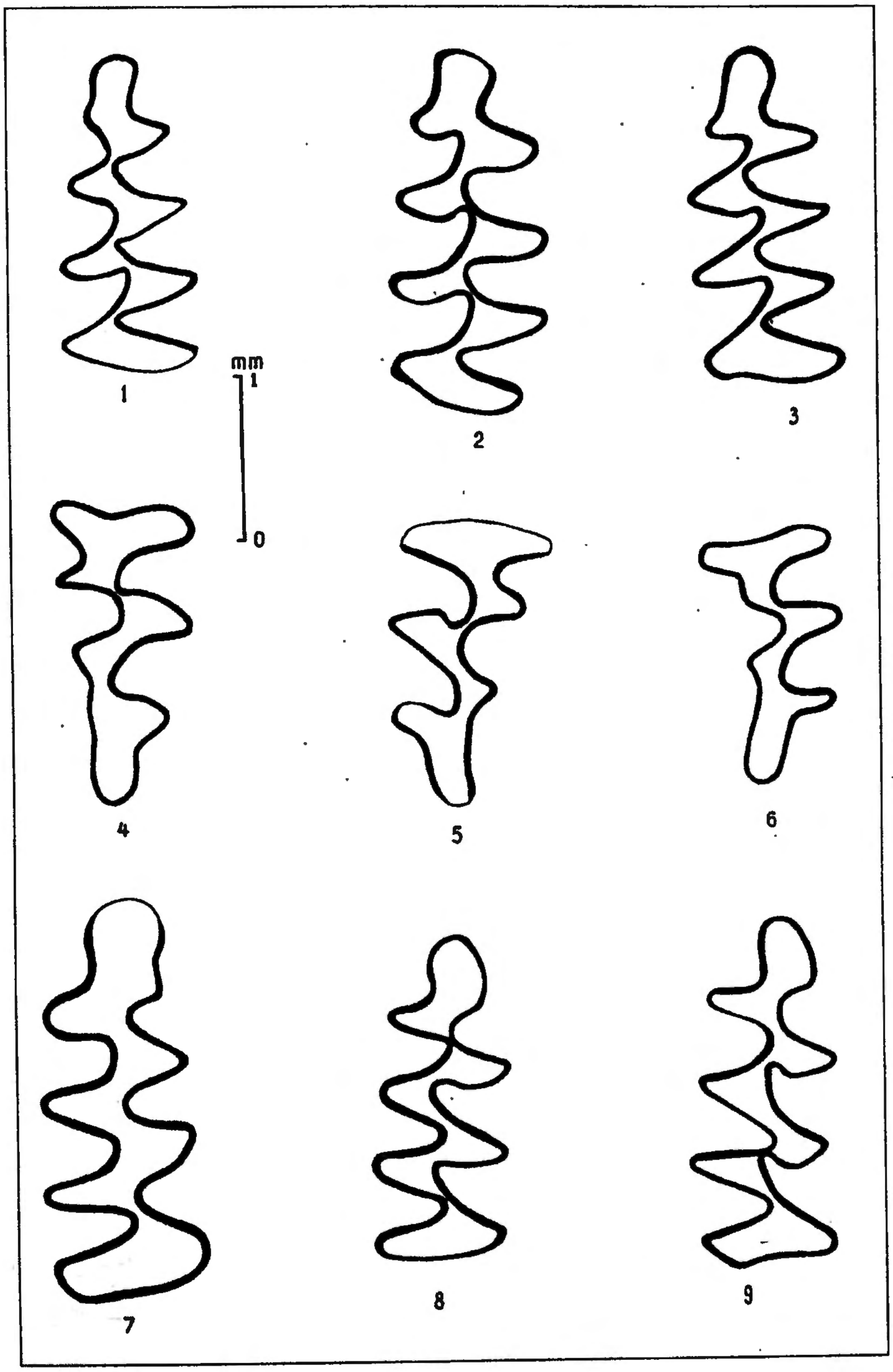


Fig. 2. *Alticola argentatus* (Severtzov, 1879) from the caves of the Baikalian region.

Alticola argentatus *(Severtzov, 1879) des grottes de la région Baïkalienne.*

M_1: 1. Kurtinskaya; 3, 6. Uzurskaya; 4. Tonta; 7. Bolshaya Baidinskaya; 9. Sluchainaya. M^3: 2. Kurtinskaya; 5. Tonta; 8. Sluchainaya.

Rodentia Bowdich, 1821
Cricetidae Fischer, 1817
Arvicolinae Gray, 1821
Alticola Blanford, 1881
Alticola argentatus (Severtzov, 1879)

The remains of *Alticola* occurred in all caves except Khurganskaya and Brekchievaya (Table 1). The dental pattern is identical to that of the recent *Alticola argentatus* (Fig. 2, *1–9*).

The modern species occupy the rocky areas of the mountain chains of Pamir-Alai and Tian-Shan in Kirgizia and Tadjikistan, Altai-Sayan mountainous area in Russia, Hangai and Kentei Mountains, and Khubsugul area in Mongolia. In the studied area, in Prebaikalia, this species is distributed on the western coast of the Lake Baikal, on the territory of relict Tazheran steppes and on the Olkhon Island (Shvetsov *et al.*, 1984).

Clethrionomys Tilesius, 1850
Clethrionomys rufocanus (Sundevall, 1846)
(Fig.3, *1–5;* Table 2)

Clethrionomys rufocanus is one of the abundant species of the faunas of all caves of the region. This species is characterized by its large size. The molars are relatively broad; the triangles of the masticatory surface are narrow. The anteroconid complex of M_1 is rather complicated. The anterior mushroom-like cap is of asymmetrical type and almost completely separated from T5.

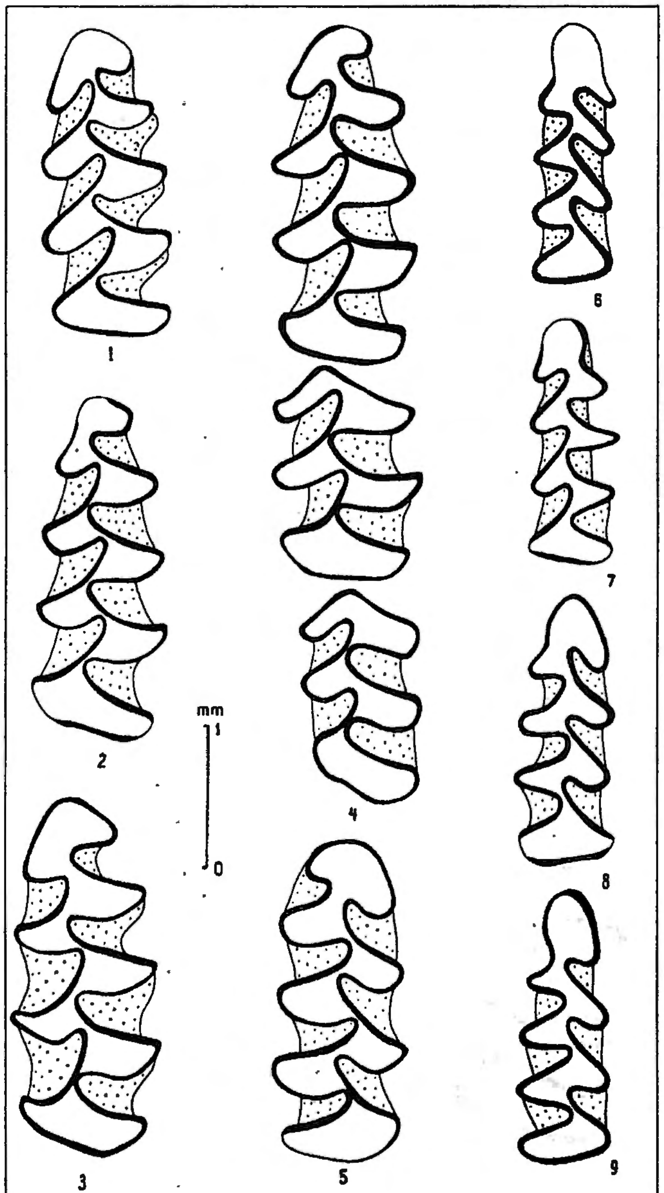


Fig. 3. First lower molar (M_1) of *Clethrionomys* from the caves of the Baikalian region. *Clethrionomys rufocanus* Sundevall, 1846: 1: Kurtun-I; 2: Tonta; 3: Kadilinskaya; 5: Kurtinskaya. *Clethrionomys rutilus* Pallas, 1779: 6,7: Kurtun-I; 8, 9: Kurtinskaya. Lower molars (M_1-M_3) of *Clethrionomys rufocanus* Sundevall, 1846: 4: Khurganskaya.

Le premier molaire (M_1) de Clethrionomys *des grottes de la région Baïkalienne.* Clethrionomys rufocanus *Sundevall, 1846: 1: Kurtun-I; 2: Tonta; 3: Kadilinskaya; 5: Kurtinskaya.* Clethrionomys rutilus *Pallas, 1779: 6,7: Kurtun-I; 8, 9: Kurtinskaya. Molars inferieurs (M_1-M_3) de* Clethrionomys rufocanus *Sundevall, 1846: 4: Khurganskaya.*

Table 2. Dimensions of the molars of *Clethrionomys* from the cave Kurtun-1.
Dimensions des molars de Clethrionomys *de la grotte Kurtun-I.*

M_1	*Clethrionomys rufocanus*			*Clethrionomys rutilus*		
	N	*x*	lim	*N*	*x*	lim
Length	106	2.6	2.4 – 3.50	64	2.26	2.00 – 2.50
Width	106	1.15	1.0 – 1.23	80	0.99	0.85 – 1.15

This species inhabits montainous-taiga regions of northern Eurasia, in particular the south-eastern Siberia.

Clethrionomys rutilus (PALLAS, 1779)
(Fig. 3, *6–9*, Table 2)

Clethrionomys rutilus PALLAS is next abundant species of the region. Its fossil remains were found in all caves except for Sluchainaya cave. It is a medium size vole. Unpaired anterior loop of M_1 has a wide confluence with T5; other posterior loops have connections of different values, which differ this form from *C. rufocanus* (Fig. 3, *6–9*).

This species inhabits mainly forest-tundra and forest-steppe zones, as well as shrubs of northern Eurasia from Sweden in the west through the Urals, Kazakhstan, Altai-Sayan mountain range to Japan in the east and Bering Island in the north-east.

Dicrostonyx GLOGER, 1841

Dicrostonyx sp. (Fig. 4, *1*)

Fossil remains of this taxon were discovered in the caves Kurtun-1, Unylskaya and Brekchievaya. They are represented by isolated teeth (M_1 and M^3) of different preservation. During the Late Pleistocene, *Dicrostonyx* was widely distributed in the studied region; however it was not found in all known sites.

At the present time this species is characterized by a circumpolar distribution in the tundra and the northern forest tundra, far northern than their previous Late Pleistocene inhabiting area.

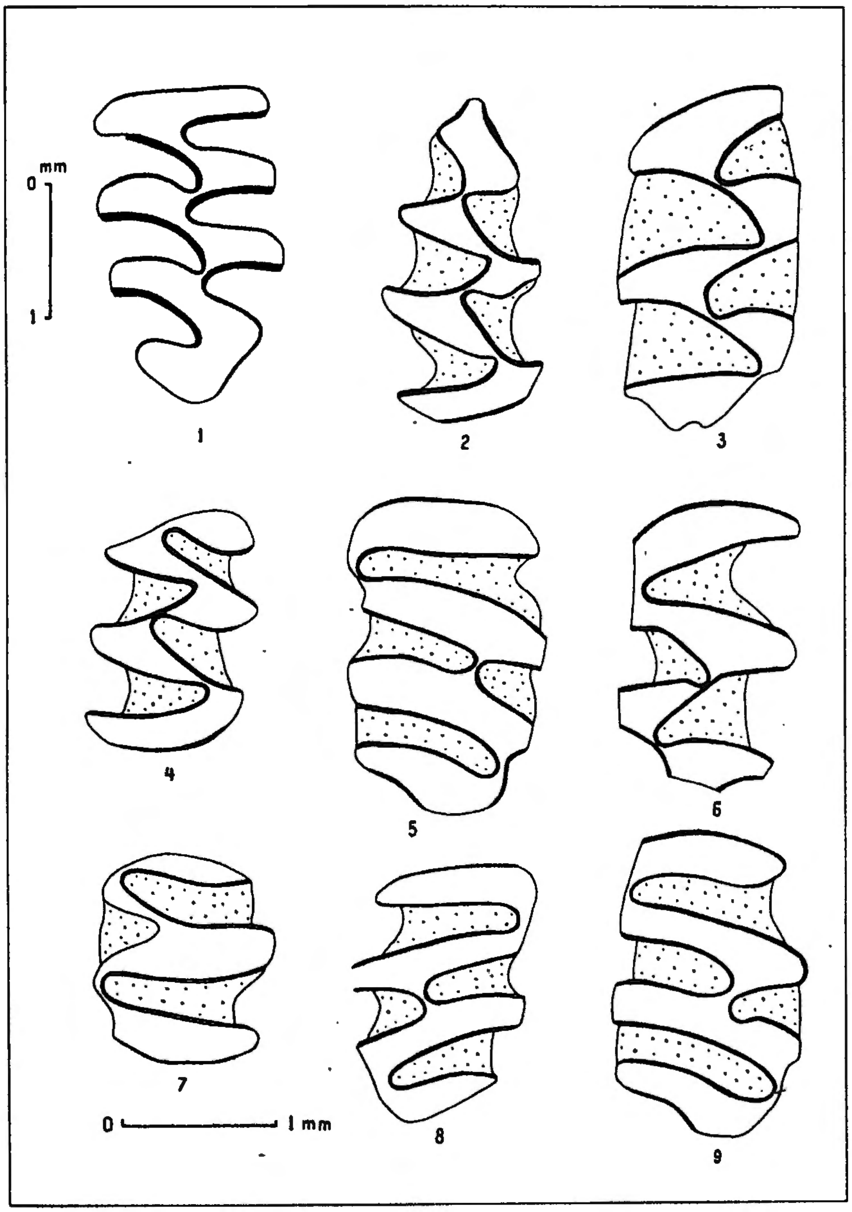


Fig. 4. Molars of lemmings from the caves of the Baikalian region.

Molaires de lemmings des grottes de la région Baïkalienne.

Dicrostonyx sp. *1*. M^3, Kurtun-I. *Myopus schisticolor* (LILLJEBORG, 1844) 2. M_2, *3*. M_3, Kurtun-I; *4*. M_1, Kurtinskaya; *5*, *6*, *8*, *9*. M^3, Kurtun-I; *7*. M^1, Kurtun-I.

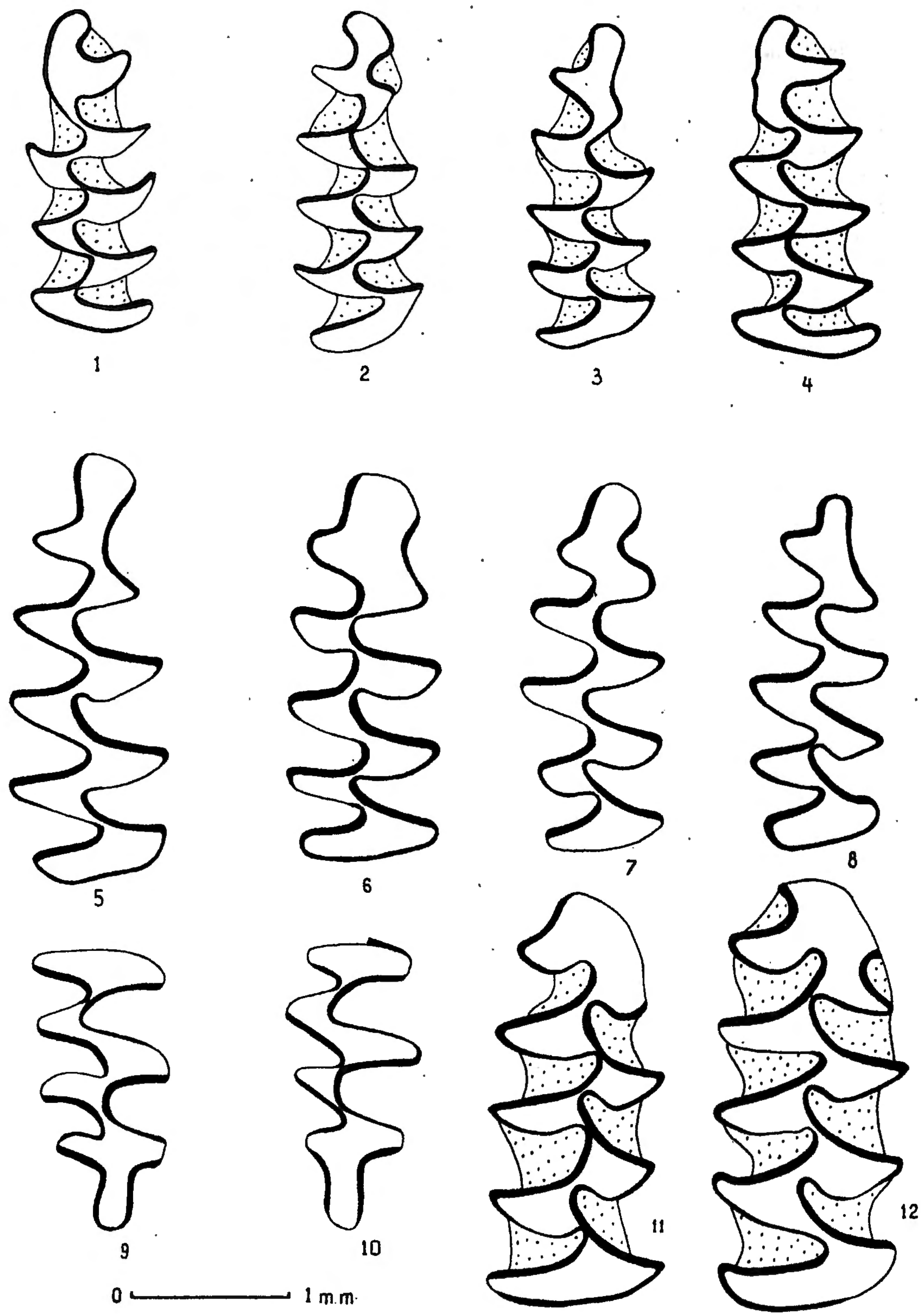


Fig. 5. Molars of the voles from the caves of the Baikalian region.

Molaires de souris des grottes de la région Baïkalienne.

M_1: *Microtus gregalis* (PALLAS, 1779): *1*, *2*. Kurtun-I; *3*. Kurtinskaya; *4*. Khurganskaya. *Lagurus lagurus* (PALLAS, 1773), *5–8*. Uzurskaya. *Microtus fortis* BUECHNER, 1889: 11. Shamanskaya, 12. Kadilinskaya. M^3: *Lagurus lagurus* (PALLAS, 1773): *9*, *10*. Uzurskaya.

Table 3. Dimensions of the molars of *Lagurus lagurus*, extinct and extant.
Dimensions des molaires de Lagurus lagurus, *éteint et existant.*

Dimensions (mm)		Caves					Recent (Kazakhstan)		
		Uzurskaya			Shamanskaya				
		n	*x*	lim	*n*	*x*	*n*	*x*	lim
M^1	Length				1	2.2			
	Width				1	1.1			
M^2	Length	1		1.75	1	1.8			
	Width	1		1.10		1.1			
M^3	Length	2	2.12	2.10 – 2.15					
	Width	2	0.97	0.95 – 1.00	1				
M_1	Length	7	2.84	2.65 – 3.15	1	2.65	42	2.61	2.25 – 2.90
	Width	7	1.07	1.00 – 1.10		0.95	42	0.93	0.80 – 1.00
M_2	Length	5	1.64	1.50 – 1.75			38	1.50	1.30 – 1.65
	Width	5	0.94	0.85 – 1.00	1		38	0.84	0.70 – 1.10
M_3	Length	1		1.75	1	1.65	22	1.62	1.45 – 1.75
	Width	1		0.80		0.65	22	0.70	0.60 – 0.75

Myopus Miller, 1910

Myopus schisticolor (Lilljeborg, 1844)
(Fig. 4, *2–9*)

Myopus schisticolor was widespread in the Late Pleistocene faunas of the region. The dental pattern (Fig. 4, *2–9*) and size of extinct forms are identical to that of the recent forest lemming. The modern area of distribution occupies vast forest territories from Sweden and Norway to Far East through Siberia and Baikalian region.

Lagurus Gloger, 1841

Lagurus lagurus (Pallas, 1773)
(Fig. 5, *5-10*, Table 3)

The remains of *Lagurus lagurus* in the Prebaikalian caves are not very numerous; they were discovered in the caves Shamanskaya, Uzurskaya, Kurtun-1 and Unylskaya. They are known as well from some archaeological sites (Malta, Krasnyi Yar, etc.) of the region.

The occlusal pattern of the molars is typical for the recent *Lagurus lagurus* (Fig. 5, *5-10*). The teeth are rootless, and there is no cement in the re-entrant angles. The dimensions of molars for studied specimens differ from those of recent lagurids, being slightly larger, especially for the specimens from Uzurskaya cave (Table 3).

Lagurus lagurus inhabits plains and steppes from the eastern borders of Europe and the western parts of Asia, through northern part of Kazakhstan, south Siberia to north-west China and Mongolia. During the Late Pleistocene the western part of its range has reached Great Britain and France, Germany, Romania a.o. and the south-eastern part of the Transbaikal area.

Microtus Schrank, 1795

Microtus gregalis (Pallas, 1779)
(Fig. 5, *1–4*)

The fossils of *Microtus gregalis* (Pallas, 1779) were discovered in all caves except for Sluchainaya and Kalcitovaya. This species is close to the recent forms by size and dental structure, having both archaic and progressive type of M_1 (Fig. 5, *1–4*), which is characteristic for the Late Pleistocene voles. Its recent area of distribution occupies a vast territory of Northern Eurasia including mountain tundra, forest tundra and different steppes.

Microtus fortis Buechner, 1889
(Fig. 5, *11, 12*)

This is a large size vole, having relatively broad teeth. All triangles are completely separated. This species was not so numerous in the faunas; its fossil remains were discovered in five caves (Table 1). By the dental pattern (Fig. 5, *11, 12*), as well as by its large size, this form is close to the recent species. Modern species inhabits marsh-meadow and flood-plain meadow areas of forest and forest-steppe zones of southeast Siberia through Transbaikal area, Amur region to China and Korea.

Conclusions

The review of the cave faunas show that almost all of them are Late Pleistocene and Holocene in age. They mainly consist of species inhabiting the region nowdays except of *Lagurus lagurus* and *Dicrostonyx* sp., the area of distribution of which is now outside further to the north and south and west. Only the unique Aya cave hosts Early-Middle Miocene faunas.

Acknowledgements

We are greatful to professor Costin Rădulescu, Silviu Constantin, Alex Petculescu and the other organizers of the "Theoretical and Applied Karstology" Symposium for the opportunity to participate in the meeting and to contribute to this volume. This study was supported by the Russian Fund of Fundamental Investigation, current grant 01-05-97239, "Baikal-RFFI".

References

ERBAJEVA, M.A. & FILIPPOV, A.G. (1997) Miocene small mammalian faunas of the Baikalian region.In: *Actes Congrés BiochroM'97* (AGUILAR, J.-P., LEGENDRE, S., & MICHAUX *Eds.*), Mem. Trav. E.P.H.E., Inst. Montpellier, **21**, pp. 249–259.

FILIPPOV A.G. (1993) The Caves of Irkutsk region. *Caves*, pp. 71–83 (*in Russian*).

FILIPPOV A.G. (1993) The Caves of Buryatia region. *Caves*, pp. 83–93 (*in Russian*).

FILIPPOV A.G., ERBAJEVA M.A., & KHENZYKHENOVA F.I. (1995) *The application of the Late Cenozoic small mammals of the south East Siberia for stratigraphy.* Irkutsk, 117 p. (*in Russian*).

FILIPPOV A.G., ERBAJEVA M.A., & SYCHEVSKAYA E.K. (2000) Miocene deposits in Aya Cave near Baikal. *Russian Geology and Geophysics*, **41**, *5*, pp. 755–764 (*in Russian*).

GORYUNOVA O.I., FILIPPOV A.G., VETROV V.M., & BERDNIKOVA N.E. (1996) *The Caves of the Pribaikalian National park. Archeological legacy of Baikal Siberia.* **1**. Irkutsk, pp. 101–109. (*in Russian*).

GROMOV I.M. & ERBAJEVA M.A. (1995) *The mammals of Russia and adjacent territories, lagomorphs and rodents.* St. Petersburg, 522 p. (*in Russian*).

SHVETSOV J.G., SMIRNOV M.N., & MONAKHOV G.I. (1984) *Mammals of Baikal basin area.* Nauka Press, Novosibirsk, 258 p. (*in Russian*).

received: 26 May 2002
revised: 5 September 2002
accepted: 5 September 2002

Theoretical and Applied Karstology, 15 (2002), pp. 111–116

Martes genus representatives in the Würmian of Romania

Emanoil Ştiucă[1*] & Răzvan Arghir[2]

[1] *The "Emil Racoviţă" Institute of Speleology, str. Frumoasă 11, 78114 Bucureşti, Romania.*
[2] *Bucharest University, Dept. of Geology, Bd. N. Bălcescu 1, 70111 Bucureşti, Romania.*

Abstract

Remains of various mustelides (*Martes martes, Martes foina, Mustela nivalis, Putorius putorius*) have been recovered from the cave Peştera nr. 4 din Scocul Scorotei (Retezat Mountains, Hunedoara county, Romania). This new fossil site of the Southern Carpathians may be assigned to the Late Pleistocene (Middle Würmian). Allometrical and morphological study of the skulls and dentition indicate a climate warming that corresponds to the lower sediment layers (3 and 2), followed by a cooling that corresponds to the upper layer, as well as the existence, during the Würmian of two different types of *Martes*.

Key words: *Martes* genus, Peştera nr. 4 din Scocul Scorotei, Middle Würmian, Romania.

Représentants du genre Martes *dans le Würmien de Roumanie*

Résumé

*Des restes des plusieurs mustélidés (*Martes martes, Martes foina, Mustela nivalis, Putorius putorius*) ont été trouvés dans la Peştera (=grotte) no. 4 de Scocul Scorotei (Montagnes de Retezat, département de Hunedoara, Roumanie). Ce nouveau site des Carpates Méridionales peut être attribué au Pléistocène supérieur (Würm moyen). L'étude allométrique et morphologique des crânes et de la dentition indique un échauffement correspondant aux couches inférieures (3 et 2), suivi d'un refroidissement correspondant à la couche supérieure (1), de même que l'existence au cours du Würmien de deux types de* Martes.

Mots-clés: Martes, *Peştera nr. 4 din Scocul Scorotei, Würm moyen, Roumanie.*

Introduction

Peştera nr. 4 din Scocul Scorotei (=Cave no. 4 from Scocul Scorotei, further on named Scocul Scorotei Cave for simplicity), is located on the outskirts of the calcareous sector of the Retezat Mountains (Western Jiu Valley). The cave lies at an elevation of 1150 m, on the left bank of Scocul Scorotei Valley, *c.* 150 m above the river bed.

At 75 m from the entrance a 23 m-deep shaft is located (Ponta *et al.*, 1984) (Fig. 1). Diggings carried out at the base of this shaft, in 1986, by members of "Hidrocarst" Club in Vulcan town gave access to a lower level of the cave and also yielded numerous fossil bones, including *Canis lupus*, *Vulpes vulpes*, *Gulo gulo*, *Capra ibex carpathorum*, etc. The researches carried out by us in 1986, 1987 and 2002 allowed the discovery of a large number of fossil remains belonging to the *Martes* genus.

The marten is less referred for the Upper Pleistocene, as the discovered remains are rare. The origins of the two modern species, *Martes martes* and *Martes foina*, are unclear even though the *Martes* genus is known since the Miocene.

In Romania remains of the forest marten (*Martes martes*) were found in the Upper Pleistocene deposits of Peştera Muierilor (Parâng Mountains), in "La Adam" Cave (Central Dobrogea), Peştera Cioarei (Vâlcan Mountains) and Peştera Măgura (Sighiştel Valley, Apuseni Mts.). The discovery of nine, almost complete, *Martes martes* skulls and three *Martes foina*

* corresponding author. *E-mail address*: emil_iser@rol.ro

skulls in Peştera nr. 4 din Scocul Scorotei, is interesting because this is the first time when the rock marten (*Martes foina)* was found in Romania.

The good conservation state of some essential pieces, like the skulls, have given us the opportunity of making some observations on the character and the affinities of the forms that populated this area during the Upper Pleistocene, more precisely during the Lower Würmian interstadial to the Middle Würmian (the equivalent of Würm II–III of the French chronology).

Materials and methods

Stratigraphic data

The excavations carried out in Scocul Scorotei cave, in E2 and A0 squares (Fig. 1) reached the level of 75 and 25 cm, respectively. In 2002 other three points were sampled, situated at the lower level (codes: PSS4-L, PSS4-1, and PSS4-2). The deposit, relatively homogenous, consists of a fine, dark-yellow clay (Code 2,5Y 6/4 in the international nomenclature-MUNSSEL 1954). The, most complete stratigraphic succession was encountered in the E2 square (Fig.1.a, b) and it consists, from top to bottom, of:

- *Layer 1*: 5 cm thick, overlaps a calcite flowstone that does not exceed 1–1.5 cm in thickness;
- *Layer 2*: 6–7 cm thick, includes a secondary calcite crust at the bottom, with the same thickness as the previous one;
- *Layer 3*: visible over a 60 cm depth was divided (Fig.1c) into four levels (3a–3d) based on fossil fauna criteria (RADULESCU *et al.*, 1991).

In total, remains belonging to about 15 marten individuals were discovered; in this study we only used five skulls with connected mandibles and other four skulls and mandibles for which it could not be established with certainty if they belonged to the same individuals (Fig. 2).

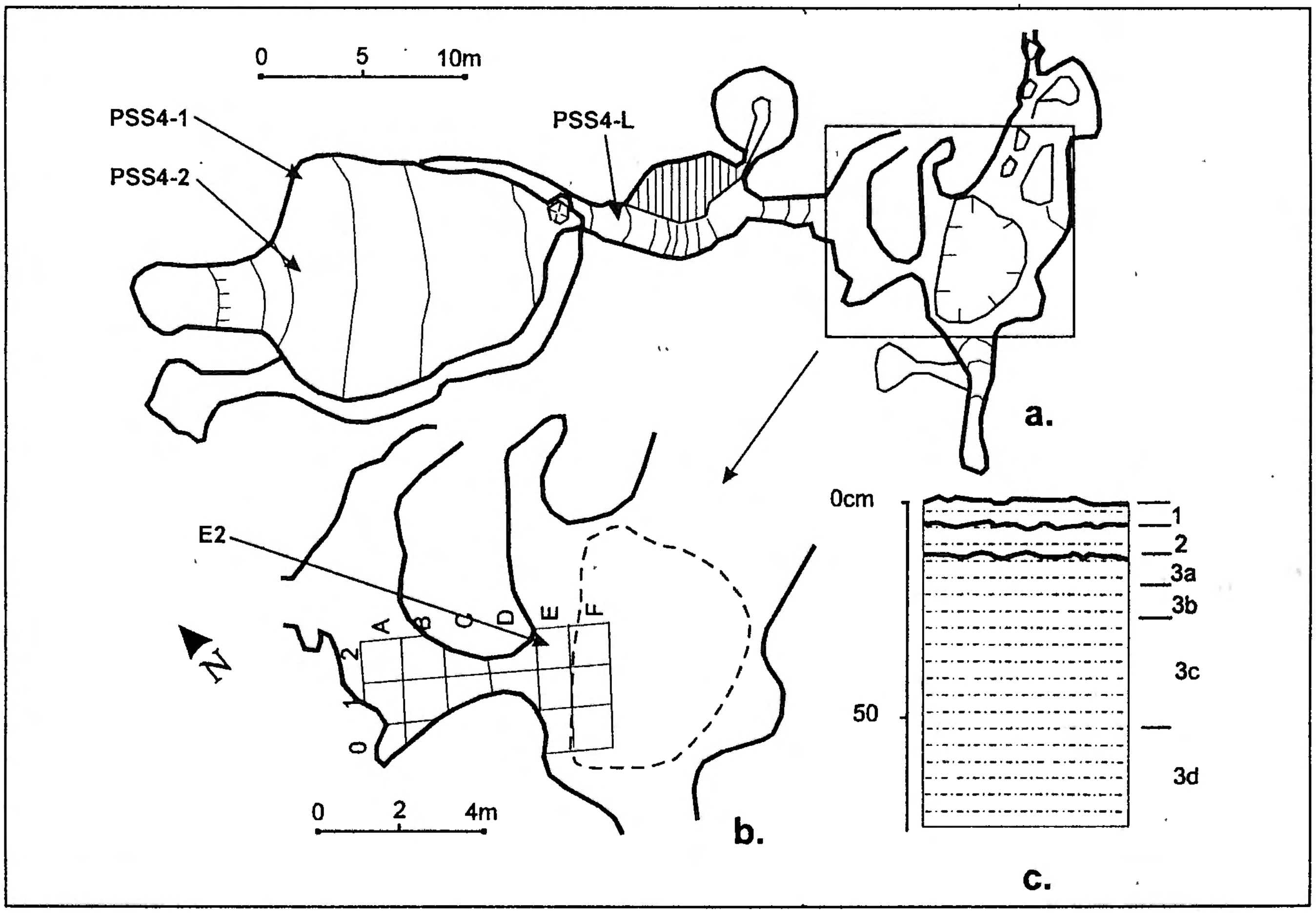


Fig. 1. Map of Scocul Scorotei cave: a. the lower passage (surveyed by "Hidrocarst Vulcan", 1986, *unpublished*); 2. excavation sites in 1987; 3. stratigraphic log at the limit between E1 and E2 squares.

Carte de la grotte de Scocul Scorotei: a. la galerie inférieure (d'après la carte levée par «Hidrocarst Vulcan», 1986, manuscrit); 2. situation des fouilles en 1987; coupe stratigraphique entre les carrés E1/E2.

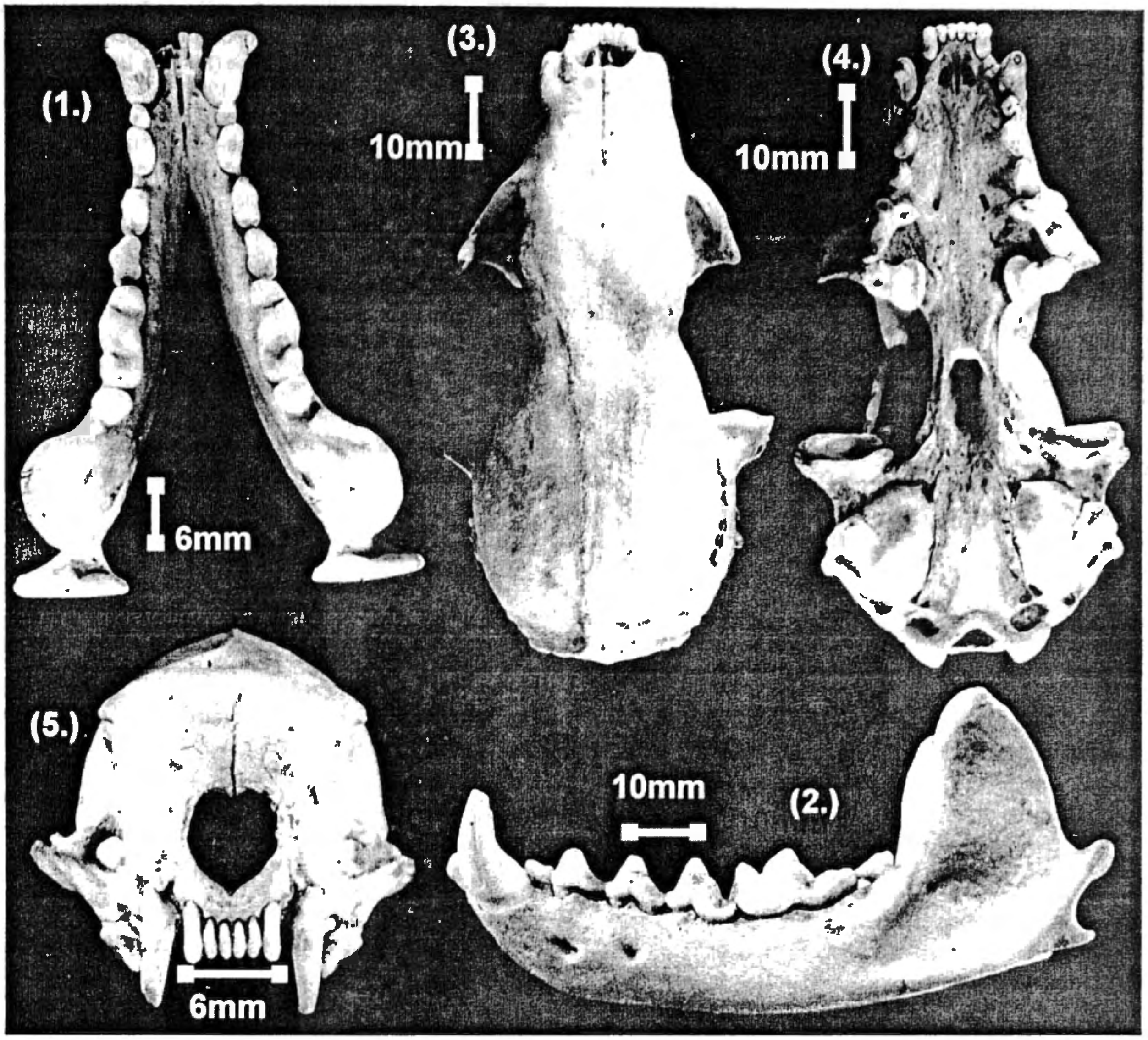


Fig. 2. *Martes martes*: 1, 2: mandible (oclusal and lateral view); 3, 4, 5: skull (ventral, oclusal and dorsal view).
Martes martes: 1, 2: mandibule (vue occlusale et latérale); 3, 4, 5: crâne (vue ventrale, occlusale et dorsale).

A preliminary statistical analysis that took into account all discovered fossil remains of *Martes martes* yielded a non-normal distribution with a variability coefficient $V > 10$. The fossil material was separated accordingly into two dimensionally homogeneous forms: a bigger one characteristic to layers 2 and 3 and a smaller one, characteristic to layer 1; the latter is accompanied by *Martes foina.*

Statistical analysis

For the statistical analysis we also considered, besides the nine above-mentioned specimens, the following: a maxilla fragment from "La Adam" Cave (Central Dobrogea, Dumitrescu *et al.*, 1963), the skull discovered in Peştera Măgura (Terzea, 1970), 35 skulls of modern forest marten and 12 skulls of modern rock marten from Romania (Southern Carpathians and the Apuseni Mountains).

In order to clarify the connections with the modern fauna we also took into consideration the data from the literature regarding *Martes martes martes* from Europe (Anderson 1970) and *Martes martes ruthena*, a smaller-size subspecies from the European part of Russia (Ogniev, 1931).

In the first phase, in order to compare the main cranial and dental characters of the discovered fossil remains with the ones taken from literature and the actual forms, we drew a ratio diagram applying Simpson's method (1941) (also Simpson *et al.*, 1960) (Fig. 3). In this diagram the horizontal distance between two points is proportional to the difference in size between two animal groups, because the method consists in subtracting from the logarithm of a parameter characteristic for the compared species the logarithm of the same parameter for the standard species. The standard species utilized by us was *Martes martes martes* from Norway.

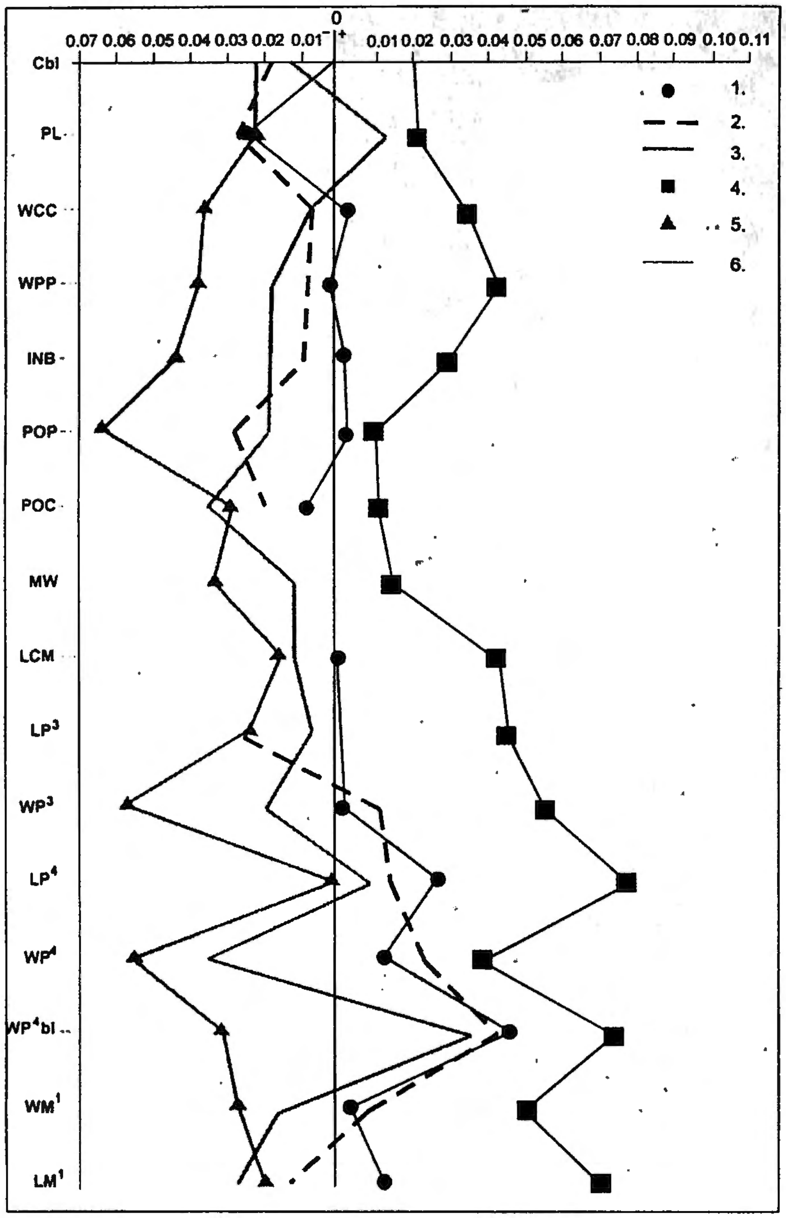


Fig. 3. Ratio diagram for different fossil and modern marten forms from Europe vs. the Norwegian standard. 1. fossil, Europe (Martin, 1968; Argant, 1991; Kurtén & Rausch, 1959; Orlov, 1941) 2. postglacial Europe (Miller, 1912); 3. modern, Romania; 4. fossil Romania, large-sized form; 5. fossil Romania, small-sized form; 6. standard, Norway. See the text for abbreviations.

Diagramme des rapports morphométriques des diverses formes fossiles et récentes de martres de l'Europe par comparaison au standard norvégien. 1. fossile, Europe (Martin, 1968; Argant, 1991; Kurtén & Rausch, 1959; Orlov, 1941); 2. postglaciaire, Europe (Miller, 1912); 3. actuel, Roumanie; 4. fossile, Roumanie, forme de grande taille; 5. fossile, Roumanie, forme de petite taille; 6. standard norvégien. Voir le texte pour les abréviations.

Fig. 4. The matrix of reciprocal variation between different species of marten.

Matrice des variations réciproques pour les différentes espèces de martres.

CBL, PL, WCC, POC, WPP, INB, POP	*M. martes martes* (Europe)	*M. martes* (Romania, modern)	*M. martes rutena* (modern)	*M. martes* (Europe fossil)	*M. martes* (Romania fossil+)	*M. martes* (Romania fossil–)	*M. foina* (modern)
M. martes martes (Europe)	—						
M. martes (Romania modern)	0.00939	—					
M. martes rutena (modern)	0.01177	0.01040	—				
M. martes (Europe fossil)	0.01090	0.01812	0.01429	—			
M. martes (Romania fossil+)	0.01450	0.1211	0.01258	0.01732	—		
M. martes (Romania fossil–)	0.01460	0.00893	0.01369	0.02258	0.01957	—	
M. foina (modern)	0.01521	0.02255	0.01886	0.00616	0.01909	0.02752	—

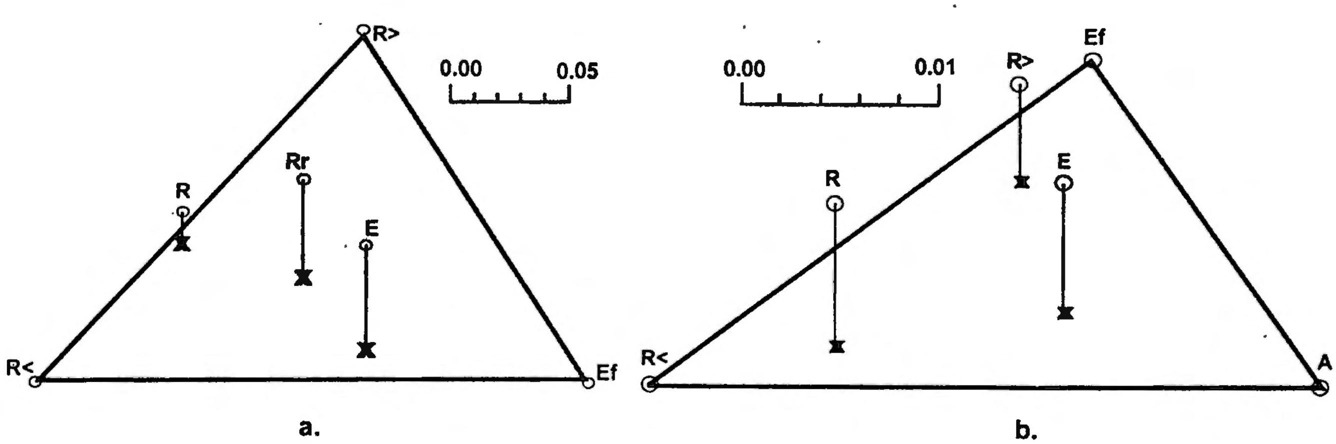


Fig. 5. a. The diagram of relative differences for the skulls of *Martes martes*: b. The diagram of relative differences for the inferior dentition of *Martes martes*: R< = the small-sized fossil from Romania; R = modern form from Romania; R> = the large-sized fossil form from Romania; r = *Martes martes ruthena* (Asia); E = the modern form from NW Europe; Ef = the fossil form from NW Europe; A = *Martes martes* from "La Adam" cave (Romania).

Diagramme des différences relatives pour les crânes de Martes martes (a) et pour la dentition inférieure (b). R< = la forme fossile de petite taille de Roumanie; R = la forme actuelle de Roumanie; R> la forme de grande taille de Roumanie; r = Martes martes ruthena (Asie); E = la forme actuelle du NO de l'Europe; Ef = la forme fossile du NO de l'Europe; A = Martes martes de la grotte «La Adam» (Roumanie).

For the skull, the following seven characteristic measurements were taken into account: the *condylobasal length* (CBL), the *palatal length* (PL), the *width across the canines* (WCC), the *width across carnassial* (WPP), the *inter-orbital breadth* (INB), the *width at postorbital apophyse* (POP), and the *length of postorbital constriction* (POC).

Based on these measurements, the relative distances between different types were calculated and the matrix of reciprocal variation was established. This matrix (Fig. 4) establishes the differences, or relative distance between zoological or anthropological types as a series of numerical data proportional to the standard deviation between the analyzed types. Based on the calculated data and using a simple descriptive geometry method we have represented these differences in Fig. 5.

Figure 5a shows that the two fossil types from Romania and the fossil type from Europe are at the biggest distance to one another. The modern European marten is closer to the large-sized type from Romania and also to the European fossil type.

	Martes martes martes (Sweden)	*Martes martes* (Germany)	*Martes martes ruthena* (CSI)	*Martes martes lorenzi* (CSI)	*Martes martes* (modern Romania)	*Martes martes* (fossil Romania)	*Martes martes* (fossil Europe)	*Martes vetus*
CBL/WCC	M		M	M+	M	F	F	
CBL/POC	M	M	Mr+	M	Mr+	Mr		
POP/POC	M		M	M	M	M	M	
WCC/WPP	M,				M	M	M	
CBL/LCM1/	M		M	M	M/F	M/F		
LCM/LC4	M	M	M+	M+	F	F	F	M
LC4/WM1	M	M+	F	M	F	F	F	F
LM1/WM1	M	M	M	M	M	M	M	F
L/W P3	M				F	M	M	F+
L/W P4	M				F/M	F	F–	F
LP3/LP4	M				F	F	F	M

Fig. 6. Mosaic distribution of different characters for *Martes* species (+: strong character; – weck character; M: *Martes martes*; F: *Martes foina*; F/M: *M. foina/M. martes* intermediary; Mr: *Martes ruthena*.

Distribution en mosaïque des différents caractères des espèces de Martes (+: caractère puissante; – caractère faible; M: *Martes martes*; F: *Martes foina*; F/M: intermédiaire *M. foina/M. martes*; Mr: *Martes ruthena*.

On the other hand, the recent forest marten from Romania and the *Martes martes ruthena* are dimensionally close by the two fossil types from Scocul Scorotei: the first one with respect to the small-sized shape, and the second one with respect to that of the large-sized type.

For the upper dentition we have taken into consideration the following seven parameters: the length and the width P^3, the length P^4, the width at principal cuspid P^4, the length and the width M^1, and have calculated the distances between the given types as shown above (Fig. 5b).

Discussions and conclusions

The faunal association from Peştera nr. 4 din Scocul Scorotei prove the existence of a forestry environment, which persisted during the sedimentation of layers 3 and 2. Sedimentation of layer one corresponds to a colder stage, which favored the grassland extension against the forest. (RĂDULESCU *et al.*, 1991)

The difference between the forest marten and the rock marten remains still a difficult paleonological problem because, unlike other species or genra, they both coexisted in the same geographic area and show mixed morphological characters (the so-called mosaic distribution) (Fig. 6).

From the graphic representation in Fig. 5 one may notice that the large-sized type from Scocul Scorotei and the smaller one are relatively distinct one from another even though they belong to the same area. The large-sized type, like the modern European marten shows some affinities with the fossil marten from Europe. Also noticeable is the position quite isolated of marten type from the "La Adam" Cave in Central Dobrogea.

The analysis has also shown that the European forest marten, the large-sized fossil type from Scocul Scorotei and that from "La Adam" Cave, show affinities with the Pleistocene fossil types of Europe, while the small-sized type from Scocul Scorotei is closer to the modern forest marten from Romania.

In conclusion, after this first analysis of *Martes* fauna from Scocul Scorotei we have shown:

- Two types of *Martes martes* coexisted during the Upper Pleistocene, more precisely during the interstadial Lower – Middle Würmian.
- The large-sized forest marten was replaced by a type with a smaller size and having the appearance of a rock marten, which shows the occurrence of a climatic deterioration at the level of layer 1.
- The similarity between fossils marten and the present marten from Romania with the Russian subspecies *Martes martes ruthena*, shows a filiation that has included a series of eastern immigrants.

References

ANDERSON, E. (1970) Quaternary evolution of the genus Martes. *Acta Zool. Fennica*, **130**, pp. 1–131.

ARGANT, A. (1991) Carnivores quartenaires de Burgogne. *Doc. Lab. Gèol. Fac. Sci. Lyon*, **115**, pp. 1–300.

DUMITRESCU, M., SAMSON, P., TERZEA, E., RĂDULESCU, C., & GHICA, M. (1963) Peştera "La Adam", staţiune pleistocenă. *Trav. Inst. Speol. "Emil Racovitza"*, **I–II**, pp. 229–284.

KURTÈN, B. & RAUSCH, R. (1959) Biometric comparisons between North American and European mammals. *Acta Arctica*, **XI**, pp. 1–44.

MARTIN, R. (1968) Les mammiferes du gisement du quaternaire de Villereversure (Ain). Etude des carnivores, des cervides et equides. *Doc. Lab. Gèol. Fac. Sci. Lyon*, **27**, pp. 1–153.

MILLER, G. S. (1912) *Catalogue of the Mammals of Western Europe*. Collection of the British Museum, Cloves and Son.

MUNSELL (1954) *Soil color charts.*, Baltimore.

OGNIEV, S.I. (1931) The fauna of USSR and of neighboring countries. Moscow. (*in Russian*).

ORLOV, J. A. (1941) Tertiary Mammalia and localities of the remains. Tertiary Carnivora of West Siberia. III Mustelinae. *Trav. Inst. Paleont. Acad. Sci. USSR*, **3**, pp. 30–39 (*in Russian*).

PONTA, G., ALDICA, G., BĂDESCU, D., PANAIOTU, C., & SOLOMON, A. (1984) Cercetări speologice în perimetrul Jiul de Vest-Cernişoara. *Bul. Speologic*, **8**, pp. 77–117.

RĂDULESCU, C., SAMSON, P., & ŞTIUCĂ, E. (1991) Les faunes de mammiferes wurmiens de la Grotte No. 4 de Scocul Scorotei (Dep. de Hunedoara, Roumanie). I. Insectivora, Rodentia. *Trav. Inst. Speol. "Emile Racovitza"*, **XXX**, pp. 75–87.

SIMPSON, G. G. (1941) Large Pleistocene Felines of North America. *American Museum Novitates*, **1136**, pp. 1–27.

SIMPSON, G. S., ROE, A., & LEWONTIN, R. C. (1960) *Quantitative zoology.*, New York, 440 p.

TERZEA, E. (1970) La faune de mammiferes quaternaires de la grotte Măgura de Sighiştel (Bihor, Roumanie). *Trav. Inst. Speol. "Emil Racovitza"*, **IX**, pp. 201–230.

received: 26 September 2002
revised: 22 October 2002
accepted: 25 November 2002

Theoretical and Applied Karstology, 15 (2002), pp. 117–123

The history of karst resources exploitation: an example of iron industry in Kranjska (Slovenia)

Andrej Kranjc*

Karst Research Institute ZRC SAZU, Titov trg 2, SI-6230 Postojna, Slovenia.

Abstract

In Slovenia the karst surface covers 43% of the territory. About 57% is Dinaric and 21% Alpine karst. Dinaric karst consists of Jurassic and Cretaceous limestone, while Alpine karst of Triassic carbonate rocks. Everywhere the iron ore is present. Two types can be distinguished, the form of limonite pieces, and the "ironstone" (iron hydroxides), so-called "broad bean ore". In the 8th Century BC the iron industry prospered in two karst regions: in the Alps and on Dinaric karst. Technology of extracting iron from the ore was simple. The early metallurgists gathered iron ore on the surface and in karst underground. The ore was melted in shaft furnaces with dug-in fireplaces. Because of the ironwork technology, iron industry was scattered all over the country thus no important concentrated pollution appeared. Yet, local impact could have been important in places. The consumption of wood and charcoal was significant including cutting down the forests. In the 10th Century iron industry restarted. Between the 13th and the 15th centuries ironworks began to develop, based on water energy. Extracting and working of iron moved from the plateaux down to the valleys and the ironworks (joint of smelting furnace, fireplaces to heat the iron red-hot, bellows and ironwork hammer) resulted. In 1581, the list of ironworks for Kranjska enumerates 20 smelting furnaces. The direct impact on karst consists of traces of digging on the surface, in dolines, caves and potholes, disused mine shafts and galleries, and "ore pools" scattered across the land. As a direct impact, large quantities of charcoal were consumed and the water was polluted. There were much less forests left than nowadays. The indirect impact consisted mainly in the high concentration of industrial plants and inhabitants.

Key words: iron industry on karst, pollution, Kranjska, Slovenia.

Histoire de l'exploitation des ressources du karst: l'exemple de l'industrie du fer en Slovénie

Résumé

Le karst couvre 43% du territoire slovène, dont 57% représente le karst dinarique et 21% le karst alpin. Le premier est formé de roches carbonatées jurassiques et crétacées, tandis que le deuxième, de roches triasiques. Le minerai de fer se trouve partout, en général sous deux formes: pièces de limonite et hydroxydes de fer ("Bohnenerz"). Au cours du 8-ème siècle av. J.-C., l'industrie du fer fleurit sur le karst dinarique, ainsi que dans les Alpes. Les premiers métallurgistes obtenaient le minerai de fer aussi bien de la surface du karst que de gissements souterrains, et la technologie d'extraction du métal était simple. Le minerai était fondu dans des fours enterrés avec le foyer creusé à la base. Par suite de cette technologie, l'industrie de fer était disséminé à travers tous le pays et il n'y avait pas une pollution concentrée. Cependant, l'impact aurait pu localement plus fort. La consommation de bois et de charbon était très importante et la conséquence en fut un fort défrichage. A partir du 10-ème siècle, l'industrie de fer a recommencé à se développer, cette-fois-ci basée sur la force de l'eau. Les activités ont été transférées des hauts plateaux karstiques dans les vallées et les vraies fonderies (comprenant les hauts fourneaux, les foyers pour chauffer au rouge le fer, les soufflets de forge et les masses) sont apparues. En 1581, dans Kranjska (Carniole) il y avait 20 hauts fourneaux. Tout cela a eu une influence directe sur l'environnement, comme l'atteste, par exemple, les traces de fouilles à la surface, dans les dolines ou dans les grottes et les gouffres, les galléries de mines abandonnées et les basins de flottation dispersés dans tout le pays. Il faut mentionner la consommation importante de charbon et la pollution de l'eau. La surface des forêts était plus restreinte qu'aujourd'hui. L'impact indirect s'est manifesté par une fort concentration des entreprises industrielles et de la population.

***Mots-clés:** industrie du fer sur le karst, pollution, Kranjska, Slovénie.*

* corresponding author. *E-mail address*: kranjc@zrc-sazu.si

Related to human activity and its impact on karst it is interesting to see, what are the consequences of some past intensive activities, including industries which do not exist any more. Not only the impact is important, but also to see if the effects of these activities are still visible today; this either means that they are permanent or, in some cases, that through centuries and millenaries the nature regenerated and returned to its natural state. In this paper we shall analyze this, using the example of iron industry.

In Slovenia, karst surface covers about 45% of the territory. About 57% is Dinaric and 21% Alpine karst. From a morphological point of view Dinaric karst is divided into highland and lowland karst. Highland karst forms high karst plateaux (800–1200 m of altitude) stretching from the NW Slovenia (Friuli border) to the Kolpa river in the SE. They continue towards SE across Croatia. On both sides of the highland karst lies the "lowland karst". On the south-western side this is littoral (Periadriatic), while on the north-eastern side lies the karst of Dolenjsko (Peripannonian). They consist of lower plateaux, less than 500 m asl. Most of the Slovene Alps, namely Julian and Kamnik Alps consists of karst terrains. This central, high mountainous range (above 1500 m) is surrounded by plateaux (1000–1500 m) like Pokljuka, Jelovica or Menina (Fig. 1).

Dinaric karst consists mostly of Jurassic and Cretaceous deposits, while Alpine karst of Triassic carbonate rocks. Everywhere the iron ore is present, in non-consolidated sediments covering the rock base or in the rock itself. In Slovenia, on the surface or in the underground there are two types of iron ore relatively easy accessible. Iron ore in the form of limonite pieces is found mostly in the Dinaric karst. The second type is the "ironstone" (iron hydroxides: $Fe_2O_3 \cdot nH_2O$) with onion-like structures, forming concretions up to 6 cm large. This type is called "broad bean ore" ("Bohnenerz" in German) and it is found mostly in the Alpine karst. Broad bean ore contains 30 to 50% iron. Iron ore can be found also in the form of bulbs and geodes (STRMOLE, 1987).

The position of the Slovenian territory, lying on the crossroad of two main directions, was very important for the development of iron industry. The first direction, leading along the

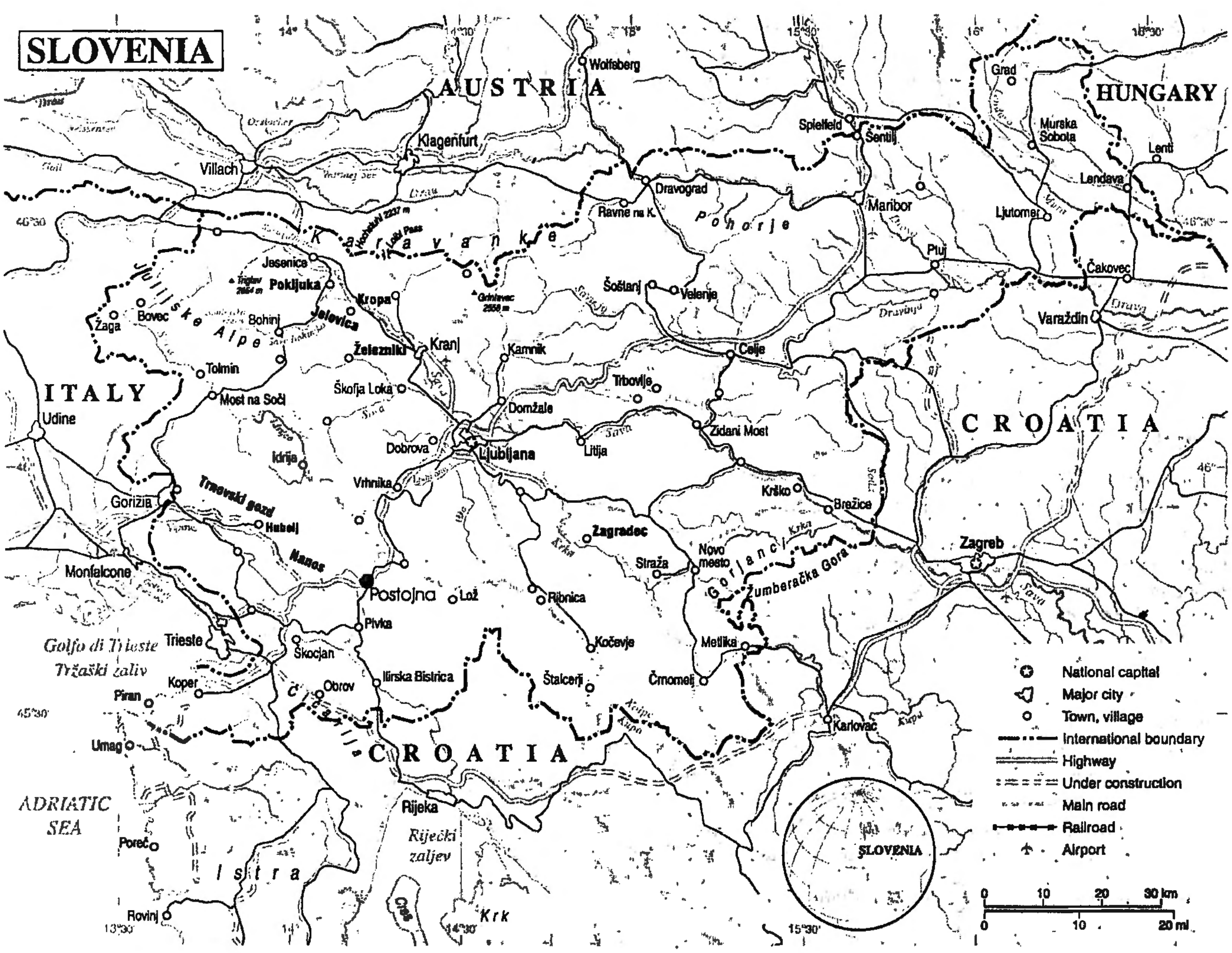


Fig. 1. Map of Slovenia with the location of the main localities mentioned in the text.
Carte de la Slovénie avec la situation des principales localités mentionnées dans le texte.

Danube, has spread the influences from the East, while the other one has spread the influence from the Mediterranean and Italy across the Adriatic.

In the 13th Century BC the Hittites started to extract the iron; the Greeks mastered this technique in the 11th Century BC and this knowledge reached the Slovene territory relatively early. The oldest iron object imported in Slovenia dates to the 10th Century BC and was found in Mušja jama cave near Škocjan (Kras). The Early Iron Age (Hallstatt) extended, in Slovenia, from 750 to 300 BC. The inhabitants not only knew the new metal, but also used and extracted iron from the ore.

On karst, iron industry first prospered in the 8th Century BC already. It mostly developed in two karst regions: in the Alps, in the region Bohinj including the Triglav massif, and on Dinaric karst of Notranjsko and Dolenjsko, including Bela Krajina. Archaeologists classify Hallstatt inhabitants in six culture groups. Among those working in the iron industry, there are members of "Sveta Lucija" (western) group in Bohinj, as well as the members of "Dolenjska" and "Notranjska" group (Dular & Božič, 1999).

The technology of extracting the iron from the ore was relatively simple. The iron ore was simply gathered on the surface and underground; seldom was it excavated. The greatest concentrations of broad bean ore lie at the bottom of dolines and in karst caves and shafts (Rjazancev, 1966). The ore was melted in shaft furnaces with dug-in fireplaces. For a better melting, limestone was added (Rjazancev, 1963a). Some examples at Novo mesto show that the furnaces were about 2 m-high clay cones. The air was directed through special conduits; therefore the location of the furnace was very important, specially its exposure to wind. Furnaces were often located on the slopes to allow a good use of the upwards wind (Rjazancev, 1962c; Rjazancev, 1963d) (Fig. 2). Branches of spruce and beech charcoal were used as a fuel (Rjazancev, 1962a). This iron-work technology requires a location that must be near the iron ore deposits, near the source of wood, and also exposed to appropriate wind; therefore the iron industry was not concentrated but scattered all over the country. This is proved by archaeological investigations during which slag was found in the most *oppida*, in the settlements themselves as well as out of the walls. At the foot of high karst plateaux numerous remains of prehistorical smelting furnaces were discovered: under Trnovski Gozd, near the important karst spring of Hubelj, under Nanos, near the village of Strane, and near the Bela sinking stream (Lamut, 1988). Recently, in the cave Antonkov Skedenj at Dolenjsko, the remains of a smelting furnace were discovered. It was placed in the cave, near a small shaft, thus using the air current from the cave towards the entrance (Bizjak *et al.*, 2001) (Fig. 3).

During the Hallstatt the Slovenian territory was densely populated, even in those parts of karst which are now practically unpopulated. It was a cultural landscape and the Dolenjska and Notranjska groups of Hallstatt people have reached a protourban degree of civilization. Without doubt the role of iron industry was very important as well as the location of ore deposits on karst.

Today the impact of the iron industry on the karst environment is difficult to asses. There was no substantial concentrated pollution because the iron industry was relatively small and dispersed all over the country. Nevertheless subsequently, these changes can seriously impact upon the local areas.

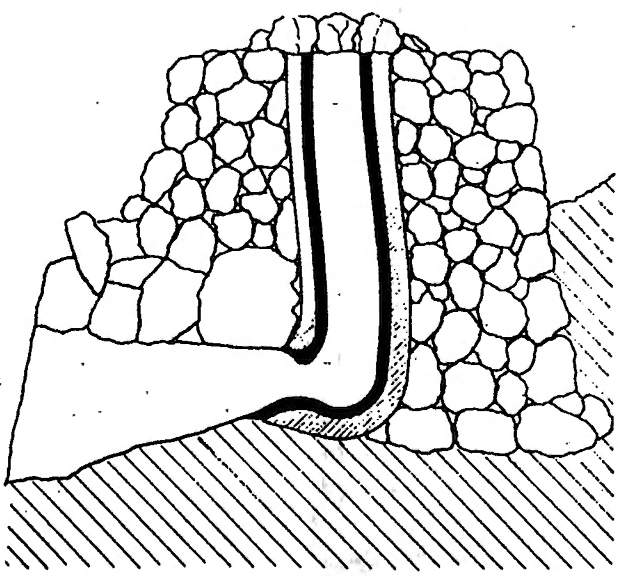


Fig. 2. Cross section of "wind furnace" above the Studor village (Bohinj) (Rjazancev, 1962b).
Coupe du « fourneau à vent » situé au-dessus du village de Studor (Bohinj) (Rjancev 1962b).

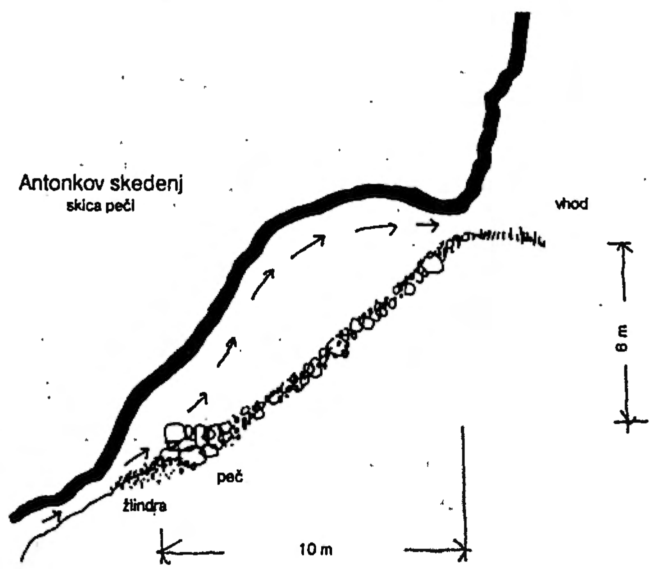


Fig. 3. Location of the prehistoric furnace in the Antonkov skedenj cave (Bizjak *et al.*, 2001). (Vhod = entrance, peč = furnace, žlindra = slag).
Situation du fourneau pré-historique de la grotte d'Antonkov skedenj (Bizjak et al., 2001). (Vhod = entrée, peč = fourneau, žlindra = scorie).

In the surroundings of Straža village (near Novo mesto) the remains of 24 smelting furnaces 1.5 m apart, were found (DULAR & BOŽIČ, 1999). Without doubt, the consumption of wood and charcoal was substantial. Cutting the forest could locally trigger an accelerated soil erosion as proves the practice in the near past, when farmers in the mountains have burned forests in order to create arable land (KRANJC, 1979). Iron industry has forced people to be more mobile. They had to search for iron ore deposits and carry the iron products at great distances. People from Bohinj have transported the flint used as the alloy to the ore from the Karavanke Mountains, which is at least 8 hours of walking distance (RJAZANCEV, 1963e).

During the Late Iron Age (La Tène) and the Roman period there were no essential changes concerning the iron industry. Traces are found in places of ancient towns, villages, hamlets and even single farms. The Slovene territory was included into the Roman Empire but its iron industry did not held any important position. Deposits of iron ore were relatively small and privately owned (HORVAT & ŠAŠEL-KOS, 1999). The situation was different in the NW of Slovenia where Bohinj lies. This area belonged to "*Regnum Noricum*" — the union of Noric tribes. It mostly prospered during the second century BC. It was annexed by the Romans in the year 10 BC, and became a Roman province under Claudius (41–54). Iron from Noricum contained also titanium and manganese of similar quality as steel and this is why it was highly appreciated throughout the empire (RJAZANCEV, 1963c). As they say, even Homer have spoken about "ferrum noricum". This was the type of iron from Bohinj area (RJAZANCEV, 1962b; RJAZANCEV, 1966) and its products were exported mostly to Rome. In Noricum there was a special administration of mines having its head office at Virunum (ŠAŠEL-KOS, 1993).

After the fall of the Roman Empire, the ancestors of Slovenes settled this land, and, after a hiatus of 500 years, at the end of the Middle Ages, the iron industry became again an important economy branch. In a document from 1004, the village Stara Fužina (Old Ironwork) was called Staro Kladvo (Old Hammer) which is the oldest written proof. There are more indirect written proofs than material remains. In 1340, the bishops of Freising moved the special workers for ironworks from Friuli

Fig. 4. A furnace as a part of ironworks in the 16th Century (AGRICOLA, 1950).
Un fourneau faisant partie d'un attelier sidérurgique du 16-ème siècle (d'après AGRICOLA, 1950).

to their estates in Slovenia (Bat & Vraničar, 2001). In 1381, the iron mine under Golica in Karavanke Mountains got the mine act from Frederick of Ortenburg (Lamut, 1988).

In the beginning, this iron industry was similar to that in the prehistory and antiquity, that is "a simple forest ironwork". The metal workers have searched iron ore on karst plateaux and melt it near the deposits using charcoal from the surrounding forests. Between the 13th and 15th centuries ironworks began to develop, based on water energy (Fig. 4). Extracting and working of iron has moved from the plateaux down to the valleys, close to the water courses. Extracting and working grew up as an industry in the modern sense of the word and the ironworks resulted. Ironwork of the time meant a joint of smelting furnace, fireplaces to heat the iron red-hot, bellows and ironwork hammer. Sometimes the forges (blacksmith's workshops) were included into the ironworks too. In the beginning the furnaces were small (Agricola, 1950), similar to the ones from prehistoric times, but they became bigger and bigger until they reach the dimensions of real smelting furnaces. Streams are rare on the karst and so the water availability was a restrictive factor and big karst springs become very important. The base for the ironworks in this period was the same as before, the deposits of broad bean ore and limonite iron ore in pieces which were gathered and dug out in Julian Alps, in Notranjsko and Dolenjsko region. New were the iron ore deposits in Karavanke Mountains ridge, in the carbonate rocks of Golica and Stol Mountains.

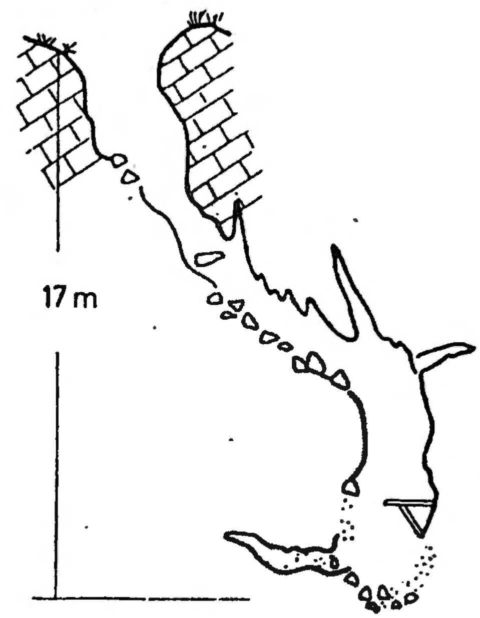


Fig. 5. The Brezno na Viševniku shaft (Julian Alps) with traces and remains of mining activity (Gospodarič & Pohar, 1966).
Le puits de Brezno na Viševniku (Alpes Juliens) avec des traces d'activité minière (Gospodarič & Pohar, 1966).

In 1581 the list of ironworks for Kranjska and Goriška (county of Gorica – Goritia) enumerates 20 smelting furnaces. Many of the ironworks used the water energy of big karst springs and rare karst rivers to run bellows and hammers. Such were the ironworks of the Alps region in Bohinj (the village Bohinjska Bistrica lies on the bank of the Bistrica stream with an important karst spring), in the foothills of Jelovica plateau (on the strong karst streams Kroparica and Lipnica), in the Notranjsko region — in the foothills of the plateau Trnovski gozd (karst spring Hubelj and the Bela stream), and in Dolenjsko region mainly along the Krka river (Zagradec, Dvor).

Iron ore was gathered both on surface and in karst caves. Better extraction technology also allowed the use of other types of iron apart from the broad been ore. Iron ore was mined up to altitudes of about 1700 m. As the concentration of iron ore is the highest in the caves, they were preferred for digging. In the Alps, several shafts are known where the traces of digging and the remains of mining installations can still be seen nowadays. In Brezno na Aušterlovcu, a 26 m-deep shaft, one may found the remains of a wooden construction. In Brezno na Viševniku (1630 m a.s.l., Fig. 5), a 17 m deep shaft, a wooden winch, wooden scaffold and poles were found (Gospodarič & Pohar, 1966). Two such shafts are also known on Uševnik. Dolines were used for other two purposes. They were a source for clay used to cover the furnaces; in some of them quartz sand was found which was added to the ore in order to lower its melting point. Some dolines were transformed to "ore pools" were the rainwater was collected for ore washing. Old place names (Stara Fužina [Old Iron work] in Bohinj, Železniki in the Selška Sora valley, Fužina [Iron Foundry Ironwork] pri Zagradcu), orographic names (Rudnica) [Metal Ore Hill], toponyms (Rudno polje [Metal Ore Field], Rudna dolina [Metal Ore Valley], Rudno), water names (the Plavževka [Blast Furnace] stream) and house names (Pri Plavžarju [at the Smelting Furnace], Fežnar) prove the past mining and iron industry.

It is self-understanding that such activities have had an impact on the karst land and its surroundings. In the middle of the 19th Century the ironwork in Bohinj only had 57 placers where the ore was excavated. Digging to the a depth of 30 m was usual, but there are cases of digging at the bottom of 62 m deep vertical shaft (Belar, 1889); according to some unverified information (Brenčič, 1991) miners penetrated even to the depth of 300 m. The iron ore was lifted up from the shafts in wooden buckets, using wooden winches. Not only placers but also dolines were used as "ore pools". At the end of the 18th and in the beginning of 19th Century ironworks at Dvor (Dolenjsko) got the iron ore from an area with a radius of 30 km. In Karavanke Mts. there were real mine galleries; Savske Jame mine, for example, has 7.6 km of underground rails. In 1855, 10350 tones of iron ore were excavated or gathered altogether in Kranjska. Two thirds of this quantity came from only two mines in Karavanke Mts. (Ocepek & Redakcija, 1996a; 1996b).

From 1580 up to the 18th Century the iron industry was in crisis in the alpine parts of Austria. In Kranjska other difficulties occurred also. First, Bohinj went short both in iron ore and fuel – charcoal. At the end of the 18th century, the owner of ironworks Ž. Zois tried to use soft (spruce tree) instead of hard (beech tree) charcoal (Rjazancev, 1963b). In 1874 the ironworks in Bohinj have excavated 841 t of ore while the production decresead to only 422 t in 1875 and 487 t in 1876 (Rjazancev, 1962a). In 1738 there were about 1000 ironwork workers in Bohinj, while in 1811 only 386 remained (Rjazancev, 1963a).

Not only lacking of primary material but also the competition led to the termination of the iron industry on the karst of Kranjska. In 1835, the first modern ironworks of Rosthorn were built in the Slovene part of Koroška (Carinthia), in Prevalje, and the old type of ironworks were no more competitive (Leskovec, 1989). In Slovenia, during the 19th Century (Kropa 1880, Stara Fužina in Bohinj 1890 and Bohinjska Bistrica 1891) and at the beginning of the 20th Century (Železniki 1902 – 1909) all the old types of ironworks have ceased to function (Šmitek, 1992; Vidic, 1998; Vojvoda, 1987). The modern iron or steel industry, which has remained in Slovenia, is neither based on domestic iron ore, nor it extracts iron but processes imported base-products or semimanufactures.

The impact of the past industry on karst was both direct and indirect. The direct impact consists of traces of digging on the karst surface, in dolines, in the caves and shafts and disused mine shafts and galleries and "ore pools" scattered across the landscape. On the karst plateaux of Pokljuka and Jelovica only, there are remains of thousands of caves, hollows and shafts where the broad bean ore and limonite were excavated. On the plateau of Pokljuka, in the place called Rudno Polje [=Metal Ore Field] which is a sort of a very shallow and flat uvala, morphological changes can still be seen due to large stock of iron ore stored there. On this plateau the digging lasted several tens of years, the ore was stored nearby and it was transported into the valley during the winter. A direct impact is also the big quantity of charcoal consumed (the so-called Slovene furnace needed 50-60 % more charcoal than ore) and the pollution of water used for the washing of the crushed ore. Not only on the Dinaric part of the karst but also on the karst of the Alps there were much less forests than nowadays. An early photography of the ironworks at Bohinjska Bistrica shows bare mountains – white rocks - in the background (Müllner, 1909). Nowadays coniferous forests cover the slopes. The indirect impact consisted mainly in the high concentration of industrial plants and inhabitants. During the 18th and 19th centuries at Železniki there were two smelting furnaces, seven ironworks and 110 blacksmith's fires, altogether giving work for about 2000 people. Today although Železniki is an administrative centre there are only 3100 inhabitants altogether. In the middle of the 19th century, Kropa had two smelting furnaces and 240 nailmakers. In 1869 there were 1119 inhabitants while now there are only 875 (Bat & Vraničar, 2001; Šmitek, 1992).

References

Agricola, G. (1950) *De re metallica*. **I–XXXI**, Dover Publications, New York, 638p. (*translated from the first Latin edition of 1556*).

Bat, M. & I. Vraničar (2001) *Železniki. Enciklopedija Slovenije*. **15**, pp. 311–312.

Belar, A. (1889) Eine Grotte im Wocheiner Bohnerz-Reviere. *Mitteilungen der Section für Naturkunde des ÖTC*, **I**, *9*, pp. 71–72.

Bizjak, J., Jamnik, P., & Oberstar, A. (2001) Arheološke prvine v kraških jamah Suhe krajine. *Naše jame*, **43**, pp. 118–127. (Archaeological elements in karst caves of Suha krajina, *in Slovene*)

Brenčič – Kuki, M. (1991) Rudniki na krasu. *Bilten JK Železničar*, p. 26. (Mines on karst, *in Slovene*)

Dular, J. & Božič, D. (1999) Železna doba. In: *Zakladi tisočletij*, Modrijan, Ljubljana, pp. 98–183 (The Iron Age. In: Treasures of Millennia, *in Slovenian*).

Gospodarič, R. & Pohar, J. (1966) Geološka svojstva nahajališč železovih rud. *Železar Tehnična priloga*, **VIII**, *1*, pp. 7–25. (Geological properties of iron ore deposits, *in Slovene*).

Horvat, J. & Šašel-Kos, M. (1999) Rimska doba. In: Zakladi tisočletij, Modrijan, Ljubljana, pp. 184–291. (The Roman Era. In: Treasures of Millennia, *in Slovenian*).

Kranjc, A. (1979) Kras v povirju Ljubije. *Geografski vestnik*, **51**, pp. 31–42. (Karst in the Ljubija waterhead, *in Slovenian*).

Lamut, J., (1988) Črna metalurgija. *Enciklopedija Slovenije*, **2**, pp. 155–159. (Black Metallurgy, *in Slovene*).

Leskovec, A., 1989: Fužinarstvo. *Enciklopedija Slovenije*, **3**, pp. 170–172. (Ironworks, *in Slovenian*).

Müllner, A. (1909) *Geschichte des Eisens in Krain, Görz und Istrien*. Halm und Goldmann, Wien & Leipzig, 763 p.

Ocepek, D. & Redakcija, (1996a) Rudarstvo. *Enciklopedija Slovenije*, **10**, Ljubljana, pp. 306–309. (Mining, *in Slovene*).

Ocepek, D. & Redakcija, (1996b) Rudnik. *Enciklopedija Slovenije*, **10**, Ljubljana, pp. 311–313, (Mine, *in Slovene*).

Rjazancev, A. (1962a) Bobovci Julijskih Alp. *Železar Tehnična priloga*, **IV**, *2*, pp. 1–13, (Bean-ore of Julian Alps, *in Slovene*).

Rjazancev, A. (1962b) Poskusno taljenje bobovca v vetrni peči v Studorju. *Železar Tehnična priloga*, **IV**, *2*, pp. 14–24. (Experimental melting of bean-ore in "wind furnace" at Studor, *in Slovenian*).

Rjazancev, A. (1963a) Po poti železarskega Bohinja. *Železar Tehnična priloga*, V, *2*, pp. 43–67. (Following the iron Bohinj, in Slovene).

RJAZANCEV, A. (1963b) Vesti o bobovcih iz Julijskih Alp. ***Železar Tehnična priloga***, **V**, ***2***, pp. 67-70. (News related to bean-ore in Julian Alps, ***in Slovene***).

RJAZANCEV, A. (1963c) Bobovci Julijskih Alp. ***Železar Tehnična priloga***, **V**, ***2***, pp. 71–85. (Bean-ore of Julian Alps, ***in Slovenian***).

RJAZANCEV, A. (1963d) Drugo poskusno taljenje bobovca na Ušejci nad vasjo Studor. ***Železar Tehnična priloga***, **V**, ***2***, pp. 85–97. (The second experimental melting of bean-ore at Ušejca village near Studor, ***in Slovenian***).

RJAZANCEV, A. (1963e) Od bobovca do železa. ***Železar Tehnična priloga***, **V**, ***2***, pp. 97–99. (From bean-ore to iron, ***in Slovenian***).

RJAZANCEV, A. (1966) Kemizem bobovcev in njih primerjava ter tehnološki pogoji antičnih talilnic. ***Železar Tehnična priloga***, **VIII**, ***1***, pp. 33–66. (Chemistry of bean-ore, their comparison and technological conditions in antique smelters, ***in Slovenian***).

STRMOLE, D. (1987) Bobovec. ***Enciklopedija Slovenije***, **1**, Ljubljana, p. 293. (Bean-ore, ***in Slovenian***).

ŠAŠEL-KOS, M. (1993) Norik. ***Enciklopedija Slovenije***, **7**, Ljubljana, pp. 415–416. (Noricum, ***in Slovenian***).

ŠMITEK, J. (1992) Kropa. ***Enciklopedija Slovenije***, **6**, Ljubljana, p. 39.

VIDIC, M. (1998) Stara Fužina. ***Enciklopedija Slovenije***, **12**, Ljubljana, pp. 272–273.

VOJVODA, M. (1987) Bohinjska Bistrica. ***Enciklopedija Slovenije***, **1**, Ljubljana, p. 300.

received: 30 July 2002
revised: 27 November 2002
accepted: 27 November 2002

Theoretical and Applied Karstology, 15 (2002), pp. 125–132

Rapid communication

Recent paleontological investigations in some caves of the Crimean mountain-range (SE Ukraine)

Matei M. Vremir[1*] & Bogdan Ridush[2]

[1] *Babeş-Bolyai University, Dept. of Geology-Paleontology, str. Kogălniceanu 1, 3400 Cluj-Napoca, Romania.*

[2] *Yuri Fedkovych Chernivtsi National University, Dept. of Geography, Kotsubynskogo 2, Cernivtsi 58012, Ukraine.*

Abstract

Preliminary results of the most recent speleo-palaeontological investigations made in the Crimean high-mountains are presented. Several caves were investigated in the Chatyrdag massif; also new information regarding fossil remains from caves in several other plateaus (Aj-Petri, Yaltinskaya, Karabi) are added. The most interesting results come from the Emine Bair Khozar cave, which significantly contribute to highlight the Late Pleistocene and Holocene vertebrate faunas existing in the remote mountains of the Crimea.

Key words: vertebrate palaeontology, Late Pleistocene/Holocene, Crimea, Ukraine.

Recherches paléontologiques récentes dans quelques grottes de la zone montagneuse de Crimée (sud-est de l'Ukraine)

Résumé

On présente les résultats des recherches spéléo-paléontologiques les plus récents faites dans la haute montagne de la Crimée. Plusieurs grottes du massif de Chatyrdag ont été fouillées; en outre, on a ajouté de nouvelles informations sur les restes fossiles des grottes situées sur d'autres plateaux (Aj-Petri, Yaltinskaya, Karabi). Les plus intéressants résultas sont ceux obtenus dans la grotte d'Emine Bair Khozar parce qu'ils contribuent à la connaissance des faunes de Vertébrés du Pléistocène supérieur et du Holocène des montagnes lointains de la Crimée.

Mots-clés: paléontologie des Vertébrés, Pléistocène supérieur/Holocène, Crimée, Ukraine.

Introduction

Since the beginning of the XXth Century, many archaeological explorations and diggings were carried out in Crimea, especially in the caves and rock-shelters developed in the middle range of the Crimean Mountains. Some of them are worldwide known, as the *Kiik-Koba* Mousterian site providing Neanderthalian remains (STEPANCHUK, 2002), as well as the *Kizil-Koba* cave, famous for its culture-layers. Paleontological studies on Late Pleistocene faunas were related especially to these archaeological sites. Explorations on the main mountain range were rare; in fact until the 1960th no paleontological investigations were carried out. Even afterwards, very few information was available on the palaeontological sites of the high-plateaus of Crimea (BACHYNSKY, 1970; DUBLYANSKY & LOMAEV, 1980; LYSENKO, 1998).

Following the 1999 and 2001 speleo-paleontological investigations performed by us in three caves of the Chatyrdag plateau, several preliminary results were published (VREMIR, 2000) and a large-scale excavation project emerged.

Spring 2002 was the starting moment for new excavations and extensive field investigations in the southern mountain range of Crimea, carried out by a joint team of "Babeş-Bolyai" University in Cluj (Dept. of Geology) and Chernivtsi Univ. (Dept. of Geography). A second campaign was organised in the autumn of 2002; this time it focused on the Emine Bair Khosar cave, as well as on several new cave-sites. Two new

* corresponding author. *E-mail address*: vremirmatyi@yahoo.co.uk

sites have been studied in the Emine Bair Khosar cave; also an extensive excavation has been started in one of the previously known locations (Skull Chamber). New information regarding "bone-bearing caves" located in other high-plateaus (Aj-Petri, Yaltinskaya, Karabi) were gathered. All of these strongly recommend the Crimean high-mountain range for future paleontological investigations.

Investigated areas and sites

The Chatyrdag Plateau

The Chatyrdag Plateau is situated 30 km S from Simferopol, in the middle part of the main mountain range, being the second highest mountain in Crimea (Ecliziburun Peak — 1527 m a.s.l.). Like most of the Crimean yaylas ("yayla" is a local Tatarian geographical term, meaning a flat mountain-top surface, usually strongly karstified, characterised by steppe flora), Chatyrdag has a flat-top relief (Fig. 1). It includes two levels named the Upper (1400 m a.s.l.) and the Lower (1000-1100 m a.s.l.) Plateau, respectively.

From a geological perspective, a flysh-type marine sequence, represented by the *Tavricheskaya Series* (Upper Triassic-Lower Jurassic) is unconformably overlapped by a very thick, up to 1000 m, carbonatic series, consisting of Oxfordian conglomerates and massive, Lower Tithonian, limestones.

The limestone plateaus and cliffs are extensively developed between the elevations of 700 and 1500 m, and more than 100 potholes and caves are registered.

At the present time, on the Chatyrdag lower plateau (1000 – 1100 m a.s.l.), five caves present interest from a paleontological point of view: the *Emine Bair Khosar*, *Emine Bair Koba*, *Krapivnyj*, *Cherepa* and *Mramornaya* caves. In the Chatyrdag upper plateau (1400 m a.s.l.) the *Angar-Burun* pothole was investigated and a bone accumulation was identified.

Mramornaya Cave

Mramornaya is an approximately 2 km-long, partially show-cave, developed in Late Jurassic limestones. It includes large chambers and passages, as well as some pits which connect the two main, inactive, levels.

During the expedition in 1999, almost the whole cave was searched, and a very few vertebrate remains were founded in the lowest level of the cave, as well as in the main fossil passage.

In the lowest level (site MrA), the most interesting discovery was a partial cave lion skeleton (*Panthera leo spelaea*). The preservation of the bones is rather poor, the skeleton being disarticulated and partially destroyed by exposure (Bahrensmeyer's weathering stages 2–5). Some of the bones show rodent gnawing marks, which are partially covered by calcite crust. In the same chamber, three fox (*Vulpes vulpes* (*corsac*?)) and a hear (*Lepus timidus*) complete skeletons were discovered, preserving the outlines of the body and internal organs. Some rodents (*Cricetidae*) remains as well as a few goat teeth (*Capra* sp. cf. *C. ibex*) were also found.

In the main level of the cave (site MrB), we find several poorly preserved skull fragments belonging to a deer (*Cervus elaphus*).

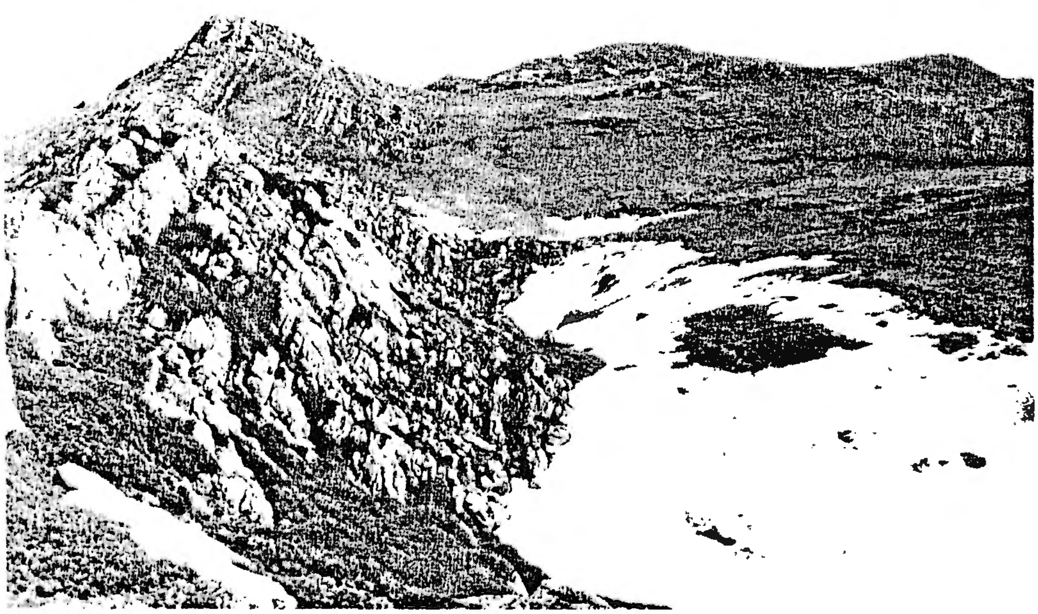


Fig. 1. Chatyrdag — the upper plateau.

Chatyrdag — le haut plateau.

A hear (*Lepus timidus*) and a young wild boar (*Sus scrofa*) skeletons were discovered in a side-passage (site MrC), which also preserve the outlines of the body and soft tissues.

Except for the lion, the goat and the deer remains, all materials are recent in age. From a biostratinomical point of view, the majority of the specimens (especially the hears and the wild boar) were trapped in the cave following accidental penetrations, and show no further disturbance. Bone accumulations or potentially rich paleontological deposits are absent in this cave, due to its particular morphology. The only important find is the cave-lion skeleton (rarely preserved as a whole), a species which was identified in other Crimean caves as well: Krystalnaya (Aj-Petri Plateau) (BACHYNSKY, 1970) and Emine Bair Khosar (Chatyrdag Plateau).

Emine Bair Khosar Cave

Emine Bair Khosar is the most interesting paleontological cave in the plateau. It is located on the northern edge of the Lower Chatyrdag plateau, very close to the Mramornaya cave complex and belongs to the same karstogenetic cycle. With a total length of 1460 m and a depth of –125 m, it is one of the biggest cavities in the plateau. The collapse-pit entrance (Fig. 2) is situated on the northern slope of Chatyrdag, but all known passages are oriented not towards the closest erosion base-level, but inside the mountain massif (DUBLYANSKY & LOMAEV, 1980, p. 41). This peculiar configuration is probably related to the hydrothermal origin of the cave, which presents two main levels: the upper one is composed by large chambers and passages which progressively descend to –50 m, while the lower level, connected by pits, is subhorizontal, and develops at a depth of –125 m. Fossil bones were identified within both levels, however the most important accumulations are in the upper one.

Fig. 2. Emine Bair Khosar — the base of the entrance shaft.
Emine Bair Khosar — la base du puits d'entrée.

In 1960, at the beginning of the speleological exploration, the cave provided 180 bones, which were found in a small chamber near the Access Passage, under a flowstone crust. This osteological material belongs to 24 individuals of cave bear (*Ursus spelaeus*), wolf (*Canis lupus* L.), corsac (*Vulpes corsac* L.), cave lion (*Felis spelaea* GOLDF.), northern lynx (*Lynx lynx* L.), horse (*Equus caballus* L.), red deer (*Cervus elaphus* L.), hare (*Lepus* sp.). DUBLYANSKY & LOMAEV (1980) consider that this bone accumulation was formed not far from the former entrance (subsequently closed by a breakdown), following a long inhabitation by large carnivores (*op.cit.*, pp. 136–137). Due to recent construction-works, this site is no more available for studies. In the 1990th more bones were collected from different sites inside the cave, but unfortunately there are very few information regarding the specimens found and their original locations.

We have searched several fossiliferous sites within the main (upper) passage. In the entrance area (sites BA1 and BA2) (Fig. 3a, b) we could recognise a complex taphocenosis containing faunal elements which belong to different biotopes, accumulated here in a long period of time. The mixed bone material is abundant in a huge debris-cone deposit accumulated in the lower part of the large, pitch-type, entrance (site BA1). The site BA2 (Museum Chamber) is located several tens of meters away from the natural entrance, at a depth of –28.4 m. This represents the edge of a sliding cone pressed in a lateral passage, which also contains a large amount of bone material. This site was partially excavated for fitting purposes; later it was transformed in a small Museum Chamber.

Generally, all the bones were collected as isolated elements. The most interesting specimens are represented by large herbivores such as the mammoth (*Mammuthus primigenius*), wholly rhino (*Coelodonta antiquitatis*), some bovines (*Bos primigenius; Bison priscus*), red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*) and equids (*Equus caballus*). Several other mammals are also present, such as the wild hog (*Sus scrofa*), cave lion (*Panthera leo spelaea*), mustelidae and rodents (a complete taxonomic identification is still required).

The second, newly investigated, site (BB) is represented by a very narrow passage with a bone-breccia type infill, which is

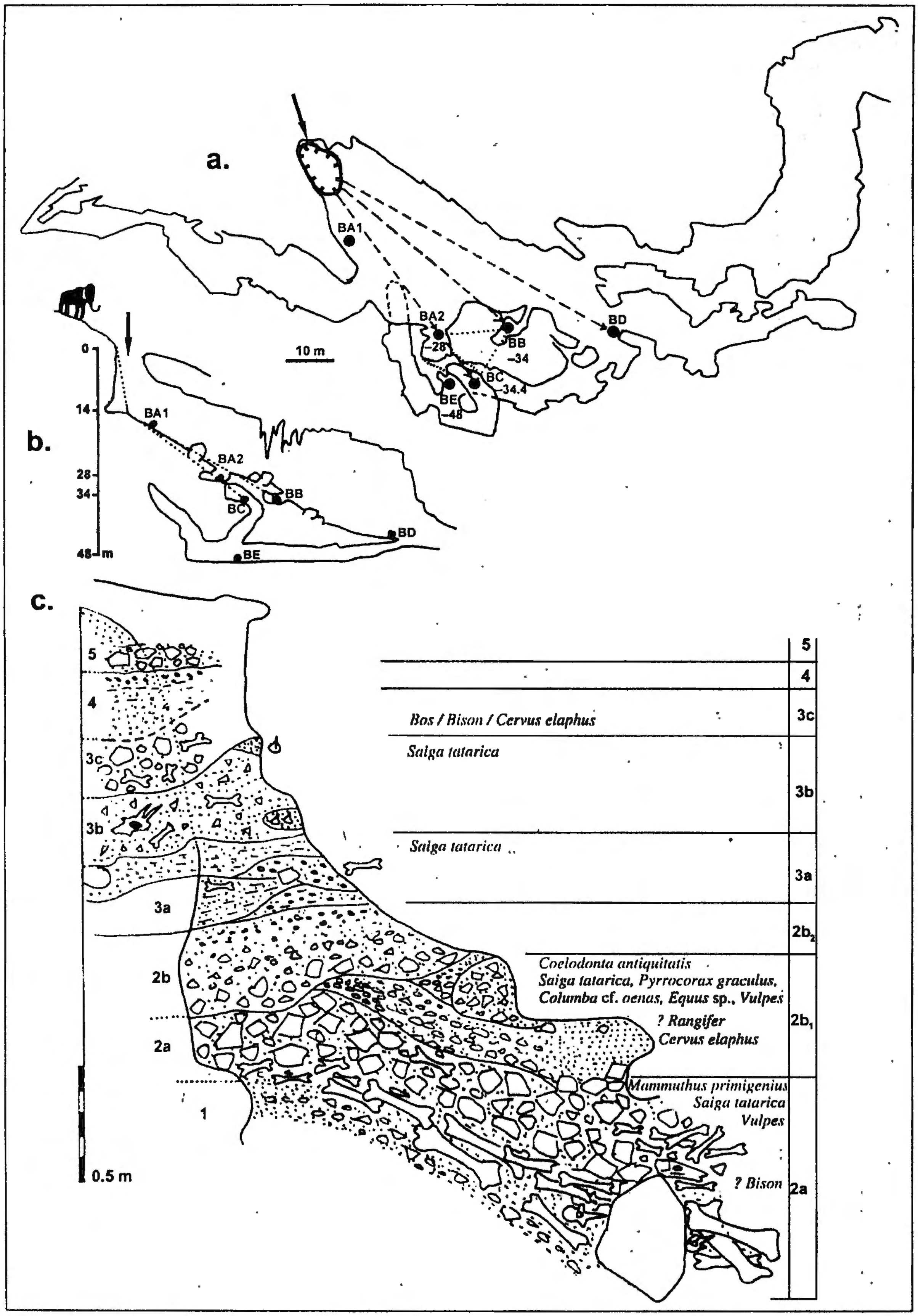


Fig. 3. Locations of the fossiliferous sites in the Emine Bair Khosar cave (a: plan; b: long profile). c: stratigraphic section on the BC site (Skull Chamber).

Situation des sites fossilifères dans la grotte d'Emine Bair Khosar (a: plan; b: profil). c: coupe stratigraphique dans le site BC (Salle du Crâne).

developed at the depth of –34 m, under the debris-cone. The bones are very well preserved, sometimes covered by calcite crusts. From this site we recovered for identification some cranial and postcranial elements belonging to wholly rhino (*Coelodonta antiquitatis*), possible wisent (?*Bison priscus*), horses (*Equus* cf. *mosbachensis*, *Equus hemionus*), and red deer (*Cervus elaphus*). Most of the bones are cemented in flowstone and bone-breccia, or between large boulders. The taphonomic characteristics suggest the arrival of isolated skeletal elements (especially long bones and vertebras, but skulls and other elements are also present), after a short transport with or within the collapse material accumulated here. It is very likely that the finer sediments were subsequently washed away (even nowadays, during the wet season a small stream cascades through this hole). This site represents one of the "undisturbed" and promising accumulations, which however is not accessible at the present-time because of the very narrow entrance passage.

A chamber infill with clayey and stony sediments represents the third location (site BC, The Skull Chamber) (Fig. 3). The bones are also very abundant, and we could recognise a similar kind of faunal assemblage as in the previous sites (large herbivores including mammoth (Fig. 4), wholly rhino, bovides, cervides, equids as well as antelopes, carnivores, rodents and birds). However the taphonomical characteristics are rather different. The ascendant passage is located above the Skull Chamber at the depth of –34 m and somehow below the main debris-cone (last levelling place this site a few meters under the Museum Chamber), representing in fact the lower section of the Museum Chamber profile. Besides the large mammals with the dominancy of bovides, cervides and antelopes (*Saiga tatarica*) the carnivores (*Panthera leo spelaea*, *Vulpes*) and human remains are also present. Complete skeletons, skulls and other skeletal parts in anatomical connection were recovered, suggesting the initial presence of more or less complete carcasses mixed with isolated bones or disarticulated skeletons.

The fourth newly searched site (BD) is located at the junction of Dublyanskogo Chamber and Skull Passage: a few bones collected from here belong to a fox (*Vulpes vulpes*), horse (*Equus* sp.) and a red deer (*Cervus*). The cave fitting works, recently disturbed this site.

The fifth site (BE) is located close to the Skull Chamber at the depth of –48 m, near the tourist path. In a small niche partially covered by flowstone, rodents (Cricetidae) and small carnivores (Mustelidae) remains were accumulated (study in progress).

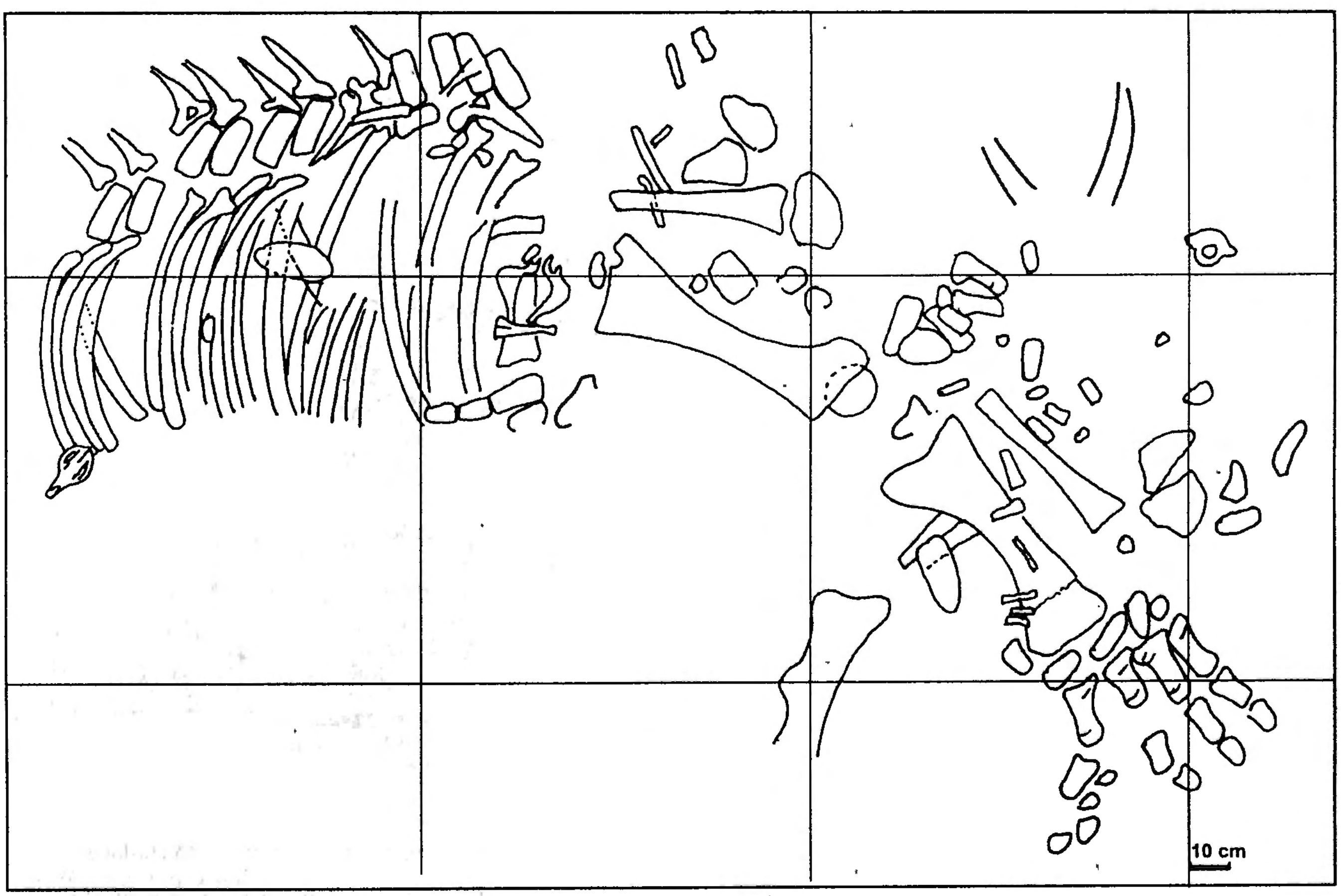


Fig. 4. Excavation survey: partial mammoth skeleton in BC site (September 2002).
Carte de la fouille: squelette partiel du mammouth dans le site BC (septembre 2002).

From a taphonomical point of view, the pitch-type entrance of the cave (above site BA1 and BA2) functioned for a long time as a natural trap. Several thousands of bones (disarticulated skeletons) can be accumulated inside the debris cone. More detailed information will be available following the statistical data processing and interpretation. The most important results come from the site BC (Skull Chamber) which preserves partial carcasses or complete skeletons in anatomical connection, being accumulated very close one to another probably in a short time. From a few square meters of digging, more than 1000 bones were recovered, belonging to several large herbivores (*Mammuthus primigenius, Coelodonta antiquitatis, Bos primigenius, ?Bison priscus, Cervus elaphus, Rangifer tarandus, Equus* – probably two species), as well as saiga antelope (*Saiga tatarica*), carnivores (*Panthera leo spelaea, Vulpes vulpes*), lagomorphes (*Lepus timidus*) rodents, birds (*Pyrrocorax graculus, Columba* cf. *oenas*, a.s.o.) and finally a human vertebra.

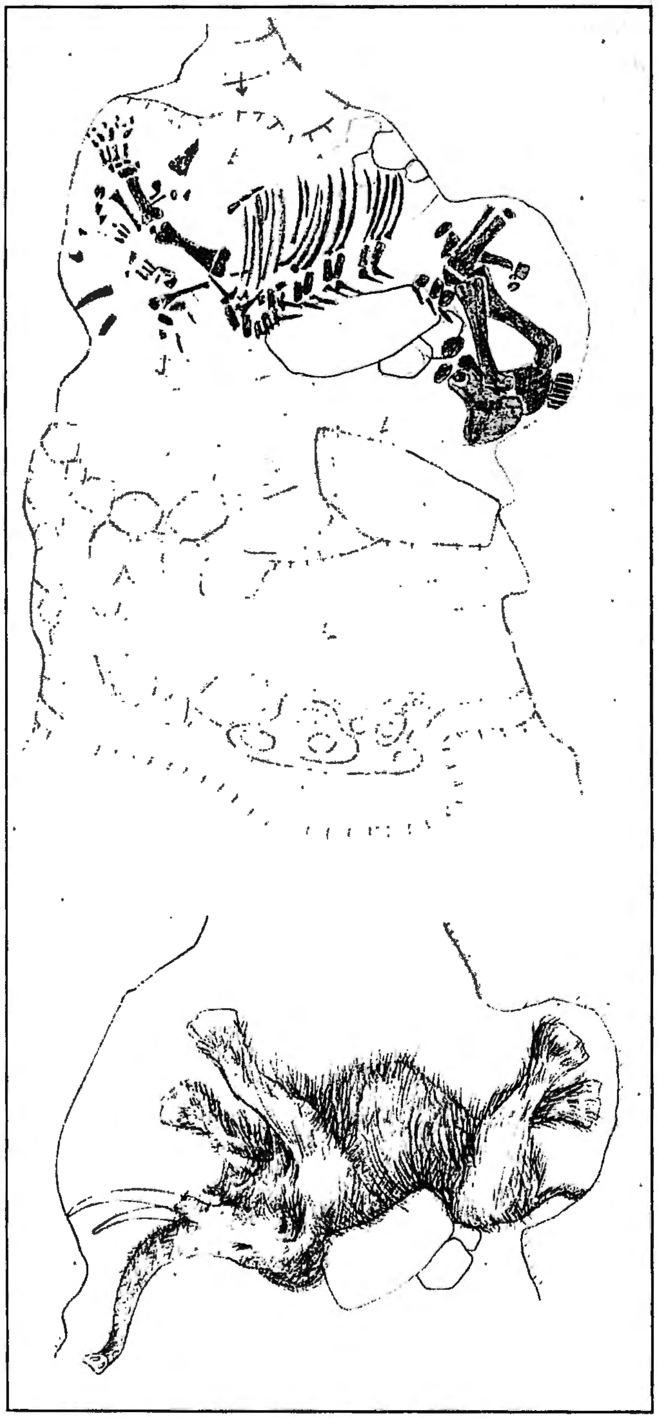


Fig. 5. Mammoth skeleton in BC site (April/September 2002) (top) and reconstruction of the original position of the carcass (bottom).

Squelette du mammouth dans le site BC (avril/septembre 2002) (en haut) et reconstitution de la position originale de la carcasse (en bas).

We have to notice the presence of a mammoth skeleton (young specimen) (Fig. 5, 6), one auorachs skeleton, three deer skeletons, partial horse and bovid carcasses, a saiga skeleton, hear, fox and other small mammal partial skeletons or isolated bones. The preservation and spatial distribution of the bone material, the stratigraphic and microambiental data as well as the passage configuration suggest a very peculiar taphofacies. At the present time, an underground glacier with a steep slide is the most adequate model for this kind of layered accumulation; all carcasses have been pressed in a relatively narrow passage at the bottom of slide and the decomposition processes took place *in situ*.

The paleontological potential of this cave is huge. We can recognise faunal assemblages which belongs to the last glacial stage (cold steppe elements, data supported by pollen analysis as well), also to interstadials and postglacial (mostly related to grassland and forested landscapes in a warmer climate. The

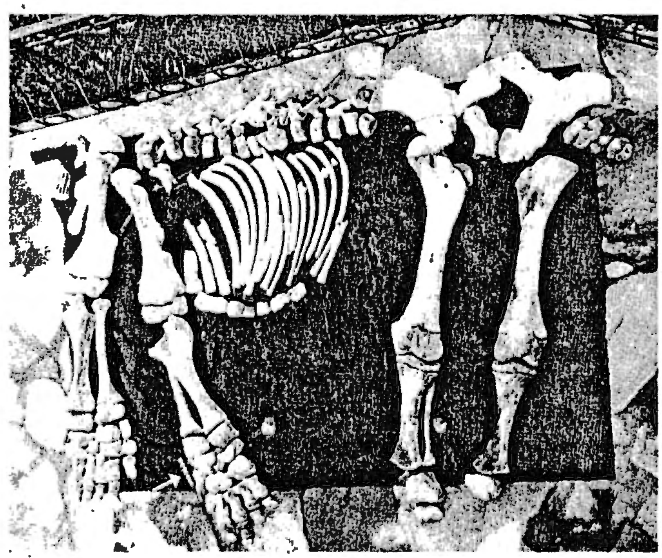


Fig. 6. The mammoth skeleton retrieved from BC site, Emine Bair Khosar. The scale-bar indicated by an arrow is 15 cm-long.

Squelette du mammouth récupéré du site BC de la grotte d'Emine Bair Khosar. L'échelle est indiquée par la flèche de 15 centimètres de longueur.

large amount of bones, the state of preservation, the taphocenosis and the affluence of taxa, as well as the complex assemblages accumulated in a long period of time, grant a special status to this cave, which can solve questions concerning the palaeo-biogeographic, palaeoecologic and palaeoclimatological problems of this region.

Krapivnyj Grotto

It is located 0.7 km south from the Emine Bair Khosar cave, on the edge of the lower plateau. From a morphological point of view, it is a sub-horizontal cave, developed a few meters below the surface, and opened by erosion processes. The entrance area is formed by a chamber of 7 × 15 × 7 m (site Kr.1), which continues with a narrow passage, 10 m in length (site Kr.2), recently excavated by the cavers from Simferopol.

The entrance chamber (Kr.1) represents a new archaeological site. The preliminary search revealed the presence of a large amount of pottery belonging to different cultures, from the Late Bronze/Early Iron Age till late Middle Age, as well as bone materials (domestic and wild species). The bones are mostly fragmented, but on the basis of a few teeth and mandibular fragments the cervids (*Cervus elaphus*), bovids (*Bos*), equids (*Asinus*, *Equus*) as well as small carnivores were documented.

The most interesting find is a skullcap belonging to a mustellid, which was excavated from the site Kr.2. The fossil is well preserved, being cemented in a very thick (over 1 m) flowstone formation, which closed the inner passage. The age of this bone is as yet unknown.

In the process of speleological digging both sites were superficially disturbed, and no stratigraphical or taphonomical data are available.

Cherepa Cave

The preliminary investigation in this relatively small cave, with a narrow pothole- type entrance, situated close to the Emine Bair Khosar cave, revealed a subfossil bone accumulation, which contains numerous horse, ox, deer and goat remains. Cavers from Simferopol made some diggings (explorative purposes), which disturbed the site, and the original tafofacies. Further excavations are needed.

The Karabi Plateau

The only skull of musk-ox (*Ovibos moschatus*) comes from *Lunnava Cave* from Karabi Plateau (material deposited at the Geographical Dept. of Vernadsky Tavrichesky University, Simferopol). The finds of *Ovibos* in the Eastern Europe are numerous, but only north from 50° parallel. They are mostly related to Late Paleolithic sites (Gromova, 1965, p. 104). In the Western Europe the most musk-ox remains belong to the last glacial stage; towards the South they were found as far as Hungary and the SW of France. At that time *Ovibos* have reached also Dobrogea in Romania (Gromova, 1965, p. 102), but it was not numerous. Vereschagin & Barishnikov (1980) considered that the musk-ox probably did not penetrate into Crimea. They have noted as well the absence of *Bos primigenius* in the Palaeolithic. It seems that this is the first *Ovibos* record in Crimea and also the southernmost in Eastern Europe.

Another shaft-cave from this plateau (Mammoth Cave), provided fossil bone materials, which were attributed mainly to the wholly mammoth (*Mammuthus primigenius*).

The Aj-Petri Plateau

On the western side of Aj-Petri, in the shaft of Crystal Cave, an almost complete cave lion and a fox skeletons were found (Bachynsky, 1970). Radiocarbon dating of the cave-lion (Dr. Doris Nagel, Wien, *pers. comm.*) indicates 12000 BP.

Preliminary results and conclusions

Information regarding speleal bone-accumulations or bonecaves in the Crimean mountains were scarce until now. At least ten caves/potholes situated on four high-plateaus were recorded, which potentially could yield information on Late Pleistocene and Holocene mammalian faunas of the remote Crimean highlands.

The best-documented area is the Chatyrdag Plateau, where six caves/potholes were searched, two of them (Mramornaya and Emine Bair Khozar caves) being properly investigated. Other caves also provide some information, which led to the following conclusions:

- Some of the large shaft-caves and potholes, functioned for a long time as natural traps.
- Bone accumulations are frequently mixed and/or disturbed.
- Very few layered and/or undisturbed bone-deposits are known.
- The identified faunal elements, belong to different assemblages, habitats, and periods, suggesting a complex taphocenosis (at least in some of the sites).
- The Last Glacial Stage is well documented in almost all investigated caves, being characterised by a cold-steppe fauna with mammoth, wholly-rhino, musk-ox, wisent, reindeer, a.s.o. Warmer steppe elements are represented by horse, Asiatic wild asses, aurochs and antelopes. The forested landscape is indicated by roe deer, red deer, wild hog, wolf, fox, lynx, cave lion and bear. More recent faunal elements are also recorded.
- The presence of different faunal elements (including fossil man) together in the same deposit, suggest a complex taphonomic history, but also the possibility of coexisting faunas due to the geomorphologic conditions.

- The first complete mammoth (*Mammuthus primigenius*) skeleton in Crimea has been found.
- The first documented aurochs (*Bos primigenius*) and the first Saiga antelope skeleton and skulls in Crimea have been found.
- The first musk-ox (*Ovibos moschatus*) record in the Crimea.

Extensive field investigations are needed in all of the high-plateaus (Aj-Petri, Yaltinskaya, Dolgonukovskaya, Babugan, Chatyrdag, Demergi, Karabi), since obviously many of the large shaft-caves or potholes identified until now, could have functioned as natural traps. Bone accumulations were recorded in more than ten caves (four plateaus), but the potential seems to be much higher. It is very likely that the undisturbed-layered bone deposits will yield valuable information regarding the vertebrate faunas of the Crimean high-mountains, during the Last Glacial Stage and the Holocene time.

Acknowledgements

We are grateful for the help during the field investigations to the following students and cavers: Alexandra Oprişan (Omega - Cluj); Pop Lucian; Balogh Miklós (CSA – Cluj); Kovács Alpár, Tomas Róbert, Burián Szabolcs, Tóth Attila and Józsa Sándor ("Babeş Bolyai" University in Cluj, Dept. of Geology) and the cavers from Simferopol and Yalta (Crimea). We thank for the help on taxonomic identification to: Gal Erika – Cluj (birds), Dr. Doris Nagel – Wien (carnivores) and Gasparik Mihaly – Budapest (micromammals). The present research was partially supported by a scholarship awarded to MV by Domus Hungarica Scientiarium et Artium. Also we thank the following sponsors for their help: "Romgaz" Mediaş; "Oncos" Cluj; "ATTA" Cluj; "Orbital" Cluj aş well as "Onyx Tour" and Alexandr Kozlov, Simferopol.

References

Bachynsky, G. A. (1970) The taphonomic characteristics of fossil vertebrate sites in karst caves of Ukraine. *Fizychna geographija ta geomorphologia*, 4, pp. 153–159 (*in Ukrainian*).

Dublyansky, V.N. & Lomaev, A.A. (1980) *Karst Caves of Ukraine*. Naukova Dumka, Kiev, 180 p. (*in Russian*).

Gromova, V. (1965) *The short review of Quaternary Mammals of Europe (the experience of comparison)*. Moskow, 144 p. (*in Russian*).

Lysenko, N.I. (1998) Mammoth in the Crimea. *Priroda*, 3–4, pp. 8–12. (*in Russian*).

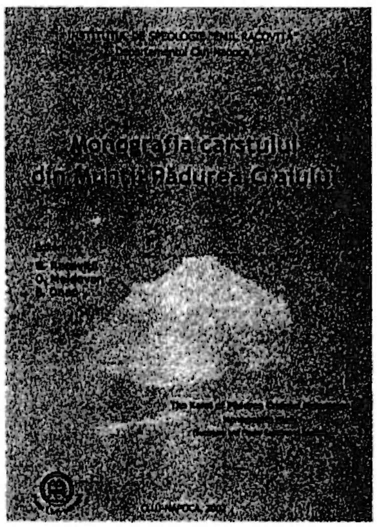
Stepanchuk, V.N. (2002) *Late Neanderthals of the Crimea: Kiik Koba site*. Kiev, 216 p. (*in Russian*).

Vereschagin, N.K. & Baryshnikov, G.F. (1980) Mammals of North-Crimean foothills in Palaeolithic time. *Proc. of the Zoological Institute Leningrad*, 93, pp. 26–49. (*in Russian*).

Vremir, M. (2000) Palaeontological investigations in some caves of the Chatirdag Plateau (Crimea; Eastern Ukraine): A preliminary report. In: *Realizări şi perpective în Studiul Cuaternarului din România* (Onac, B.P. & Tămaş T., *Eds.*), Presa Universitară Clujeană, Cluj-Napoca. pp. 35–37.

received: 29 October 2002
revised: 22 November 2002
accepted: 26 November 2002

Book Reviews



Monografia carstului din Munţii Pădurea Craiului

Gheorghe Racoviţă, Oana Moldovan, & Bogdan P. Onac, *Editors*

Ed. Presa Universitară Clujeană, Cluj-Napoca, 2002.

264 (+xii) p., 3 b&w photographs, format 18 x 24 cm.
ISBN: 973-610-101-0.

"The Karst of Pădurea Craiului Mountains. Monographic study" (in Romanian, summary and figures captions in English).

price: USD 10 plus postage; on sale at the "Emil Racoviţă" Institute, Cluj Branch, str. Clinicilor 5, 3400 Cluj-Napoca, Romania. email: bonac@bioge.ubbcluj.ro

A characteristic of the Romanian karst, where the limestones outcrop on only 2% of the territory, is the diversity and scattering of karst units. Pădurea Craiului Mountains, one of the most important karst regions of Romania, is an exception. Here, the karst plateaus are especially unitary and well-developed. The karst is hosted by a low-altitude, peneplaned massif, located in-between two large depressions; its surface exceeds 450 km² and includes Triasic, Jurassic and Cretaceous limestones. Moreover, at the limit between Tithonian and Neocomian, a bauxite-bearing paleokarst is located. The position of the karst, the permanent water input coming from the impervious deposits, the stable baselevels and its pre-Quaternary evolution allowed the formation of extensive subterranean networks (among which the 45 km-long Peştera Vântului, the longest in Romania), as well as that of an impressive exokarst.

For its importance, the karst of Pădurea Craiului was a permanent attraction for cavers and a generous research topic for karstologists. Apart from numerous articles and studies dealing with a broad range of subjects, two monographs and a hydrogeological synthesis have been published within the last 15 years. The first book, *Carstul din Munţii Pădurea Craiului* (Rusu, 1988) is a regional karstology study that includes extensive morpho-hydrographic and cartographic works of the most important researcher of this area. Taking into account the exhaustive interest of the author for this region and the care for even smallest details, one should hardly imagine, a decade ago, that a new approach to Pădurea Craiului will happen too soon. However, in 1991 the *Hydrogeological Map of Pădurea Craiului Mountains* appeared in *Theoretical and Applied Karstology* (Orăşeanu, 1991), and, this year, the "Emil Racoviţă" Institute's branch in Cluj has published the volume *Monografia carstului din Munţii Pădurea Craiului,* dedicated to the memory of Theodor Rusu.

I have mentioned these historical details in the introduction of this review in order to emphasize that the diversity and the evolution of karstology concepts over a short time-span may be integrated into an attempt to continue and, especially, unify various researches. This is the first impression one will have when skimming through the book and it will definitely become clear after reading it.

The volume is a collection of contributions of ten authors (D. Borda, R. Bucur, A. Fekete, C. Ghemiş, S. Iepure, O. Moldovan, B.P. Onac, G. Rajka, G. Racoviţă, M. Venczel) making 13 chapters that include both new research and updates of studies already published. All these complete the "big picture" of the karst of Pădurea Craiului and finally yield a unitary, systematic and complex image of the region.

The first two chapter outline the subject by presenting a history of karst research (G. Racoviţă) and the geologic and geographic background (B.P. Onac). The latter chapter includes a synthesis on the exokarst features, systematically presenting the repartition of karren, sinkholes, ouvalas, karst depressions, karst valleys and plateaus.

The analysis of caves is much broader (B.P. Onac and G. Rajka). It starts with the hydrogeological setting (swallets and springs, underground drainages, water chemistry, hydro-karstic systems), then the caves and their speleogenetic models are dealt with accordingly. Important sections are dedicated to the mineralogy and geochronology of subterranean deposits. This chapter concludes with a presentation of the caves Litophagus, Vântului, Ciur Izbuc, Ciur Ponor, which are considered as representative for Pădurea Craiului. The underground climatology is dealt with in a separate chapter (G. Racoviţă) that includes analyses of the topoclimate from Vântului cave, Peştera cu Apă din Valea Leşului, P. de la Faţa Apei, and P. de la Vadu Crişului.

The results of biospeleological researches are described in more detail. The chapter dedicated to the aquatic fauna (S. Iepure and O. Moldovan) outlines the diversity of stygobiontic and endemic fauna, which includes twelve groups with 87 taxa and 255 species, among which 19 are endemic. The cave of Vadu Crişului (59 species and subspecies) was selected for a complete presentation of the species and their biotopes.

The terrestrial fauna is described within two other chapters: subterranean Coleoptera (O. Moldovan, G. Racoviţă and R. Bucur) and Chiroptera (D. Borda). They do not include only fauna lists but also interesting zoogeographic considerations, criteria for the speciation study (*Drimeotus*), numeric keys for the determination of the species (*Parapholeon*), problems related to behavior or genetic variability (leptodirines), genus or subgenus revisions. A special note for the presentation of bats populations from five caves. These chapters are completed by another one dedicated to the study of environmental conditions and fauna variability in two caves from northern Pădurea Craiului.

The next two chapters deal with paleontological (M. Venczel) and archaeological (C. Ghemiş) studies carried out by the Muzeul Ţării Crişurilor in Oradea. Karst paleontology studies were especially focused on the important fauna of Triassic reptiles and Cretaceous dinosaurs found in the bauxite mines but also to newer (Neogene) remains. The archaeological chapter presents the stratigraphy and the artifacts discovered in Ungurului and Napiştileu caves.

The volume ends with a short chapter dealing with the subterranean environment protection (O. Moldovan) followed by an extensive bibliographic list, which is representative especially for the papers published in Transylvania and Hungary.

Cristian Goran

Information for contributors to *Theoretical and Applied Karstology*

Contributions to TAK may be submitted for publication as **Articles** (usually up to 8000 words) or as **Short Notes** (usually up to 2000 words). Larger articles, such as **Reviews** may also be published but their subject and size should be discussed first with the Editors.

Manuscripts must be submitted in **English** or **French**, in electronic format accompanied by two hard (paper)-copies. The order of preference for electronic submission is: (1) e-mail attachment, (2) floppy-disk(s), (3) CD, (4) ZIP Disk (100 or 250 Mb). For fast submission of large files, FTP transfer may be arranged.

We currently use IBM- compatible PCs and can read most popular word-processor, spreadsheet and graphic file formats; if you are using OS/2 or AppleMac, please format your disk as a DOS disk. Also, please consult us if your graphic files were saved under an uncommon format (e.g. the *.fpw format of FigP , *.sta format of Statistica and alike) or if you used special character sets (such as East European, Turkish, etc.) for diacritical marks. In any case, the hard-copy is essential for reference as we may unknowingly lose parts of your text or formatting in the conversion process. Also note that after acceptance, all the corrections or revisions to your paper will be made only on hard-copies in order to reduce the possibility of error.

Papers should be headed by the **title** and the **author(s) full name(s)**. This will be followed by the **complete address(es)** of all the authors. If more than one author, please specify the name and address of the person to whom the correspondence and proof should be sent.

An **abstract** (up to 300 words) in the paper's language should be placed directly after the title and author(s)' name(s), followed by the **keywords**. If possible, these will be followed by the translation of the title, abstract and key-words in the 'secondary' language of the paper (English if the paper's main language is French and vice-versa); else the translation will be made by the Editors at no charge for you.

References cited in the text (and only these) should be listed, in alphabetical order, on (a) separate sheet(s), after the heading **References/ Bibliographie**, taking for example an older issue of TAK. References should be cited in the text in parentheses, in small capitals using the "name and year" ('Harvard') system, e.g. "(AHRENS, 1962)" except when the author's name is part of the sentence, e.g. "AHRENS (1962) has shown that ...". When reference is made more than once to same author and year, a, b, c, etc. should be added to date in the text and reference list. If more than two authors, it is in order to put "et al." behind the first name, e.g. "(KLEIN *et al.*, 1988)" within the text, but *all authors* should be listed in the Reference list. In general, one should follow the American Psychological Association (APA) Method of referencing. If in doubt, please consult us.

Mathematical equations should be numbered in consecutive order throughout the text, using Arabic numerals.

Figures (maps or line drawings in black Indian ink on transparent paper) should be prepared in anticipation of reduction; small symbols or fine details may reproduce poorly. If possible, the original figures shall not exceed 31 x 20 cm. The number of folded plates being limited, only one figure exceeding this size will be, as an exception, accepted. Only black-and-white **photographs** may be published, therefore, if you send color photographs make sure that the important details will be legible when converted to grayscale. Whenever possible, please send us the illustration in both electronic and hard-copy format, but, as a rule, the original will always be preferred over the electronic version.

Plates, figures and tables should be numbered consecutively, with Arabic numerals, in order of appearance. The top of the figure should be indicated whenever exists any possibility of ambiguity. Please indicate in the manuscript where the caption-figure or group of figures is to be inserted.

The **captions** and explanations of the figures and tables will be doubled-spaced typed on separate sheets, in both volume's languages, if possible.

Acknowledgements should be placed at the end of the text, after the heading Acknowledgements, before the References.

Upon acceptance, an edited proof of the contribution will be sent to the authors for final revision. Normally, the proof will be sent by email, as a PDF file. Authors are expected to print the file, make the final corrections (if necessary) sign the Agreement for Publishing and fax it, together with the revised proof, to the Editors. Authors bear sole responsibility for the content of their contribution; this includes obtaining any clearance for the use of copyrighted materials.

As a general rule, NO manuscripts will be returned, regardless if the paper was accepted or not.

Papers accepted by the Editorial Board and published into TAK will become the property of the Publisher. No article or any part thereof may be reproduced in whatever form without the written permission of the Publisher.

A total of 25 reprints of each paper will be supplied to the authors free of charge. Authors will benefit of discount prices for additional reprints if ordered before publication.

In this issue:

ISSN 1012-9308