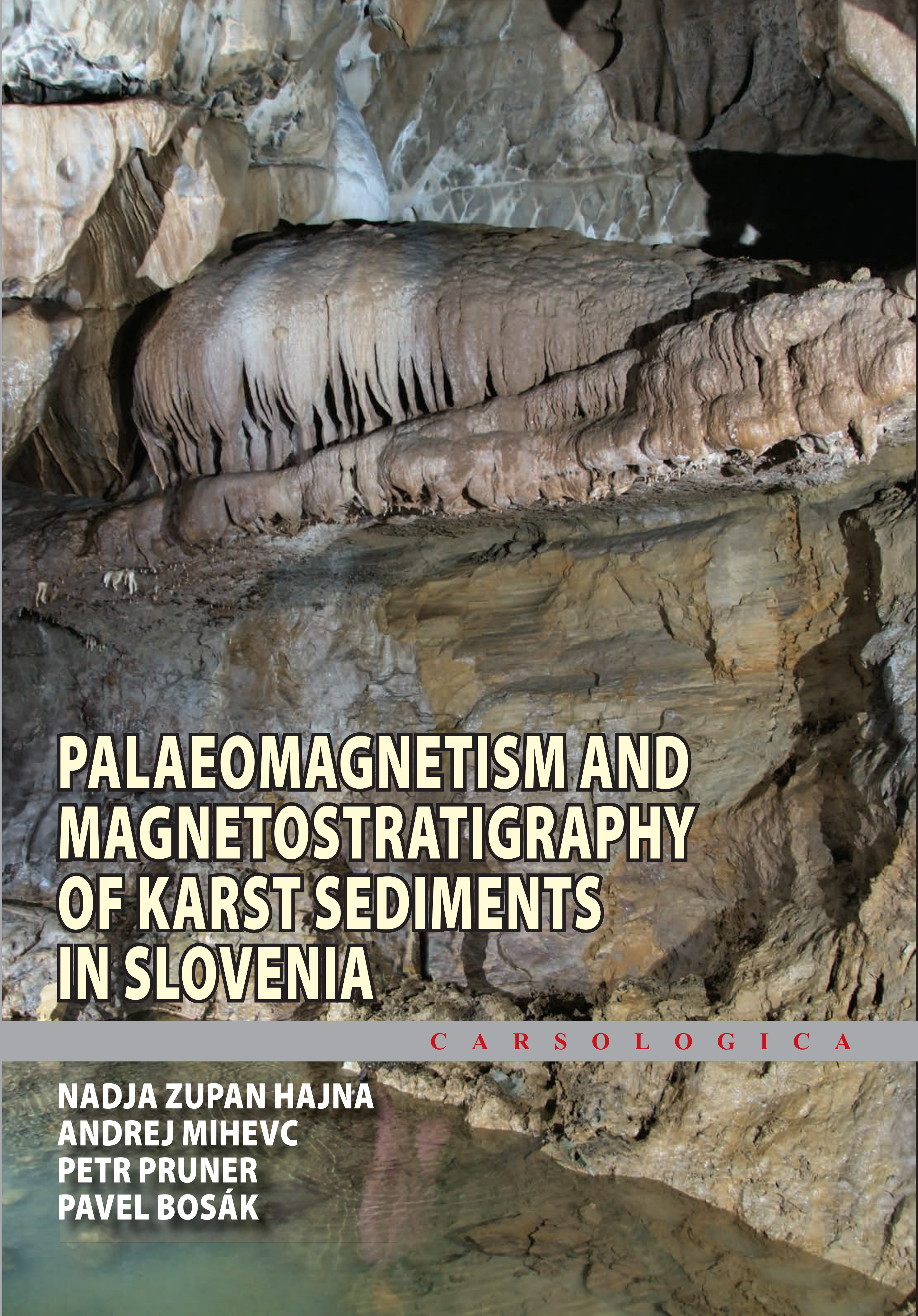

PALAEOMAGNETISM AND MAGNETOSTRATIGRAPHY OF KARST SEDIMENTS IN SLOVENIA

C A R S O L O G I C A

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CARSOLOGICA

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POSTOJNA – LJUBLJANA 2008

CONTENTS

FOREWORD

This book reports on the ten years long collaboration of the Slovene Karst Research Institute ZRC SAZU at Postojna with the Institute of Geology, Academy of Sciences of the Czech Republic at Praha (Prof. Pavel Bosak). The last institution has taken 2007 samples of sediments in the 21 profiles of the Slovene Dinaric and Alpine karst and determined their palaeomagnetism and magnetostratigraphy.

The oldest sample found in them with the age from about 1.8 to more than 5.4 Ma indicated the surprising age of a cave near the Adriatic seashore. This is the time of the upper Miocene! Toward NE of the Slovene Dinaric Karst this age is diminishing but is still 0.78 Ma in the Postojnska jama. In one of the three researched high Alpine caves in the northern Slovenia this age is between 1.2 and 5.0 Ma.

The study proved that the cave sediments represent a good tool for the reconstruction of the landscape evolution and tectonic regime in different karst regions. In collaboration with the team from Bohemia, the Slovene scientists added the results of research in many natural sciences on the Slovene caves and karst regions, already published or not yet published in the Slovenian and in the foreign literature. This is why this monograph on the Slovene karst caves and Slovene karst gives many new information. The famous French speleologist E. Martel in his book Les Abîmes in the year 1894 confirms the reputation of the Slovene Dinaric region Kras (Karst) by naming it "the classical karst" as here investigations of hydrology and caves started. The present book has repeated this reputation.

Research in the Slovene caves contributed also to the improvement of the techniques of sampling for high resolution approach of fine cave sediments with dense sample spacing.

The book is therefore important also for technology of sampling and for applying the palaeomagnetism and magnetostratigraphy for the karst sediments.

Ivan Gams,
January 2008 *Ljubljana, Slovenia*

PREFACE

This book represents the result of more than 10 years intensive study of palaeomagnetic properties and magnetostratigraphy of karst sediments in Slovenia. The research covered the most important karst regions, from lowlands to high mountains. It included both well-known and documented sites (like in the Kras), and relatively unknown or newly found locations in caves and surface sedimentary cover in karst.

The whole story started in 1997 during the 5th Karstological School – Classical Karst – Caves held in Postojna on June 30 to July 2, 1997, when two of the authors (NZH and PB) visited a site opened by the construction of the highway from Razdrto to Kozina – Divača profile near Divača village, the Kras plateau, during one of excursions. The discussion was concentrated on one substantial question – how cyclically arranged cave fluvial and lacustrine deposits can be dated, when fossils are not preserved or their preservation is too poor for proper determination. Also some other comparative methods could not be used, like heavy mineral assemblages, evolution of clay mineral assemblages, due to the fact that the principal source rocks, siliciclastics of Eocene flysch sequences, were the same for all cave sites since the emergence of the territory from the sea. The palaeomagnetic method was selected because of simple reasons: it was accessible in one of the institutes – in the Institute of Geology of the Academy of Sciences of the Czech Republic – and one of authors (PB) had some experience with its application on cave deposits. The method was selected in spite of number of disadvantages – in particular it does not produce numerical dates and when not fixed by other methods, the correct age can be obtained only with difficulty and uncertainty.

On September 1997, the sampling started at several sites – Divača profile, and Divaška jama and Trhlovca. The results were exceptionally good, even when obtained in rather primitive conditions. They indicated that the cave fills are substantially older than expected earlier. This fact was not in accordance with the previous karstological models of the evolution of karst in Slovenia, but illustrated and proved the new ideas and data on much older ages of karst relief obtained by numerical dating, the discovery of unroofed caves and their dating by the geomorphic means.

The first results were presented at the 6th Karstological School – Classical Karst – Alpine Karst held in Trenta on June 29 to July 1, 1998. The audience was outstanding – Prof. Dr. Ivan Gams, Prof. Dr. Peter Habič, Prof. Dr. France Habe, Prof. Dr. Jurij Kunaver, Dr. Andrej Kranjc, and many others. There were some long minutes of silence after the lecture, entitled ***Palaeomagnetic research of cave sediments in SW Slovenia****, was finished. We had to explain the principles of the method and deal with a number of other questions. But it was clear that our results, although accepted with caution, were carefully evaluated. Our preliminary results were later supported by data acquired from research at other sites and their acceptance by the audience was without any substantial problems.*

The work appeared at the time of the discovery of unroofed caves and their interpretation as an important element of the surface karst landforms, and the palaeomagnetic method started to be applied quite extensively. We can state that it strongly supported the concepts about the development of unroofed caves that arose, proving the exceptional age of their fills.

The continuing research resulted also in improvements of the method. When early sites were re-sampled, we discovered that the separation of samples had been too long, resulting in some narrow magnetozones with different directions of magnetization being missed in the log. Therefore, we started with so-called high-resolution magnetostratigraphy sampling, i.e. very dense sampling in soft sediments and continuous sampling in speleothems by cutting narrow trenches. The method was applied for the first time in Snežna jama.

Close mutual co-operation of the Institute of Geology, v.v.i., Academy of Sciences of the Czech Republic in Praha (hereafter IG AS CR) with the Karst Research Institute Scientific Research Centre of Slovenian Academy of Sciences and Arts in Postojna (hereafter IZRK ZRC SAZU) and their staffs was based on the Agreement on Scientific Co-

operation of both Institutes. It was signed on September 16/24, 1997 before the start of the first sampling campaign, establishing the fundamental contacts, co-operations, projects, and grants.

We believe that this co-operation and its fruitful results encouraged the renaissance of the application of palaeomagnetic and magnetostratigraphy methods in broader World context, as indicated by recent bibliographies.

Nadja Zupan Hajna
Andrej Mihevc
Petr Pruner
Pavel Bosák

Postojna, Prague, January 2008

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Dr. Bojan Otoničar assisted in research of Hrastje site and Dr. Tadej Slabe helped to select Kozina profile (both from IZRK ZRC SAZU); Dr. Marko Vrabec (Department of Geology, Faculty of Natural and Technical Sciences, Ljubljana University, Slovenia) selected the Velenje site and assisted in research; Mr. Jože Žumer (†, Koper, Slovenia) helped with activities in the Črnotiče Quarry; and Dr. Jaroslav Kadlec, Mgr. Stanislav Šlechta and Mgr. Petr Schnabl (IG AS CR) assisted in one or more of following sites: Jama pod Babjim zobom, Račiška pečina, Divaška jama and Trhlovca. Dr. Ruggiero Calligaris and Dr. Antonella Tremul coordinated research in sites of Briščiki and Jama pod Kalom (Trieste region, Italy).

Paleomagnetic analyses were performed by Dr. Daniela Venhodová, Mrs. Jana Drahotová, Dr. Martin Chadima, Dr. Jaroslav Kadlec, Mgr. Stanislav Šlechta, Mgr. Petr Schnabl, Mr. Jiří Petráček, and Mgr. Jana Slepičková. Software for evaluation of palaeomagnetic measurements was prepared by Dr. Ota Man. Samples for palaeomagnetic analyses were cut by Mr. Jiří Petráček, Mr. Stanislav Šlechta and Mr. Jakub Kanta (all from the Laboratory of Palaeomagnetism, IG AS CR).

Samples for the X-ray analysis and evaluation were prepared by Dr. Karel Melka, Dr. Roman Skála and Mr. Jiří Dobrovolný, thin sections were produced by Mrs. Ivana Konopáčová. EDAX and microprobe analyses (Črnotiče I) were carried out by Dipl. Ing. Anna Langrová (all from the Laboratory of analytical methods, IG AS CR). Part of X-ray analyses were done by Dr. Meta Dobnikar (Department of Geology, Faculty of Natural and Technical Sciences, Ljubljana University, Slovenia).

Prof. Dr. Ivan Horáček (Department of Zoology, Faculty of Science, Charles University, Praha, Czech Republic) carried out palaeontological analyses from Račiška pečina and Črnotiče II sites. Palynological analyses were kindly carried out by Dr. Metka Culiberg (Jovan Hadži Institute of Biology, ZRC SAZU, Ljubljana, Slovenia) from Divača and Kozina profiles, and by Dr. Maryna Komar (Institute of Geological Sciences, National Academy of Sciences of Ukraine, Kiev, Ukraine) from Trhlovca, Snežna jama and Račiška pečina.

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Acad. Prof. Dr. Ivan Gams, Prof. Dr. Petar Habič, Acad. Dr. Andrej Kranjc, Prof. Dr. Tadej Slabe, as well as other members of the Karst Research Institute ZRC SAZU from Postojna helped us by valuable consultations on geology, geomorphology and karst evolution in Slovenia.

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Special thanks to Prof. Dr. Derek Ford who has provided us useful suggestions to improve the book.

LIST OF ABBREVIATIONS

AF = Alternating field (demagnetization)
BP = Before present
CRM = Chemical remanent magnetism/magnetization
DC = Direct current
DCF = Direct current field
DRM = Detrital (sometimes depositional) remanent magnetism/magnetization
GPTS = Geomagnetic polarity timescales
HFC = High-field component
IRM = Isothermal remanent magnetization
IZRK = Karst Research Institute
JZS = Speleological Association of Slovenia
ka = Thousands of years
LFC = Low-field component
Ma = Millions of years
MAVACS = Magnetic Vacuum Control System
MS = Magnetic susceptibility
N = Normal polarization/polarity
NRM = Natural remanent magnetization
R = Reverse polarization/polarity
RM = Remanent magnetization
SIRM = Saturation isothermal remanent magnetization
TD = Thermal demagnetization
TRM = Thermal remanent magnetism/magnetization
ZRC SAZU = Scientific Research Centre of the Slovenian Academy of Sciences and Arts

INTRODUCTION

The infill of underground caves and surface or near-surface karst forms has been a focus of its students since the development of speleology and karstology as independent scientific disciplines (for review see e.g., Shaw 1992). It was caused by the rich fossil contents of many cave/karst sites, yielding mammal, bird, amphibian, insect, plant and other remains, and archaeological finds. Therefore, karst voids started to be described as conservers of the geological past (*cf.* Bosák et al. 1989).

The stratigraphic analysis of cave/karst fills is based on a number of methods, some yielding numerical output, some other calibrated-age, relative-age, and correlated-age (Colman & Pierce 2000). The proper and exact dating of karst processes, including filling of cave/karst voids, is most often the only means of reconstructing the evolution of individual karst features, extensive karst regions, speleogenetical or fossilization processes. The application of a number of dating methods in past decades enabled also the more exact dating of processes in the karst (Ford & Williams 1989, 2007; Bosák 2002). Nevertheless many of such methods cannot be applied to karst materials, and/or their span is too short to be able to cover long time ranges of karst/cave evolution (e.g., the Th/U method).

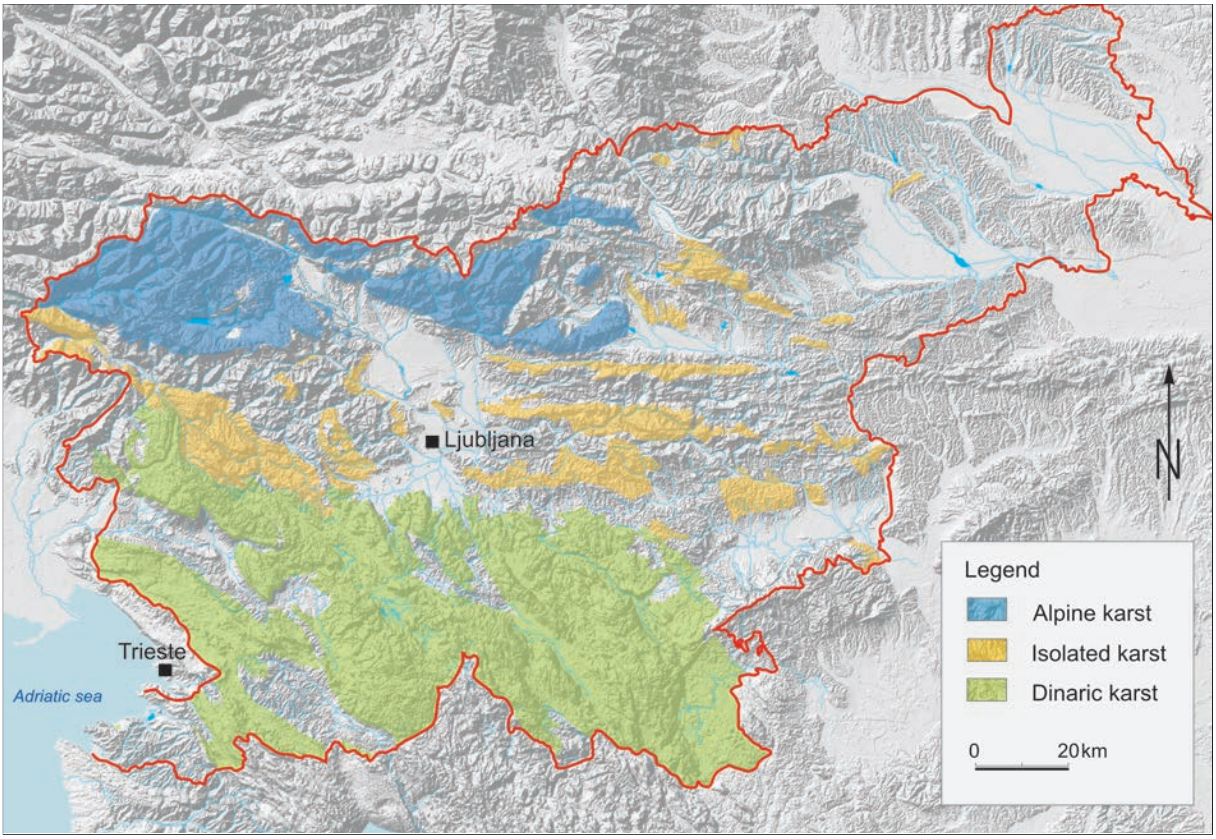


Figure 1 *Distribution of major karst areas in Slovenia.*

The palaeomagnetic method can yield correlated-ages over the entire Phanerozoic time-scale. Nevertheless, if not supported by other dating methods such as detailed palaeontological determinations of fossils, matching with the standard magnetostratigraphic scale (determined by numerical dating of volcanic products) is a truly hard problem. Something easier is the application of palaeomagnetic methods in areas with young block rotations, as in young orogenic belts and their forelands. Some of the palaeomagnetic parameters allow the determination of angles of rotation: knowing such parameters from dated correlated sediments covering karst or in adjacent basins, approximate dating is then possible.

The territory of Slovenia, with its numerous karst regions (Fig.1), long history of karst evolution and relatively good knowledge of the karst sediments represents an ideal testing ground for comprehensive research on individual infilling processes, their stages and periods.

REVIEW OF THE PROBLEM

The question concerning the time span of karst evolution in Slovenia, of the age of karst surfaces and speleogenesis and, consequently, the rates of processes has been an important issue in most of the previous karst studies and syntheses. The majority of dating of karst sediments has been carried out in south-western Slovenia (i.e. in the north-western part of the Dinarski kras (Dinaric Karst)), which is known as the Kras. Eocene flysches are the last marine deposits preserved in the geologic record. The Oligocene to Quaternary period has been a terrestrial phase with surface denudation and erosion processes prevailing. Therefore, only karst sediments preserved on the surface are rare, but caves have functioned as giant traps of clastic, chemical and organic sediments derived from local as well as more distant environments during the life of the cave. Cave sediments represent the most variable deposits that form in continental environments and tend to be preserved for great time spans (Ford & Williams 2007).

The first estimates of the age of the karst in the western Slovenia were made by geologists and karst geomorphologists. They utilized geologic data such as the age of the last marine sedimentation and the tectonic evolution of the Dinaric Mountains and the Alps (Grund 1914), sediments on the karst surface and some distinct forms of the relief. They suspected that the karst started to evolve during Pliocene times. Roglič (1957) defined (1) a pre-karst phase, when rivers were flowing across the karst surface and deposited fluvial sediments, and (2) the karstification phase when rivers began to sink at the edges of the karst.

Some relief forms and sediments were explained in the terms of evolution in different climates under the influence of the climatic geomorphology. Conical hills, levelled surfaces and red soils were explained as product of tropical climates during the Pliocene (Melik 1955; Roglič 1957; Radinja 1972b; Habič 1982). Collapses in caves, fluvial deposits in contact karst areas and some fine-grained varved sediments in caves were interpreted as impacts of the cold Pleistocene climate (Melik 1955; Gospodarič 1985).

The first systematic studies of cave sediments were carried out during the archaeological and palaeontological excavations of sediments in entrance parts of some caves (Brodar 1952, 1958, 1966, 1970; Rakovec 1954, 1975; Šercelj 1966; Osole 1968). More extensive and detailed study of cave sediments was performed by Gospodarič (1972, 1974, 1976a, b, 1977, 1981, 1984, 1985, 1988). He applied a relative method of the comparison of cave sediments from different sites to establish the age of deposits, but also used different numerical and other dating methods (like ^{14}C, Th/U, ESR; Franke & Geyh 1971; Gospodarič 1972; Ikeya, Miki & Gospodarič1983; Ford & Gospodarič 1989). R. Gospodarič, in his geochronologic ranging of cave sediments (1988), based on recognitions and descriptions of several profiles from Postojnska jama, Planinska jama, Križna jama and Škocjanske jame, classified different deposition phases in the subsurface. In the Kras, he linked the karstification of the area with glacio-eustatic oscillations of the Adriatic Sea and the global palaeo-climate evolution during the Pleistocene. He suspected that the cave sediments are not much older than 350 ka (Fig. 2).

A better understanding of cave sediments and their age and the chronological sequence of speleological events was achieved by more concentrated dating by the Th/U method (Zupan 1991; Mihevc 1999a, 2001b, 2002; Mihevc & Lauritzen 1997). Speleothems from several caves of Notranjski and Primorski kras (central and western Slovenia) were dated. Data showed that (1) speleothem growth corresponds to warmer periods during the Pleistocene, and (2) there are large numbers of speleothems older than the limit of the Th/U dating method (i.e. recently 550 ka).

The study of cave deposits in Alpine caves and in unroofed caves of the Kras provided entirely new insights into the age of cave and karst sediments and introduced new ideas concerning the development of karst. Geomorphic comparative method used for dating of processes and landforms showed that many accessible caves in the Kras are of Pliocene age at least or even older (Mihevc 1996, 2000, 2001a). Nevertheless, palaeontological finds indicated only Pleistocene ages for fauna in the cave sediments studied (Brodar 1952, 1958, 1966, 1970; Rakovec 1958; Turk & Verbič 1993; Turk et al. 1993; Aquillar et al. 1998; Turk 2007).

The application and interpretation of palaeomagnetic analysis and magnetostratigraphy of the cave sediments, both clastic and chemogenic, which began on the Kras in 1997, suggested substantial changes in the lower limiting ages of cave fill deposition (Bosák, Pruner & Zupan Hajna 1998; Bosák et al. 1999, 2000a, b, 2003; 2004a, b; Šebela & Sasowsky 1999, 2000; Pruner & Bosák 2001; Mihevc et al. 2002; Sasowsky, Šebela & Harbert 2003; Zupan Hajna et al. 2005, 2007). Magnetostratigraphy data and the arrangement of obtained magnetozones often indicated

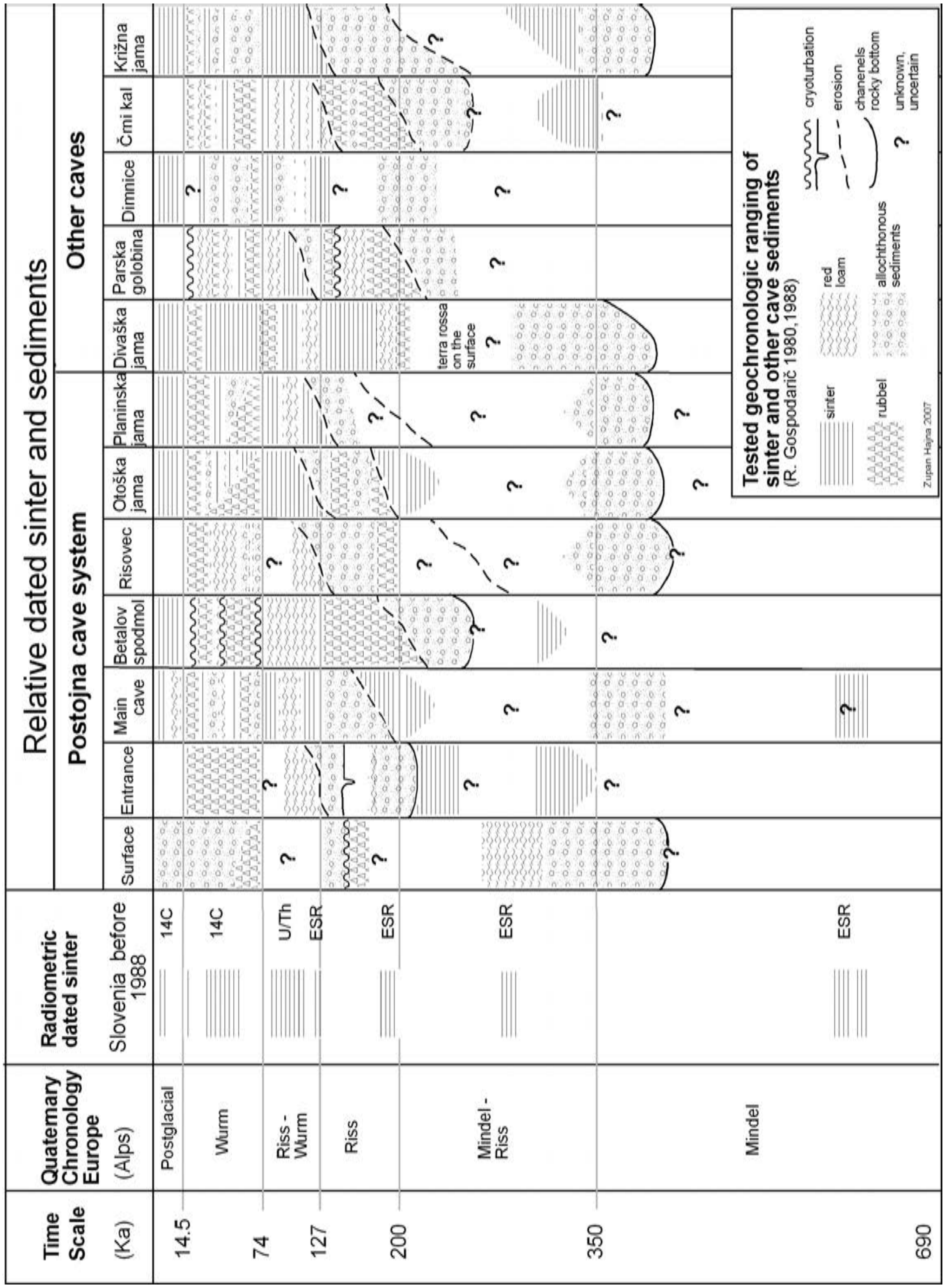


Figure 2 *Stratigraphy and age of cave sediments in some of Slovene caves (modified after Gospodarič 1980 and 1988).*

ages of the fill >1.77 Ma with possibility of some lower limits of deposition even greater than 5 Ma (Bosák, Pruner & Zupan Hajna 1998).

Clastic sediments and speleothems were dated in caves, unroofed caves, quarries and engineering construction sites in different parts of Slovenia. The study of cave sediments from Črnelsko brezno (Kanin plateau, Julian Alps) by Audra (2000a) also indicated age >1 Ma for cave deposits in a deep shaft. Palaeontological finds in the Račiška pečina and Črnotiče Quarry partly proved the age interpreted from magnetostratigraphy (Bosák et al. 2004b; Zupan Hajna et al. 2007; Horáček et al. 2007) – cave fills are often Pliocene in age and even older.

TERMINOLOGY

Karst is a type of landscape with special surface, underground and hydrologic features and phenomena. Its main characteristic is dissolution of the rock as the dominant morphological process, removing it in the form of solution and prevailing underground drainage that forms caves (*cf.* Ford & Williams 2007).

There has been long-lasting discussion concerning the understanding and use of the term *palaeokarst* (also *fossil karst*; for discussion see Bosák, Ford & Głazek 1989). There have been deep differences in the understanding of this term among geologists, karstologists, geographers, and other students of karst resulting both of different schools and, mostly, differing field experiences as reflections of the geologic/geomorphic evolution of different areas under study. Therefore, here we try to explain used terms in more detail, even if it seems, that the application of the term of palaeokarst *s.s.* is not necessary in most of regions studied by us in Slovenia.

Palaeokarst is generally referred to inert karst forms decoupled from the contemporary hydrological system (Bosák, Ford & Głazek 1989), independent of whether the karstification is halted definitely or only temporarily (Klimchouk & Ford 2000b; Bosák 2007). The most common reasons for such interruptions or cessations are metamorphism, mineralization, marine transgressions/ingressions, burial by continental deposits or volcanic products, tectonic movements (uplift, subsidence), climatic change (desertification, glaciation), fill by karst sediments etc. (for review see Bosák 1989b).

Temporary and/or final interruption of karstification represents the conservation – fossilization – of the achieved state (*sensu* Bosák 1989b). The term *fossilization* will be used here in this sense.

The introduction of new energy (hydraulic head) to a system may cause the *reactivation* of the karstification. The most common reasons for reactivation are regression, deglaciation and uplift (for review see Osborne 2002). Multiple reactivations result in polycyclic nature of karst formation, which is its characteristic feature (e.g., Panoš 1964, 1965; Ford & Williams 1989, 2007; Wright 1991; Osborne 2002). The term *polycyclicity* used here is not related to the so-called karst cycle of Grund (1914; also Cvijić 1918) or cycle of erosion of Davis (1899; also Sawicki 1908, 1909). The *polygenetic nature* of many karst features that evolved during several different steps should be stressed instead (Ford & Williams 1989, 2007); these may take the form of, for instance, an overprint of cold karst processes on earlier deep-seated/hydrothermal products, which themselves followed meteoric early diagenesis (e.g., Bosák 1997) or the succession of other processes (a.o. Osborne 2000, 2002; Osborne et al. 2006).

However, the understanding of above-mentioned meaning of palaeokarst is not uniform and depends substantially on the systems of karst stratigraphy that are applied. The karst stratigraphic approach is principally based on (see Bosák 2002): (1) the carbonate sedimentological/sequence stratigraphy model (Choquette & James 1988), and (2) the general karst model (Bosák, Ford & Głazek 1989). The first one is generally based on the *Caribbean model* of karst (Esteban 1991, p. 93; brief exposure times, unstable carbonate mineralogy, shallow burial, minor tectonics, minor deep – freshwater – phreatic zone, with primary and fabric-selective porosities predominant, restriction to tropical to semi-arid environments, diffuse recharge-diffuse flow only, affected by mixing marine zone processes but not by hydrothermal mixing), the latter one on the *general model* of karst (Esteban 1991, p. 93; longer exposure time, stable mineralogy, deep burial, one or several tectonic events, an important deep phreatic zone, secondary and fracture porosities predominant, a wider range of climatic environments, confluent recharge, pipe and confined flow, absence of mixing marine zone effects and presence of hydrothermal mixing; see also Klimchouk & Ford 2000a).

In the first model the palaeokarst is buried and lithified; human beings cannot enter such forms (palaeokarst *s.s.*); this type represents palaeokarst in the sense of most Slovene specialists (*cf.* Otoničar 2007). The second one explains that palaeokarst "developed largely or entirely during past geological periods" (Bosák, Ford & Głazek 1989, p. 31; Panoš 2001, p. 140-141) "under morphogenetic conditions differing from the present" (Gams 1973; Panoš 1978); human beings may be able to enter such form (palaeokarst *s.l.* or modern karst for some students).

Palaeokarst can be classified in number of categories: *buried karst* (covered by later consolidated sediments and other rocks; *covered karst* (covered by unconsolidated sediments); *relict karst* (never buried), *exhumed karst* (also reactivated or rejuvenated karst; exposed by the erosion of former covering strata, which fossilized the karst for some time; Bosák, Ford & Głazek 1989; Ford & Williams 1989, 2007).

The terms of karst period and karst phase will be used here in accordance to definitions given by Bosák, Ford & Głazek (1989). *Karst period* defines long-lasting times of groundwater circulation and continental weathering, which were terminated by an ensuing marine transgression. They are recognized by higher order unconformities or disconformities (= *interregional karst* of Choquette & James 1988). Their karst features can usually be divided into several generations (karst phases). Głazek (1989) defined the tectonic conditions for karst periods as being induced by orogenesis. Those lengthy periods are caused by the post-collisional uplift of orogens and their fringes. The periods are marked by unconformities and disconformities over broad areas and need not to be confined to individual modern continents. These long periods may display diachronicity and contain many lesser phases. They are longest in duration and most complex at former mountain crests and become gradually shorter on the former mountain slopes and their broad fringes along adjacent continents. These periods result from major changes of plate motion patterns and they divided structural complexes corresponding to orogenic cycles (Głazek 1973).

A *karst phase* is caused by a geodynamic or major climatic change, e.g., uplift or down-warping, sea-level change, a phase of permafreezing, etc. (Bosák, Ford & Głazek 1989). From the tectonic point of view, Głazek (1989) distinguished two kinds of karst phases: (1) represented as unconformities within the limited areas of one past shallow marine platform and its continental fringes, or of one continent created by the collision of two plates (= *local karst* of Choquette & James 1988); and (2) disconformable or paraconformable surfaces resulting from glacial-eustatic fluctuations of sea level or from local tectonic events (= *depositional karst* of Choquette & James 1988).

The general term *karst sediments* is used here for all kinds of sedimentary fill occurring in karst, i.e. surface and near-surface fills and cover, including soils, residual deposits, weathering products, and cave sediments, both clastic and chemogenic in origin.

The names of caves and shafts in the text will be given in Slovene original. Terms of *jama* and *pečina* mean *cave*, *spodmol* is *abbri*, *brezno* is *shaft*, *jezero* is *lake, potok* is *brook*, *and gora* is *mount* or *hill* and *kras* is *karst*.

GENERAL CHARACTERISTICS OF CAVE/KARST FILL

Karst sediments are a special kind of geologic materials. The development of karst and/or part of the karst system can be "frozen" and rejuvenated for a multiplicity of times (Bosák 1989b, 2002, 2003), and the dynamic nature of karst can lead to re-deposition and reworking of classical stratigraphic order. Those processes can make the karst record unreadable and problematic for interpretation (see Osborne 1984). Temporary (e.g., filling by cave sediments) and/or final interruption of karstification (fossilization *s.s.*) is due to the loss of the hydrological function of the karst (Bosák 1989b, p. 583). The introduction of new energy (hydraulic head) to the system may cause reactivation of karstification reflected in the polycyclic and polygenetic nature of karst formation.

The karst environment favours both the preservation of palaeontological remains and their destruction. On one hand, karst is well known for its wealth of palaeontological sites (e.g., Horáček & Kordos 1989), but most cave fills are completely sterile on the other hand. The role of preservation is very important because karstlands function as traps or preservers of the geologic and environmental past, especially of terrestrial (continental) history where correlative sediments are mostly missing, but they carry also marine records (Horáček & Bosák 1989).

The methodology applied to obtain correlated-age (magnetostratigraphic) results depends on the nature of the geologic material filling the karst. The fills of exokarst landforms (especially some epikarst forms) offer more possibilities for the preservation of fossil fauna and flora than do cave interiors. Troglobitic fauna and flora are usually much too small in number and volume to be significant (Ford & Williams 1989, 2007). Therefore, fossil remains within a cave, that come from the surface (carried in by sinking rivers) or from trogloxenes (e.g., cave-using bats, some birds and mammals), are more important. Airborne grains (pollen, volcanic ash) can only be important when favourable air-circulation patterns are developed within a cave. Nevertheless, cave sediments, especially far from the ponor or other entrance, tend to be highly depleted in fossil fauna (Bosák, Pruner & Zupan Hajna 1998) and/or the preservation of the fossils is too poor for precise determinations (Bosák et al. 2000a).

The cave environment can be divided from the sedimentological point of view into an entrance facies and an interior facies. The *entrance facies* includes fine-grained sediments transported from the vicinity of the cave by wind and water and coarser clasts transported into the cave by slope processes. The entrance facies represents the most valuable section of the cave from a stratigraphic point of view. The cave entrance contains pollen as well as datable archaeological and palaeontological remains that are protected from surface erosion, weathering and biochemical alteration (Ford & Williams 1989, 2007). The *interior facies* develops in those parts of the cave that are more remote from the surface. Sedimentary sequences here can be extensive, consisting of fluvial gravels and sands overlain by flood or injecta deposits of laminar silts and clays often intercalated by speleothems. They can also contain dejecta, colluvial material and outer clastic sediments (including marine ones) often redeposited and/or injected for longer distances within the cave (*cf.* Ford & Williams 1989, 2007). They form in vadose conditions. Due to the dynamic environment of cave interiors and periodicity of events, sedimentary sequences often represent a series of depositional and erosional events (sedimentary cycles). They are separated by unconformities (breaks in deposition), in which substantial time-spans can be hidden (Bosák et al. 2000b; Pruner & Bosák 2001; Bosák 2002, 2003; Bosák, Pruner & Kadlec 2003). The erosional phases can be much longer that depositional events. Relics of phreatic silts and clays are relatively rare and they typically contain no fossils.

The stratigraphic order in sedimentary sequences is usually governed by the law of superposition, according to which the overlying bed is younger than the underlying one under normal tectonic settings. The law is valid for the majority of sedimentary sequences. However, river terraces and karst environment may present exceptions. The succession of processes connected with entrenchment of river systems cause higher levels of sediments to be older than lower ones. Karst, owing to its dynamic nature, polycyclic and polygenetic character carries some other thresholds – the karst records can be damaged by the simple process of erosion and re-deposition. The reactivation of karst processes often mixes karst fill of different ages (collapses, vertical re-depositions in both directions, etc., e.g., Horáček & Bosák 1989). Contamination of younger deposits by re-deposited fossil-bearing sediments has been known elsewhere in caves (Bosák, Pruner & Kadlec 2003). Well-known are also sandwich structures, described by Osborne (1984): younger beds are inserted into voids in older ones. Those processes degrade the record in karst archives (Horáček & Bosák 1989).

The final accumulation phase has been dated in caves in most cases, i.e. when the cave is in a quasi-stationary state because the input of energy (water) has been interrupted, detaching the cave from the local hydrological regime for different reasons and for highly differing time-spans; the cave becomes fossilised, at least temporarily. The temporary fossilisation of the cave (i.e. fill by cave sediments) and rejuvenation (excavation of sediments) mostly reflect changes in the resurgence area, especially vertical change (in both directions) of base level at the karst springs. The rejuvenation of the karst process can excavate the previous cave fill/fills completely, which is the most common case resulting from the polycyclic nature and dynamics of cave environments (e.g., Panoš 1963, 1964; Kadlec et al. 2001). Under favourable settings, fills belonging to more infill phases (cycles) separated by distinct hiatuses (unconformities) can occur in one sedimentary profile. Such amalgamation is typical especially in ponor (sinkhole) parts of the cave (e.g., Kadlec et al. 2001).

GEOGRAPHY, GEOLOGY AND KARST IN SLOVENIA

A brief review of the general characteristics of the Slovenian territory is given here to specify the frame of our studies (Figs. 3 and 4). Detailed descriptions are given in the chapters dealing with specific regions and sites.

GEOGRAPHY

Slovenia is situated in central Europe (46° N and 14° E) on the junction of four geographical regions, i.e. two distinct orographic systems (the Alps and the Dinaric Mountains), and two basins (the Pannonian and Mediterranean basins) which also belong to different tectonic units (Fig. 3).

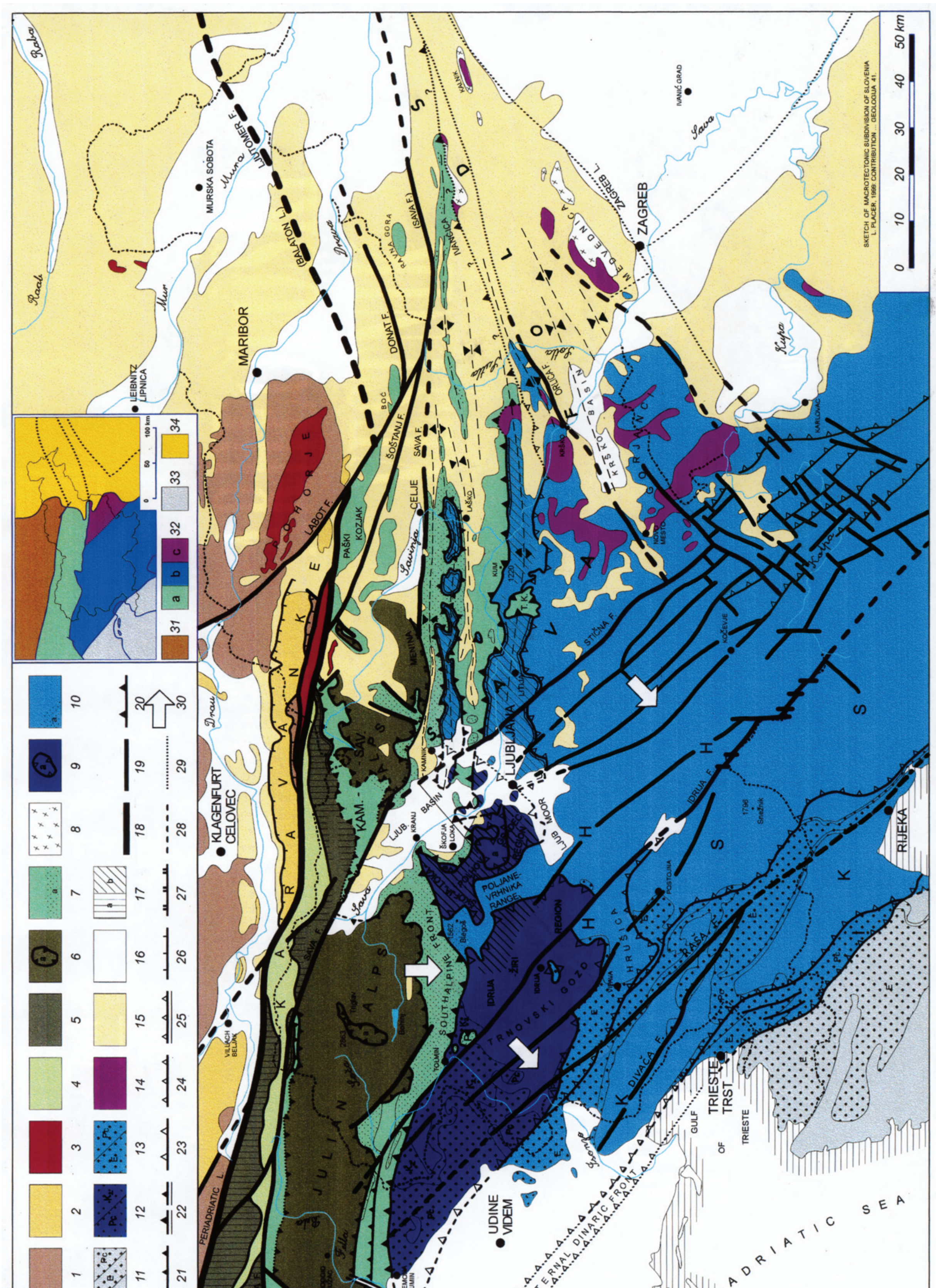
The Alps in the northern part of the state form two large mountain groups: the Julian and Kamnik–Savinja Alps, with dominant W–E trend. The central part of the Alps consists of limestone and dolomite. The highest peaks (Triglav, 2864 m a.s.l.) and sharp ridges with deeply entrenched rivers occur in the north. Southwards, the Alps descend in steps into a succession of karst plateaus from elevations of 2500 m a.s.l. down to 1100 m a.s.l. Farther to the south, steep fluvial relief prevails on non-carbonate lithologies. The southern edge of the Alps is rimmed by several tectonic basins filled by extensive alluvial fans derived from mountain erosion.

The Dinaric Mountains occupy the central and southern parts of Slovenia; NW–SE trends are typical for them. They are built dominantly of carbonate rocks with high degrees of karstification. The central part of the mountains consists of high karst plateaus at 700 and 1400 m a.s.l. with the highest summit in the Snežnik mountain (1790 m a.s.l.). The mountainous relief descends in a succession of plateaus and extensive levelled surfaces to lower elevations. The low plateaus of the Dinaric Mountains reach the coast on the west with the littoral zone only few km wide.

The mountains above 1100 m a.s.l. were glaciated during the Pleistocene and valley glaciers reshaped originally fluvial valleys. Some small remnants of glaciers are still present at about 2500 m a.s.l.

The Alps and Dinaric Mountains transform towards the southeast into substantially lover relief characterized by hills with soft morphologies and large plains belonging to the eastern promontory of the Pannonian Basin.

The climate varies from alpine to temperate continental and Mediterranean, depending on the elevation. Precipitation is about 1,300 mm at the coast, increasing from 1,800 to 3,000 mm in the mountains, and only 700 mm in the Pannonian Basin.


SKETCH OF MACROTECTONIC SUBDIVISION OF SLOVENIA
L. PLACER, 1999: CONTRIBUTION ... GEOLOGIJA 41.
50 km
MARIBOR
MURSKA SOBOTA
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CELJE
KLAGENFURT
CELOVEC
UDINE
VIDEM
TRIESTE
TRST
RIJEKA
KARLOVAC
PERIADRIATIC L.
SOUTHALPINE FRONT
EXTERNAL DINARIC FRONT
GULF OF TRIESTE
ADRIATIC SEA

GEOLOGY

The evolution of the structure of Slovenia is associated with the history of the Tethys Ocean, which closed during the Mesozoic and Cenozoic as a result of the convergence of the Africa and Eurasian Plates. Intermediate microplates played an important role in ocean shortening. The present geological structures resulted from post-collision processes in the Alpine orogenic system, which started before about 35 Ma.

From the tectonic perspective, Slovenia is situated in a complicated area at the contact of different tectonic units: Dinarides, Eastern Alps, Adriatic Foreland, and Pannonian Basin (Fig. 3). The Dinarides and Eastern Alps are separated by Periadriatic fault, which now function as dextral fault (Vrabec & Fodor 2006).

The simplified geological map of Slovenia (Fig. 4) represents the major stratigraphic units; map was done by M. Pleničar for Slovenian Geological Society. This review of regional geology and geologic evolution is summarized mainly from Buser (1989) and Pirc (2007).

Eastern Alps consist of metamorphic Palaeozoic rocks overlain by Mesozoic strata in two belts. The northern one belongs to the Northern Limestone Alps, and the southern, so-called Drava belt, comprises the North Karavanke mountains. Tertiary rocks are deposited in Mežica and Mislinja valleys and on the northern side of mountain Pohorje. The metamorphic basement was overthrust northwards during Early Palaeozoic and Late Tertiary. The Periadriatic fault was formed approximately 35 Ma ago and is aligned with intrusions of tonalite and granodiorite in places (Pohorje about 17 Ma). Rapid extensional exhumation of the Eastern Alps, during the opening of the Pannonian Basin, happened in the Miocene. All kinds of metamorphism and low-temperature rock alteration processes affected the region. The North Karavanke was thrust northward over Palaeozoic and Tertiary basement rocks after the Miocene.

The *Dinarides* consist of the Southern Limestone Alps, Internal and External Dinarides. They are characterized by large thrust sheets of Mesozoic carbonates in complicated mutual juxtaposition. The *Southern Limestone Alps* include: Julian Alps, South Karavanke, Kamnik–Savinja Alps, and their eastward extensions into the Pannonian Basin. Mesozoic rocks were deposited on the shallow marine Julian Carbonate Platform (JCP) and in the deeper waters of the Slovenian Basin. The thrust sheets formed mostly during the Eocene and Middle Oligocene with W–E trending structural elements resulting from N–S stress. In the Slovenian Basin, Palaeozoic rocks represent the basement of Mesozoic deposits in larger thrust sheet structures. The Julian thrust sheet consisting dominantly of rocks belonging to the JCP represents the higher tectonic unit. The Southern Alps are separated from the External and Internal Dinarides on the south by Southern-Alpine Overthrust Front. The

← **Figure 3** *Simplified tectonic map of Slovenian territory. Legend: 1 Region of the metamorphic rocks; 2 Northern Karavanke Mountains (Drava range); 3 Regions of the periadriatic igneous rocks; 4 Košuta unit; 5 Javornik unit; 6 Julian nappe, a – Zlatna structure; 7 „Tolmin nappe", a – Supposed Slovenian basin, P – Ponikve tectonic klippe, T.K. – Preveški hrib tectonic klippe; 8 In tectonical sense undefined region; 9 Trnovo nappe, a – Škofja Loka-Polhov Gradec horsts; 10 H – Hrušica nappe, S – Snežnik thrust sheet, K – Komen thrust sheet, I – Kras imbricate structure, a – Pseudozilja beds in the Blegoš region; 11 Autochthon-Istria (Adriatic or Apulian foreland), Pc – Paleocene, E – Eocene; 12 Deeper water sedimentary rocks of Dinaric platform in the Trnovo nappe, K_2 – Upper Cretaceous, Pc – Paleocene; 13 Paleogene of External Dinarides, Pc – Paleocene, E – Eocene; 14 Upper Triassic, Jurassic and Cretaceous pelagic sediments of the transitional region between External and Internal Dinarides; 15 Tertiary and Plioquaternary of the Pannonian basin and marginal depressions; 16 Quaternary; 17 Paleozoic, soft bed of the nappe structure of the Dinarides, isostatic and supplantic uplifted region, a – In Southern Alps, b – In External Dinarides; 18 Periadriatic and Balaton lineaments; 19 Important fault; 20 Southalpine front; 21 Overthrust boundary in the Southern Alps region; 22 Detachment plane of the Southalpine overthrust structure; 23 Trnovo nappe boundary; 24 Nappe and overthrust boundary in the External Dinarides region; 25 Detachment plane of the External Dinarides overthrust and nappe structure; 26 Overthrust boundary in the North Karavanke Mountains unit; 27 Thrust boundary of local importance in the Sava compressive wedge; 28 Inaccurately defined or covered fault and thrust line; 29 Hypothetic fault and thrust line or fault and thrust zone; 30 Direction of overthrusting; 31 Eastern Alps; 32 Dinarides, a – Southern Alps, b – External Dinarides, c – Transitional region between External and Internal Dinarides; 33 Adriatic or Apulian foreland; 34 Pannonian basin (after Placer 1999, with permission).*

Ljubljana, Celje and Velenje basins, as well as smaller tectonic depressions in front of Alps filled by Tertiary formations belong to Southern Limestone Alps.

The *External Dinarides* are formed by Mesozoic shallow marine Dinaric Carbonate Platform deposits, which vary in extent. The *Internal Dinarides* consist of deeper-sea sediments. The width of the transitional zone between the External and Internal Dinarides is marked by variable extents of shallow-marine platform carbonates. Extensive Upper Cretaceous to Eocene flysch deposition continued in the External Dinarides. The structure of Dinarides is characterized by thrust sheets with south-western convergence, which started to form during the Upper Eocene and at Eocene/Oligocene boundary. The External Dinarides themselves are thrust over the Adriatic Foreland (Istria, according to Placer 1999) which represents a weakly deformed zone in the front of the Dinaric thrust. The sub-thrusting belt strikes generally NW-SE, dipping NE (Placer 2007).

The north-eastern and eastern parts of Slovenia belong to the Pannonian Basin filled by Tertiary marine (Miocene) and freshwater (Pliocene) sediments. Its basement consists of units which were formed from parts of the mega-structural units of the Alps and Dinarides (Placer 1999)

The territory of Slovenia is dissected by many faults due to movement of the lithospheric plates. There are four principal directions: E-W (Alpine), N-S (transverse Alpine), NW-SE (Dinaric) and NE-SW (transverse Dinaric). At the present, the most important movement is represented by the rotation of the Adria Microplate since 6 Ma (Vrabec & Fodor 2006), which has caused the dextral movement of most of the Dinaric faults (Sava, Idrija, Raša faults, etc.), and sub-thrusting of Adriatic–Apulian foreland under the External Dinarides (Placer 2007) which started from Middle Miocene.

The Southern Alps (Julian Alps, etc.) and External Dinarides (part of Dinaric Mountain) function as two totally different morphological units, both with different geology and relief evolution.

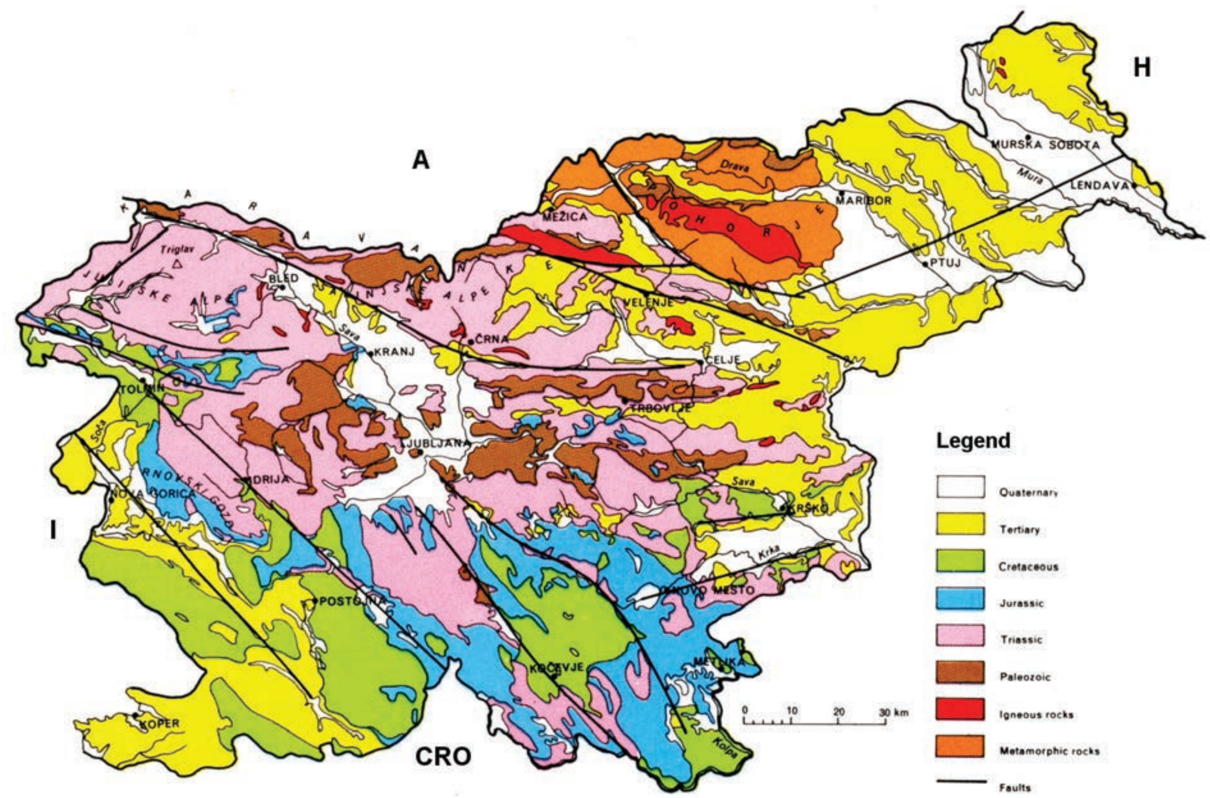

Figure 4 *Simplified geological map of Slovenia (after M. Pleničar, Slovenian Geological Society).*

KARST

The distribution of karst is determined by the distribution of the soluble rocks, both on the surface and in the subsurface. The karst relief, caves and karst sediments depend on lithology and structure of the host rocks, topographic position, position within the hydrological system, evolution, amount of precipitation and other factors. The karst has formed over long geologic periods in which other geomorphic processes were also active and influenced the origin of surface morphology. Some of them, a.o. orographic and small scale tectonic movements, oscillations of the climate, fluvial activity, also left traces on the surface and can be readily traced within the karst landscape.

Karst in Slovenia has developed on carbonate rocks, limestone and dolomite, which cover about 8,800 km^2 (43 % of the total surface of the nation). It has been traditionally divided according to the general morphological and hydrological conditions, and the evolution history, into three principal karst areas: Alpine Karst, Dinaric Karst, and Isolated Karst (Fig. 1). Today we know that there are more than 9,000 karst caves, which we have registered in the Cave Register of the Speleological Association of Slovenia (JZS) and IZRK ZRC SAZU.

Alpine Karst or karst of the high mountains is characterized by extensive vertical gradients, and a mix of fluvial, glacial and karst elements in the landscape resulting in deeply entrenched fluvial valleys in mountains and plateaus. Deep shafts and vertical cave systems are typical there. Alpine karst covers large parts of northern Slovenia continuously.

Isolated Karst occurs as small patches of karst surrounded by and developed under the impact of allogenic inflow from non-carbonate rocks, in the contrast to the large karstified areas in the Alps or Dinarides. Horizontal caves have been formed by sinking rivers, generally with high clastic sediment loads. Ponors and springs are common. The karst hydrology and features are principally defined by the position of each karst area, while the general evolution of the large-scale relief has been less important.

Dinaric Karst (Dinarski kras) is the major karst area of Slovenia. The dominant relief features are rather extensive levelled surfaces at different elevations, large closed depressions (e.g., poljes), and conical hills. Fluviokarst features like dells are common on dolomites. Karst rivers appear only in the bottoms of poljes, where they result from high level of karst water. Allogenic rivers flowing from non-carbonate regions either sink at the karst boundary forming blind valleys, or cross the karst through deep karst valleys and canyons. There are numerous extensive and complicated cave systems formed by sinking rivers and connected with the surface also by numerous vadose shafts. The surface karst morphology is typified by the abundance of karren, dolines of various diameters and depths, sometimes extensive collapse dolines, cave entrances, unroofed caves, etc.

In past centuries, the Dinarski kras of Slovenia represented one of the world‘s prime sites of early scientific exploration of karst phenomena (Kranjc 1997; Shaw 1992) due to the large number of outstanding karst features such as caves, large sinking rivers and flooded poljes. Speleology, karst hydrology and biospeleology were born here. The most prominent phenomena are situated in the north-western part on the plateau named Kras.

In Slovene language, *kras* means a rocky, barren surface. The name is often used as toponym (Kranjc 1994, 1997). *Kras* plateau (Fig. 5) became a textbook example for such kind of landscape because of the extraordinary karst phenomena, and explorations done in the 19th Century. The name Kras in the German form of the word (der Karst) became an international scientific term. The area where these early explorations took place is called the *Classical Karst* (term introduced by Radinja 1966, also 1972a as Matični Kras; which should not be confused with the misinterpretation by Šušteršič 2000).

The Kras is a distinct plateau, especially when viewed from the seaward side. There are steep limestone slopes few hundreds meters high rising directly from the sea or from the neighbouring lowlands on the north-west. On the north-east, the plateau ends above the broad and low lying Vipava valley. Higher relief on flysch on the east separates the Kras from the Pivka region. On the south-east, the border of Kras is again well defined by contact with the non-carbonate flysch of the Brkini hills and the valley of the Reka river. Toward the south, the transition to karst ridges and Matarsko podolje karst plateau is less obvious.

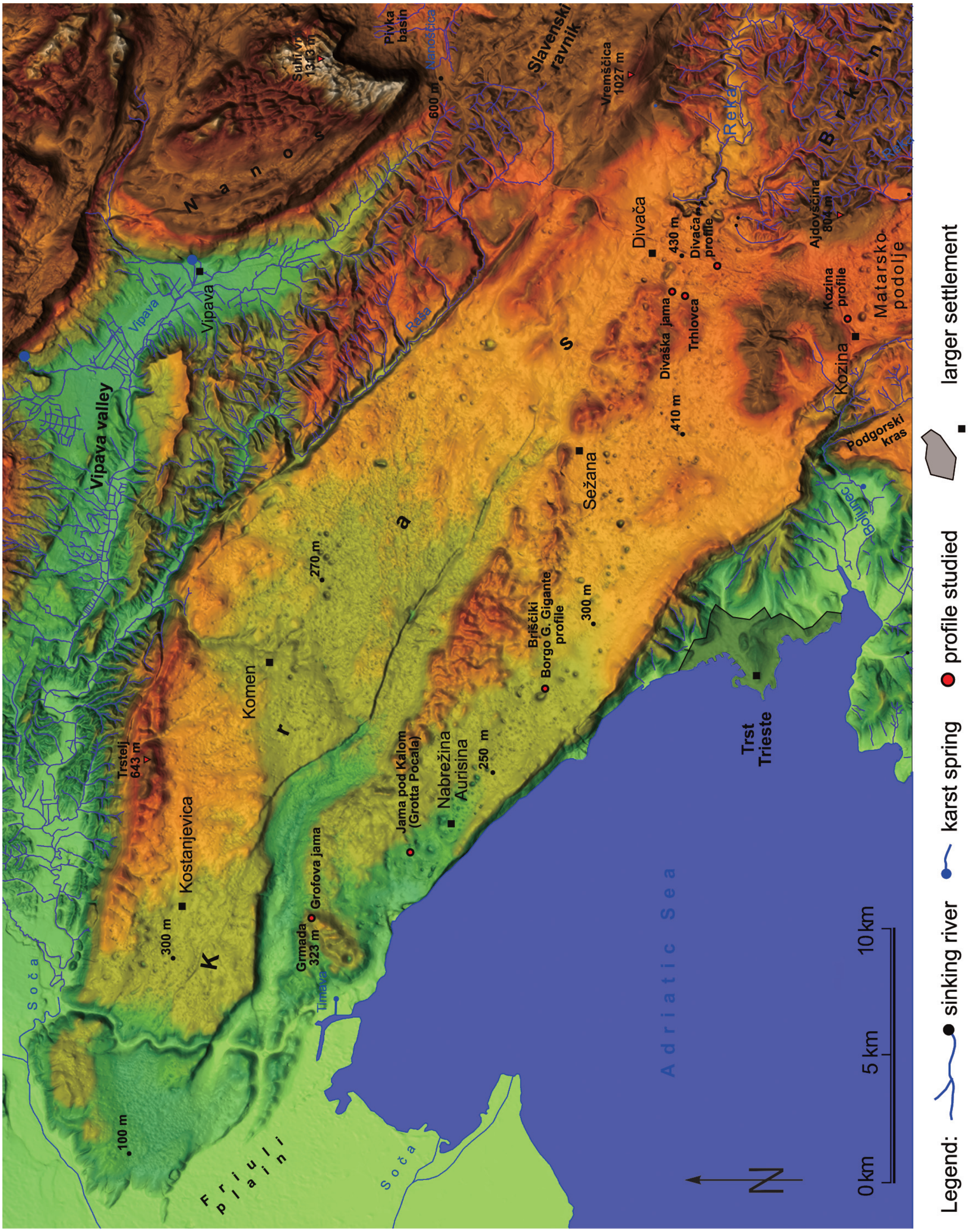

Figure 5 *Kras is karst plateau between Adriatic Sea and Vipava valley (SW Slovenia); form where the Slovene word (Kras) in German version (Karst) was entered into international terminology.*

PALAEOMAGNETIC METHODS AND MAGNETOSTRATIGRAPHY

Palaeomagnetism is study of the intensity and orientation of the magnetic field of the Earth as it preserved in the magnetic orientation of certain minerals found in rocks formed throughout geologic time. It is one of the disciplines in geophysics, having uses in diverse fields such as geomagnetism, tectonics, sedimentology, volcanology, palaeontology and palaeogeography. British physicists K.M. Creer, E. Irving & S.K. Runcorn (1954) were pioneering scientists who studied palaeomagnetism.

Palaeomagnetic method studies the ancient magnetic field by measuring the orientation of magnetic minerals in rocks and sediments, then use geomagnetic theory to determine what configuration of the Earth's magnetic field may have resulted in the observed orientation. The goals of palaeomagnetism can be divided into two fields: (1) study of polar wandering – the magnetic north pole is constantly shifting relative to the axis of rotation. This is responsible for the shifting magnetic declination required for compass work and orienteering, and (2) periodically, the magnetic field reverses polarity. The reversals have occurred at irregular intervals throughout the Earth's history.

The study of palaeomagnetism is possible because iron-bearing minerals such as magnetite may record past directions of magnetic field of the Earth. Palaeomagnetic signatures in rocks can be recorded by different mechanisms:

(a) Iron-titanium oxide minerals in basalt and other igneous rocks may preserve the direction of the Earth's magnetic field when the rocks cool through the Curie temperatures of those minerals. The Curie temperature of magnetite, a spinel-group iron oxide, is about 580 °C, whereas most basalt and gabbro are completely crystallized at temperatures above 900 °C. Hence, the mineral grains are not rotated physically to align with the Earth field, but rather they may record the orientation of that field. The record so preserved is called the TRM. Because complex oxidation reactions may occur as igneous rocks cool after crystallization, the orientation of the Earth's magnetic field is not always accurately recorded, nor is the record necessarily maintained. Nonetheless, the record has been preserved well enough in basalts of the ocean crust to have been critical in the development of theories of sea-floor spreading related to plate tectonics (Vine & Matthews 1963).

(b) In a completely different process, magnetic grains in clastic detrital sediments may align with the magnetic field during deposition; the field is then said to be recorded by the DRM.

(c) In a similar process, magnetic grains may be deposited from a circulating solution, or be formed during chemical reactions, and may record the direction of the magnetic field at the time of mineral formation. The field is said to be recorded by the CRM. The mineral recording the field here is commonly hematite, another iron oxide. Red beds, clastic sedimentary rocks (such as sandstones) and speleothems that are red primarily because of hematite formation during or after sedimentary diagenesis, may have useful CRM signatures, and magnetostratigraphy can be based on such signatures.

Palaeomagnetic evidence, both reversals and polar wandering data, was instrumental in verifying the theories of continental drift and plate tectonics in the 1960s and 70s. Continental drift is the geological theory that the relative positions of the continents on the Earth surface have changed considerably through geologic time. The first detailed theory of continental drift was put forth by German meteorologist and geophysicist Alfred Wegener in 1912. On the basis of geology, biology, climatology, and the alignment of the continental shelf rather than the coastline, he believed that during the late Palaeozoic and early Mesozoic eras, about 275 to 175 Ma ago, all the continents were united into a vast super-continent, which he called Pangaea. Later, Pangaea broke into two super-continental masses – Laurasia to the north, and Gondwanaland to the south. The present continents began to split apart in the latter Mesozoic era about 100 Ma ago, drifting to their present positions.

The magnetic field of the Earth is approximately a magnetic dipole, with one pole near the North Pole and the other near the geographic South Pole. An imaginary line joining the magnetic poles would be inclined by approximately 11.3° from the planetary axis of rotation. The cause of the field is probably explained by dynamo theory. Two different types of magnetic poles must be distinguished. There are the "magnetic poles" and the "geomagnetic poles". The magnetic poles are the two positions on the Earth surface where the magnetic field is entirely vertical. Another way of saying this is that the inclination of the Earth field is 90° at the North Magnetic Pole and -90° at the South Magnetic Pole. The Earth field is closely approximated by the field of a dipole positioned at the centre of the Earth. A dipole defines an axis. The two positions where the axis of the dipole that best fits the Earth field intersects the Earth surface are called the North and South geomagnetic poles.

Periodically, the geomagnetic field shifts its "polarity", that is, there have been times in the past where magnetic north on a compass would point in the direction of the current position of the South pole in Antarctica. The exact causes of geomagnetic polarity "reversals" are not well understood, however their presence has aided greatly in constructing the GPTS.

When a rock forms it usually acquires the magnetization parallel to the ambient magnetic field referred to as "primary magnetization". This can give information about the direction and intensity of the magnetic field in which the rock was formed. The magnetization first measured in the laboratory is called the NRM. The mechanism by which the NRM is required depends upon the mode of formation and subsequent history of the rocks as well as the characteristics of the magnetic minerals they contain. To distinguish the primary and secondary magnetization, palaeomagnetists apply various demagnetization procedures to the NRM. The two most commonly used techniques are the AF demagnetization and TD. In palaeomagnetic studies, the direction of magnetization of a rock sample is specified by declination and inclination. Therefore, the palaeomagnetic directions may record of tectonic rotation for the region, as well as palaeo-secular variation. Rocks which magnetizations are in the same sense as the present field are termed N, whilst in the opposite sense are R.

Magnetic inclination also changes with latitude and the thus the palaeo-latitude of the rock at the time it formed can also be reconstructed by measuring the NRM. This can aid greatly in reconstructing plate tectonic history. On the other hand, if the position of the rock at the time it formed is already known, palaeomagnetic studies can aid in constructing a "palaeopole", or the position of magnetic north at the time the rock cooled. Such studies can help elucidate the shape and orientation of the geomagnetic field throughout the time.

PALAEOMAGNETISM OF KARST SEDIMENTS

Palaeomagnetic studies of cave deposits can serve as helpful tool to interpret the age of karst sediments as well as to understand the evolution of karst. Cave deposits are generally a significant source of information on palaeomagnetic polarities and on rock-magnetic data as well (*cf*. White 1988; Ford & Williams 1989, 2007). The aim of such studies was to determine the principal magnetic polarity directions both in clastic and chemogenic deposits, to compare them with the GPTS (Cande & Kent 1995), and to prepare data for the stratigraphic correlation of studied sections.

The geomagnetic field has reversed many times in the past as evidenced from independent sources. One problem that may appear is that over long time spans observed reversals of rock magnetization can result from both self-reversal and/or geomagnetic field reversals. Self-reversal requires the coexistence and interaction of two ferromagnetic constituents; it can be a complicating factor in some studies. However, numerous lines of evidence indicate that most reversals of magnetization in rocks are due to reversals of the geomagnetic field. If the field-reversal theory is correct, there must be a precise stratigraphic correlation of normal and reverse magnetized strata throughout the world. The GPTS covering the Cenozoic has been built up from a number of independent numerical dating studies and is consistent with astro-chronology (Cande & Kent 1995). Use of records of ancient variations or reversals as a dating tool, not only in cave sediments, relies on matching the curves of declination, inclination and intensity in a given deposits with established GPTS.

HISTORICAL REVIEW

Palaeomagnetic studies conducted in caves have been aimed at determining the age of sediments based on magnetic polarity (magnetostratigraphy) and/or palaeo-secular variations, and on palaeoenvironmental applications of mass-specific MS. In caves, palaeomagnetic studies have been applied principally to fine-grained deposits (fine-grained sands, silts, clays) and some calcite and aragonite speleothems.

The results of palaeomagnetic analyses are usually not applied only to the dating of infilling processes themselves, but are also means of reconstructing landscape evolution and climate changes, especially when combined with other dating methods (*cf*. Bosák 2002). Some parameters allow the determination of flow direction of underground streams.

The first attempts to apply palaeomagnetic analysis and magnetostratigraphy to cave deposits were carried out by J.S. Kopper and K.M. Creer. Kopper (1975) noted R chrons in two Majorcan caves (Spain). Pons, Moyá & Kopper (1979) dated fossil-bearing deposits in Cova de Canet (Esporles, Spain).

Victor A. Schmidt (1982) conducted the pioneering successful large-scale magnetostratigraphic dating in relic and active passages of the Mammoth Cave – Flint Ridge system (Kentucky, USA). He dated the oldest fine-grained sediments back to about 2.1 Ma. This first large-scale attempt to use palaeomagnetism and magnetostratigraphy for dating of cave fill resulted in the spread of the method over the world. Noel and Bull (1982) studied sediments from Clearwater Cave (Mulu, Sarawak, Malaysia). Reversal in Early Quaternary deposits was detected by Noel, Shaw & Ford (1984) in Mason Hill (Derbyshire, Great Britain). Williams et al. (1986) interpreted palaeomagnetism of cave sediments from a karst tower at Guilin (China). Schmidt, Jennings & Bao (1984) dated cave sediments in the New South Wales (Australia). Hill (1987) detected the R polarity of silts from Carlsbad Caverns (New Mexico, USA). Kadlec et al. (1992, 1995) dated sedimentary fill in the Aragonitová Cave (Czech Karst, Czech Republic). Müller (1995) dated sediments in Ofenloch Cave (Switzerland). Šroubek & Diehl (1995) indicated the presence of sediments older than 0.78 Ma in caves of the Moravian Karst (Czech Republic). Hercman et al. (1997) used magnetostratigraphy as the control of Th/U dating of speleothems in the Demänovská Ice Cave (Slovakia). Hobléa (1999) dated sediments in Granier System (Chartreuse, France). Pruner et al. (2000) dated fill of principal caves and cave systems in Slovakia. Šebela et al. (2001) dated cave sediments in the Baiyun Cave (Yunnan Karst, China). Kadlec et al. (2000a, b, 2002, 2003, 2004c), Kadlec, Hlaváč & Horáček (2002) and Kadlec & Táborský (2002) dated cave fill and karst sediments in several places of the Moravian Karst, and in the Czech Karst (Czech Republic). Pruner et al. (2002) proved the expected age of principal galleries in Stratenská Cave (Slovakia). By magnetostratigraphy and Th/U dating of aragonite, Bosák et al. (2002a, 2005a) proved Quaternary age of principal speleogenetical processes in the Ochtinská Aragonite Cave (Slovakia). Audra et al. (in prep.) confirmed the Th/U data from the Grotte de la Clamouse (Hérault, France) by magnetostratigraphy. Bosák et al. (2004a) combined palaeomagnetic and Th/U dating in the Baradla Cave (Hungary). Kadlec et al. (2004a, b) applied magnetostratigraphy for dating of multi-level cave systems in the Nízké Tatry Mts. (Slovakia). Bosák et al. (2005b) dated sediments in the Pocala Cave and Borgo Grotta Gigante (Trieste region, Italy) obtained by full-core drilling. Bella et al. (2005) reconstructed the evolution of hypogenic Belianská Cave (Tatra Mts., Slovakia).

Palaeomagnetic data are also used in archaeological sites. Kopper & Creer (1976) described the application of palaeomagnetic dating for stratigraphic interpretation of archaeological sites. Creer & Kopper (1974) dated cave paintings in Tito Bustillo Cave (Asturias, Spain). Papamarinopoulos (1977), Poulianos (1980) and Papamarinopoulos et al. (1987) dated site with so-called Petralona Man (Petralona Cave, Chalkidiki, Greece). Noel (1990) applied the method in caves of Guanxi (China). The famous South African hominid sites of Makapansgat and Swartkrans were studied by Brock, McFadden & Partridge (1977), McFadden, Brock & Partridge (1979), Herries (2003) and Herries et al. (2006a, b).

Palaeomagnetic analysis and magnetostratigraphy of cave clastic sediments are often applied to the reconstruction of landscape and climate evolution of karst regions. Audra & Rochette (1993) reconstructed glaciations from sediment dating in Valliers Cave (Vercors, France). Sasowsky, White & Schmidt (1995) determined river incision by magnetostratigraphy of cave sediments in the Appalachian plateaus (USA). Quaternary evolution of the British South Pennines was reconstructed by Th/U and palaeomagnetic data by Rowe, Austin & Atkinson (1988). Audra (1996, 2000b) reconstructed the karst evolution of Dévoluy Massif (Hautes–Alpes, France). Audra, Lauritzen & Rochette (1999) applied magnetostratigraphy in Muruk Cave (Nakanaï Mts., New Britain, and East Papua–New Guinea). In the combination with the Th/U dating they proved the very young speleogenesis and uplift. Kadlec et al. (2001, 2002) reconstructed evolution of semi-blind valleys in the Moravian Karst (Czech Republic) with the application of four dating methods. Audra, Camus & Rochette (2001) dated the start of the entrenchment of a deep underground canyon in Aven de la Combe Rajeau (Ardèche, France) to about 2.0 Ma and correlated it with terrace systems of the Ardèche River. Kadlec et al. (2001) verified magnetostratigraphy of sediments and speleothems by radiometric dating ($^{10}Be/^{26}Al$ and Th/U methods) in the Moravian Karst (Czech Republic) and used the data for the reconstruction of cave evolution in the northern segment of this region. Audra, Quinif & Rochette (2002) applied palaeomagnetic analysis of cave sediments for analysis of evolution of Tennengebirge karst (Austria). Musgrave & Webb (2004) analyzed Pleistocene landscape and climate evolution of the basis of palaeomagnetic analysis of sediments in the Buchan Cave (south-eastern Australia). Sasowsky et al. (2004) interpreted the time-span of the development of Kooken Cave (Pennsylvania, USA). Kadlec et al. (2004a) applied magnetostratigraphy, Th/U, fission track and cosmogenic nuclide methods in cave deposits of multi-level cave systems in the Demänová and Jánská Valleys for the reconstruction of karst landscape evolution and valley incision of the Nízke Tatry Mts. (Slovakia). Stock et al. (2005) applied combination palaeomagnetic and numerical dating methods in landscape evolution studies and Audra et al. (2006, 2007) in the reconstruction of cave genesis in Alps from Miocene.

The most common measured magnetic property, mass-specific MS (χ), is a function of concentration, grain size and mineralogy of magnetic minerals found in the sediments. It has proved to be a sensitive detector of the long-term, large-scale terrestrial climatic change in cave deposits (Sroubek et al. 2001). The susceptibility has been applied to a study of palaeo-secular variation (Ellwood 1971; Creer & Kopper 1974, 1976; Papamarinopoulos et al. 1991). Kopper & Creer (1973) fitted the declination and inclination curves to a ^{14}C controlled record in Majorcan caves. Anisotropy of magnetic susceptibility was applied to characterise the sedimentary fabrics and palaeo-flow directions (Noel & St. Pierre 1984; Noel 1983, 1986a; Turner & Lyons 1986; Kostrzewski et al. 1991). Ellwood et al. (1996), Šroubek & Diehl (1995), and Sroubek et al. (1996, 2001) described environmental magnetic properties of cave sediments. Ellwood (1999) compared kappa highs with palaeoclimatic changes in caves of Albania and correlated the data with some other caves of the Mediterranean area. Matching susceptibility curves obtained from cave sediments with known the secular variation curve for a region enables establishment of a chronology for the sediments (e.g., Ellwood 1971; Noel 1983, 1986a, b). Thistlewood & Noel (1991) applied the plots of declination, inclination, intensity of magnetization and magnetic susceptibility to the correlation of several sedimentary sections in Peak Cavern (Great Britain). Kadlec (2003) determined the flow regime from the anisotropy of magnetic susceptibility in the Ochozská Cave (Moravian Karst, Czech Republic).

On the other hand, there have also been many unsuccessful attempts to apply magnetostratigraphic methods. Bosák et al. (1982) sampled an excellent profile of palaeontologically dated Pleistocene sediments in Žabia Cave (Cracow–Wieluń Upland, Central Poland). Measurements were completed but problems with the interpretation of very weak signals resulted in no real results being obtained at that time.

The palaeomagnetism of calcite and aragonite speleothems has been used to test for N or R polarities where the sample is known to be older than 350 ka or older than about 1.25 Ma (Th/U and U/U methods), and to obtain dated, high-resolution curves of recent secular variations (Ford & Williams 1989, 2007). Latham, Schwarcz & Ford (1979) made the first analyses, using speleothems from Canada and Great Britain. In spite of very low magnetic intensities, speleothems can carry the NRM either as a chemical precipitate (CRM) or as floodwater or filtrate detrital grains (DRM; Latham 1981, 1989). The carrier of magnetism is magnetite. The R magnetic signature in speleothem was detected by Latham et al. (1982) in British Columbia and by Šroubek and Diehl (1995) in the Moravian Karst. Latham, Schwarcz & Ford (1986, 1987) and Latham et al. (1989) studied secular variation on stalagmites from Mexico and Canada obtaining good secular variation curves and evidences for a drift. Palaeosecular variations were studied also by Openshaw et al. (1993) on Xingweng stalagmite (China) and Lean, Latham & Shaw (1995) on stalagmites from the Vancouver Island (Canada). Martin (1991) detected palaeoinclination changes in the last 4–20 ka for stalagmite and flowstone in Gardner Cave (Washington, USA). Brooks et al. and Ford (in Hill 1987) applied palaeomagnetic analysis to speleothems from the Carlsbad Caverns. Palaeomagnetic and rock magnetic studies on speleothems were carried out also by Kyle (1990) in Gardner Cave (USA), Morinaga, Inokuchi & Yaskawa (1898) in Japan, Liu et al. (1988) from Ping Le (China) and Perkins & Maher (1993) in Great Britain. Bosák et al. (2002b) dated a 2.5 m thick profile in flowstones in Snežna jama, Slovenia.

Very shortly after the first applications of paleomagnetism in caves, general comments, definitions of limits and thresholds appeared (e.g., Homonko 1978; Stober 1978, Papamarinopoulos 1978; Noel 1982, 1985; Papamarinopoulos & Creer 1983; Noel & Thistlewood 1989; Ellwood 1999). Verosub (1977) and Noel (1986b) determined that clastic sediments can suffer much post-depositional alteration of the declination and inclination signals, especially if they have drained. Noel & Bull (1982) suggested that bioturbation of sediments may also be a major problem. Williams et al. (1986) emphasised that carriers of remanent magnetisation are usually detrital grains of magnetite. The findings of magnetostratigraphic research of cave sediments based mainly on research in Slovakia and Slovenia was presented by Bosák et al. (2000b), Bosák & Pruner (2001), and Pruner & Bosák (2001).

Bosák et al. (2000b) and Bosák, Pruner & Kadlec (2003) summarized the principal thresholds in the application of the magnetostratigraphy in cave deposits: e.g., the general lack of fossils in interior cave facies, redeposition of fossils from older sediments and dejecta, cyclic character of cave fill deposition, unconformities hiding substantial geological time, limited number of numerical methods. The described character of deposition resulted that the velocity of sedimentation cannot be calculated in such profiles. The time duration of individual magnetozones cannot be calculated properly and the geometric character of obtained magnetostratigraphic picture cannot be compared with the GPTS.

THE HISTORY OF PALAEOMAGNETIC RESEARCH OF KARST SEDIMENTS IN SLOVENIA

The application of palaeomagnetic and magnetostratigraphic method was started Rado Gospodarič. He summarized the age of infill processes in numerous caves of the Kras (Gospodarič 1972 to 1985). Based on this detailed study and his doubts on real ages of cave sediments, he sampled profiles in the Trhlovca and Divaška jama (Divaški kras). Samples were delivered to a palaeomagnetic laboratory in Potsdam (of the former Academy of Sciences of the German Democratic Republic), but results were never obtained. The Gospodaric sampling sites were still recognizable during sampling in 1997 (Bosák, Pruner & Zupan Hajna 1998).

Fifteen years after Schmidt's pioneer studies at Mammoth Cave (USA), the team of the IG AS CR started extensive magnetostratigraphic research upon clastic cave deposits in the Central European region. After the method was successfully applied with reliable results (Bosák, Pruner & Zupan Hajna 1998), Slovenian and French karstologists also began to utilise the method as well. The research was focused on wholly fossilized sites; mostly unroofed caves (*sensu* Mihevc 1996) found during highway construction and opened by quarries, or accessible caves with known sediment profiles. Fossil were studied by Bosák et al. (1999, 2000a, b), Bosák, Mihevc & Pruner (2004), Mihevc et al. (2001, 2002), Pruner & Bosák (2001), Šebela & Sasowsky (2000). Audra (2000a), Bosák et al. (2000b, 2002b, 2005c), Pruner & Bosák (2001), Šebela & Sasowsky (1999) and Sasowsky, Šebela & Harbert (2003) applied magnetostratigraphy to date the fill of some fossil/relict and active passages in accessible caves. All of these studies contributed substantially to the current interpretation of the succession and age of speleogenetic processes, substantially changing the earlier views on the ages of cave-forming processes (Zupan Hajna et al. 2005).

FIELD PROCEDURES

In early work, the sampling of profiles was usually carried out in two steps: (1) collection of so-called 'pilot' samples spaced 10 cm and more apart, followed by (2) detailed sampling along and across the boundaries of magnetozones detected with different polarization (Fig. 6). The second step was taken only after laboratory processing and evaluation of palaeomagnetic properties of the samples taken in the first step. The disadvantages of such an approach appeared very soon – the need to return to a profile that might be poorly accessible, or the rapid progress of highway construction destroying sites so that there could be no possibility of repeat sampling. As a result we changed to high-resolution sampling of profiles during the first visit (Fig. 7).

Unconsolidated samples of the initial sites (Divača profile, Divaška jama and Trhlovca) were sampled with a non-magnetic trough made of bronze, and samples were cut from the derived sediment column by knife (Fig. 8). This very inefficient method was replaced during the next sampling by use of boxes (Fig. 9) made from non-magnetic plastics (Natsuhara Giken Co., Ltd., Japan) with a size of 20 x 20 x 20 mm and volume of about 6.7 cm^3 (Fig. 10).

Samples from consolidated rocks and speleothems were collected from the profile in large oriented pieces (Fig. 11). The continuous sampling of speleothems started in 2001 by cutting narrow trench(es) with a powered circular saw (Fig. 12). A powered drill was used in Jama pod Babjim Zobom (Fig. 238).

All field hand specimens were oriented *in situ*: the direction of dip was measured by the geological compass (Fig. 13) and the direction of north was drawn on the samples (Fig. 14). All data were recorded on field drawings at the site (Fig. 15).

In situ magnetic susceptibility was measured by Kappameter KT-5 on some profiles.

Figure 6 *Measurements of the profile in Markov spodmol, where several boundaries between magnetozones were detected.*

Figure 7 *Dense sampling with plastic boxes in unconsolidated sediments; example from Tajna jama in 2006.*

Figure 8 *First unconsolidated samples were taken with a non-magnetic tube and samples were cut by aluminium knife; sampling in Divaška jama in 1997.*

Figure 11 *Sampling of solid rocks; speleothems in Račiška pečina.*

Figure 9 *Sampling of unconsolidated sediments by plastic boxes; example from Markov spodmol.*

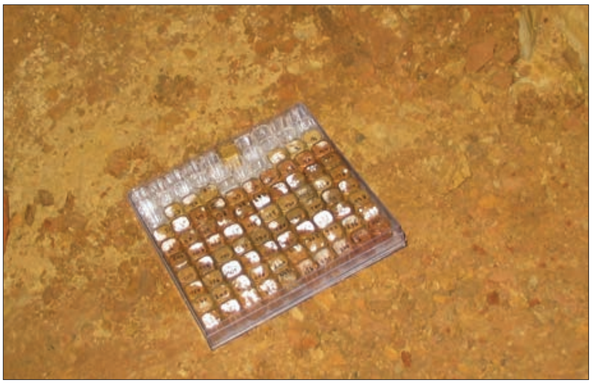

Figure 10 *Collection of samples in small non-magnetic plastic boxes (100 in one set).*

Figure 12 *Trench cut in flowstone by circular saw in the Račiška pečina.*

Figure 13 *Measurement of the north direction by geological compass in the Trhlovca.*

Figure 14 *Sampling of solid samples in Trhlovca. Note orientation of the sample to the north (black arrows) and stratigraphic description of samples (Latin letters and numbers).*

Figure 15 *Field office in Račiška pečina (2004) with principal cave bureaucrat.*

LABORATORY PROCEDURES

Palaeomagnetic analyses were completed in the Laboratory of Palaeomagnetism, IG AS CR in Praha–Průhonice. Procedures were selected to allow the separation of the respective components of the RM and the determination of their geological origin. Oriented hand samples from consolidated rocks and speleothems were cut into cubes of 20 x 20 x 20 mm and subjected to AF demagnetization and/or TD. Samples from unconsolidated sediments were demagnetized only by the AF.

The RM was measured on JR–5 or JR–6A spinner magnetometers (Jelínek 1966) and tested by the progressive TD using the MAVACS apparatus. The MAVACS secures the generation of a high-magnetic vacuum in a medium of thermally-demagnetized specimens (Příhoda et al. 1989). The majority of specimens were subjected to AF demagnetization up to a field of 100 mT. The Schonstedt GSD–1 or LDA–3 apparatus was employed for the AF demagnetization.

The NRM of specimens in their natural state (NRM) is identified by the symbol J_n, the corresponding remanent magnetic moment by the symbol *M*. Graphs of normalized values of $M/M_o = F(t)$ were constructed for each analyzed specimen.

Phase or mineralogical changes of magnetically active (mostly Fe-oxides) minerals frequently occur during laboratory thermal tests, especially at low temperature intervals. These changes can be derived from the graphs of normalized values of $k_t/k_n = f(t)$, where k_n designates the volume MS of specimens in the natural state and k_t the susceptibility of specimens demagnetized at temperature *t* (°C). The k_t and k_n values were measured on the KLY–2 and/or KLY–3 kappa-bridges and a KLF–4A Automatic Magnetic Susceptibility Meter (Jelínek 1966, 1973).

Multi-component analysis technique of Kirschvink (1980) was applied to separate the respective RM components. Fisher statistics (1953) were employed for the calculation of mean directions of the CRM components derived by the multi-component analysis.

The IRM acquisition paths were measured by progressive magnetization. The specimen was treated in 19 steps with an increasing DC field up to a maximum of 900 mT. The DCF magnetizer instrument was applied to reach the SIRM. Then the AF demagnetization of the SIRM in 16 steps up to 100 mT was carried out.

PROCESSING

All samples were subjected to detailed AF demagnetization in 12–16 steps and/or TD method in 11–15 fields. Typical results are presented on Figures 16 and 17. As noted, multi-component analysis was applied to separate the respective RM components for each sample. We confirmed that the complete step/field apparatus offered by both demagnetization methods have to be applied. The application of complete analysis only to pilot samples and shortened, selected field/step approach to other samples did not offer a sufficient data set for reliable interpretation (Bosák, Pruner & Kadlec 2003).

Results of the multi-component analysis of remanence show that the sediment samples display a three-component RM. The A-component is undoubtedly of viscous origin and can be demagnetized in the AF and at a temperature range of 6 (10) mT or 80 (120) °C. The B-component is also of secondary origin but shows

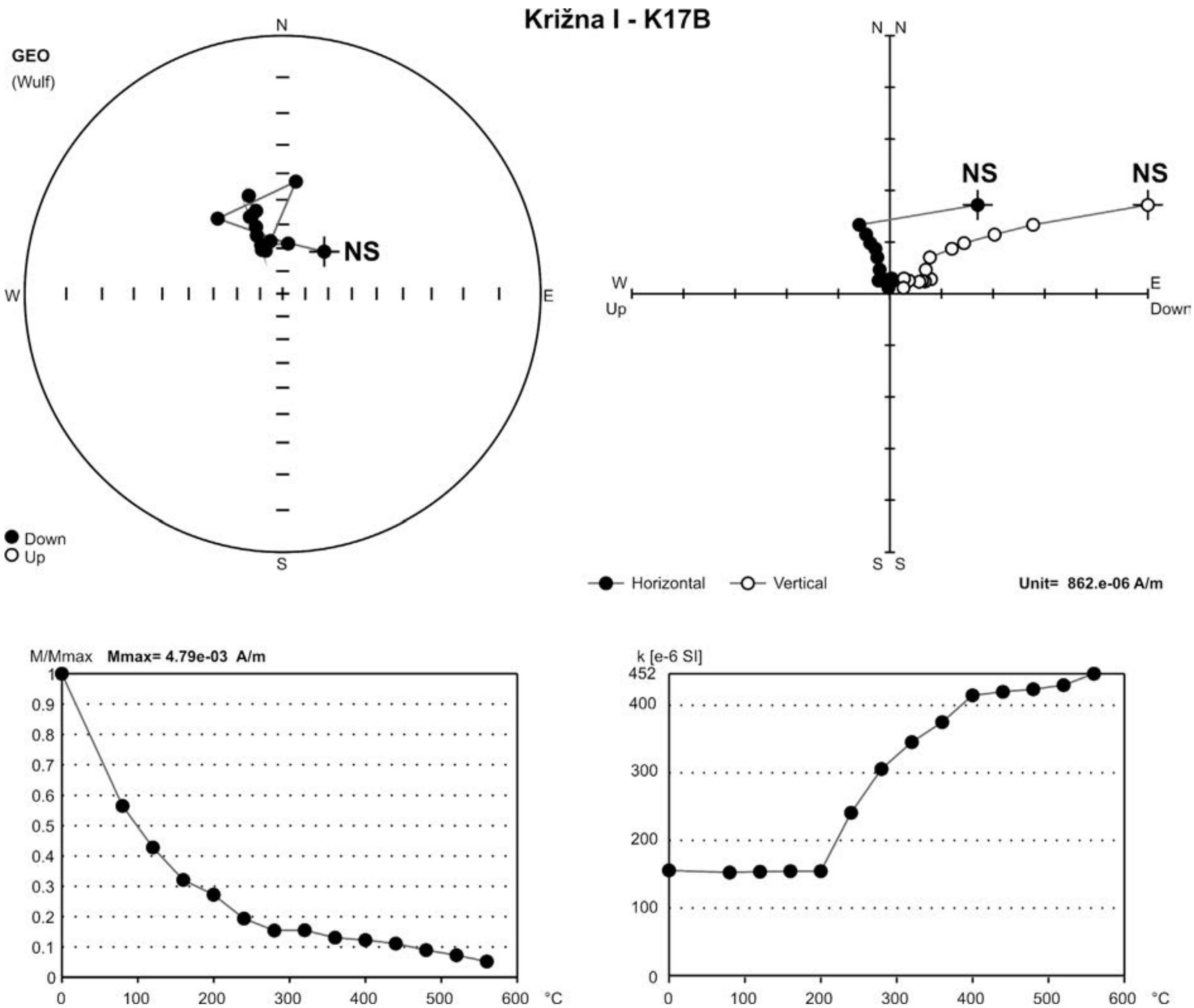

Figure 16 *Results of progressive TD of sample from Križna jama with normal palaeomagnetic polarity. Top left: A stereographic projection of the RM of a sample in the natural state and after progressive TD to the temperatures of the demagnetization fields [°C]. Top right: Zijderveld diagram – solid circles denote projection on the horizontal plane (XY), open circles denote projections on the N–S vertical plane (XZ). Bottom left: A graph of normalized values of the RM moments (M) as dependent on thermal fields [°C]. Bottom right: A graph of the values of the volume MS (k) versus the TD fields.*

harder magnetic properties and can be demagnetized in the AF or at temperature range of 6 to 20 mT or 80 to (200) 240 °C. The C-component is the most stable one and can be demagnetized in the AF or at temperature range of ca 20 to 80 (100) mT or 320 to 520 (560) °C.

Magnetomineralogical analyses of pilot samples and unblocking temperatures (520 to 560 °C) determined indicate that magnetite is the carrier of the RM for all samples analysed, which is in accordance with published data (Bosák, Pruner & Kadlec 2003). The analysis of microcoercivity spectra showed that the tested samples display medium to high magnetic hardness. The sediments contain mostly weak- or medium-magnetic materials.

The systematic acquisition of palaeomagnetic data within a studied section allowed the construction of a detailed magnetostratigraphic profile with a high resolution. In intervals with polarity change, the frequency of sampling was so high that an almost continuous record of the magnetic and palaeomagnetic parameters was obtained.

The principal task was to subdivide the magnetostratigraphic profile into intervals corresponding to N and R polarity of palaeomagnetic field, solely on the basis of the analysis of the RM directions determined for the individual samples collected from the section.

Each magnetostratigraphic profile contains several columns with the NRM moduli values, values of volume MS of samples in the natural state, palaeomagnetic D and I (of the CRM-components of the RM inferred by multi-component analysis), and polarity scale (e.g., Fig. 34).

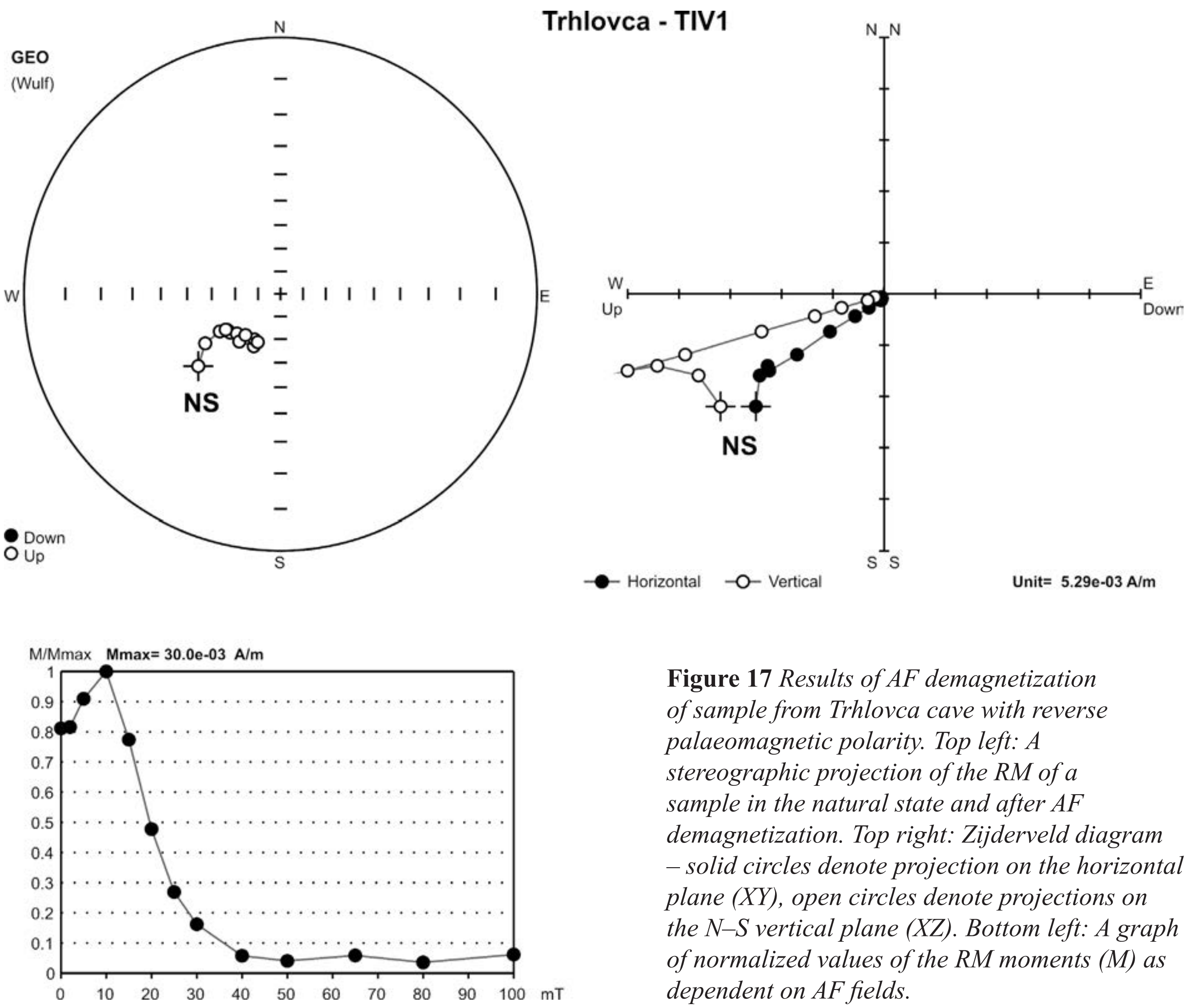

Figure 17 *Results of AF demagnetization of sample from Trhlovca cave with reverse palaeomagnetic polarity. Top left: A stereographic projection of the RM of a sample in the natural state and after AF demagnetization. Top right: Zijderveld diagram – solid circles denote projection on the horizontal plane (XY), open circles denote projections on the N–S vertical plane (XZ). Bottom left: A graph of normalized values of the RM moments (M) as dependent on AF fields.*

Laboratory of Palaeomagnetism, IG AS CR in Prague – Průhonice.

Liquid helium-free Superconducting Rock Magnetometer (SRM), type 755 4K SRM: the set includes a measurement system, alternating field demagnetizer, three-layer permalloy degauss shield, automatic sample holder.

OTHER METHODS

MINERALOGICAL ANALYSES

X-RAY ANALYSIS

X-ray powder diffraction analyses were performed in (1) the Laboratory of Physical Methods, IG AS CR in Praha (analysts RN Dr. Karel Melka, CSc., Mgr. Roman Skála, PhD., Jiří Dobrovolný), and (2) at the Geological Institute of Faculty of Natural Sciences and Engineering in Ljubljana (analyst Dr. Meta Dobnikar).

In the Czech laboratory all powder patterns were collected with a Philips X´Pert APD diffractometer. Copper radiation was monochromatized with a graphite secondary monochromator. Cobalt radiation was monochromatized with a curved graphite pyrolytic monochromator placed in a diffracted beam. The fixed divergence slit had an opening of 1/2°. Receiving and anti-scatter slits were 1 mm and 1/2° wide, respectively. For each specimen, except one where calcite was identified as a dominant phase, five individual patterns were acquired. The first set of pattern was collected for randomly-oriented material top-pressed into proprietary aluminium Philips holder (which may result in peaks appearing in the patterns) in the angular range of 2–75° and 3–85° 2Θ. The second set of patterns was taken for oriented specimens; these were cemented onto microscopic glass slides at ambient temperature. The third set was acquired for glycolated specimens; glass slides with specimens were processed in vapours of ethylene glycol for four hours and temperature of 80 °C. The fourth set was collected for the samples heated to 400 °C under ambient atmosphere. Oriented, glycolated, and heated specimens were examined in angular range from 3 to 40° 2Θ. For all samples, also, a region involving 060 reflections of clayey and micaceous minerals was scanned between 70 and 74° 2Θ. All diffraction patterns were taken in the continuous scanning mode with scanning speed of $1°.min^{-1}$. The X-ray generator was powered using high voltage of 40 kV and currents of 32 or 40 mA.

The qualitative mineral composition of samples in Ljubljana was determined by X-ray powder diffraction with a Philips diffractometer. The concentrations of minerals were determined from the height of the main reflection of each particular mineral in the X-ray record. The conditions at the recording were: anode CuK_{α}, 40 KV, 30 mA and Ni filter.

THERMAL ANALYSIS

DTA-TG analyses were performed in the Laboratory of Physical Methods, IG AS CR in Praha (analyst Dr. K. Melka, PhD.) on a Q 1500 D derivatograph (Orion, Hungary) with computerized registration of the own construction. Analyses were carried out by a gradual heating ($10°C.min^{-1}$).

EDAX ANALYSIS

Some samples were analyzed by EDAX (LINK connected to a JEOL-JXA-50A microprobe in the Laboratory of Physical Methods, IG AS CR in Praha (analyst Dipl. Ing. A. Langrová).

HEAVY MINERAL ANALYSIS

The procedures were performed in the Laboratory of General Geology, IG AS CR in Praha (analyst V. Sedláček). Samples were filtered, dried, sieved (40 to 315 μm) and decanted on the sieve. The different sized fraction was floated to obtain quartz and feldspar. The rest was separated by magnetic separator with current intensity of 0.2 to 10 A. Each of the fractions was settled in heavy liquids (bromoform and/or methyleneiodide with 2.53, 2.82, 3.16 and 3.30 $g.cm^{-3}$) for separation of light and heavy mineral fractions.

TH/U DATING

Th/U (U-Series) analyses were performed in (1) Geochronology Laboratory, Institute of Geological Sciences, Polish Academy of Sciences in Warsaw (analysts Prof. Dr hab. Helena Hercman, Dr. Tomasz Nowicki), and (2) Uranium Series Laboratory, Department of Geology, University of Bergen (Head Prof. Dr. Stein Erik Lauritzen; analysts AM).

Standard chemical procedures for uranium and thorium separation from carbonate samples were used (Ivanovich & Harmon 1992). In Warsaw activity was measured by α-spectrometry, using an ORTEC OCTETE PC. Spectral analyses and age calculations were made with URANOTHOR 2.5 software, which is the standard software in the Geochronology Laboratory in Warsaw (Gorka & Hercman 2002). The quoted errors are one standard deviation. Measurements in Bergen also used α-spectrometry but the data were processed by the program, Age4U2U (Lauritzen 1993).

The age limit of α-spectrometric Th/U method is about 350 ka. Minimum age estimation for samples with a low-U content is the safest solution. Minimum ages were estimated from the measured activities ratios and their accuracy (measured activity ratios minus error). Corrected minimum age limits take into account any detrital contamination and have been estimated assuming an initial $^{230}Th/ ^{232}Th$ activity ratio in detritus equal 1.5±0.5. Where $^{234}U/ ^{238}U$ activity ratios in equilibrium are obtained within the error range it is possible that an age is over 1.2 Ma. For samples with significant detrital contamination we must allow that not only Th but U as well, may be mobilised at the time of dissolution of the sample. At the time of uranium mobilisation enrichment of ^{234}U is characteristic. Higher values of $^{234}U/ ^{238}U$ activity ratios in samples with significant detrital contamination may suggest that not only Th but also U contamination has occurred. It means that results of Th/U dating for such samples are not reliable.

PALAEONTOLOGY

MAMMALIAN STRATIGRAPHY

Samples of sediments weighing tens to a few hundred kilograms were washed, sieved and any fossil bones extracted by hand. Teeth enamel was etched by diluted acids and studied on a CAMECA 100 microprobe (Laboratory of Physical Methods, IG AS CR in Praha) and a JEOL 6386 scanning electron microscope (Faculty of Science, Charles University, Praha) to identify the internal structure of the tooth. Determinations were undertaken by Prof. Dr. Ivan Horáček (Department of Zoology, Faculty of Science, Charles University, Praha).

PALYNOLOGY

Palynological analyses of the clastic cave sediments were performed in Jovan Hadži Institute of Biology ZRC SAZU, Ljubljana (Dr. Metka Culiberg). Speleothems were studied in the Institute of Geological Sciences, National Academy of Sciences of Ukraine, Kiev (Dr. Maryna Komar).

Samples analyzed in Slovenia were treated by common palynological maceration. In the Ukraine speleothem samples were dissolved in concentrated HCl, then washed by water until neutral pH was obtained. Light and heavy fractions were separated by heavy liquids and in a centrifuge.

THE STUDY SITES

The palaeomagnetic research was carried out in Slovenia from 1997 to 2006. There were a total of 21 sites (19 in Slovenia and 2 in Italy; Fig. 18) with 36 profiles; all except one were cave or karst surface sediments. The sites are located mainly in the Dinarski kras (Kras, Matarsko podolje, Podgorski kras, Notranjski kras, Dolenjski kras) and four of them in other areas, especially due to the fact that localities with suitable sediments are nearly absent in the Alps. Two sites from Julian Alps, Spodmol nad Planino Jezero and Jama pod Babjim zobom, and one from Kamnik–Savinja Alps, Snežna jama na Raduhi, were studied. In the Isolated Karst of the pre-Alps, sediments from Tajna jama were sampled and Plio/Quaternary fluvial sediments from the tectonic Velenje basin were analysed for comparison.

Figure S1 is a map with the location of the studied caves/sites. Table 1 summarizes dates of visits and personnel involved in the individual trips.

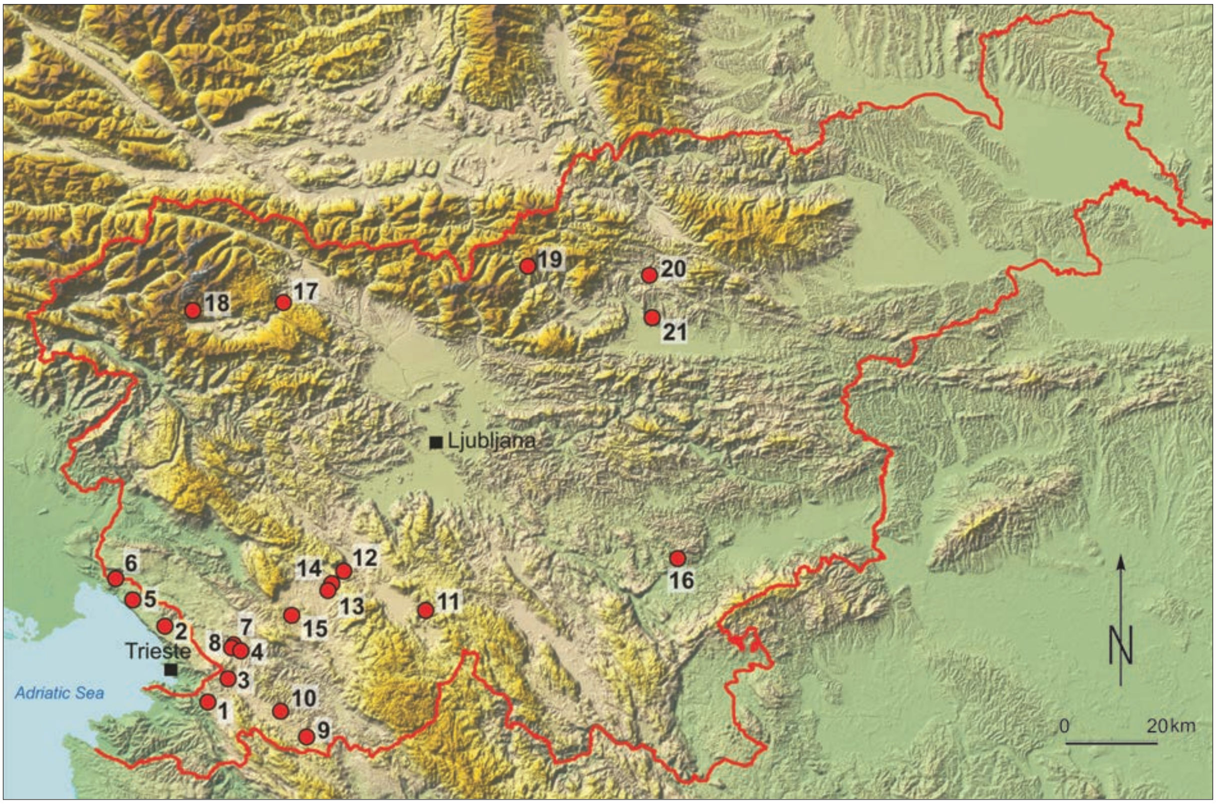

Figure 18 *Location of studied sites in Slovenia and Italy. Legend: 1 – Črnotiče profile; 2 – Briščiki; 3 – Kozina profile; 4 – Divača profile; 5 – Jama pod Kalom; 6 – Grofova jama; 7 – Divaška jama; 8 – Trhlovca; 9 – Račiška pečina; 10 – Pečina v Borštu; 11 – Križna jama; 12 – Planinska jama; 13 – Postojnska jama; 14 – Zguba jama; 15 – Markov spodmol; 16 – Hrastje profile; 17 – Jama pod Babjim zobom; 18 – Spodmol nad Planino Jezero; 19 – Snežna jama; 20 – Velenje profile; 21 – Tajna jama.*

Table 1: Review of studied sites in 1997–2006 and personnel involved

Name of site	Name of profile	Date	Personnel
Divača		24. 9. 1997	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák
Kozina		2. 9. 1999	Nadja Zupan Hajna, Tadej Slabe, Petr Pruner, Pavel Bosák
Črnotiče	**I**	9.10.1998	Andrej Mihevc, Petr Pruner, Pavel Bosák
	II	30. 6. - 2. 7. 2000	Andrej Mihevc, Petr Pruner, Pavel Bosák, Jože Žumer
Briščiki		22. 11. 2000	Ruggiero Calligaris, Petr Pruner, Pavel Bosák
		10. 11. 2001	Ruggiero Calligaris, Antonella Tremul, Petr Pruner, Pavel Bosák
Jama pod Kalom		22. 11. 2000	Ruggiero Calligaris, Petr Pruner, Pavel Bosák
		10. 11. 2001	Ruggiero Calligaris, Antonella Tremul, Petr Pruner, Pavel Bosák
Divaška jama		25. 9. 1997	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák
		2. - 5. 6. 1998	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák, Andrej Mihevc
		18. 11. 2004	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák, Petr Schnabl, Stanislav Šlechta
Trhlovca	**Sediment**	25. 9. 1997	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák
		2.- 5. 6. 1998	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák
		17. 11. 2004	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Petr Schnabl, Stanislav Šlechta
		24. 6. 2005	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák, Andrej Mihevc
		22. 6. 2006	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák, Andrej Mihevc
	Flowstone	22. 6. 2006	
Račiška pečina		25. 6. 2002	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák, Jaroslav Kadlec
		29. 6. 2003	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák
		23. 6. 2004	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák, Jaroslav Kadlec
		14. - 16. 11. 2004	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák, Petr Schnabl, Stanislav Šlechta, Franjo Drole, Jurij Hajna
	Fold test	16. 11. 2004	
Križna jama	**Medvedji rov I**	27. 6. 2003	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák, Alojz Troha, Matej Kržič
		15. 6. 2004	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák
	Medvedji rov II	15. 6. 2004	
		23. 6. 2005	
Planinska jama	**Rudolfov rov**	30. 6. 2003	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák, Jurij Hajna

Postojnska jama	**Spodnji Tartarus North**	28. 6. 2003	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák
		16. - 17. 6. 2004	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák, Franjo Drole, Jurij Hajna
		21.6.2005	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák, Jurij Hajna
	Spodnji Tartarus South	21.-22.6.2005	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák, Jurij Hajna
	Spodnji Tartarus White sandstone	22. 6. 2005	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák
	Umetni tunel I	28. 6. 2003	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák
		20. 6. 2007	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák, Andrej Mihevc
	Umetni tunel II	28. 6. 2003	Nadja Zupan Hajna, Petr Pruner, Pavel Bosák
	Biospeleološka postaja	30. 6. 2003	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák
	Male jame	22. 6. 2005	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák
	Pisani rov	3. 4. 2006	Nadja Zupan Hajna, Andrej Mihevc, Pavel Bosák
	Stara jama	3. 4. 2006	Nadja Zupan Hajna, Andrej Mihevc, Pavel Bosák
		13. 3. 2007	Nadja Zupan Hajna, Andrej Mihevc, Pavel Bosák, Ivan Horáček
Pečina v Borštu		5. 7. 2003	Andrej Mihevc, Petr Pruner, Pavel Bosák
Markov spodmol	**I**	17. 6. 2004	Andrej Mihevc, Nadja Zupan Hajna, Petr Pruner, Pavel Bosák
		23. 6. 2005	
	II	23. 6. 2005	
Zguba jama	**I**	5. 4. 2006	Nadja Zupan Hajna, Andrej Mihevc, Pavel Bosák
	II	5. 4. 2006	
Grofova jama		9. 10. 2006	Nadja Zupan Hajna, Andrej Mihevc
		11. 3. 2007	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák
Jama pod Babjim zobom		23. 6. 2002	Nadja Zupan Hajna, Andrej Mihevc, Petr Pruner, Pavel Bosák, Jaroslav Kadlec
Spodmol nad Planino Jezero		17. 6. 2005	Andrej Mihevc, Nadja Zupan Hajna
		17. 7. 2005	Andrej Mihevc, Philipp Häuselmann
Snežna jama		8. 11. 2001	Andrej Mihevc, Petr Pruner, Pavel Bosák
Tajna jama		2. 2. 2005	Nadja Zupan Hajna, Andrej Mihevc
		2. 10. 2006	Nadja Zupan Hajna, Andrej Mihevc
Hrastje		9. 6. 2005	Nadja Zupan Hajna, Bojan Otoničar, Franjo Drole
Velenje		15. 7. 2004	Nadja Zupan Hajna, Marko Vrabec

Table 2: Review of studied sites in 1997–2006 and number of samples

Type of site	Region	Name of site	Name of profile	AF	TD
Unroofed Caves	**Dinaric Karst**	**Divača**		16	13
		Kozina		38	0
		Črnotiče	**I**	0	27
			II	55	0
		Briščiki		35	0
Caves	**Dinaric Karst**	**Jama pod Kalom**		60	1
		Divaška jama		106	0
		Trhlovca	**Sediment**	158	0
			Flowstone	40	22
		Račiška pečina	**Profile**	192	38
			Fold test	12	8
		Križna jama	**I**	32	6
			II	112	0
		Planinska jama	**Rudolfov rov**	85	0
		Postojnska jama	**Spodnji Tartarus North – red**	134	0
			Spodnji Tartarus North – yellow	70	0
			Spodnji Tartarus South	176	0
			Spodnji Tartarus White sandstones	14	8
			Umetni tunel I	14	0
			Umetni tunel II	14	0
			Biospeleološka postaja	15	0
			Male jame	33	0
			Pisani rov	53	12
			Stara jama	26	0
		Pečina v Borštu		31	8
		Markov spodmol	**I**	58	0
			II	22	0
		Zguba jama	**I**	40	0
			II	8	0
		Grofova jama		59	0
	Alpine and Isolated Karsts	**Jama pod Babjim zobom**		14	5
		Spodmol nad Planino Jezero		6	0
		Snežna jama		100	23
		Tajna jama		114	0
Surface sediments	**Dinaric Karst**	**Hrastje**		34	0
	Alpine Karst	**Velenje**		31	0
Total		**21**	**36**	2007	171

Table 2 summarizes the number of samples processed by palaeomagnetic analyses in the Laboratory of Palaeomagnetism (IG AS CR Praha–Průhonice).

Numerous caves were visited for several times due to the complexity of the profiles and their magnetostratigraphic patterns (e.g., Divaška jama, Trhlovca, Križna jama, Račiška pečina, some sites within the Postojnska jama, Markov spodmol), or due to the fact that only pilot samples were taken during the first visit (e.g., Divaška jama, Trhlovca, Tajna jama). Other sites were sampled only during the single visit (e.g., Divača and Kozina profiles, Snežna jama and more sites within Postojnska jama).

The basic data for the caves are from the Cave Register of the Speleological Association of Slovenia (JZS) and Karst Research Institute ZRC SAZU.

Map drawings based on DMR 12.5 and 25, Survey and Mapping Authority of the Republic of Slovenia, 2005 and on Atlas Slovenije 1: 50.000 (1992).

KARST AREAS IN SLOVENIA

GEOLOGY AND GEOMORPHOLOGY OF THE DINARSKI KRAS

The karst area of south-western Slovenia belongs to the Dinaric Mountains, which tectonically (see Fig. 3) are a part of the External Dinarides (Placer 1981). The main area is on the Hrušica thrust sheet but part of Visoki kras (Trnovski gozd and Banjščica) belongs to the Trnovo thrust sheet (Placer 1999). Complex tectonic structure is characteristic especially for the Hrušica thrust sheet, which consists of smaller thrust sheets over-thrust one over the other with southward convergence (Hrušica, Snežnik and Komen thrust sheet). The Hrušica unit is thrust over the Istria Autochthon (Adriatic or Apulian foreland). The area consists of Triassic to Palaeogene limestones and dolomites.

The general WNW–ESE-trending compression related to the counter-clockwise rotation of Adriatic Microplate is still active here (Vrabec & Fodor 2006). It and sub-thrusting (Placer 2007) of the Adriatic–Apulian foreland (Istria–Friuli) under the External Dinarides (Kras, Čičarija), are the main factors influencing regional relief evolution in south-western Slovenia. Main tectonic patterns in the area are represented by fault zones of Dinaric (NW–SE) and cross-Dinaric (NE–SW) directions, S–N and NE–SW-trending fissures and over-thrust structures in carbonate rocks.

Large scale relief is influenced by the tectonic structures. Because of the dominance of carbonate rocks, karstification is the main geomorphic process. Extensive plateaus and closed depressions (poljes, uvalas, dolines) are the principal relief features of the Dinarski kras. Dolines are formed by locally enhanced solution and underground drainage. Karst poljes are situated along major Dinaric faults, their bottoms being levelled by dissolution at the height of the karst ground water table. The plateau surface was formed above a deep vadose zone by dissolution from precipitation.

Caves are an important element of the Dinarski kras. They represent both active and relict drainage paths. Different sediments are accumulated in them as the consequence of the general evolution of the karst. Nevertheless, fine-grained clastic sediments are extremely rare facies in the caves and thus it was not easy to find good localities for palaeomagnetic analysis and the sampling sites are not evenly distributed. The selected were chiefly in the Classical Karst, i.e. from the Kras plateau, two adjacent karst plateaus of Matarsko podolje and Podgorski kras, Postojnski kras and from Križna jama. One of the sites was located in the south-eastern part of the Dinarski kras in the Dolenjska region.

KRAS

The Kras is a low NW–SE-trending limestone plateau lying between Trieste Bay, the northernmost part of the Adriatic Sea, Vipava valley in north-east, and Friuli–Venezia Giulia lowlands and river Soča in north-west (Fig. 5) The 45°45´N and 14°00´E lines of latitude and longitude cross the Kras near Divača village. Climate is sub-Mediterranean with warm dry summers. Cold winters, with most of the precipitation, show strong influence of the continent.

The Kras belongs to Adriatic–Dinaric Carbonate Platform of the External Dinarides composed of shallow marine fossil-bearing Cretaceous and Palaeogene carbonates. Eocene flysch rocks encircle the carbonate plateau. Kras and Matarsko podolje tectonically belong to Komen thrust sheet (Placer 1999), which is thrust over Eocene flysch and Palaeocene/Eocene limestone of the Podgorski kras, a part of Kras imbricated structure (before known as Čičarija imbricated structure; Placer 2007). The whole structure is sub-thrust by the Istria unit.

The main part of the plateau is essentially levelled, inclined slightly towards the north-west, with numerous dolines, caves and other karst features. There is a belt of slightly higher relief in the central part of the plateau, formed by conical hills (Fig. 19) like Grmada (324 m a.s.l.), Volnik (545 m a.s.l.) and Stari tabor (603 m a.s.l.), and dissected by large depressions. The higher relief divides the Kras into two separated levelled surfaces. The southern one is named Nabrežinsko podolje. In the north-western part, the plateau descends to below 50 m a.s.l. on the edge of the Friuli Plain; on its south-eastern edge altitudes are about 500 m a.s.l There is about 300 m of accessible vadose zone with caves formed at all altitudes from the surface to the sea level and below it. . No superficial streams occur on the Kras surface, because all rainwater immediately infiltrates to carbonate rocks. There are two dry valleys crossing the plateau and some NW–SE-trending belts of lower relief which were believed to represent primary river valleys also because they contain remnants of fluvial sediments dated to a pre-karstification phase (Melik 1954; Radinja 1985).

Figure 19 *Kras plateau from slopes of Trstelj hill towards Grmada hill and Adriatic Sea.*

Geomorphologic and speleogenetic studies and especially new interpretations of fluvial sediments from the Kras surface as the fluvial fill of now unroofed caves have enabled a new explanation of the evolution of the Kras (Mihevc 1996, 1998, 1999a-c, 2001b, 2007). The shape of unroofed caves depends on (1) the morphology of the present surface; (2) size, type and original arrangement of caves, and (3) the cave fill. Unroofed caves are usually altered by surface processes. They represent an important element of the epikarst zone. On the surface, they are expressed as narrow and often meandering shallow trenches, shallow oblong depressions, doline-like forms in rows and collapsed dolines. Mihevc (1999a) offered models of their origin and their relation to the presently accessible caves.

The appearance of old unroofed caves and their fills resulted from denudation, erosion and chemical dissolution of limestone above the cavities. Fills exposed on the present surface include speleothems and cave fluvial deposits. The ancient directions of flow, different catchment areas of sinking rivers and different organisation of the ancient underground drainage were reconstructed from several unroofed caves opened during highway construction in the Divaški kras (Mihevc 1996; Mihevc & Zupan Hajna 1996). The thickness of rock overburden removed above cavities was established to have been 50–100 m. The age of cave fills was calculated from denudation rates and the expected thickness of missing overburden to 0.7–5 Ma (Mihevc 1996, 2001b). This large time range resulted from the expected minimum (20 $m.Ma^{-1}$) and maximum denudation rates (50 $m.Ma^{-1}$) calculated or measured in the area (Gams 1962; Cucchi, Forti & Ulcigrai 1994). Unroofed caves were also described by Šebela & Mihevc (1995), Šebela (1995, 1999), Mihevc, Slabe & Šebela (1998), Šušteršič (1998), Knez & Slabe (1999a, b).

NABREŽINSKI KRAS

Nabrežinski kras (Nabrežina Karst) is the north-western part of the Kras around the village of Nabrežina (Aurisina in Italian). It is only about 150–180 m a.s.l. There are several old collapse dolines on the surface, more than 300 m wide and to 50 m deep. Smaller solution dolines are less abundant, most of the surface having plain or slightly undulating relief.

Towards the north-east, the surface of the

Nabrežinski kras gradually transforms into the slopes of the Volnik (545 m a.s.l.) hills and Grmada (324 m a.s.l.; Fig.19). An abrupt change of the surface occurs in the south-west, where the surface drops from about 160 m a.s.l. to the sea level on the distance of 300 m only.

There are numerous caves, some of them are over 100 m deep, but they do not reach the underground karst water level or the main flow of the underground Reka river that appears in springs at sea level only about 7 km to the north-west.

DIVAŠKI KRAS

Divaški kras (Divača Karst) is the karst surface above Škocjanske jame; it is sometimes called also the Škocjanski kras (Fig. 20). The Divaški kras is situated in the south-eastern edge of the Kras between ponors of the river Reka and Divača village. It is composed chiefly of Cretaceous and Palaeogene limestones. The surface is levelled at altitudes between 420 and 450 m a.s.l., inclined slightly north-westwards and dissected

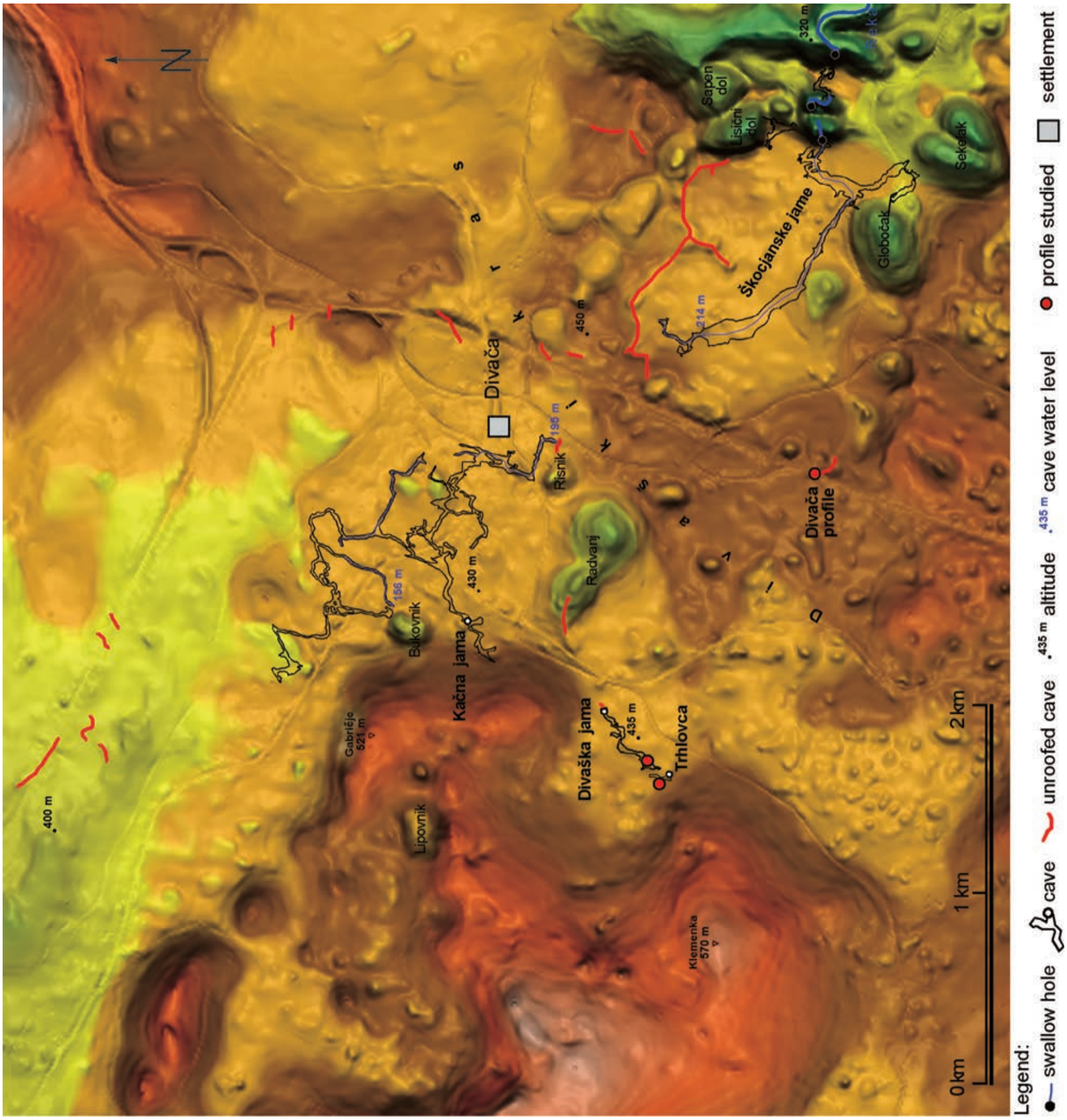

Figure 20 *Divaški kras with deep collapse dolines and ground plans of Divaška jama, Kačna jama and Škocjanske jame.*

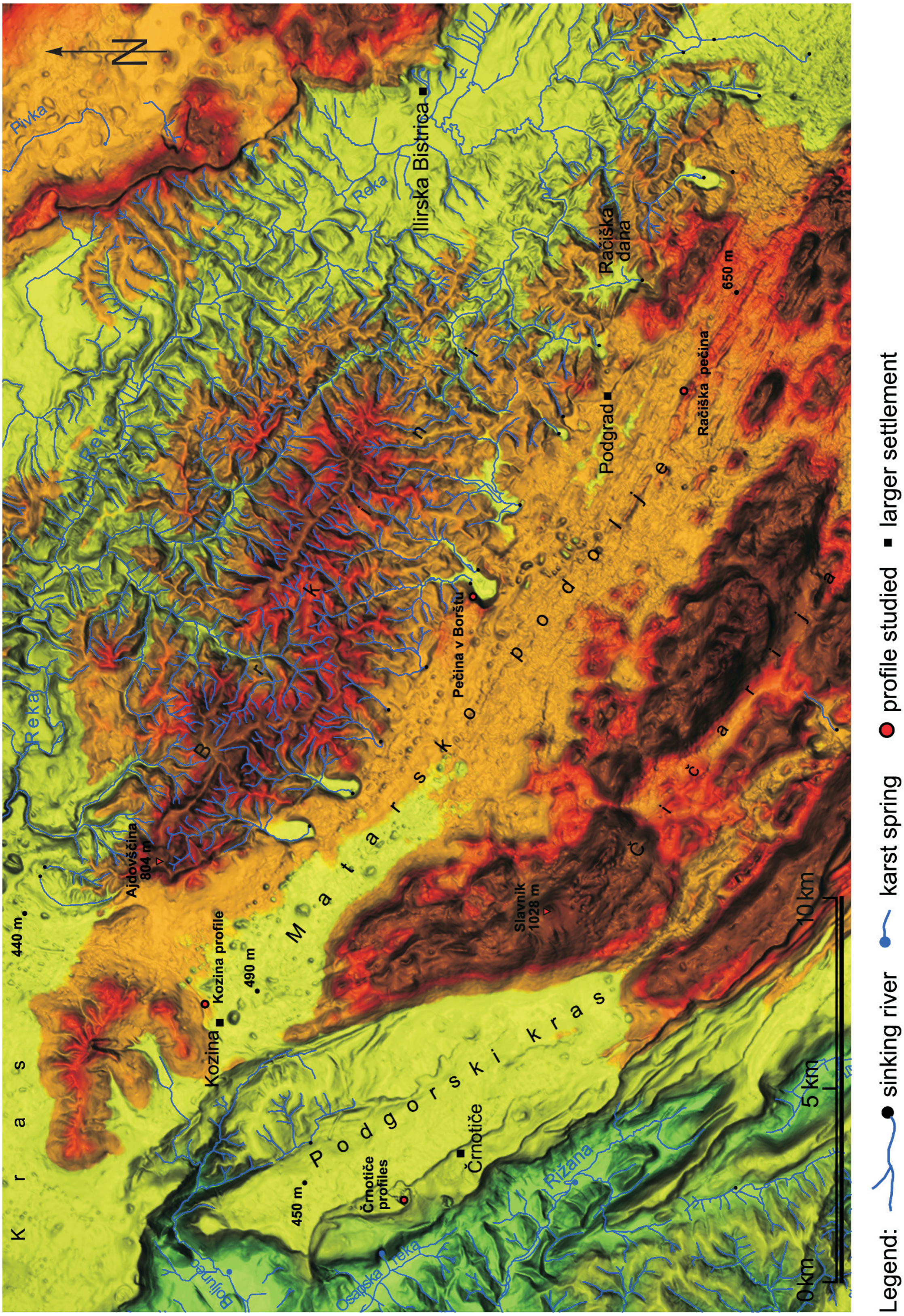

Figure 21 *Matarsko Podolje and Podgorski kras (SW Slovenia). Well expressed are blind valleys on the NE edge of Matarsko Podolje, where small brooks sink into the karst.*

by karst denudation. There are outstanding karst features covering an area of 32 km^2, including ponors of the Reka river and two smaller streams, 15 large collapse dolines, 64 caves, among them Škocjanske jame, Kačna jama, Divaška jama and Trhlovca, plus hundreds of dolines. The Reka river sinks in Škocjanske jame and flows into Kačna jama. Explored passages of Divaška jama and Trhlovca are situated some 200 m above the underground water course and contain a lot of fluvial sediments. A number of fossil caves completely filled with sediments were uncovered during the highway construction in the area.

KARST OF MATARSKO PODOLJE

The Matarsko podolje is a 20 km long and 2–5 km wide flat valley-like karst surface between mountain Slavnik and the Brkini hills (Fig. 21). The surface is not an erosional plain as cross-sections indicate south-westwards inclination of the bottom, dissected by a number of dolines. The longitudinal section shows that the surface gently rises from about 490 m a.s.l. at Kozina village (in the north-west) to 650 m a.s.l. on the south-eastern end. The lowered surface continues to the south-east.

The Brkini hills are composed of marls, quartz sandstone and conglomerates dissected by the fluvial relief. Contact karst with 17 sinking allogenic streams from the Brkini hills characterises the podolje margin along their contact with the Cretaceous and Palaeogene limestones. The allogenic discharge into the karst is responsible for creation of several large blind valleys and large caves filled with allogenic sediments (Mihevc 1993, 1994). Streams sink at 490 to 510 m a.s.l.; some can be followed in accessible caves down to terminal sumps at 370 to 430 m a.s.l. The deepest cave is 150 m in depth, and the longest is more than 6 km.

More than hundred vadose caves are known in the karst plain. Great oscillation of karst ground water was observed. Water tracing showed that the sinking streams flow to three groups of springs: (1) submarine springs along the coast in the Kvarner Bay on the south, (2) springs in Istria on the south-west, and (3) the Rižana springs at 70 m a.s.l. on the west (Krivic et al. 1987; see Fig. 280).

PODGORSKI KRAS

The Podgorski kras (Podgora karst) is about 5 km wide and up to 15 km in length, an erosional karst plateau between Slavnik mountain (1025 m a.s.l.) on the north-east and littoral hills of the Koprska brda on the south-west (Fig. 21). The plateau represents the continuation of the Kras towards the south-east, but is separated from it by an important tectonic line with a drop of about 50 m.

The area belongs to the Čičarija imbricated structure (Pleničar, Polšak & Sikić 1973; Placer 1981). Several flysch and limestone thrust slices are elongated in NW–SE, with a dip of about 20–30^o towards the north-east. The structure resulted from the sub-thrusting of Istria since the Middle Miocene (Placer 2007). The sub-thrusting is well expressed in the relief as an escarpment at the south-western edge of Podgorski kras, where carbonate rocks are thrust over marl and flysch. The alternation of limestones and flysch sequences underground is not completely impervious. The principal subsurface water routes cross the structure, draining an extensive karst area to the Rižana and Osapska reka springs near the coast at about 50 m a.s.l.. The maximum spring discharge is several m^3•s^{-1}.

The plateau is planed at 500 to 450 m a.s.l. Only small allogenic surface streams exist on its surface and they sink at the carbonate/flysch contact karst zone. Numerous shallow dolines with flat bottoms in which some sediments are preserved represent the principal surface karst forms. There are also several unroofed caves, remnants of larger cave systems indicating that the karst is ancient. Old caves both, empty and filled, are dissected by younger vadose invasion shafts in places. Shaft development is associated with the lowering of the karst water level, which now lies about 200–300 m below the surface, and with the evolution of the vadose zone.

A total of 92 caves are known on the plateau. Their maximum depth reaches is up to 150 m. One cave follows a sinking stream, but none of them reach the main ground water level discharging towards the springs.

KARST OF NOTRANJSKA

The karst of Notranjska (Inner Carniola) is not single distinct karst unit, but rather a large proportion of the central and highest parts of the Dinaric Mountains. It displays different geomorphic units such as high-karst plateaus, planated surfaces at lower positions, small flysch basins with sinking rivers, and karst poljes (Fig. 22).

The area is composed of Triassic to Palaeogene limestones and dolomites and some smaller areas of Permian and Eocene non-carbonate rocks. Complex tectonic structure is typical for the region, which consists of sheets thrust one over the other from the south

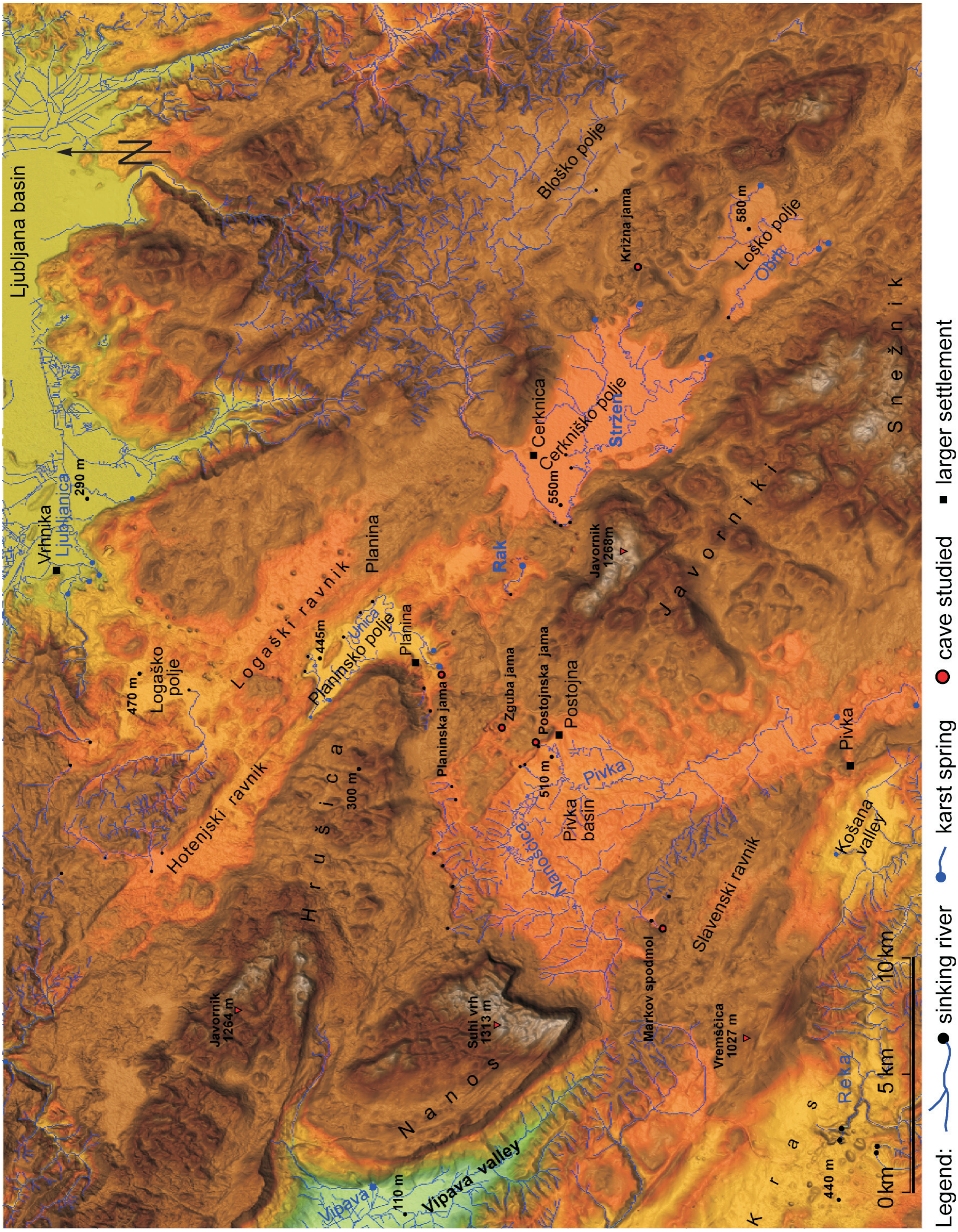

Figure 22 *Notranjski kras with karst poljes (Planinsko, Cerkniško, Loško) along Idrija fault.*

(Hrušica and Snežnik thrust sheets). The main tectonic patterns of the area are Dinaric trends (NW–SE) and cross-Dinaric faults.

Most of the area is drained underground. Surface streams formed on dolomite or non-carbonate rocks sink when they reach the limestone. Water appears in poljes during high levels of the karst water. The area is drained to springs of the Ljubljanica river at 300 m a.s.l. at the edge of the Ljubljana basin near Vrhnika village. A lesser part in the west is drained by springs of the Reka river.

High-karst plateaus of Hrušica, Javorniki, Nanos and Trnovski gozd at 800 and 1400 m a.s.l. are the highest parts of the Notranjska kras, with masses such as Snežnik mountain (1796 m a.s.l.) rising from them. The surfaces of the high plateaus are dissected by conical hills and large karst depressions. All precipitation is drained directly into the karst. Numerous deep vadose shafts are known but no horizontal caves have been discovered.

The High-Dinaric plateaus are dissected by lower and generally level karst surfaces at 400 to 700 m a.s.l. that contain dolines and small conical hills. The modern karst water table lies about 50 to 200 m below the surface. There are numerous caves, but vadose shafts prevail. Some of them lead to large river passages or to caves draining karst poljes. There are also relicts of old horizontal caves, some of them containing fluvial sediments.

Karst poljes are developed in the lowest parts of the area, where karst water tables appear at surface and contribute to lateral corrosion. Because of their low elevation, the poljes represent the confluence area waters from wide catchment areas. The largest cave systems in the area were formed at polje margins by emerging or sinking rivers. Loško, Cerkniško and Planinsko poljes are the largest ones in the area.

There are some smaller basins on non-carbonate rocks. The Pivka basin (named after river that sinks in Postojnska jama), is the largest. Water flows in three different directions from the basin; the main outflow is through Postojnska jama to springs of the Ljubljanica river, and lesser flows are into the Vipava and Reka rivers.

The karst of Notranjska can be divided into smaller karst units on the basis similar morphostructural, speleological and hydrological characteristics and evolution.

POSTOJNSKI KRAS

Postojnski kras (Postojna karst) lies between the Pivka basin on the west and Planinsko polje on the north-east (Figs. 23 and 22). The two high-karst plateaus of Javorniki and Hrušica are to the south and north respectively. The karst surface is at 600 m a.s.l. above the sinks of the river Pivka and over 700 m a.s.l. at its highest elevation. In general, the surface is about 100 m above the Pivka basin.

The area belongs to the External Dinarides, being a part of the Snežnik thrust sheet, which is divided on the north-east by the Idrija fault from the Hrušica tectonic unit of Notranjsko podolje (Placer 1999). The overthrust tectonics and folding began at the Eocene/Oligocene boundary and continued during the Miocene and Pliocene (Placer 1981). Overthrusting was from the southwest. The fold axes are perpendicular on it, i.e. of the Postojna anticline and Studeno syncline. The anticline crest is fractured parallel to the axial plane (Čar & Gospodarič 1984). NW–SE-trending fault zones, not belonging to the thrust deformations (Placer 1981), are neotectonic.

The Postojna karst lies between two dextral strike-slip faults zones of the Dinaric trends, the Idrija and Predjama faults (Placer 1996). Čar and Gospodarič (1984) determined four different generations of Neogene to Quaternary disjunctive fault zones, which are accompanied by crushed, brecciated and N–S-trending fissured zones as well as by cross-Dinaric trends. Dinaric faults together with reactivated cross-Dinaric faults represent the youngest trends (Rižnar 1997). The Postojnska jama system is developed in the ~800 m thick Upper Cenomanian and Turonian to Senonian limestone unit (Buser, Grad & Pleničar 1967).

The surface displays only karst morphology, i.e. numerous dolines and large collapse dolines. There are no traces of surface flow. Lower relief is linked only with linear features developed along Dinaric faults. These faults predisposed the general position of collapse dolines and collapses in cave passages (Habič 1982).

Pivka river and several lesser streams have created some contact karst (Mihevc 1990). Streams on the northern side are small and sink immediately at the flysch/limestone contact; some small and short caves are accessible. The Pivka river has a mean annual of 5.2 $m^3 \cdot s^{-1}$ and has created a large blind valley Risovec, along the limestone contact, with a floor at 530 m a.s.l. The most recent sink is entrenched by slope retreat at 510 m a.s.l. Postojnska jama is the main draining route from the Pivka basin to Planinsko polje. The cave system has more than 20 km of passages developed between 529 m a.s.l. (the paleo-Pivka ponors) and 477 m a.s.l., the terminal sump. There are also some smaller horizontal caves at higher elevations, but they probably resulted from smaller rivers and do not represent past main drainage routes from the Pivka basin.

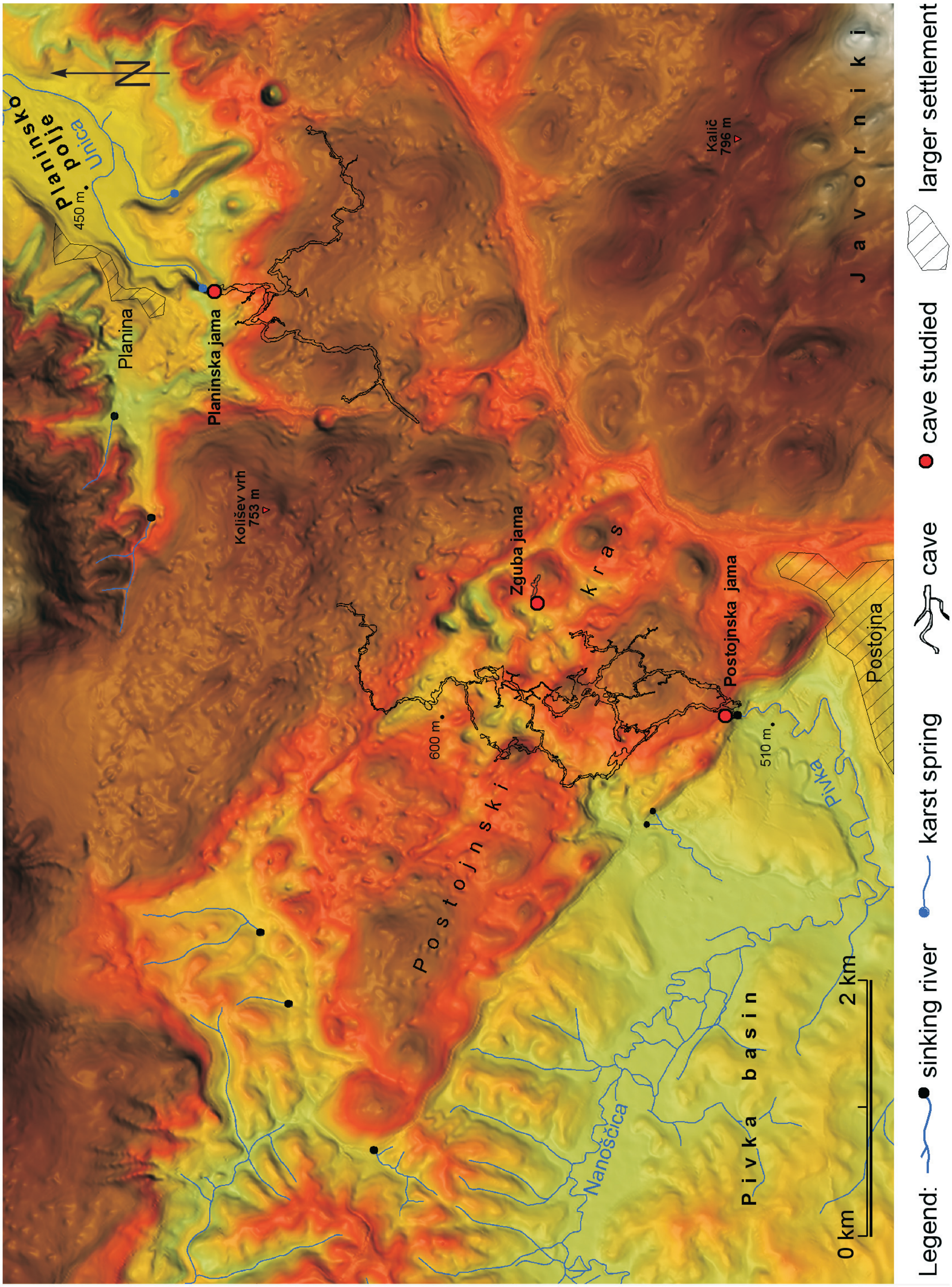

Figure 23 *Postojnski kras; karst between Postojna and Planinsko polje with ground plans of Postojnska jama and Planinska jama.*

SLAVENSKI RAVNIK

Slavenski ravnik is a nearly planed karst surface located between the flysch of the Pivka basin in the north, Vremščica (1027 m a.s.l.) in the west, Košana valley in the south and karst part of the Pivka basin in the east (Fig. 22). It is a part of the Komen thrust sheet (Placer 1981). In the north-east it is composed of Palaeocene limestone and limestone with chert, while the main part of the area consists of Cretaceous limestones (Buser, Grad & Pleničar 1967). The general dip of these thick-bedded limestones is towards the north-east.

The larger part of this surface lies between 550 and 650 m a.s.l., with some higher summits at its border. A series of ridges above the Košana valley in the south reaches more than 800 m a.s.l., while in the east and north sides they extend to ~700 m a.s.l. The surface of the karst plain is uneven, dissected by many dolines and uvalas. Contact karst with three blind valleys is developed along its northern border with the flysch.

There are known 80 caves, most being shallow and short. The average depth reaches only 20 m and the deepest is 79 m. Vodna jama v Lozi is the longest cave with 6 km of active epiphreatic passages descending to a depth of 75 m. It is connected with Markov spodmol via a sump. There are many remnants of horizontal cave systems with passages blocked from the surface. Modern stream caves are situated at the depth of about 100 m below the surface.

Several unroofed caves are found on the surface. The largest one, 3 km long, at about 560 m a.s.l. is the remains of a large cave with up to 20 m wide passages filled with speleothems and fluvial sediments transported from the flysch.

There are no surface flows today. Many streams from the Pivka basin sink at the limestone boundary (Mihevc 1990). Water tracing tests showed that waters coming from the north and sinking at the Ravnik border flow underground towards the Timavo springs at low water levels. There are several blind valleys on the northern part of the Slavenski ravnik. Two of them are relict and one is active, i.e. Sajevški potok sinking in the Markov spodmol. The formation of large blind valleys at higher elevations shows that the Slavenski ravnik was the principal outflow from the Pivka basin for a long time and that this role is now taken over by the Postojnski kras.

KARST OF KRIŽNA JAMA

The Križna jama karst is developed in the belt of lower relief that formed in the Idrija fault zone between two karst poljes: Loško polje on the south-east with a floor at about 570 m a.s.l. and Cerkniško polje on the north-west at about 550 m a.s.l. (Fig.22). The relief includes conical hills (the highest one is Križna gora, 856 m a.s.l.), closed depressions, and numerous dolines. The hills rise 150–200 m above depressions. Some of the latter have wide flat bottoms resembling small poljes. They developed at same altitude as Cerkniško polje, where important karst springs are located.

There are numerous shafts and caves, two of them being large and important. Križna jama is 8.2 km long cave system with an extensive principal passage and tributaries. It contains an underground river flowing from Bloško polje that disappears into deep sumps and reappears in springs at the edge of Cerkniško polje. The entrance parts of the cave are dry with thick layers of sediments preserved in them.

DOLENJSKI KRAS

The karst of Dolenjska (Lower Carniola) is an area between the Ljubljana Moor, Krško, Dobrepolje and Želimlje depressions and Gorjanci mountains (Fig. 24); it is also described as covered lowland karst of Dolenjska (Gams 1974; Kranjc 1990).

Tectonically the area corresponds to the eastern part of the Hrušica thrust sheet, which is the part of north-eastern External Dinarides (Placer 1999). The rocks are Triassic to Cretaceous shallow marine carbonates overlain by up to few meters thick Pliocene-Quaternary deposits and soils in places (Pleničar & Premru 1977). Dolines, uvalas, karst poljes and rounded hills predominate in the relief. The surface is covered with a thick layer of red karst soil due to the low elevation. The red soils above dolomites are thicker and more cohesive than those above limestones (Gams & Vrišer 1998). The river Krka cuts the shallow canyon into the edge of the karst surface.

GEOLOGY AND GEOMORPHOLOGY OF ALPINE AND ISOLATED KARSTS

JULIAN ALPS

The Julian Alps consist mostly of the Upper Triassic so-called “Dachstein Limestone” and dolomite, forming a succession of more than one thousand meters of shallow-marine carbonates. Deeper marine sediments, carbonates and siliciclastics of Early and Middle Jurassic, are preserved only in small patches. Late Cretaceous flysch terminated marine sedimentation in the area, but there are some Oligocene marine depos-

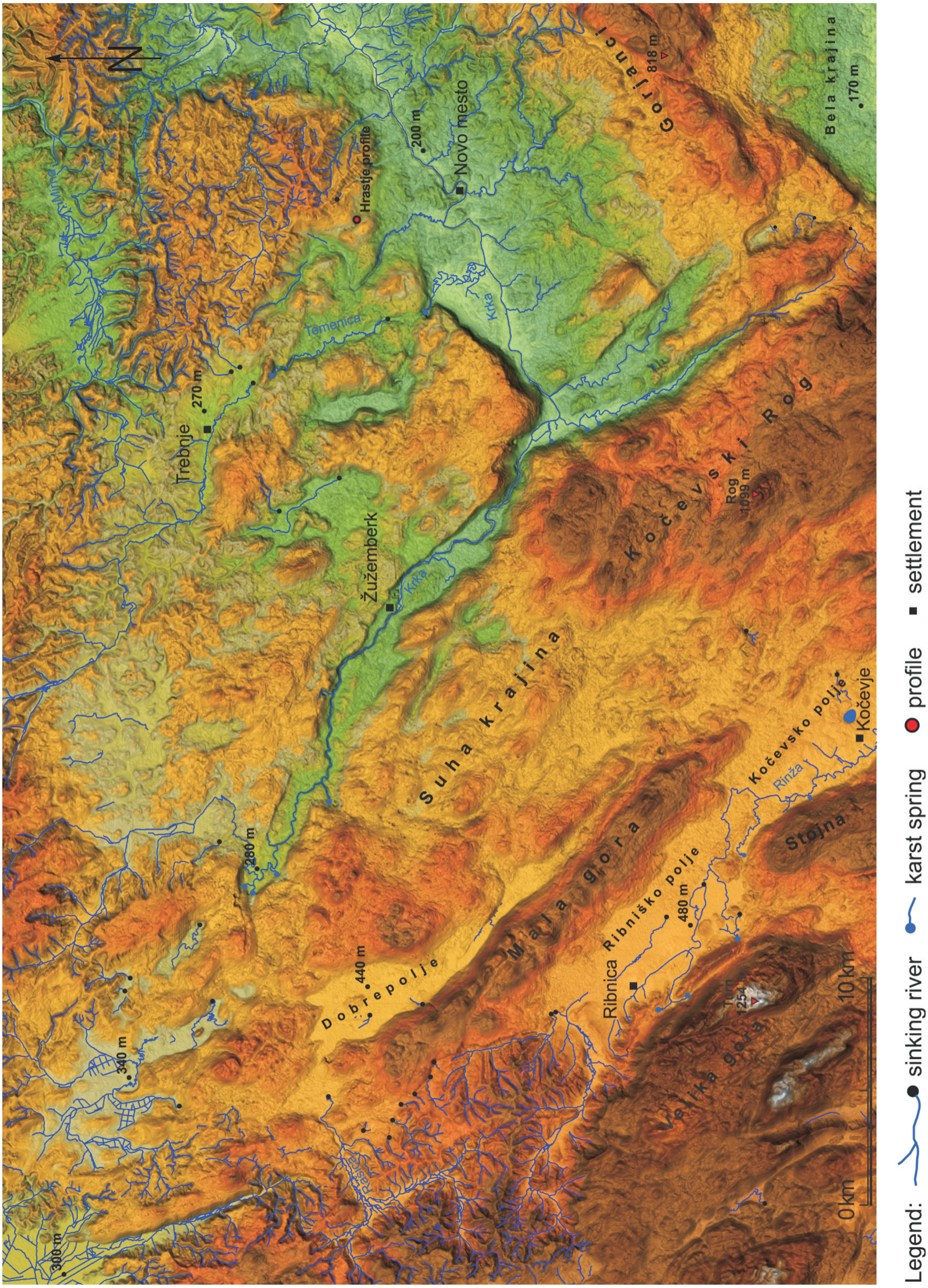

Figure 24 *Dolenjski kras is karst area in the SE part of Slovenia.*

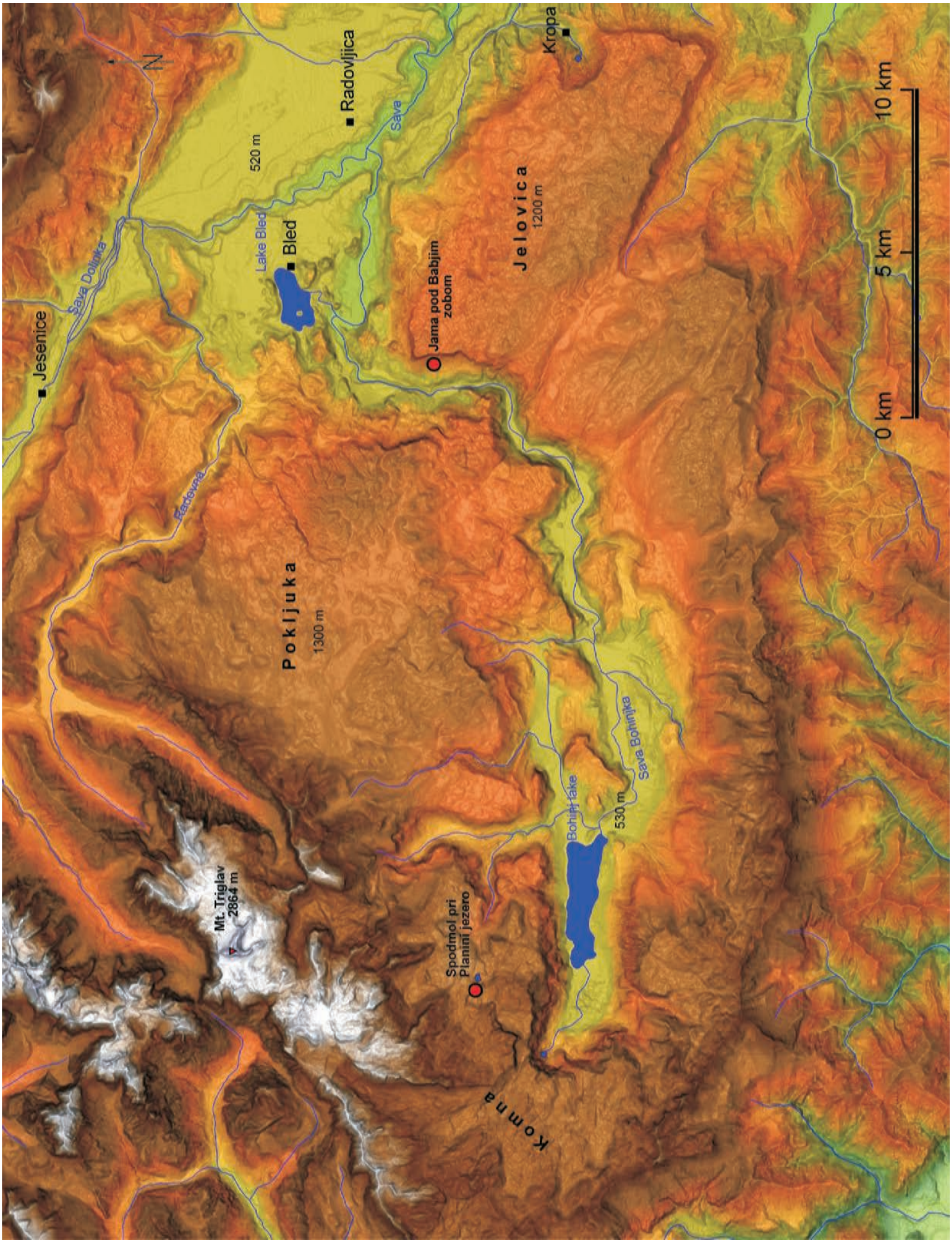

Figure 25 *Julian Alps (NW Slovenia) with high karst plateaus Pokljuka and Jelovica.*

its in the surroundings of Bohinj lake. Late Palaeozoic siliciclastics and carbonates outcrop at the northern boundary. They are the basement of the major Julian thrust sheet, which is thrust over the Tolmin thrust sheet (the supposed Slovenian Basin; Placer 1999). The Tolmin thrust sheet is thrust over the Trnovo thrust sheet, which includes the so-called Intermediary karst in the western part of Slovenia.

The modern network of fluvial and glacial valleys is filled with Quaternary sediments. The northern part of the Julian Alps is deeply incised by the Soča and Sava valleys and their tributaries with sharp ridges and high peaks between. The high karst plateaus of Komna, Pokljuka and Jelovica (Fig. 25) are farther to the south the latter separated by the deep Sava canyon. The plateaus and other surfaces are without surface waters. Karst springs appear in the bottoms of the valleys. There are numerous closed depressions, dolines and deep vadose shafts but horizontal caves are only few. The high plateaus and valleys were glaciated. Glaciation only slightly transformed the pre-glacial karst landscape.

KAMNIK-SAVINJA ALPS

The Kamnik–Savinja Alps include Julian thrust sheet Early and Middle Triassic limestones and dolomites (Savinja Alps sector) and the Tolmin thrust sheet of alternating sediments (carbonates, sandstones, marls) and volcanics (keratophyre, porphyre and diabase) of the same age (Kamnik Alps sector – Placer 1999).

Tributaries of the Sava and Savinja rivers have dissected the mountains into narrow ridges and valleys. The karst plateaus of Velika planina, Menina and Dobrovlje are found on the south-east. Remnants of several horizontal caves are preserved, but deep shafts prevail. Fluvial sediments can be found in some horizontal caves, e.g., Potočka zijalka and Snežna jama na Raduhi. These sediments were deposited by sinking rivers before the main valley entrenchment that followed the fast tectonic uplift of this part of Alps.

The Raduha massif (Fig. 26) is an eastern carbonate promontory of the Kamnik–Savinja Alps. Deeply entrenched valleys separate it from other mountain ridges, i.e. the river Savinja and its tributaries from the Kamnik-Savinja Alps on the west, tributaries of the Meža river from the Karavanke ridge on the north, and less distinctive valley of the Lakovnikov potok from the mountain Smrekovec on the east. The Raduha massif is a carbonate ridge about 8 km long overlying non-carbonate basement. There are steep slopes on the southern and eastern sides and rocky walls several hundreds meters high on the northern side.

The Raduha ridge is an uplifted block of massive and thick-bedded Upper Triassic limestone. Lower Triassic sandstones, shales and thin bedded limestones occur to the north. Upper Oligocene andesitic tuffs and tuffites on the east constitute the mountain Smrekovec (Fig. 251). Strong tectonic activity along the Periadriatic fault, north of the Raduha massif, after Oligocene times caused dextral slip faulting, folding and strata tilting as well as general and differential uplift (Mioč 1997; Fodor et al. 1998). This provoked strong erosion in some areas removing Oligocene cover from the Triassic sequences.

Several caves, mostly deep shafts, are known in the massif. Snežna jama (Snow Cave) is the most extensive. The waters that infiltrate into the Raduha karst reappear in karst springs in the Savinja valley at about 580 m a.s.l. (Fig. 251).

PONIKOVSKI KRAS

The Ponikovski kras (Fig. 26) is an isolated karst about 40 km^2 between two pre-Alpine tectonic basins, the Celje basin to the south and Velenje basin to the north. The area is formed by a variety of rocks. Upper Triassic limestones and Oligocene andesite tuffs, volcanic and limestone breccias prevail (Buser 1978).

There are valleys of the Paka and Savinja rivers to the west and Pirešica river to the east. The landscape is composed of a mixture of karst and fluvial elements between 470 and 560 m a.s.l. Small karsts plateaus or ridges, dolines, blind valleys and caves are interspersed with non-carbonate rocks with fluvial landforms. There are several small rivers sinking into the karst and then emerging on the other sides of ridges. The fluvial valley thalwegs are controlled by the elevations of ponors or springs, thus the whole area is morphologically affected by the karst.

VELENJE BASIN

The Velenje basin (Fig. 26) is a tectonic depression about 5 km wide and 10 km long between Ponikovski kras on the south and Paški Kozjak mountain ridge, (part of the Alps), on the north. The surface of the basin is at 460 m a.s.l. on the southern side, where the river Paka flows through it. Gentle fluvial relief formed in young sediments that were deposited by small rivers flowing from the Alps occurs toward the north. The basin is filled by about 1,000 m of Pliocene and Quaternary lacustrine and fluvial sediments. It is a typical pull-apart basin (Vrabec et al. 1999) formed

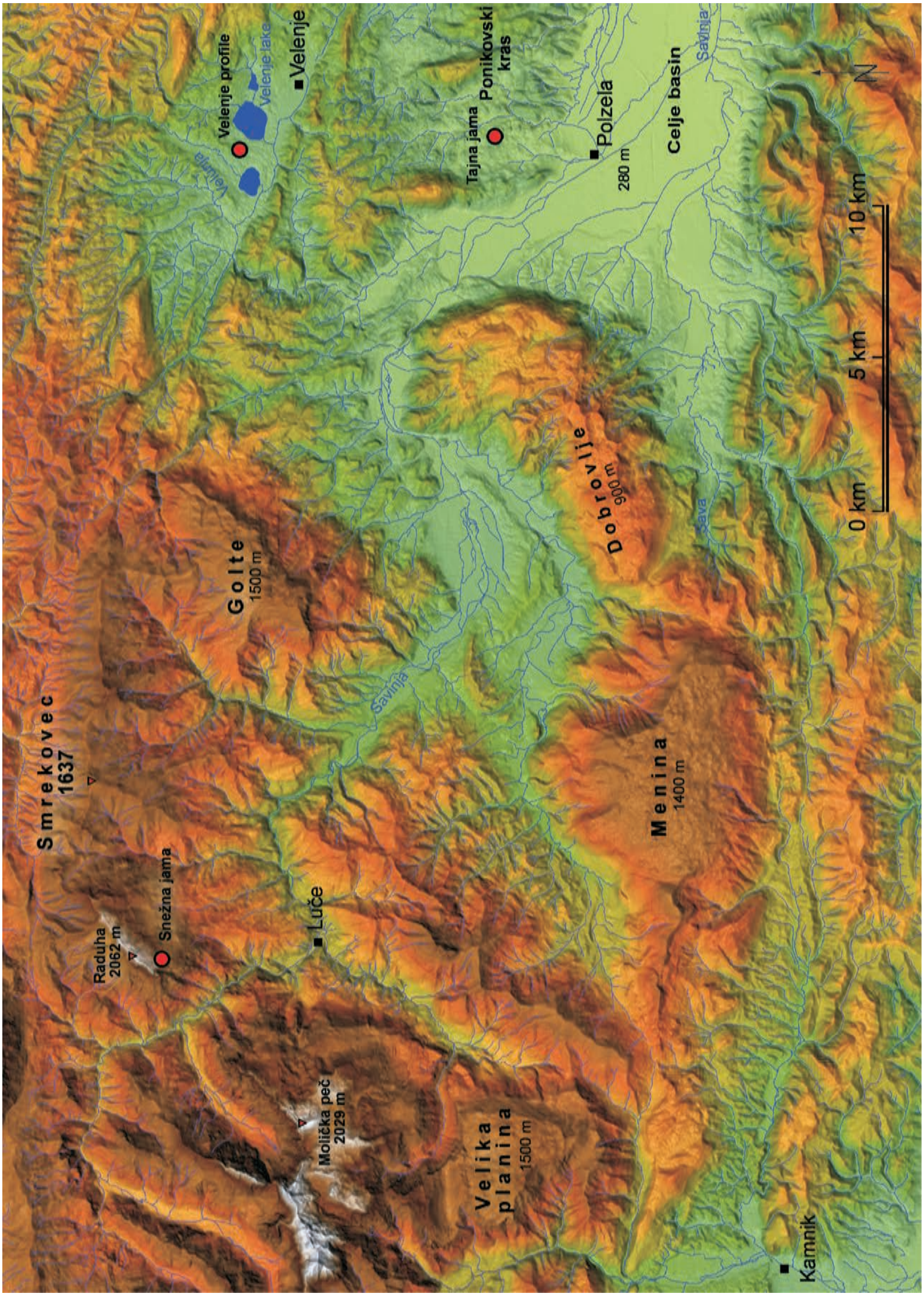

Figure 26 *Savinja Alps, Velenje and Celje basins (N – central part of Slovenia).*

along faults of the Periadriatic fault system (Vrabec, Pavlovič Prešeren & Stopar 2006). Still active dextral strike slip along Šoštanj fault (Vrabec 2005) is the most important element in the formation of the basin. Thick coal beds indicate the slow and continuous subsidence of the basin. Its bottom consists mainly of Lower Triassic dolomite on the northern side and Oligocene tuff on the southern side (Mioč & Žnidarčič 1977). Pliocene silts with a basal coal bed overlie the basement. Pliocene mudstones and sands and Quaternary fluvial sediments terminate the sedimentary sequence. Quaternary sediments filled the lake from the north.

ČRNOTIČE QUARRY

SITE LOCATION AND CHARACTERISTICS

The Črnotiče and Črni Kal quarries are situated on the western margin of the Podgorski kras (Fig. 20), ca 6 km from the Adriatic coast (Figs. 18 and 27). Črnotiče Quarry is about 40 m deep and has an area of about 300 by 300 m carved in the levelled surface at an elevation of 440 m a.s.l. (45°33´57″N, 13°52´48″E). The plateau is on Eocene bedded alveolinid and nummulitid limestone and narrow zones of flysch in imbricated structure with dips of about 20–30° towards the north-east (Pleničar, Polšak & Šikić 1969; Fig. 28). A total of 92 caves are known on it, with maximum depths up to 150 m. Numerous caves have been opened during the Črnotiče Quarry operations. Most of them were completely filled by sediments. Two types of caves can be observed in both quarries: (1) old horizontal caves with flysch-derived allogenic fluvial fill, and (2) vertical shafts filled only by autochthonous angular gravel, bone breccia, and terra rossa-types of soils. An 80 m deep shaft was opened in 1991 in the northern part of the quarry at about 400 m a.s.l. This shaft, with a volume of several thousands of cubic meters, remains unexplored. Other shafts opened in the western part of the quarry were filled by gravel with a matrix of terra rossa-derived clayey sediments. Stalagmites and stalactites covered the walls. Broken speleothems and numerous large mammal bones occurred in the gravel. The bones have not been studied yet. The gravel was cemented in places, calcitic cement being dated by the Th/U method to 211 ± 45 ka (Mihevc 2001b).

A cave inclined from the north-west to south-east and about 200 m long was opened progressively by quarry operations in 1990–1998 (Fig. 29). In successive years it was quarried away. It was not possible to contour the cave shape precisely owing to strong impacts of blasting. Only remains are left today in the faces on the edge of the quarry (Fig. 30). The cave represented a relic of a huge passage with the diameter of about 10 m and about 7 m wide and more than 17 m high. The passage was filled by allogenic fluvial cave sediments overlain by several meters thick flowstone and some collapse material. The flowstones extended up to the present surface where they were exposed by karst denudation as an unroofed cave. The cave is a relict of the old cave system that was formed by a sinking river flowing from the flysch.

Two profiles from the cave were studied (Fig. 30). The first, Črnotiče I, was situated in the main cave passage and was destroyed shortly after documentation. Črnotiče II profile was situated in a side passage at least 17 m high and filled by cave fills. It was opened by the quarry operation later.

The Črni Kal Quarry is situated on the slopes be-

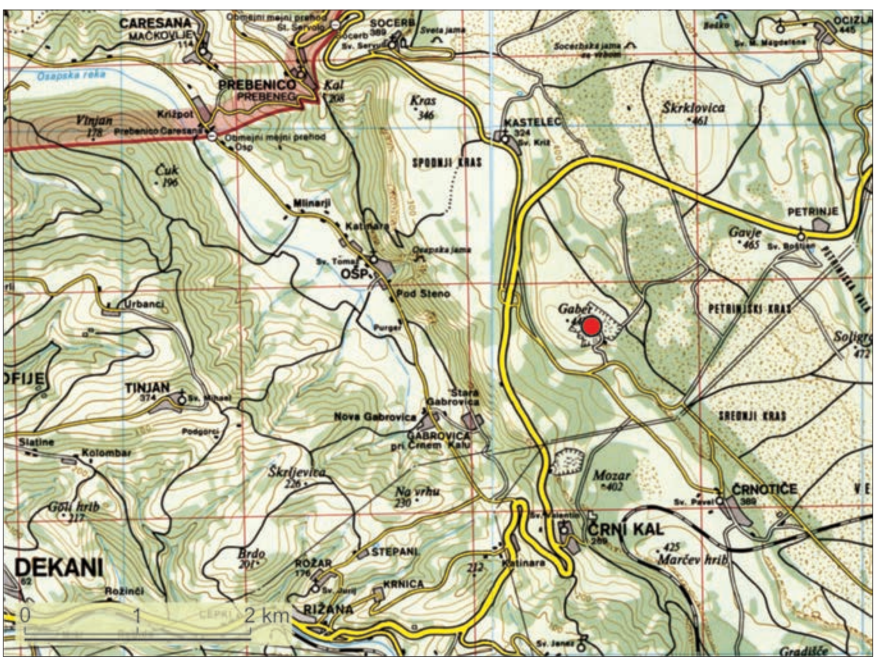

Figure 27 *Location of Črnotiče Quarry where Črnotiče I and Črnotiče II profiles were studied.*

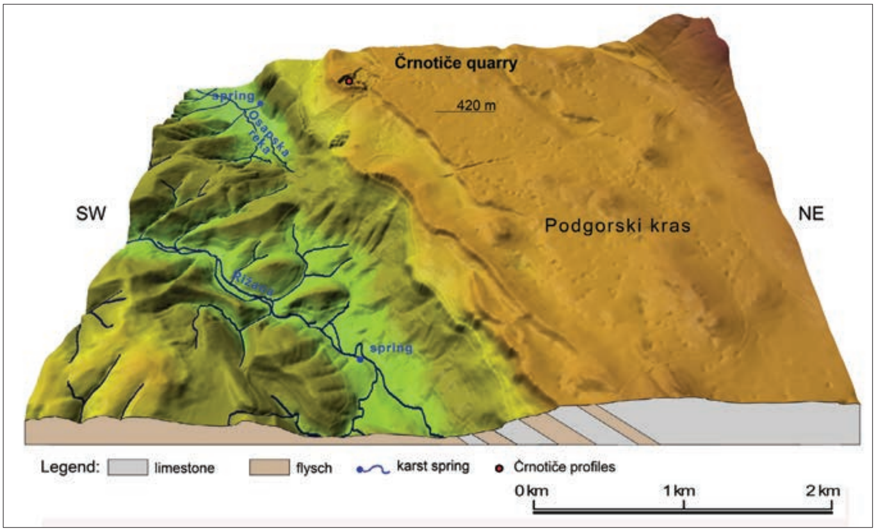

Figure 28 Schematic cross-section of the Podgorski kras with idealised geological structure and location of the Črnotiče Quarry.

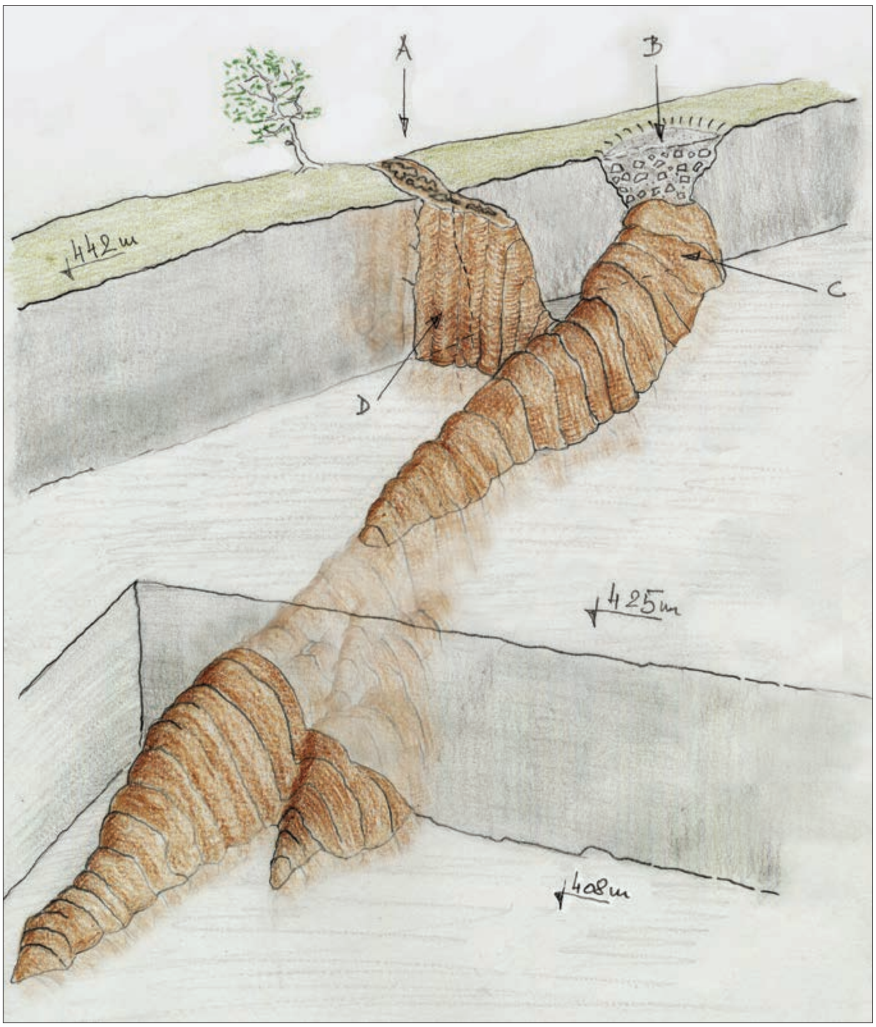

Figure 29 *Reconstruction of filled cave passages from Črnotiče Quarry. Legend: A – part of the unroofed cave; B – collapse of a cave roof; C – location of Črnotiče I profile; D – location of Črnotiče II profile.*

low the plateau itself, about one km to the south of the Črnotiče I at about 350 m a.s.l. (Fig. 27). Both horizontal caves and vertical shafts have been uncovered. A horizontal cave with Palaeolithic tools and Pleistocene large mammal fauna was discovered in 1955 on the southern side of the quarry (Rakovec 1958; Brodar

Figure 30 *Quarry bench with caves filled by sediments: Črnotiče II profile (left) and Črnotiče I profile (right).*

1958). Other three sites yielded Middle and Late Pleistocene small mammals (Aguilar et al. 1998). Gravel and terra rossa-type clays filled shafts. A carbonate cement in the gravels was dated by the Th/U method to 143 ± 13 ka (Mihevc 2001b).

ČRNOTIČE I

PROFILE LOCATION AND CHARACTERISTICS

The profile was located in the main passage opened by the quarry, about 10 m below the surface. The cave was a relic of a huge passage with the diameter of about 10 m (Fig. 29). In the eastern part, it was open up to the surface but in the western part the ceiling was still preserved (Fig. 30).

The passage was completely filled by cave sediments deposited over massive flowstones, which were several meters thick. The flowstone extended up to the present surface where it was strongly disintegrated. Gravels and conglomerates were preserved and mixed up with sand and clay on several places. Poorly rounded pebbles, up to 4 cm in size, consisted of Palaeocene limestone and flysch siliciclastics. Laminated yellow brown clays were present also in places. Stalagmites and stalactites fragments occurred within the sediment. The upper part of the profile was composed of reddish clays. Samples for palaeomagnetic analyses were taken from the upper part of cave fill, about 4 m below the surface of the karst plateau (here about 435 m a.s.l.; Bosák et al. 1999).

LITHOLOGY

The profile consisted of two parts: **(1) an older sequence** composed of coarsely re-crystallised speleothems, and **(2) a younger** sequence of laminated to banded carbonate rocks with intercalations of red clays (Figs. 31 and 32). The **older sequence** was built of nearly white, very coarse-grained, re-crystallized speleothem masses with distinct stalagmites completely surrounded by crystalline calcite. This sequence clearly continued to speleothems covering the walls of the host cave. The **younger sequence** filled a corrosional niche with a complex morphology carved in the older sequence (Fig. 33). The rocks were laminated to banded with an alternation of bands of different texture, structure and colour. Individual bands were often separated by disconformities developed either as single erosional/corrosional surfaces or as intercalations of red clays. The total preserved thickness of this sequence was about 175 cm. Laminated/banded carbonate rocks of the younger sequence are composed of several types of rocks: (1) massive bands of internally laminated carbonate rock with beige and light grey colour. Thin laminae of brown colour can locally occur. In places, small corrosional vuggy porosity can be developed. In one place the beige laminated flowstone is composed of columnar forms similar to stromatolites, separated by thin films enriched in clay; (2) bands of internally laminated carbonate rock of reddish brown, dark ochre and light brown colour, with a distinct content of impurities (clay, tiny concretions) and relatively abundant corrosional vuggy porosity; (3) band of calcite-cemented cave sediments, i.e. highly calcitized clay, layers composed of tiny dark-coloured

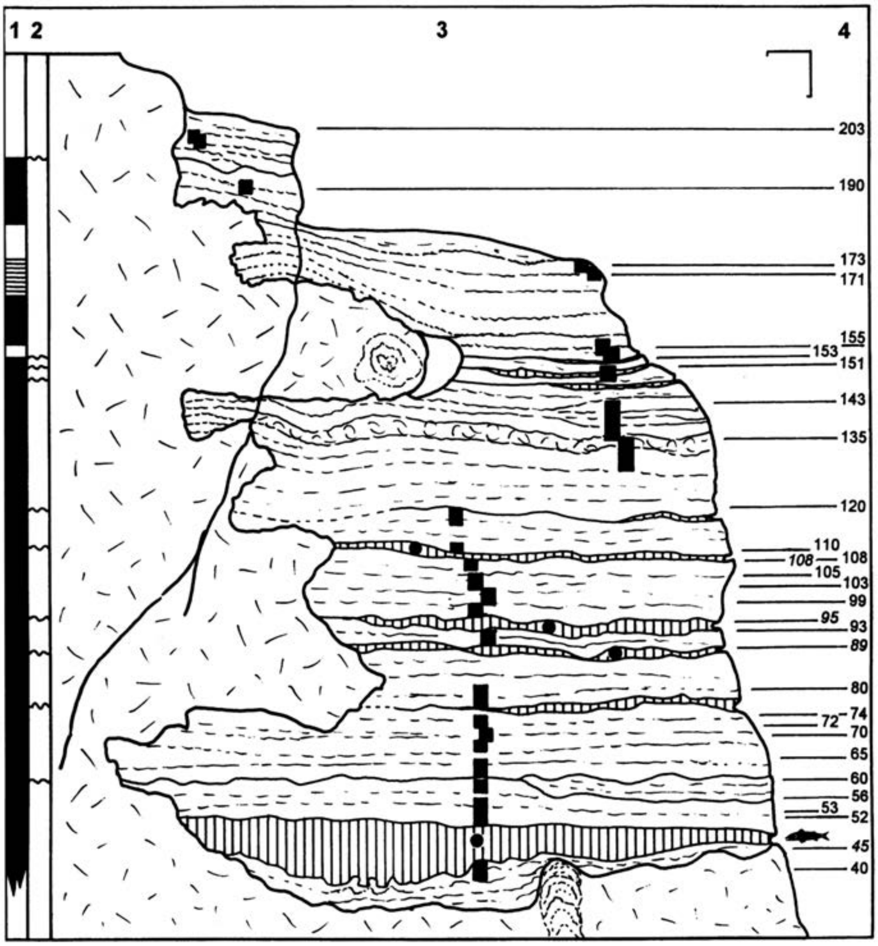

Figure 31 *Črnotiče I profile. Legend: 1– palaeomagnetic chart (black – normal polarized zone, white – reverse polarized zone, shaded – unknown polarity); 2 – erosional surfaces; 3 – lithological log; 4 – numbers of the samples; symbol – finds of fossils (from Bosák et al. 1999, with permission).*

concretions. Red clays form about 10 macroscopically distinct intercalations within the carbonate sequence; with thicknesses from several millimetres up to 16 cm. Rock surfaces overlain by clays were often corroded in detail, sometimes into uneven ridges. Clays were red to brownish red, macroscopically homogeneous; sometimes disintegrable to small pieces. Some layers were composed of irregularly shaped clasts of more lithified red clays. In places, internal cementation of clays resulted in irregularly shaped concretions. There were no coarse-grained admixtures. Clays contained numerous tiny ovate dark-coloured concretions (pellets) with lustrous surface (warnish-like coatings). They often form an admixture also in the banded carbonate rocks.

Four samples of clays were taken for analysis. Three were small, with weights of several decagrams as they were sampled from thin layers. The fourth sample from a 16 cm thick clay layer was collected in a larger amount, about 2–3 kg.

MINERALOGICAL AND CHEMICAL ANALYSES

The results of mineralogical analyses indicate relatively uniform mineralogical composition both of the red clays and the pellets. Quartz, smectite, vermiculite, kaolinite and gibbsite are the principal constituents, anatase with rutile are accessory. Common haematite is accompanied by some goethite. The composition is very similar to analyses of terra rossa type soils (*cf.* Bárdossy 1982, pp. 329–338). The pellets contain distinctly higher proportions of manganese-rich minerals (todorokite), in places. Relatively abundant vermiculite is not known from bauxites (Bárdossy 1982, p. 336), on the other hand, the content of gibbsite is remarkable.

The chemical composition of the pellets shows several important features. Central parts of some pellets are composed of clay minerals enriched in ferruginous substances with an outer zone of manganese compounds. Other pellets had nuclei of Mn-rich minerals, while their outer zones contained more kaolinite and especially Al-rich minerals. Ooidic internal structure is expressed clearly in chemical composi-

Figure 32 *View of the Črnotiče I profile (the younger sequence – laminated carbonate laminas with intercalations of red clays).*

tion: some laminae were enriched either in Mn-rich minerals or in Al-rich ones, the distribution of MnO and FeO + Fe_2O_3 within samples was very irregular, trend trends in Fe, Al and Si contents increased from outer zone to the centre and manganese amount decreased in the same direction. There is increased content of chromium in numerous analyses (0.10–0.41 % of Cr_2O_3), which can be typical for hypergenic zone – laterites and especially bauxites – where chromium is associated with aluminium as hydroxides of both metals precipitated at similar pH values. The increased Cr content can be linked with chromite found in the heavy mineral fraction in the Dimnice Cave (up to 8 %). The cave sediments were derived from Eocene flysch in the Brkini Mts., which contains up to 1 % of chromite (Zupan Hajna 1998). The chemical ratios of *Ki* (Harrassowitz 1926, i.e. SiO_2 wt. %/Al_2O_3 wt. % x 1.7) obtained for the pellets do not correspond to ratios typical of bauxites but to those typical for terra rossa, ranging from 0.9 to 2.43. Most values fall to span from 1.45 to 2.01. According to de Weisse (1948) *Ki* values from 0.5 to 2 are characteristic for terra rossa, although they can sometimes be higher or lower.

PALAEOMAGNETIC RESULTS

A total of 27 oriented laboratory samples were studied for their palaeomagnetic properties. The mean values of the J_n and k_n moduli are documented in Table 3. According to both values, the profile may be divided into three parts and categories. The sediments are characterized by a large scatter of NRM intensities (29–209 mA.m^{-1}) and MS values (403–4,738 x 10^{-6} SI units).

Figure 33 *Corrosional contact of the older sequence (coarse recrystallised speleothems) with carbonate rocks of the younger sequence in the bottom of Črnotiče I profile.*

Table 3 Mean palaeomagnetic values and standard deviations, Črnotiče I

Črnotiče I	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	55.517	1,128.4	2.03–1.20
Standard deviation	30.671	265.0	
Number of samples	11	11	
Mean value	151.937	3,420.2	1.10–0.74
Standard deviation	38.069	757.6	
Number of samples	8	8	
Mean value	53.244	1,029.5	0.72–0.40
Standard deviation	23.652	449.1	
Number of samples	8	8	

* from top to base

Samples are characterized by intermediate up to high J_n and k_n magnetic values.

Multi-component analysis of the remanence shows that the samples have a three-component RM. The *A-component* is undoubtedly of viscous (weathering) origin and can be demagnetized in a temperature range of 20 to (60) 120 °C. The *B-component* also has a secondary origin but shows harder magnetic properties which can be demagnetized in a temperature range of about 120 to 360 °C. The *C-component* is the most stable, with demagnetization in a temperature range of about 400 to 560 °C. The Fisher distribution displays two defined sets of samples with normal and reverse polarities. Stereographic projections of directions of normal and reverse palaeomagnetic C-component of samples are shown in Figures 34 and 35.

Mean palaeomagnetic directions are documented in Table 4. Owing to presence of three samples of the reverse polarity group, the calculated value of α_{95} (semi-vertical angle of the cone of confidence) is very high.

The principal palaeomagnetic and magnetostratigraphic data of the 27 samples are presented in

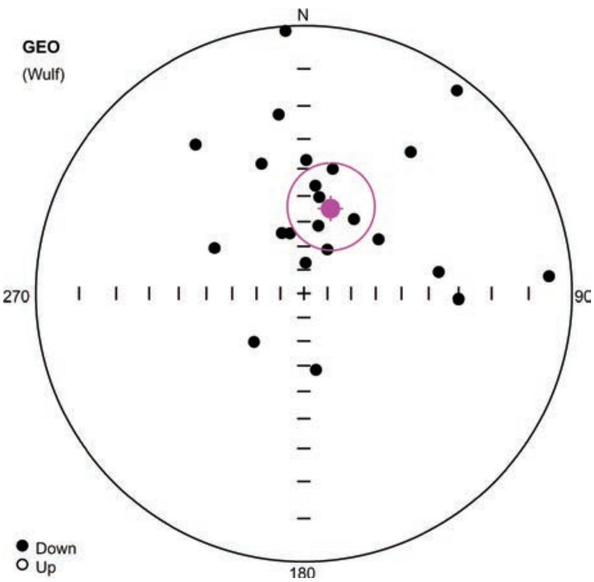

Figure 34 *Directions of C-components of remanence of samples with N polarity, Črnotiče I profile. Stereographic projection, open (full) small circles represent projection onto the lower (upper) hemisphere. The mean direction calculated according to Fisher (1953) is marked by a crossed circle, the confidence circle at the 95% probability level is circumscribed about the mean direction*.*

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*Footnote: *Figure explanation for Figures Nos. 35, 46, 47, 48, 60, 61, 66, 67, 75, 76, 80, 81, 91, 92, 100, 101, 112, 113, 122, 123, 142, 143, 150, 151, 156, 166, 168, 169, 175, 176, 183, 184, 190, 194, 199, 203, 210, 211, 213, 222, 223, 225, 232, 239, 240, 248, 256, 257, 264, 265 and 270.*

Table 4 Mean palaeomagnetic directions, Črnotiče I

Črnotiče I	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	17.38	53.28	14.12	4.27	23
	R	172.95	-31.07	48.02	2.83	3

Explanation: D, I – declination and inclination of the RM after dip correction; α95 – semi-vertical angle of the cone of confidence calculated according to Fischer (1953) at the 95% probability level; k – precision parameter; n – number of analysed samples*

Footnote: *Explanation also for tables Nos. 7, 10, 12, 14, 16, 19, 21, 24, 26, 28, 33, 35, 37, 39, 41, 44, 47, 50, 52, 54, 56, 58, 60, 62, 64, 66, 68, 72, 75, 77.

Figure 36 with the Legend to all the profiles of basic magnetic and paleomagnetic properties in Figure 37. Magnetostratigraphic investigations defined N and R polarity magnetozones. Magnetostratigraphic results indicate also one unknown polarity. The long N magnetozone was interpreted in the lower half of the log. The top part of the profile shows an R palaeomagnetic direction interrupted by two R magnetized zones.

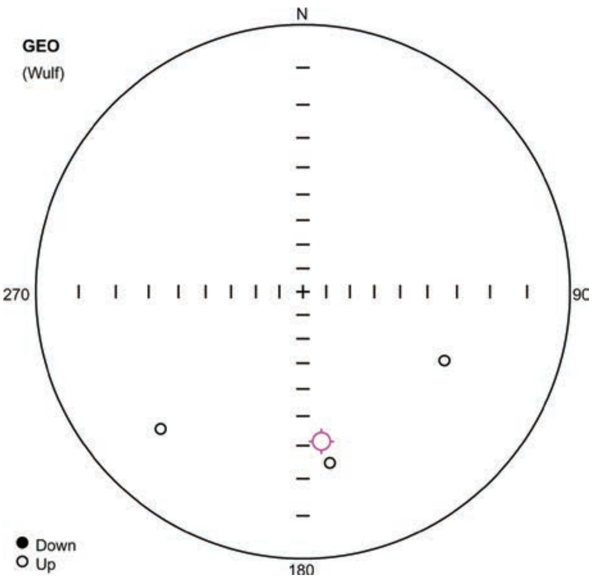

Figure 35 *Directions of C-components of remanence of samples with R polarity, Črnotiče I profile. For detail description see Figure 34.*

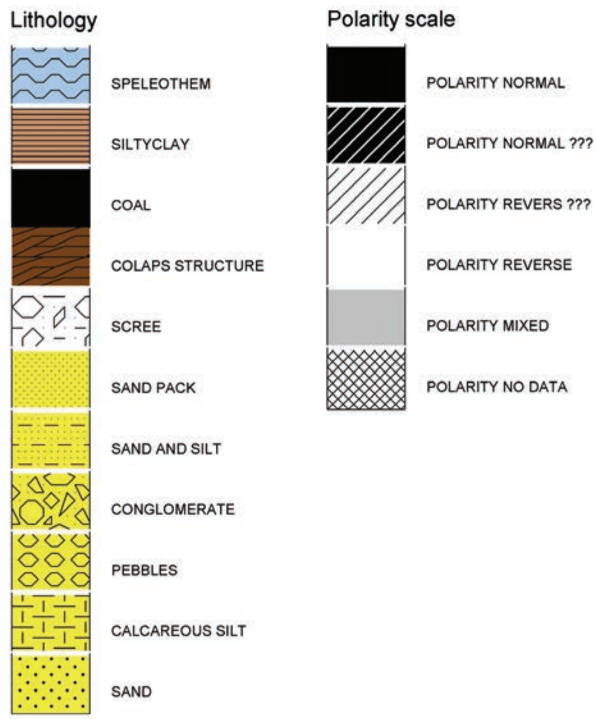

Figure 37 *Legend to all the profiles of basic magnetic and palaeomagnetic properties (figures Nos. 36, 62, 68, 77, 82, 93, 94, 102, 114, 124, 144, 152, 157, 167, 170, 177, 185, 191, 195, 200, 204, 212, 214, 224, 226, 233, 241, 249, 258, 266, and 271).*

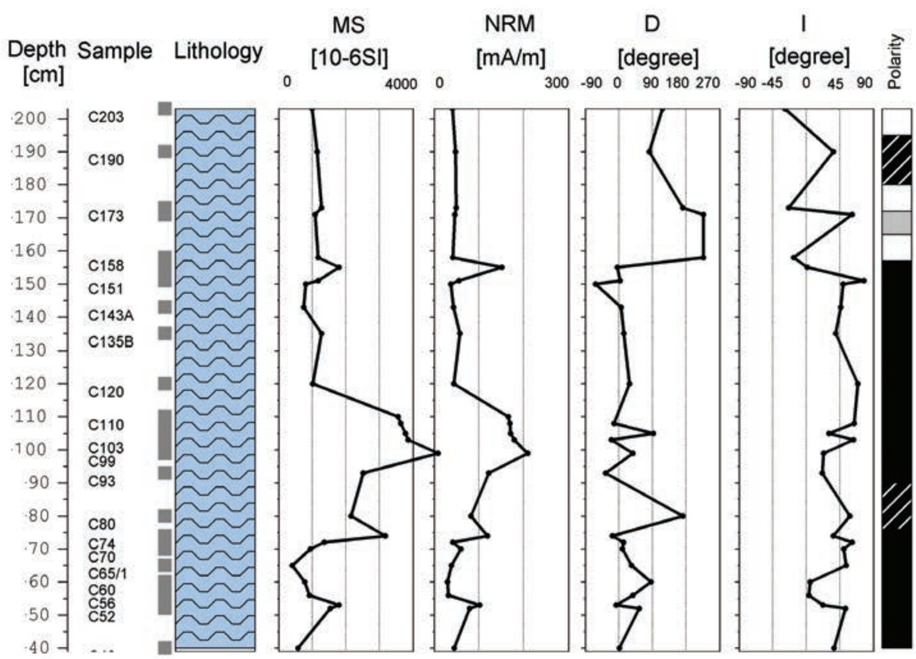

Figure 36 *Basic magnetic and palaeomagnetic properties, Črnotiče I profile. Legend: see Figure 37.*

PALAEONTOLOGY

A collection of micro-palaeontological objects (18 specimens, 18 fragments; Figs. 38 and 39) was found in the red clays after washing and sieving of samples from one layer with a weight of 2–3 kg. These objects most probably belong to the pharyngeal teeth of carpoid fishes, but the systematic position is still unclear.

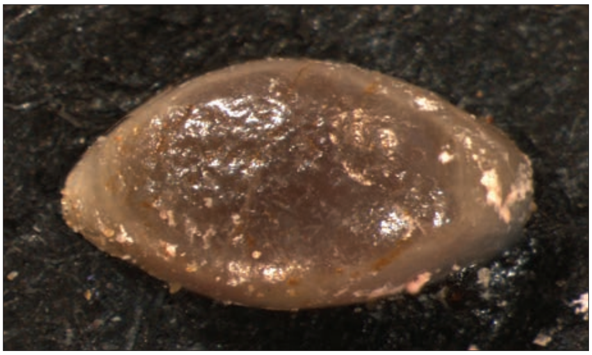

Figure 38 *Photo of not determined fossil find; dorsal view (original size = 3 mm; photo by M. Ivanov).*

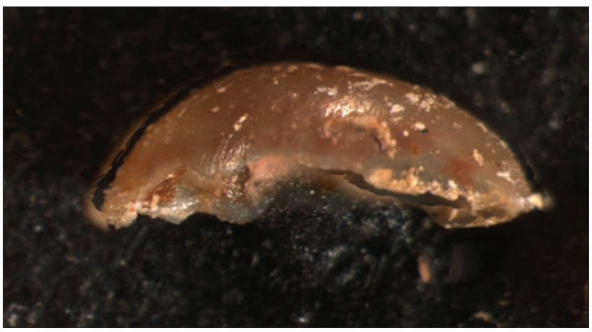

Figure 39 *Photo of not determined fossil find; lateral view (original size = 3 mm; photo by M. Ivanov).*

DISCUSSION OF RESULTS

The Črnotiče I profile is composed of banded carbonates with intercalations of red clays, deposited over corroded/eroded surfaces of older, highly re-crystallized speleothems. The banded and laminated carbonate rocks are composed of slightly re-crystallized calcilutite. The typical columnar texture of flowstones and other speleothems is missing, except in limited bands. This type of lamination may indicate an origin from organic-rich films (algal or diatom mats) on which fine carbonate grains were trapped or crystallized. These carbonates represent 'cave stromatolites'. The Črnotiče I profile yielded the first fossil examples of such lithologies to be described from any site (Bosák et al. 1999)

The chemical characteristics indicate that the red clays are closely related to the terra rossa soils known from karst areas in the Mediterranean region. They are re-deposited weathering products of the terra rossa type. Most probably, the red clays are not directly inwashed red soils, but are re-worked paludal deposits deposited from eroded lake and marsh weathering profiles on both limestones and flysch. The paludal sediments underwent an initial phase of bauxitization (increased chromium content, indications of aluminium replacement of some of Mn-rich pellets and abundant gibbsite). A paludal origin of the source sediments is indicated by the presence of abundant Fe-Mn pellets, and some mineralogical and geochemical data.

The N and R polarity magnetozones are interrupted by many unconformities of unknown duration. Therefore, any correlation with the GPTS is problematic. Nevertheless, according to the arrangement of individual magnetozones on standard scales we can assume that the whole profile is older than the top of the Olduvai event (1.77Ma). Interpretation of palaeomagnetic parameters (Bosák, Mihevc & Pruner 2004) and finds of fauna at the Črnotiče II profile (Horáček et al. 2007) clearly indicated that the age of the Črnotiče I profile can easily be as great as 4.2–5.2 Ma.

Figure 40 *Črnotiče II profile; cave filled by yellow fluvial sediments in the bottom and red clay with flowstone at the top (sampling points located by paper card with numbers).*

ČRNOTIČE II

PROFILE LOCATION AND CHARACTERISTICS

A new vertical profile in a side passage was exposed after the destruction of the main part of the cave (Fig. 29). It is situated about 40 m to the south of the Črnotiče I profile (Fig. 30). The exposed profile is about 7 m wide and 17 m high in a passage completely filled with sediments. Laminated and cyclically-arranged fluvial sediments composed the lower part of the fill. They were covered by breccia formed of blocks and fragments of massive flowstone. The modern land surface cuts across the flowstones, exposing them in the form of an unroofed cave.

LITHOLOGY

The profile was more than 13 m high and 4 to 7.5 m wide (Figs. 40 and 41). The lower part (main profile from 0 up to 7.3 m) was composed of siliciclastic fill. It was separated from the over-lying sequence 4.5–8.8 m in thickness by a sharp erosional boundary. The upper part of the profile (from 7.3 – 8.8 m up to the surface) consisted of flowstone clasts.

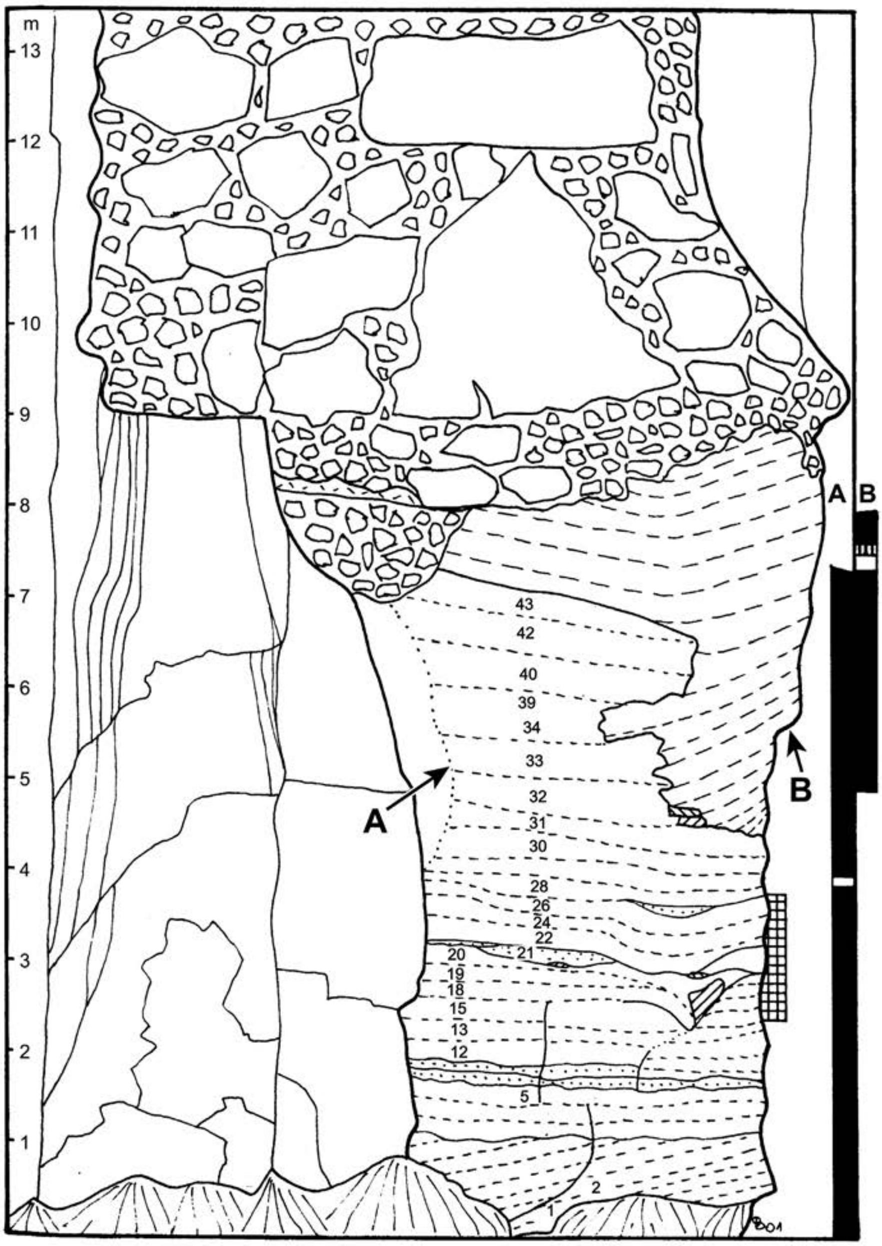

Figure 41 *Schematic sketch of the fill at Črnotiče II profile. Legend: A – the main profile; B – the right profile (from Bosák, Mihevc & Pruner 2004, with permission); net – vertical extent of Marifugia cavatica tubes on the wall. Columns A and B on right – magnetostratigraphy: black – normal polarity, white – reverse polarity, vertical lines – unknown polarity.*

Main profile

The main profile was composed of cyclically arranged sets of layers (Fig. 41; part A). The profile can be divided into two parts. The **lower part** layers Nos. 1 to 5, (Fig. 42) was mostly a multi-coloured, fine-grained laminated to banded sequence composed chiefly of clays, silts and very fine-grained clayey sands interlaminated with clays and silts. There were abundant iron and manganese mineral impregnations, locally in the form of Liesegang concentric structures. There was a depositional unconformity in bed No. 3, with beds below dipping at about 25° and those above only about 5°; they were of the same material

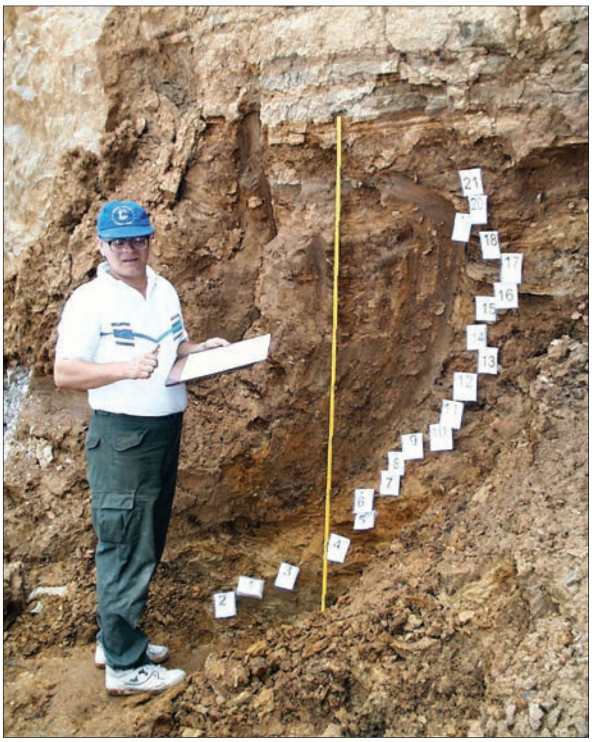

Figure 42 *The lower part of the Črnotiče II profile.*

Figure 43 *Detail of fluvial cycles in cave fill from the main (A) profile of Črnotiče II.*

The **upper part** of the main profile was composed of typical upwards-fining fluvial cycles consisting of micro-conglomerates to conglomerates, which sometimes passed to sands. Individual cycles were separated by thin inter-beds of clays to silts (Fig. 43). In the gravels individual clasts were of silts and clays, often well-rounded, sometimes flat. Some layers were cross-bedded, at least at the base. There were also abundant schlieren enriched in iron and manganese compounds. At the bases of some layers, there were limestone clasts that depressed the underlying beds, indicators of limited collapse of cave roof or fall of rock from cave walls. The top of the profile was composed of re-deposited terra rossa-type soil.

Right profile

The main profile was deeply eroded before deposition of the right upper part (Fig. 41; part B). The erosional boundary was highly uneven. At the base there were several flat slabs of limestone, and intensive impregnation by iron and manganese compounds (thin crusts). The sequence above was composed by light-

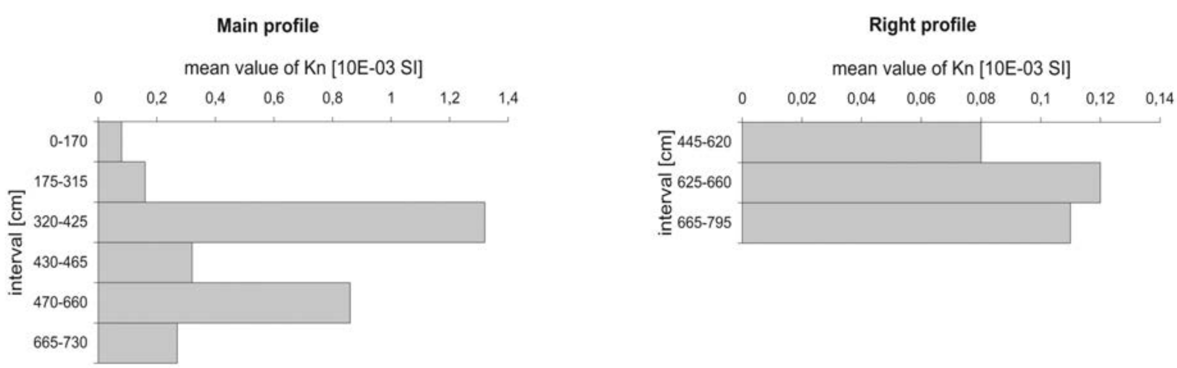

Figure 44 *Magnetic susceptibility data measured by Kappameter KT-5 from the main and the right profile (from Bosák, Mihevc & Pruner 2004, with permission).*

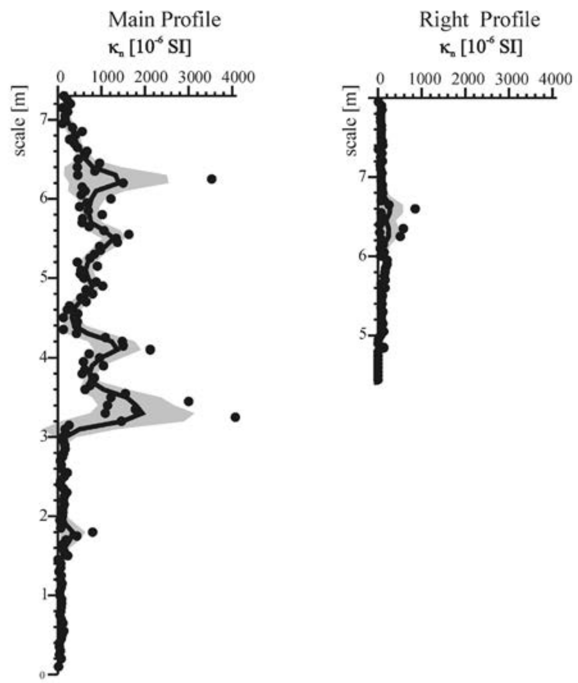

Figure 45 *Mean value of magnetic susceptibility data measured by Kappameter KT-5 from the main and the right profile (from Bosák, Mihevc & Pruner 2004, with permission).*

Table 5 Mean palaeomagnetic values and standard deviations, Črnotiče II Main profile

Črnotiče II **Main profile**	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m]*
Mean value	0.606	83.4	7.03–4.27
Standard deviation	0.708	38.5	
Number of samples	5	5	
Mean value	3.057	175.3	3.99–3.31
Standard deviation	0.688	90.3	
Number of samples	4	4	
Mean value	0.690	99.8	3.12–0.07
Standard deviation	0.842	47.3	
Number of samples	30	30	

* from top to base

Table 6 Mean palaeomagnetic values and standard deviations, Črnotiče II Right profile

Črnotiče II **Right profile**	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m]*
Mean value	0.541	75.8	7.64–5.05
Standard deviation	0.281	28.4	
Number of samples	16	16	

* from top to base

coloured, laminated to banded silts, clays and very fine-grained silty sands.

Upper part

The upper part of the profile consists of massive flowstone deposits. They were disintegrated to blocks and gravels of different sizes because of the subsidence of underlying sediment. There are two layers of flowstone clasts separated by a thin layer of silts, probably reworked deposits from the right side of the profile (Fig. 41). In the first layer smaller clasts fill the distinct erosional channel. The upper layer contains larger blocks and fragments of speleothems. Some blocks are even larger than 2 m in size. The matrix is composed of terra rossa-type clayey soil (loam).

PALAEOMAGNETIC RESULTS

A total of 54 oriented laboratory samples from the main and right profiles were studied in detail to detect their palaeomagnetic properties. The MS was measured in the field every 5 cm in both profiles by Kappameter KT-5, yielding 218 values (Figs. 44 and 45). The RM (J_n) and MS (k_n) moduli values in the natural state of rocks show small scatter. Mean values of J_n and k_n moduli are documented for main and right profiles in Tables 5 and 6. According to both values, the main profile may be divided into three parts and categories.

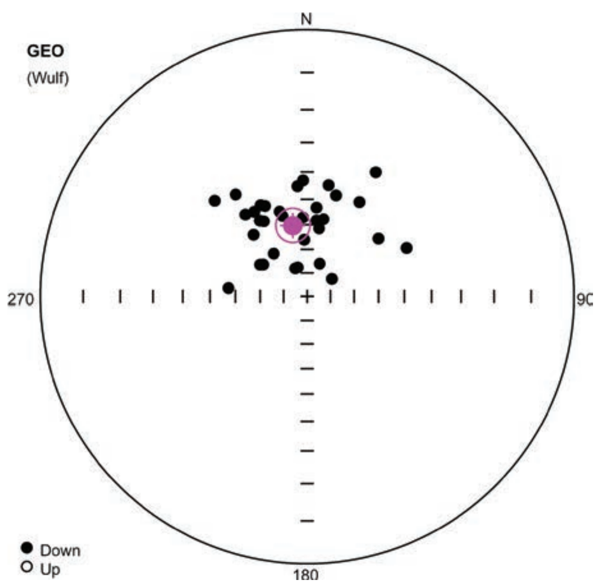

Figure 46 *Directions of C-components of remanence of samples with N polarity, main profile, Črnotiče II. For detail description see Figure 34.*

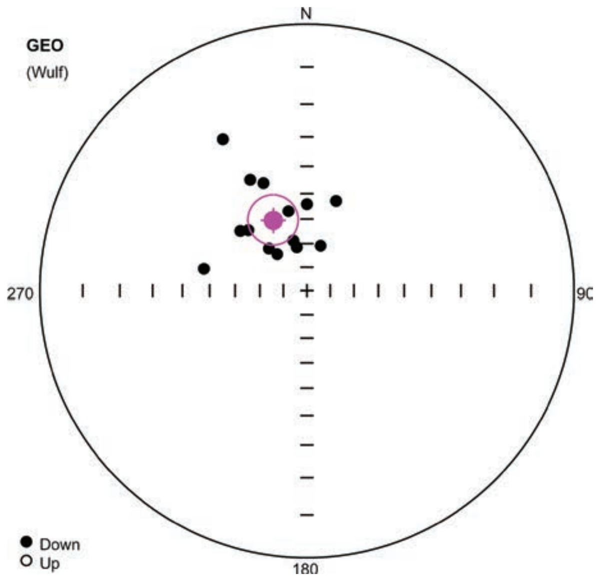

Figure 47 *Directions of C-components of remanence of samples with N polarity, right profile, Črnotiče II. For detail description see Figure 34.*

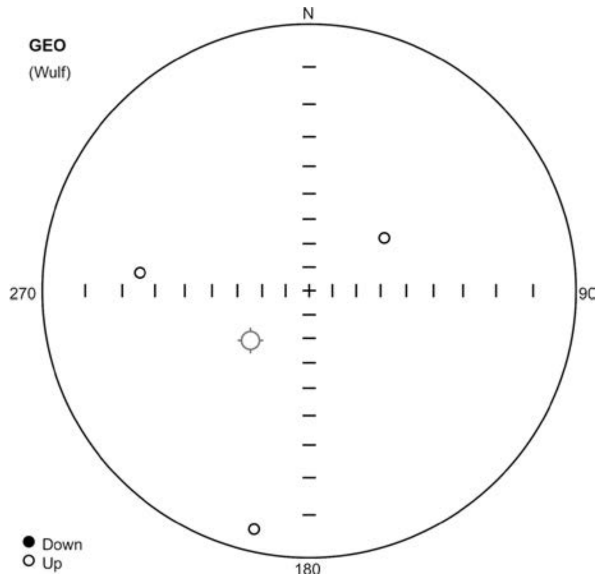

Figure 48 *Directions of C-components of remanence of samples with R polarity, right profile, Črnotiče II. For detail description see Figure 34.*

Sediments from the main profile are characterized by their small scatter of NRM intensities (0.1–3.7 $mA.m^{-1}$) and the MS values (17–331 $x10^{-6}$ SI units). Sediments from the right profile are characterized also by the small scatter of NRM intensities (0.1–1.2 $mA.m^{-1}$) and the MS values (32–157 x 10^{-6} SI units). Samples from both profiles are characterized by very low- to low J_n and k_n magnetic values.

The RM directions were tested by multi-component analysis. *A-components* of remanence have mostly viscous or chemoremanent (weathering) origin; they can be removed by AF demagnetisation with an intensity of 3 mT. Stereographic projections of directions of N palaeomagnetic *C-component* of samples for main profile are shown in Figure 46. The Fischer distribution displays two defined sets of samples with N and R polarities of samples for right profile (Figs. 47 and 48). Mean palaeomagnetic directions are documented in Tables 7 and 8: the value of α_{95} (the semi-vertical angle of the cone of confidence) cannot be calculated for the right profile (R polarity) due to the small number of samples. Palaeomagnetic profiles are shown in Figure 49 (main profile) and Figure 50 (right profile).

Table 7 Mean palaeomagnetic directions, Črnotiče II Main profile

Črnotiče II Main profile	**Polarity**	**Mean palaeomagnetic directions**		**α_{95} [°]**	**k**	**n**
		D [°]	I [°]			
	N	348.6	59.73	6.44	13.92	34

Table 8 Mean palaeomagnetic directions, Črnotiče II Right profile

Črnotiče II Right profile	**Polarity**	**Mean palaeomagnetic directions**		**α_{95} [°]**	**k**	**n**
		D [°]	I [°]			
	N	334.48	57.48	9.06	17.04	14
	R	229.9	-58.0			

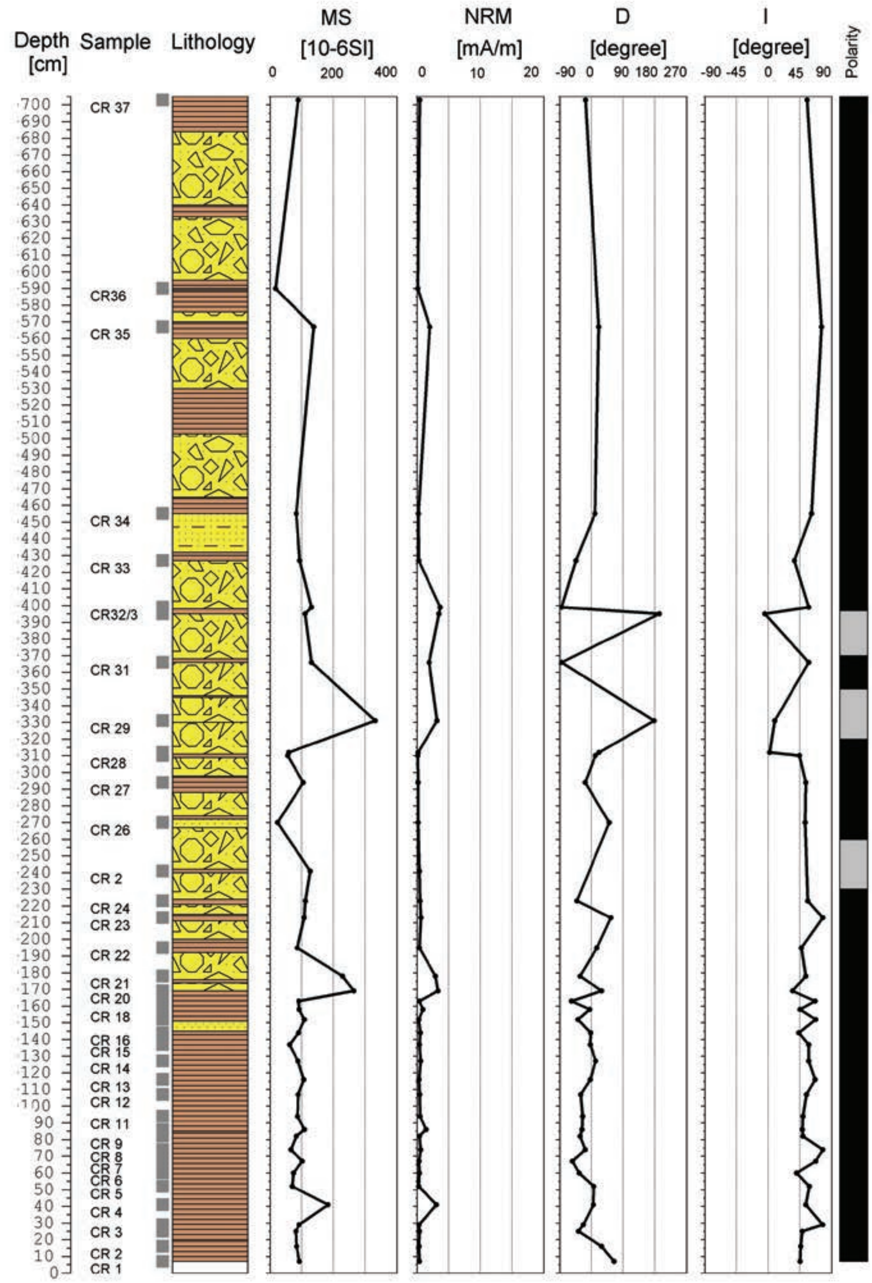

Figure 49 *Basic magnetic and palaeomagnetic properties, main profile, Črnotiče II. Legend: see Figure 37.*

The magnetostratigraphic results showed N and R polarity magnetozones. Both profiles are dominated by N polarised magnetozone. One narrow R polarity subzone (excursion) was situated in the middle (3.95–3.99 m) of the main profile and one narrow R polarity subzone (excursion) – documented on one sample only – occurred in the upper part (7.64 m) of the right profile.

PALAEONTOLOGY

Probable prints of leaves and remains of highly decomposed bones were found in some layers during the primary profile documentation (Bosák, Mihevc & Pruner 2004). Therefore, larger samples of cave fill were later washed. To obtain remains of fossil serpulids, about 30 kg of material was sampled (Mihevc 2000; Mihevc et al. 2001, 2002). The subsequent sampling of about 300 kg provided a rich hoard of mi-

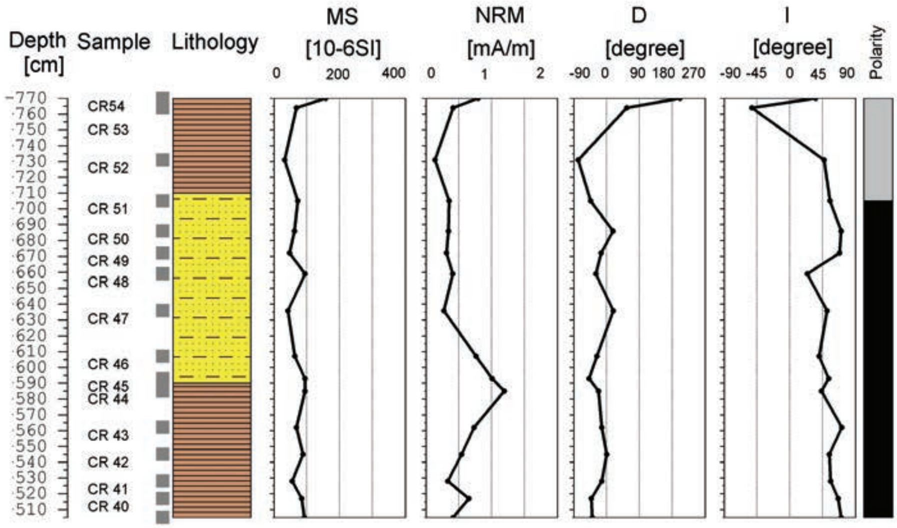

Figure 50 *Basic magnetic and palaeomagnetic properties, right profile, Črnotiče II. Legend: see Figure 37.*

croscopic fragments of vertebrate and non-vertebrate fossil remains (Horáček et al. 2007).

Marifugia cavatica

Calcareous tubes were attached to the wall in the lower part of the passage between 426 and 427 m a.s.l. (Fig. 51). The tubes may be very densely packed together in groups of up to several hundred individuals, or very distantly separated. The end of the tubes, which were perpendicular to the wall, was often broken off. The tubes were curved, max. 30 mm long. Sometimes the initial centimetre of a tube was flattened where it attached to the substratum. Cylindrical,

Figure 51 *Cave wall with the tubes of* Marifugia cavatica*; Črnotiče II profile.*

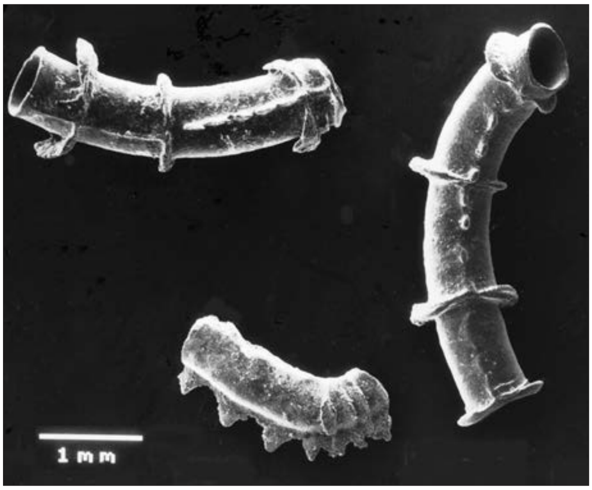

Figure 52 Marifugia cavatica *tubes under SEM.*

detached parts were more or less perpendicular to the wall and straight. The tube diameters were from 0.2 to 0.85 mm, max. 1.5 mm (Fig. 52). The maximum width of the collar-like pleats varied among specimens and populations. The stable isotope composition was very close to stable isotope compositions of recent freshwater species, differing greatly from those of marine serpulids (Mihevc et al. 2002). The fossils were compared with the recent serpulid tubes of *Marifugia cavatica* (Mihevc 2000; Mihevc et al. 2001, 2002; Bosák, Mihevc & Pruner 2004). Carefully selected tubes of *Marifugia cavatica* in a weight of about 5 g were sent to U/Pb dating. The high contents of detrital Th indicated the opening of the system or the admixture of original terrigeneous clastic material, so that no dates could be obtained (D.C. Ford, pers. comm.).

Marifugia cavatica Absolon & Hrabe, 1930 is the only recent fresh-water species of the Serpulidae family (Annelida: Polychaeta) and the only known tube worm inhabiting continental caves (Kratochvil 1939). It is never found even in brackish waters (*cf.* Sket 1986). It is a filter feeder on free-swimming larvae (Matjašič & Sket 1966). It can be very sparsely settled in clear and fast flowing streams where it may construct dense colonies. Nevertheless, thick masses of many layers of tubes (as described by Absolon & Hrabe 1930) represent a unique exception. Recently, it has become widely, although not continuously, distributed within the Dinaric Karst (Sket 1970b), biogeographically belonging to holo-Dinaric elements (*sensu* Sket 1994). Although it was originally considered to be a marine element colonising fresh cave waters directly from the sea (Absolon & Hrabe 1930), it is supposed recently that it has colonised cave waters from a habitat in fresh-water lakes since the Pliocene or Pleistocene, like other stygobionts with comparable distributions (Sket 1970a, 1997).

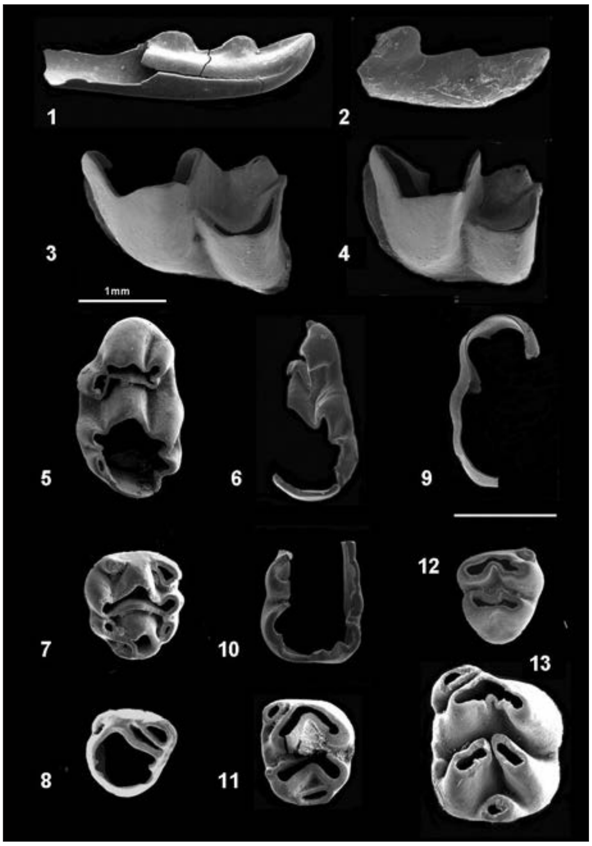

Figure 53 *Soricidae and Muridae of the Črnotiče II site (from Horáček et al. 2007, with permission). Legend: 1 –* Deinsdorfia *sp. – left I/1; 2 –* Deinsdorfia *sp., right I/1; 3 –* Beremendia fissidens *(Petenyi 1864), left M/1; 4 –* Beremendia fissidens *(Petenyi 1864), left M/2; 5 –* Apodemus (Sylvaemus) *cf.* atavus *Heller 1936, left M1/; 6 –* Apodemus (Sylvaemus) *cf.* atavus *Heller 1936, right M/1; 7 –* Apodemus (Sylvaemus) *cf.* atavus *Heller 1936, right M/1; 8 –* Apodemus (Sylvaemus) *cf.* atavus *Heller 1936, left M/2; 9 –* Apodemus (Sylvaemus) *cf.* atavus *Heller 1936, left M/2; 10 –* Apodemus (Sylvaemus) *cf.* atavus *Heller 1936, right M/3; 11 –* Apodemus (Sylvaemus) *cf.* atavus *Heller 1936, left M1/; 12 –* Apodemus (Sylvaemus) *cf.* atavus *Heller 1936, right M2/; 13 –* Apodemus (Sylvaemus) *cf.* atavus *Heller 1936, right M3/.*

Mammalian remains

The individual fossil remains were corroded and fragmented into quite small pieces as a rule. Fossils are covered by thin amorphous fossilization crust rich in Si (?opal), Ca and Cr (microprobe analysis) that is largely resistant to acid etching. This fact essentially complicated the SEM study. Altered surfaces under

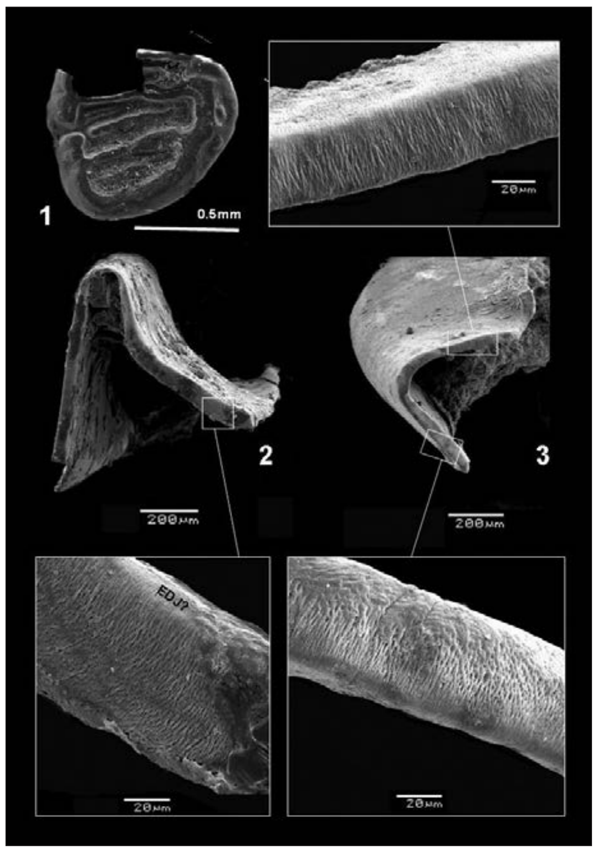

Figure 54 Gliridae *and* Arvicolidae *from the Črnotiče II site (from Horáček et al. 2007, with permission). Legend: 1 –* Glirulus *aff.* pusillus *(Heller 1936), right M3/ ?; 2 –* Arvicolidae *g.sp.* – Cseria gracilis/ carnutina *grade, ?left M1/; 3 –* Arvicolidae *g.sp. –* Cseria gracilis carnutina *grade.*

the crust are rich in Ca, Si, Fe, Cr, but lack Mn, Mg and Al (microprobe analysis).

The vertebrate record consists of 58 items, mostly poorly preserved and corroded fragments of teeth enamel. The best preserved items are shown in Figures 53 and 54. Some of them allow at least a tentative identification. Mammalian remains: Eulipotyphla (4): *Deinsdorfia* sp. (2I/1), *Beremendia fissides* (Petenyi, 1864): M/1, M/2; Rodentia (39): indet. fragments of incisor enamel (15 items), *Glirulus* aff. *pusillus* (Heller 1936): 1 M3/, *Apodemus (Sylvaemus)* cf. *atavus* Heller, 1936: 9 fragments (2 M1/, 1M2/, 1M3/, 2M/1, 1M/2, 2M/3), *Rhagapodemus* cf. *frequens* Kretzoi, 1959 (1 M/2), Arvicolidae indet. (13 fragments of molar enamel): sp. (cf. "*Cseria*" *carnutina* Rabeder 1981), sp. 2 (cf. *Mimomys (Cseria* s.s.*) gracilis*).

Non-mammalian rests

Non-mammalian rests were represented by 15 small conical and flat lanceolate teeth tips of *Chondrichtyes* indet (Fig. 55).

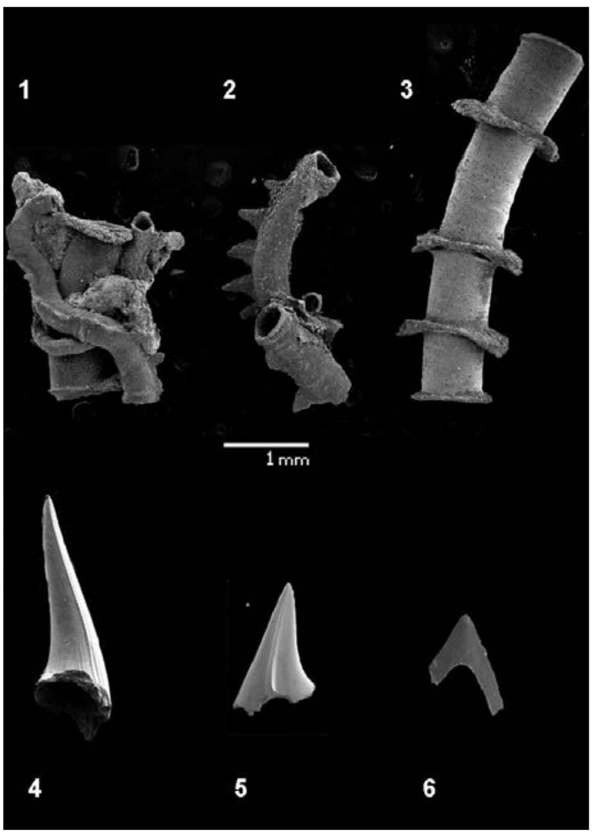

Figure 55 *Non-mammalian fossils of the Črnotiče II site (from Horáček et al. 2007, with permission). Legend: 1-3 –* Marifugia cavatica *Absolon et Hrabě 1930; 4-6 – indetermined tooth tips, supposedly a juvenile* Chondrichthyes *fishes.*

DISCUSSION OF RESULTS

The cave developed along a large subterranean river, as indicated by sedimentary fill, and large scallops on the walls. A paragenetic evolution for the passage cannot be excluded. The sessile serpulid tubes were probably buried step by step when the passage was partially filled with fine sediment. Fine-grained sediments of the lower part of left (main) profile were later eroded and replaced by a fluvial cyclic fill; there were no serpulid tubes on that part of the cave wall. The cyclically deposited fill was later deeply eroded. The hiatus could have been prolonged, as indicated by the roof collapse, iron-rich crusts on eroded surfaces and the palaeomagnetic data. The erosional surface was overlain by fine-grained laminated siliciclastics. Deposition of both parts of the profile had to be quite rapid, as indicated by the dominant normal polarised magnetozones. After the next erosional phase, autochthonous angular gravel with a red clay matrix was deposited. This fill may be the genetic equivalent of the breccias in vertical shafts, i.e. removed products of surface planation. Finally, prolonged karst denudation removed the limestone above the cave, and its ceiling and a part of the walls collapsed. Coarse-grained breccia with a matrix of terra rossa-type soils was formed. Collapse breccia containing massive speleothems indicates that the cave in its final stage was not completely filled up to the roof, enabling the growth of rich speleothems. The old horizontal caves represented the subterranean drainage routes of allogenic water streams flowing from the flysch regions into the limestones. Caves developed deep below the surface, at least to depths comparable to that of recent river caves in the area (to more than 100 m; e.g., Škocjanske jame).

Palaeomagnetic analysis detected dominant normal polarisation of the remanent magnetisation in both parts of the sedimentary fill at Črnotiče II. One narrow reverse polarised zone occurs in the middle of the main profile and another in upper part of the right side profile. Declination and inclination mean values for normal palaeomagnetic polarity in the main profile are D = 348.6°; I = 59.7°. Declination and inclination mean values for normal palaeomagnetic polarity in the right profile are D = 334.5°; I = 57.5° (Tab. 8). Differences in declination and inclination in both part of profile are within limits of the precision parameter (α_{95}). The age of the righthand section should be estimated to be at least 1.77 Ma, matching our results with geomagnetic polarity timescales (GPTS; Cande & Kent 1995). The main profile must therefore be older. The correlation of the sequence of normal magnetozones and the reverse polarised zones could indicate the Gauss chron (2.581–3.58 Ma). This original interpretation of Bosák, Mihevc & Pruner (2004) was recently supported by biostratigraphic determination of the mammalian fauna. Horáček et al. (2007) proved that this fauna belongs to MN15–MN16b mammalian biozones (about 3.2–4.1 Ma). Therefore, the long normal palaeomagnetic polarity zone in the lower segment of the fill corresponds to basal normal polarized subchron C2An.3n (3.33–3.58 Ma) within the Gauss chron, and the normal polarized upper segment can be compared to some of the higher normal subchrons of the Gauss chron (C2An.1n subchron = 2.581–3.04 Ma or C2An.2n subchron = 3.11–3.22 Ma). The combination of palaeontological and palaeomagnetic data indicates that the fauna cannot be older than about 3.6 Ma, due to the reverse polarized magnetozone at the top of the Gilbert chron terminating at 4.18 Ma. This level represents approximately also the base of the MN15 mammalian biozone. Therefore, the fauna belongs to the MN16 mammalian biozone and cannot be older than 3.58 Ma.

DISCUSSION OF RESULTS FROM BOTH PROFILES

Mean palaeomagnetic directions of the Črnotiče II profile differ from Črnotiče I , which was estimated to 4.2 to 5.2 Ma in age (Bosák, Mihevc & Pruner 2004). Declination and inclination mean values for Črnotiče I profile are as follows: for the group with normal palaeomagnetic polarity D = 17.4°; I = 53.3°, and for the group with reverse polarity D = 173.0°; I = -31.1°. Declination and inclination mean values for Črnotiče II profile are : for the group with normal palaeomagnetic polarity D = 334.5°, I = 57.5°, and for the group with reverse polarity D = 229.9°, I = -58.0°. However, the reverse polarity data of both sites cannot be taken into account owing to low number of analysed samples. Declination data from normal polarities indicate a difference of 19° in an anticlockwise rotation. Inclination data differ within the 5 % error bar of the statistical method. According to the differences in declination values, the Črnotiče I and Črnotiče II sites differ in age. The anticlockwise rotation is in general agreement with Cenozoic tectonic evolution of the Adriatic microplate (*cf.* Fodor et al. 1998). Further, the MN15 age corresponds well to important palaeotectonic movements recently interpreted in the Dinarides (Ilić & Neubauer 2005) and Southern Alps (Neubauer 2007). The palaeomagnetic data combined with the biostratigraphy indicate time difference of about 1 Ma between the infilling processes at the two sites, i.e. the time-span available for the rotation of the tectonic block.

For the first time, a combination of vertebrate fossil records and magnetostratigraphy, have proven the expected antiquity of the cave infilling and related surficial landforming processes. One of the most important older phases of speleogenesis in the region finished during MN15–MN17.

The development of vertical drawdown shafts with a predominance of later autochthonous fill resulted from vadose speleogenesis caused by the drop of karst water level related to tectonic uplift, which followed tectonic unrest during the MN 15 to MN16b mammalian biozones. Drawdown shafts connected the land surface with the active zone of phreatic speleogenesis in the depths. The uplift detached horizontal caves from the hydrological system, causing their fossilization. Intensive planation processes were active on the surface during later evolution with accelerated intensity, in the glacial periods. Planation led to the formation of the levelled surface of the Podgorski kras and to collapse of the roofs of the horizontal caves. Filling of shafts by surface-derived angular gravel mixed with terra rossa-derived matrix took part during Middle to Late Pleistocene interglacials. This is proved by finds of mammals and Th/U dates of carbonate cements in gravels (211 ± 43 and 143 ± 13 ka; Mihevc 2001). Precipitation of the cement was associated with the formation of speleothems in favourable climatic conditions. Those ages indicate also the cessation of the main phase of vertical speleogenesis in the vadose zone, which was connected with continuous uplift and shift of active phreatic speleogenesis to lower levels.

BRIŠČIKI

SITE LOCATION AND CHARACTERISTICS

Borehole No. S3 (Calligaris 2000) was drilled in the sediment fill of this unroofed cave about 1 km to the north-west from the village, Briščiki (in Italian – Borgo Grotta Gigante; 45°42´36.88˝N; 13°45´48.60˝E) in the Trieste karst (Italy; Figs. 18 and 56).

The cave was developed in the bedded limestone with rudists of the Upper Cenomanian to Maastrichtian Borgo Grotta Gigante Formation (Cucchi & Pugliese 1996). The unroofed cave is situated on the levelled corrosion surface at about 260 m a.s.l. The main morphological features in the area are small solutional dolines, usually not deeper than 8 m, although there are a few dolines deeper than 20 m and up to several hundreds meters in diameter.

The slightly meandering unroofed cave is exposed on the south-eastern side of a large dolina. The cave has a horizontal floor and sharp-edged trench appearance, width between 5 and 10 m (Figs. 57). On its south-eastern side the unroofed cave narrows and continues into a roofed cave that is filled with sedi-

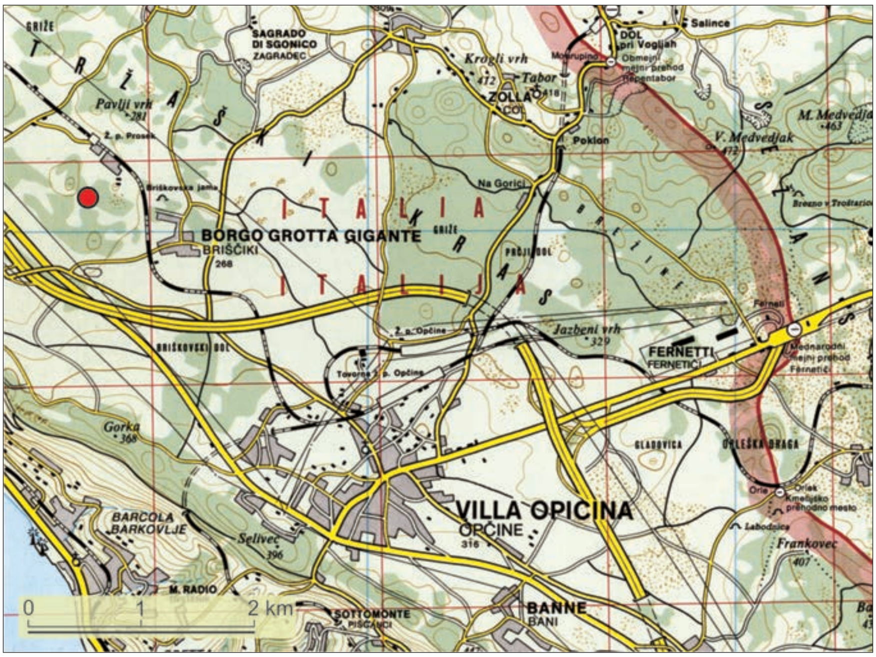

Figure 56 *Site location; Briščiki (NE Italy).*

Figure 57 *Corridor of the unroofed cave, Briščiki.*

Figure 58 *Position of the borehole No. S3 (in front of P. Bosák shoes) in the bottom of the unroofed cave.*

ments. The walls of the trench (former cave) are of thick-bedded limestone corroded by abundant deep rillenkarren. The total length of the cave is about 70 m and it terminates at the edge of the north-western end of the large doline. The location of the borehole is shown on Figure 58.

PROFILE

The borehole was fully cored (7 m). The core yields were nearly 100 %; some losses of drilling were noted only in parts with higher proportions of limestone skeleton without sedimentary matrix. The diameter of the drilling was about 12 cm. Cores were divided to two parts along the long axis. One half of the core was used for analytical purposes (Fig. 59); the second was left in the museum collections. Each core was stored separately in special plastic tubes, each 1 m long. The tube was closed to prevent the desiccation. Cores were covered by plastic foil and the space left after the use of the second half of the core was filled by old newspapers. Some of the studied cores were stored in classical wooden boxes. Boxes and tubes with cores were deposited in the collections of the appropriate department of the Museo Civico di Storia Naturale di Trieste (Italy).

LITHOLOGY

The dominant part of the core was composed of yellowish-brown and brown to brownish-red clays and silty clays with more abundant intercalations of limestones (probably larger limestone blocks) and several layers of flowstones. The matrix consisted mostly of clays and silty clays, in the upper part of brown colour, below 2.00 m brownish red (re-deposited terra rossa?), below ca 4.00 m with yellowish brown schlieren and inter-beds. At 4.65 m the colour changed to the yellowish brown with reddish stains. The carbonate concretions occurred at 7.00 m. Stains of manganese compounds were noted at 4.55 m. The principal lithological boundaries may be placed at 2.00 m, 4.37 m, and 4.65 m of the core. The bottom of the borehole was at 7.14 m.

PALAEOMAGNETIC RESULTS

The palaeomagnetic and magnetostratigraphic investigation provides data concerning principal magnetic properties and identification of palaeomagnetic directions. The RM (J_n) and the MS (k_n) moduli values in their natural state show a large scatter. The studied sediments are characterized by a large scatter of NRM intensities (2.2–321 mA.m^{-1}) and the MS values (182–10,056 x 10^{-6} SI units). The mean values of J_n and

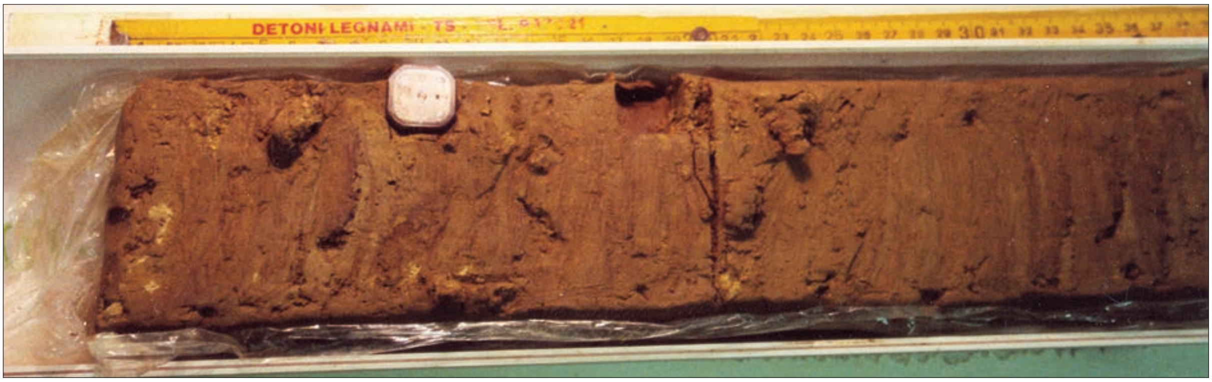

Figure 59 *Part of the borehole No. S3 from Briščiki with one of the samples.*

k_n moduli are documented in Table 9. According to both values, the profile may be divided into two parts and categories. Samples are characterized by low up to high J_n and k_n magnetic values.

Table 9 Mean palaeomagnetic values and standard deviations, Briščiki

Briščiki	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m]*
Mean value	130.271	6,553.0	0.10–4.55
Standard deviation	72.941	2,179.4	
Number of samples	23	23	
Mean value	6.703	471.4	4.70–7.12
Standard deviation	4.511	246.3	
Number of samples	12	12	

* from top to base

The RM directions inferred by the above procedures were tested using a multi-component analysis. *A-components* of remanence are mostly of viscous or chemoremanent (weathering) origin; they can be removed by an alternating field with an intensity of 1 up to 3 mT. The N and R *C-component* directions are documented in Table 10 and Figures 60 and 61. The palaeomagnetic directions of R polarity of the five samples show a large scatter (Table 10; see the semi-vertical angle of the cone of confidence – α_{95}).

The principal palaeomagnetic and magnetostratigraphic data for 27 samples are presented in Figure 62. The magnetostratigraphic results from core display both N and R polarity magnetozones: an N magnetozone at the top with an R zone at 0.90–1.50 m; the middle and lower parts of the profile display N palaeomagnetic directions. One narrow R polarity subzone (an excursion, found in only one sample) is situated in the middle part of the core.

DISCUSSION OF RESULTS

For the detailed discussion see chapter Jama pod Kalom.

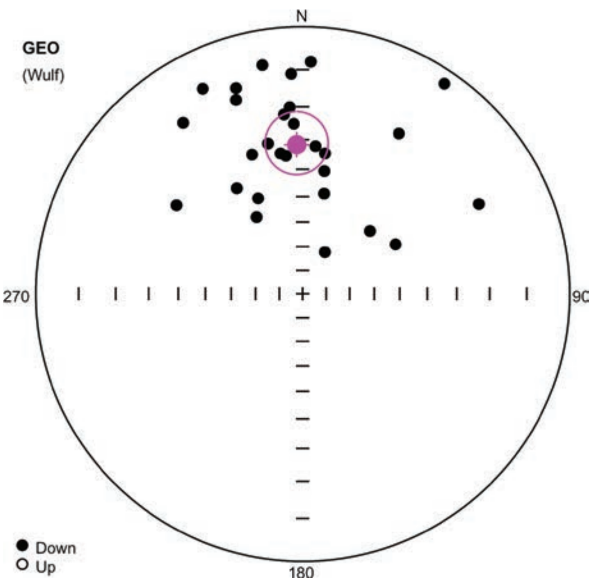

Figure 60 *Directions of C-components of remanence of samples with N polarity, Briščiki. For detail description see Figure 34.*

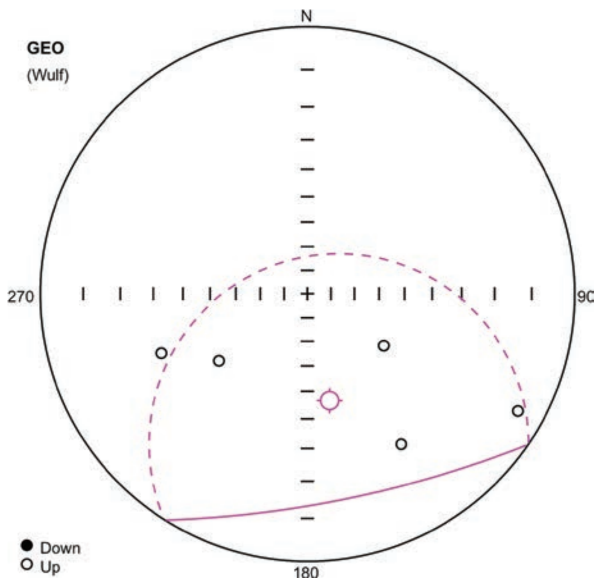

Figure 61 *Directions of C-components of remanence of samples with R polarity, Briščiki. For detail description see Figure 34.*

Table 10: Mean palaeomagnetic directions, Briščiki

Briščiki	**Polarity**	**Mean palaeomagnetic directions**		α_{95} [°]	**k**	**n**
		D [°]	I [°]			
	N	357.68	31.64	9.32	8.06	28
	R	168.22	-45.75	38.91	2.59	5

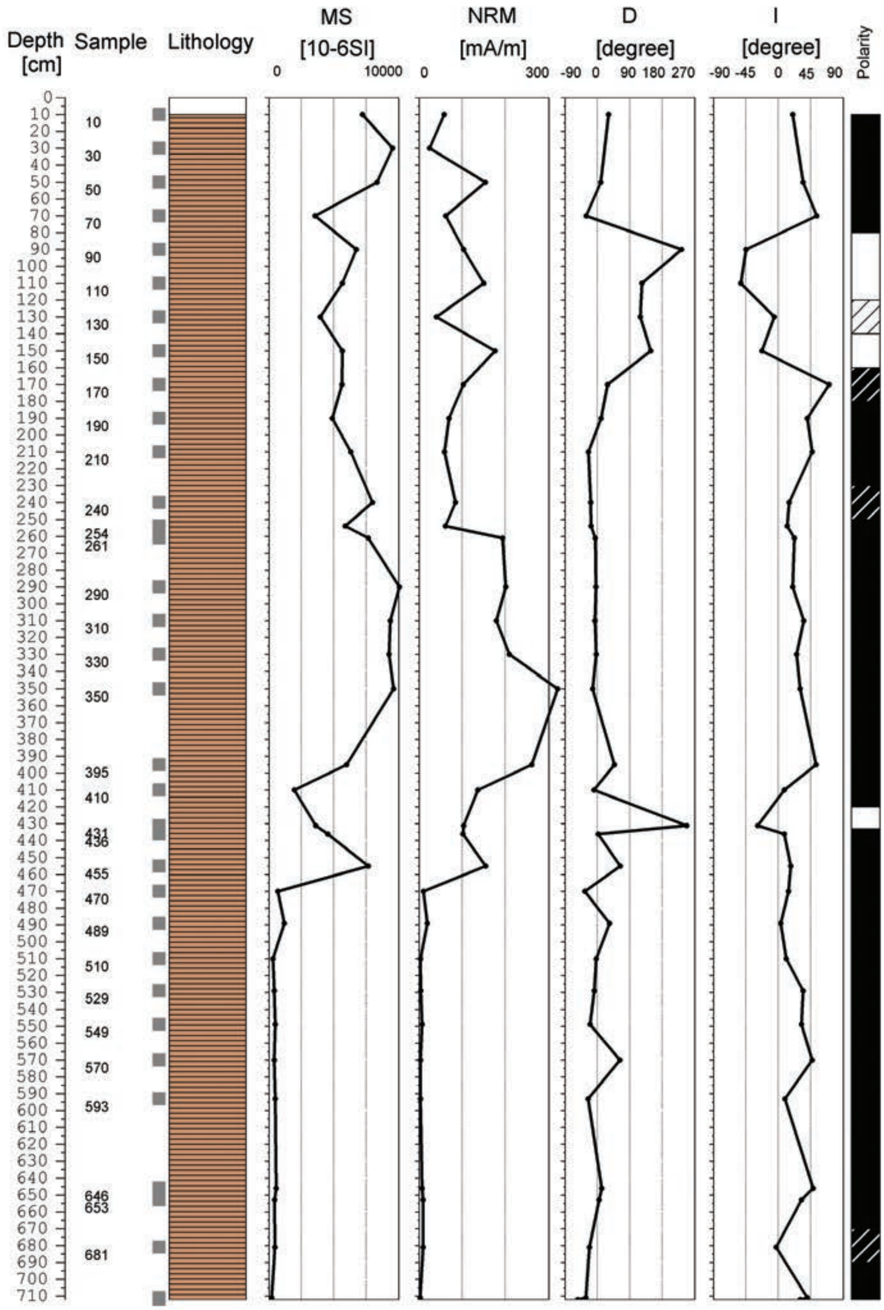

Figure 62 *Basic magnetic and palaeomagnetic properties, Briščiki. Legend: see Figure 37.*

KOZINA PROFILE

SITE LOCATION AND CHARACTERISTICS

The Kozina profile (Fig. 18) was situated in a cave filled by fluvial sediments, located about 500 m north-east of Kozina village (45°36´42.58˝N; 13°56´10.27˝E; 521 m a.s.l.; Fig. 63). The filled cave was opened during the construction of a highway. It was formed in the Upper Cretaceous grey limestone with rudists, close to the contact with the Eocene alveolinid and nummulitid limestone. Bedding dips eastwards (Pleničar, Polšak & Šikić 1969).

The network of the unroofed caves in the vicinity of Kozina was described by Knez & Slabe (1999b). The unroofed caves were filled by brown and red soils to a thickness of several metres and by fine-grained fluvial sediments, sometimes with intercalations of gravels composed of flysch sandstones. Flowstones and stalagmites formed intercalations within the fluvial cave fill in the south-west. Some of the fluvial sediments were still covered by limestone blocks, boulders and debris derived from destroyed roof.

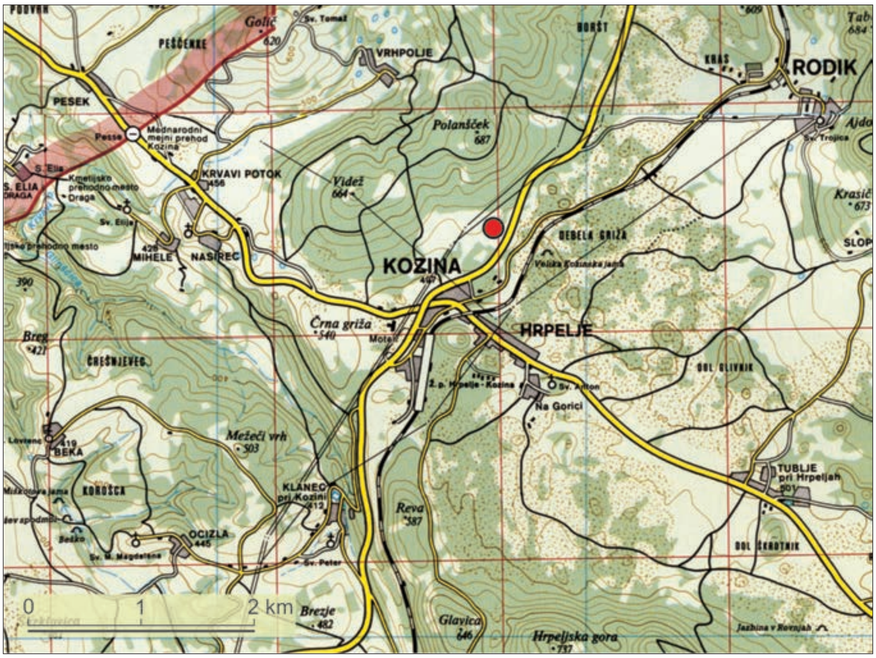

Figure 63 *Site location; Kozina profile (SW Slovenia).*

PROFILE

LITHOLOGY

The profile was located about 20 m below the "first" profile of Šebela & Sasowsky (2000). The profile consisted of more than 5 m of sediments (Figs. 64 and 65). Its base was exposed. The fill was composed of two principal sequences. The lower one with a thickness of about 3 m was of yellow to light brown sandy to clayey sediments, often with multi-coloured lamination, sometimes with ferruginized or Mn-rich laminae, calcitization of sands and a few limestone clasts. It was inclined (10 to 15°). The individual layers were often limited by sharp erosional bases and minor unconformities. This lower sequence was overlain at a sharp erosional contact by collapse breccia composed of limestone blocks to boulders (cm to m in size) and a matrix of brown loams with fine carbonate precipitates in cracks (pseudomycelia). In the upper part of the collapse breccia, the matrix was rather yellowish brown and rock fragments were smaller.

Near the contact between sediments and limestone, a narrow, inclined cave was developed in the sediments of the lower sequence. The cave walls were covered by the speleothems, which cemented the surrounding sediment. This cave represents younger vadose drainage.

PALAEOMAGNETIC RESULTS

A total of 38 samples were taken from the lower sequence of the profile. One only was cemented. The mean values of the J_n and k_n moduli are documented in the Table 11. According to both values, the profile may be divided into three parts and categories. Sediments are characterized by a large scatter of NRM intensities (0.1–29 mA.m^{-1}) and the MS values (63–998 x 10^{-6} SI units). Samples are characterized by very low up to intermediate of J_n and k_n magnetic values.

Table 11 Mean palaeomagnetic values and standard deviations, Kozina profile

Kozina Profile	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m]*
Mean value	2.696	169.3	2.95–2.00
Standard deviation	2.300	103.8	
Number of samples	6	6	
Mean value	10.829	433.0	1.90–0.74
Standard deviation	6.831	222.8	
Number of samples	17	17	
Mean value	0.776	119.1	0.66–0.02
Standard deviation	0.625	22.3	
Number of samples	15	15	

* from top to base

The samples were demagnetized by the AF up to 100 mT. The one cemented sample was demagnetized by gradual TD up to 560 °C in the MAVACS apparatus. Some samples showed a strong viscous component (up to 90 %); the primary component of magnetization and resulting polarity cannot be therefore determined. Normal and reverse polarity of *C-component* directions of the samples (Figs. 66 and 67) display two defined sets of samples with a Fisher distribution. Mean RM directions are documented in Table 12; palaeomagnetic directions of R polarity of seven samples show a large scatter (α_{95}). Basic magnetic parameters including polarity scale are documented in Figure 68.

The magnetostratigraphic results show an R magnetozone in the top and lower part of the profile. There are two N zones in the middle part of the profile.

PALYNOLOGY

Five samples were taken from the profile for palynological analyses (from ca 30 cm, 30–45 cm, 70–80

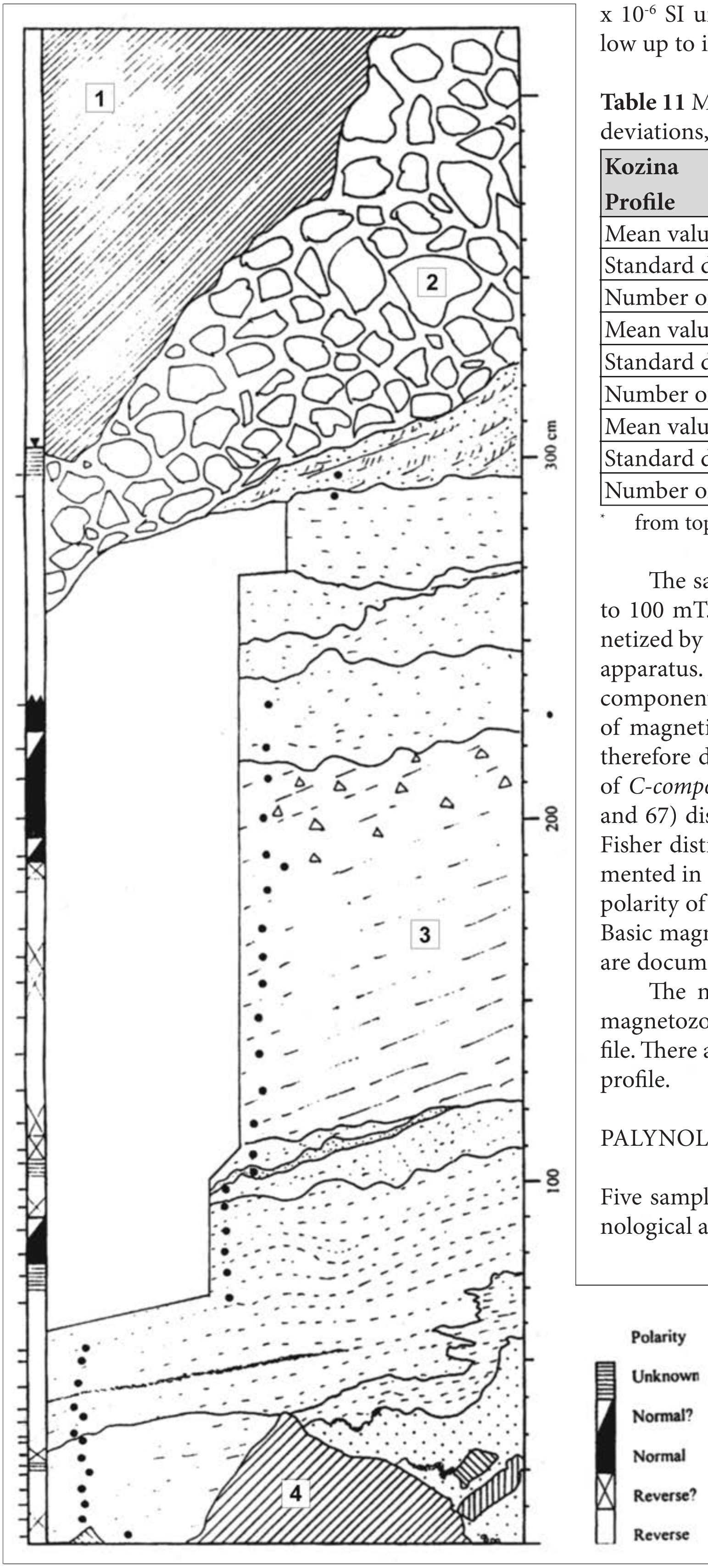

Figure 64 *Lithological sketch of the Kozina profile (from Bosák et al. 2000a, with permission). Legend: 1 – debris from blasting; 2 – collapsed cave roof with brown soil; 3 – lower sequence (yellow fluvial sediments); 4 – limestone blocks; black dots – sampling points.*

Figure 65 *The Kozina profile in a road cut NE of Kozina village.*

cm, 130–150 cm and 180–200 cm from the profile base). The sample from 70–80 cm yielded two highly corroded pollen grains belonging to herb vegetation (*Dipsacaceae* and *Apiceae* family). The sample from 130–150 cm yielded one spore (fern). Pollen grains belonging to herb vegetation are typical for dry, steppe-like region. Unfortunately they haven't any stratigraphic value.

DISCUSSION OF RESULTS

The lithology of the profile studied by Bosák et al. (2000a) clearly shows a two-phase depositional history. The lower sequence was eroded after its deposition. The erosional channel was deeper at the left side of the passage. The free space in the cave was later filled during collapse processes by blocks to boulder debris mixed with brown karst sediments. Yellowish brown intercalations in the upper part of the upper sequence may indicate the presence of eroded sediments comparable with the lower sequence. Thinning

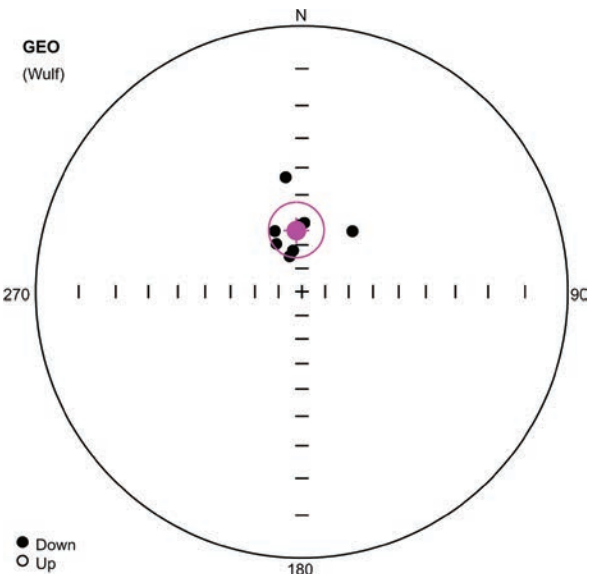

Figure 66 *Directions of C-components of remanence of samples with N polarity, Kozina profile. For detail description see Figure 34.*

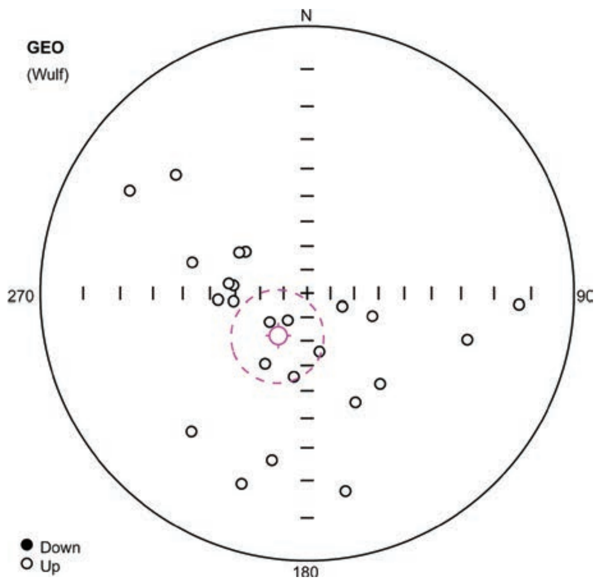

Figure 67 *Directions of C-components of remanence of samples with R polarity, Kozina profile. For detail description see Figure 34.*

Table 12 Mean palaeomagnetic directions, Kozina profile

Kozina profile	**Polarity**	**Mean palaeomagnetic directions**		**α_{95} [°]**	**k**	**n**
		D [°]	I [°]			
	N	354.92	64.05	9.75	29.48	7
	R	214.56	-68.41	15.49	3.4	24

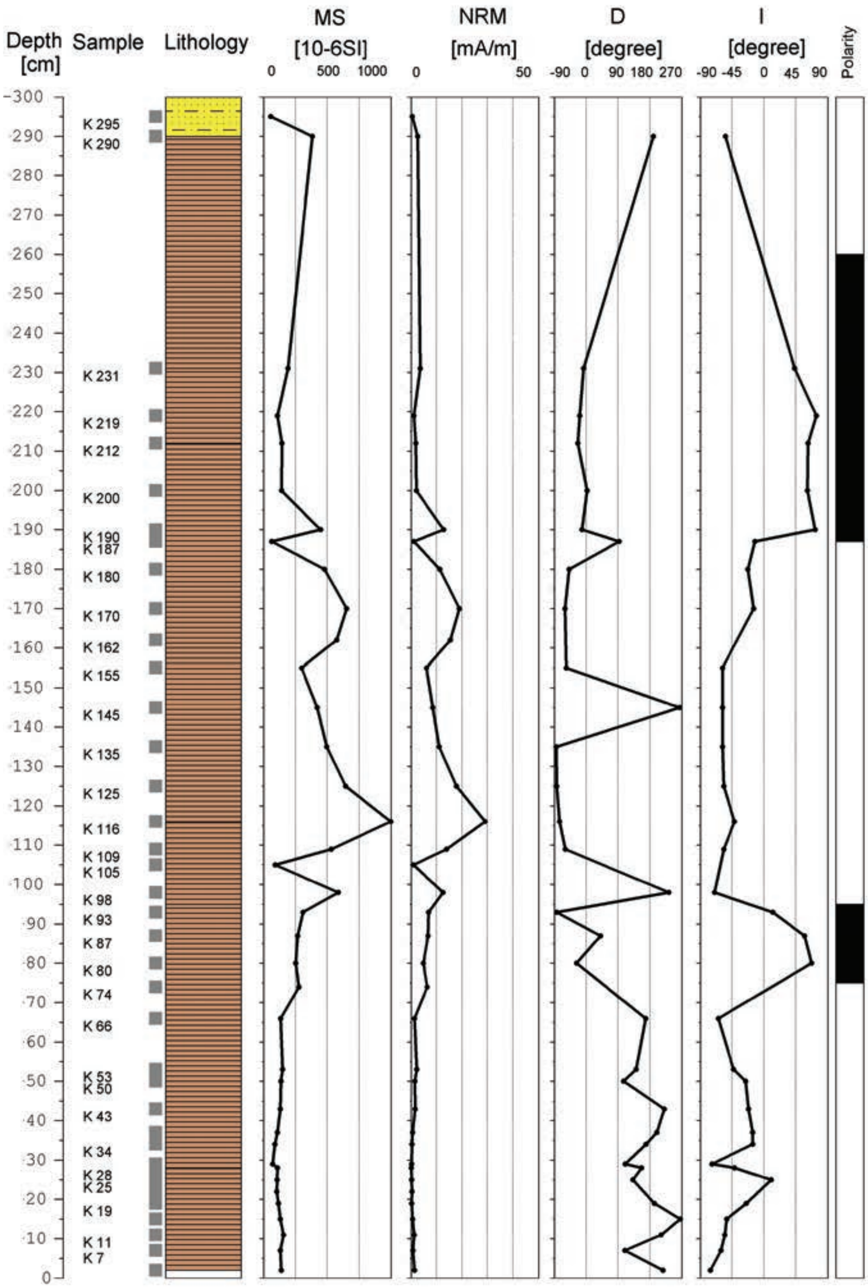

Figure 68 *Basic magnetic and palaeomagnetic properties, Kozina profile. Legend: see Figure 37.*

of the cave ceiling by erosion and karst denudation induced its collapse.

The lithological composition of the lower sequence is comparable with the Divača profile (Bosák, Pruner & Zupan Hajna 1998), especially with its sequences Nos. I and II. This part of the Kozina profile could be correlated with the base of the third sequence of the Divača profile. It seems that the sediments were derived from similar source rocks, i.e. from weathered Eocene flysch rocks.

The profile contains important erosional boundaries between the main lithological units. Contrary to the other studied profiles (Bosák et al. 2000b) these erosional boundaries are not situated at boundaries of N and R polarized zones, but within them. This finding may indicate that these breaks in deposition did not occupy substantial time-spans.

The magnetostratigraphic picture obtained in the Kozina profile is closely comparable with the magnetozones detected in the Divača profile (Bosák, Pruner & Zupan Hajna 1998; Bosák et al. 2000a, b), particularly in the sequence of the N and R polarised magnetozones and in the character of the RM moduli. The dominant part of both profiles is represented by

R magnetozones. There are two relatively N normal polarised zones. Unfortunately, there is a gap in sampling between Kozina samples No. 213 and 290, owing to rock petrography unfavourable for sampling. Some difference in the arrangement of N polarised magnetozones in both profiles can result also from different rates of deposition within both channels.

Šebela & Sasowsky (2000) also studied two profiles during the highway construction at Kozina. Ten samples were collected (4 from one location and 6 from the other) and all of them showed normal magnetic polarity, had good sample strength, and had only one palaeomagnetic component. The first profile, 1.64 m thick, was situated only several metres to the south of our site in the same depression but stratigraphically higher than our profile. It was composed of light-coloured laminated clays and covered by a 0.5 m thick roof. The second profile, 7.84 m thick, was situated about 500 m to the east of our profile in another depression. However, the original cave roof was not present. The debris were expected to be result of weathering/disintegration in a cold Pleistocene climate (Slabe & Knez 1999b). Palaeomagnetic analyses of cave sediments showed that all samples have N polarity. The age of cave sediments from their first profile was interpreted as „almost certainly younger", than those studied by Bosák et al. (2000a), i.e. younger than 0.78 Ma. The age of the fill from their second profile was difficult to interpret. Owing to the fact that sediments from unroofed caves in this area have always yielded older ages than 0.78 Ma (e.g., Bosák et al. 2000b) and that those samples were taken from the lower part of 7.5 m thick profile, there are two possibilities: the N polarization is connected with the Gauss chron (2.48–3.4 Ma) or with some of the N magnetozones (about 3.8–5.0 Ma) within the Gilbert chron.

The age of the Kozina profile studied by Bosák et al. (2000a) is older than the top of the Olduvai subchron (1.77 Ma). The closely comparable character of lithology and of the moduli values of the RM highly supports the age correlation of the Divača and Kozina profiles. The age of the first profile of Šebela & Sasowsky (2000) is therefore of the same age or younger than the profile of Bosák et al. (2000a), the second one is of the same age as profile of Bosák et al. (2000a).

As in the Divača profile, we suppose that the fossil caves at Kozina village are result of the post-Eocene speleogenetic period and its fossilization was connected with the tectonic uplift of the area, probably after Messinian (*cf.* e.g., Willet, Schlunegger & Picotti 2006). If this hypothesis is close to reality, the infilling process can started at about 5.3 Ma, as already suggested by Bosák, Pruner & Zupan Hajna (1998) and Bosák et al. (2000a, b).

DIVAČA PROFILE

SITE LOCATION AND CHARACTERISTIC

The profile is situated south of Divača village (Fig. 69), on the levelled surface of the Divaški kras (45°39´58.01˝N; 13°58´06.70˝E; 453 m a.s.l.; Fig. 18). The main relief features are numerous solutional dolines, usually less than 10 m deep. There are some collapse dolines up to 80 m deep developed above the underground course of the Reka river (Fig. 20).

The profile was exposed during construction of the Ljubljana–Koper highway (highway profile No. 30). The profile was in a cave completely filled by fine-grained sediments, situated on the southern slope of a bigger depression (Fig. 70).

PROFILE

The profile is about 6 m high and represents the cross-section of a cave completely filled by fluvial sediments (Fig. 70). The cave was developed in bedded and platy limestone, clayey limestone and limestone breccia of the Liburnian Formation, which deposited during the transition between Cretaceous and Palaeocene

Figure 69 *Site location; Divača profile (SW Slovenia).*

Figure 70 *Divača profile was exposed during highway construction near Divača village.*

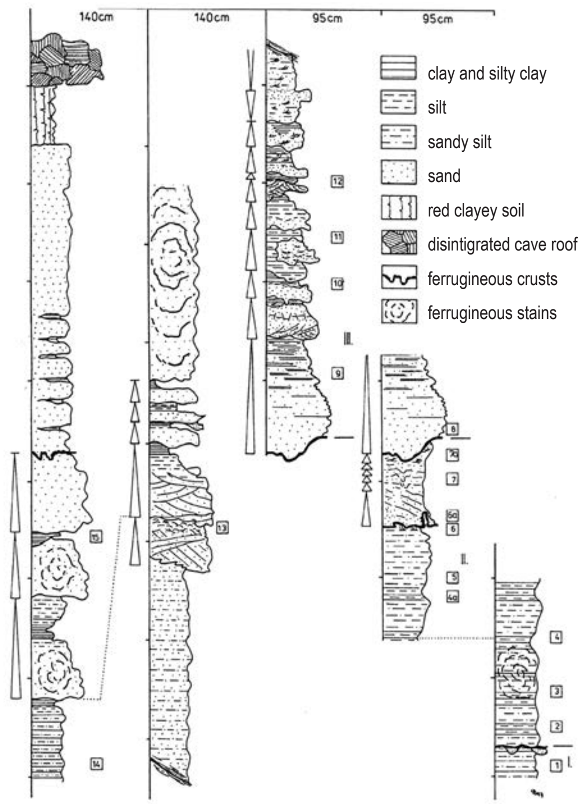

Figure 71 *Drawing of the Divača profile (after Bosák et al. 1998, with permission).*

Figure 72 *The lower part of the Divača profile with multi-coloured fine-grained quartz sand.*

(Jurkovšek et al. 1996). Beds dip towards the S at an angle of 10°.

LITHOLOGY

Four sedimentary sequences separated by distinct breaks were distinguished within the Divača profile (Fig. 71). The lowest sequence was composed of a multi-coloured clays and silty clays with some sandy admixture. It was separated from overlying sediments by a thicker ferruginized zone with limonite crust (Fig. 72). The middle sequence was built of the multi-coloured clayey silts to clays, sometimes with sandy admixture. It was terminated by a thin ferrugineous crust which emphasized the erosional base of the overlying sequence. The upper middle sequence was characterised by typical fluvial cycles from 4 to 40 cm thick consisting of whitish-beige to yellowish-brown sands, with light-coloured clayey and silty terminations of individual cycles. Sands were mostly fine-grained, cross-bedded, sometimes with small scale cross-lamination (Fig. 73). The lutites often showed planar-, hummocky-, cross- or flaser-lamination. The bases of individual cycles were sharp, usually erosional. The profile was terminated by a roughly 30 cm thick layer of re-deposited soils of the terra-rossa type. The red soil was covered by the partly decomposed cave ceiling (Fig. 74).

The sediments were in places lithified. Some sandy layers, especially white and beige, show contact types of carbonate cement but some parts were irregularly and strongly cemented by poikilitic calcite cement with abrupt transition to loose sediment. Strong secondary ferruginization was expressed as Liesegang features associated with sand-filled ferruginous concretions.

The profile was strongly fractured by a network of parallel fissures as the consequence of collapse of the right side of the cave fill. The fissures were sometimes accompanied by several mm up to 10–15 cm thick „crushed“ zones with white carbonate „pseudomycelia“, carbonate cement and infiltration of the terracotta-coloured sandy clays.

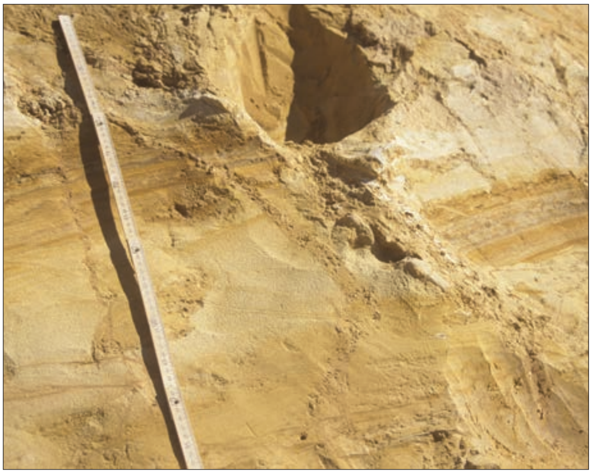

Figure 73 *The middle part of the Divača profile, where quartz sand is partly cemented by calcite.*

Figure 74 *The upper part of the Divača profile with red clays and disintegrated cave roof.*

MINERALOGY

Twenty one samples were taken from the profile. All the samples contain relatively high amount of quartz (62–93 %). The samples also contain chlorite (4–15 %), and the muscovite/illite group of minerals (4–11 %). Microcline was also detected, in one sample in a relatively high amount (10 %), but plagioclase was represented just in traces. Goethite was in two samples (about 5 %) and there was calcite in just one sample (24 %) where was a cement. The mineral association from the samples indicate that the source of the clastic sediments was the Eocene flysch siliciclastics weathered in different degree.

PALAEOMAGNETIC RESULTS

Oriented laboratory specimens of clay and sand were investigated for their palaeomagnetic properties. The mean values of J_n and k_n moduli are presented in Table 13. The J_n moduli values in the natural state are exceptionally low, largely depending on the origin of the magnetization. Volume MS values are also low but show smaller dispersion than J_n values. Selected samples were progressively isothermally magnetized by a direct field with intensities up to 900 mT. The SRM values (J_s) reached high values of several hundreds of [mA.m^{-1}].

All specimens were demagnetized by the AF procedures up to a field of 1 T. Several specimens were also experimentally subjected to the TD up to 500 °C, but generally less effective than by the AF demagnetization. The MS values dependence on the temperature *t* was investigated in all samples subjected to the progressive TD.

The samples showed in general two or three remanence components. The *A-components* are mostly of viscous or chemoremanent (weathering) origin. They can be removed by an alternating field with the intensity up to 3 mT. The Fisher distribution displays two defined sets of the samples with normal and reverse polarities (Tab. 14, Figs. 75 and 76). The number of samples with normal components was too small

Table 13: Mean palaeomagnetic values and standard deviations, Divača profile

Divača profile	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	0.645	102.9	5.95–0.05
Standard deviation	0.543	26.1	
Number of samples	29	29	

* from top to base

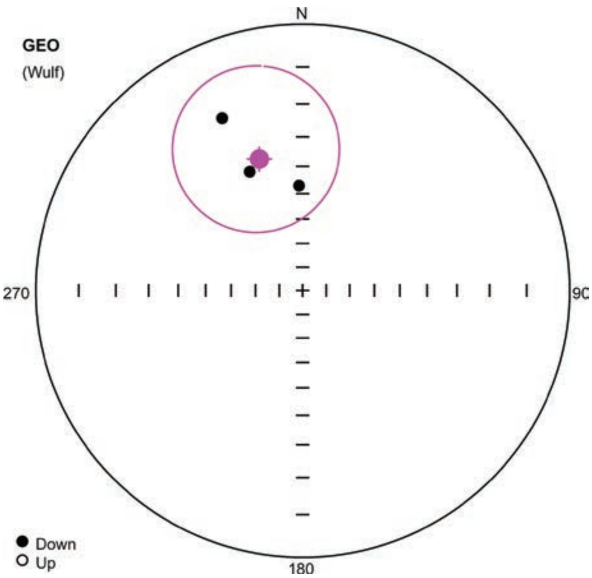

Figure 75 *Directions of C-components of remanence of samples with N polarity, Divača profile. For detail description see Figure 34.*

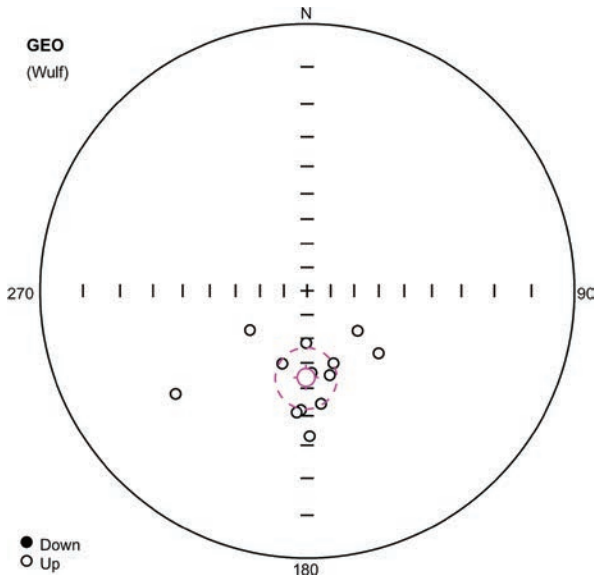

Figure 76 *Directions of C-components of remanence of samples with R polarity, Divača profile. For detail description see Figure 34.*

Table 14: Mean palaeomagnetic directions, Divača profile

Divača profile	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	341.77	35.12	17.42	21.53	3
	R	180.78	-54.24	10.72	13.13	13

(only three); that means to big value of α_{95} for the mean direction calculated after Fisher (1953) for the 95% probability level.

The magnetostratigraphic data detected two narrow N magnetozones within a long R polarity zone (Fig. 77).

PALYNOLOGY

No spores and pollen grains were found in the microscopic examination of 4 sections from each of two samples of the clastic sediments.

DISCUSSION OF RESULTS

The Divača profile represents a nearly unroofed cave with a partly disintegrated roof. The cave was completely filled by fluvial deposits. Sediments were highly ferruginized and in places strongly cemented by calcite cement. The profile is disturbed by fissures originating during slumping caused by the collapse probably due to rejuvenated karstification. In the lower part of the log there are three distinct ferricretes representing breaks in deposition, which were accompanied by fossil weathering.

Quartz, muscovite, microcline and plagioclase from sediments were derived from flysch rocks. Illite and chlorite probably originated in weathered remains of flysch rocks. Limonite crusts in the cave were formed during longer breaks in sedimentation and also in the red soil. Calcite represents concretions, which were formed by the cementation of sand.

The interpretation of magnetostratigraphic picture is problematic, as there were no palaeontological finds. The profile is older than 1.77 Ma, i.e. of the top of the Olduvai subchron. The geometry of the magnetozones could indicate an age as great as about 5.23 Ma (base of N polarized Thvera subchron within the Gilbert chron). The substantial age of the cave is supported by the thin roof, indicating substantial thickness reduction of the limestones by chemical denudation.

Bosák, Pruner & Zupan Hajna (1998) associated

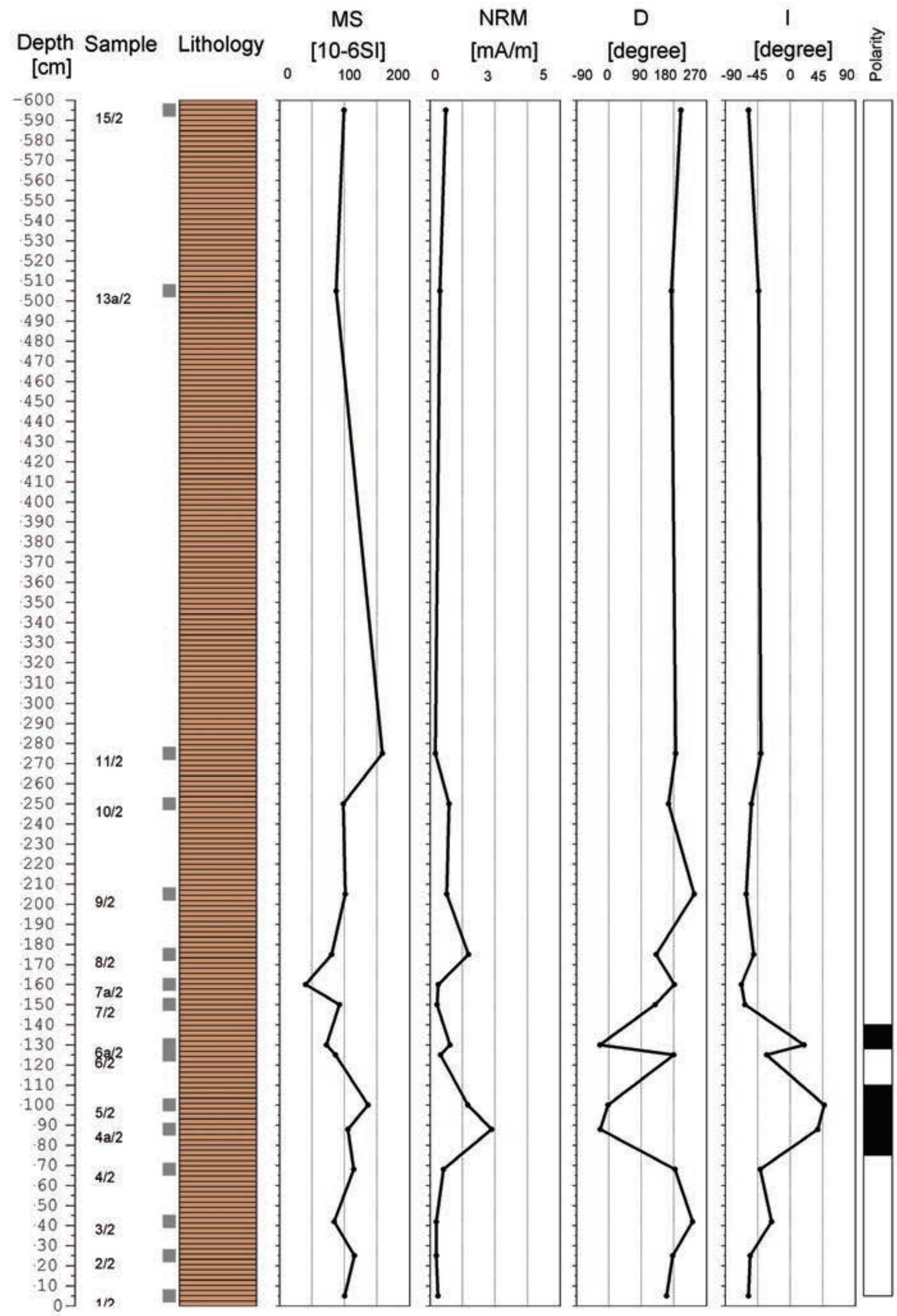

Figure 77 *Basic magnetic and palaeomagnetic properties, Divača profile. Legend: see Figure 37.*

the speleogenesis of the cave with the Messinian (especially if the N magnetozones are correlated within the reverse Gilbert epoch), when the sea level of the Mediterranean had rapidly fallen down to the level -1,600 m (Hsü, Cita & Ryan 1973; Hsü et al. 1977) and when the underground course of drainage was expected to be directed into the Mediterranean Basin from its foreland (Głazek 1993). The fill of the cave resulted from changed hydrological situation due to the gradual relief/tectonic evolution of this part of the Kras after the Messinian.

JAMA POD KALOM

SITE LOCATION

Jama pod Kalom ('Cave below the pond', in Italian 'Grotta Pocala') is a cave situated in the central part of the Kras plateau (Fig. 5) near the village of Nabrežina (in Italian, Aurisina; 45°45' 27.72"N; 13°40'27.41"E; 130 m a.s.l.; Figs. 18 and 78).

The cave entrance is in bedded rudist limestone of the Borgo Grotta Gigante Formation (Upper Cenomanian–Maastrichtian; Cucchi & Pugliese 1996). The cave is situated in the levelled surface with numerous dolines, some of them possibly of collapse origin. They are up to 50 m deep and several 100 m wide.

Jama pod Kalom is a slightly inclined, tunnel-shaped passage slightly widening down-slope. The thickness of the limestone roof is from about 3 m

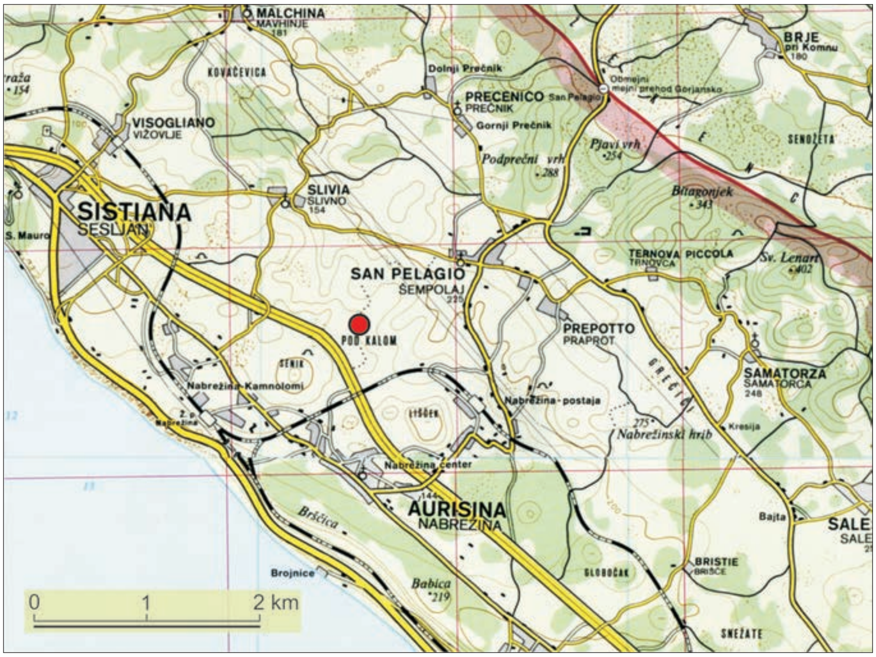

Figure 78 *Site location; Jama pod Kalom (NW Italy).*

Figure 79 *The entrance to the cave Jama pod Kalom.*

above the actual entrance (Fig. 79) to about 25 m at the end of the cave. The cave is fully blocked at its end by sedimentary fill. In the front of the surviving entrance, there is a continuation of a cave passage which is now unroofed in the length of about 100 m. There was a quarry of flowstone situated west of the cave entrance. The cave has been known as an important archaeological site (*cf*. Battaglia 1930, 1958–1959).

Borehole No. S1 was drilled through the limestone roof to the internal cave fill (Calligaris 1999, 2000) in front of the cave entrance (in the flat unroofed part of the cave).

PROFILE

The borehole was fully cored (10 m). The core yields were nearly 100 %; some losses were noted only in the parts with higher proportions of limestone clasts without sedimentary matrix. The diameter of the drilling was about 12 cm. The borehole cores were divided into two parts along the longitudinal axis. One half of the core was used for analytical purposes; the second was left in the museum collections. Each core was stored separately in plastic tubes, each 1 m long. The tubes were closed to prevent the desiccation of cores. Cores were covered by plastic foil and the space, left after the use of the second half of the core, was filled by old newspapers. Some reviewed cores were stored in the classical wooden boxes. Boxes and tubes with core were deposited in the collections of the respective department of the Museo Civico di Storia Naturale di Trieste.

LITHOLOGY

The detailed log of the core was available during the sampling. The dominant part of the borehole was composed of yellowish brown and brown to brownish red clays and silty clays with pieces of limestones and speleothems (scree). The main lithological boundaries seem to be situated at 3.50 m and 7.65 m. The upper part (0.00–3.50 m) was composed of brown to brownish red clays with pieces of limestones. The middle part (3.50–7.65 m) was lithologically more varied with alternating clays, limestone scree, sandy layers and with rather brownish colour. The lower part (7.65–9.94 m) was rather yellowish brown and brown, interlaminated with sandy laminae and with occasional pieces of limestones. The bottom was at a depth of 9.94 m.

MINERALOGY

Mineralogical analyses of the yellow sands were performed by Cucchi, Finocchiaro & Princivalle (1992). The yellow sand formed lenses in brown clays with limestone clasts just above the bottom of the cave. In the grain-size fraction below 50 μ, quartz dominated (29–76 %), followed by illite (6–21 %). Calcite (0–29 %), chlorite (0–8 %), kaolinite (0–8 %) and feldspar (0–9 %) were missing only in one sample with a high content of gibbsite (50 %). Gibbsite was present also in the grain-size fraction below 4 μ.

The detailed mineralogical and geochemical study of the borehole material was carried out by Mrs. Antonella Tremul, but the results were not published (Tremul 2001). She discovered changes in contents of Fe, Al, Cr, and other elements, assemblages of heavy minerals, and in composition of clay mineral fractions (proportion of kaolinite, illite, smectite, chlorite, eventually also montmorillonite).

PALAEOMAGNETIC RESULTS

The samples were investigated for their palaeomagnetic properties. The NRM (J_n) and MS (k_n) moduli values in their natural state show a large scatter. The mean values of J_n and k_n moduli are documented in Table 15. According to them, the profile may be divided into two parts and categories. The sediments are characterized by their large scatter of NRM intensities (0.1–106 mA.m^{-1}) and the MS values (81–6,089 x 10^{-6} SI units) and have very low up to high J_n and k_n magnetic values.

Table 15: Mean palaeomagnetic values and standard deviations, Jama pod Kalom

Jama pod Kalom	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	49.323	3,018.2	0.10–7.61
Standard deviation	27.504	1,536.4	
Number of samples	45	45	
Mean value	0.463	109.2	7.80–9.94
Standard deviation	0.290	18.2	
Number of samples	16	16	

* from top to base

All specimens were subjected to detailed AF demagnetization in 14 steps. The RM directions inferred

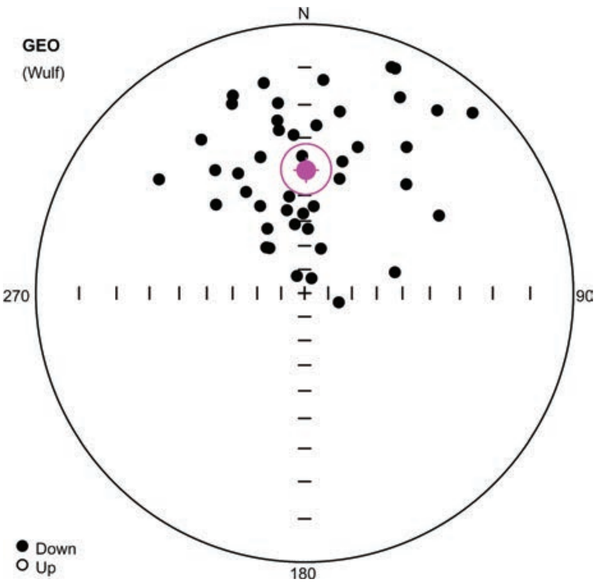

Figure 80 *Directions of C-components of remanence of samples with N polarity, Jama pod Kalom. For detail description see Figure 34.*

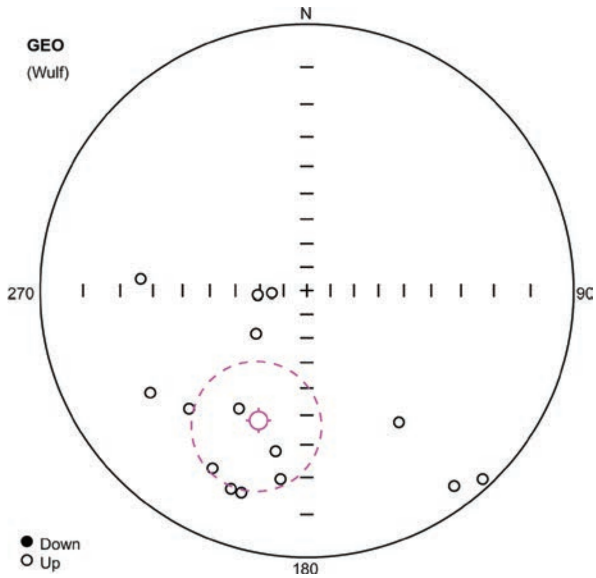

Figure 81 *Directions of C-components of remanence of samples with R polarity, Jama pod Kalom. For detail description see Figure 34.*

Table 16 Mean palaeomagnetic directions, Jama pod Kalom

Jama pod Kalom	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	0.69	40.83	8.03	6.91	44
	R	200.47	-35.19	17.81	4.12	15

the procedures were tested using a multi-component analysis. *A-components* of remanence are mostly of viscous or chemoremanent (weathering) origin; they can be removed by AF demagnetisation with an intensity of 1 up to 3 mT. The N and R *C-component* directions are documented in Table 16 and Figures 80 and 81.

The palaeomagnetic and magnetostratigraphic investigations carried out on 61 oriented laboratory specimens provided data concerning principal magnetic properties and identification of palaeomagnetic directions. Systematic acquisition of palaeomagnetic data within the studied section allowed the construction of a detailed magnetostratigraphic profile (Fig. 82). The magnetostratigraphic results show both N and R polarity magnetozones. The top of the profile is in an N magnetozone. The R zone (0.51–1.89 m) is within the long N magnetozone in the upper part of the profile. The middle and lower parts of the profile show N palaeomagnetic directions. Three narrow R polarity subzones – excursions – are situated in the upper and lower parts of the profile.

TH/U DATING

Seven samples were submitted for analysis and six of them were analysed. All are characterized by low U content (Tab. 17), which resulted in low accuracy of analyses. In addition, significant contamination by detrital Th is visible in samples W809 and W806 (^{230}Th/^{232}Th<20). ^{230}Th/ ^{234}U activity ratios are in equilibrium within an error range of one standard deviation. We can assume that the measured value is different than any other (equilibrium value = 1, in our situation) if the difference is minimum 2 standard deviations. Taking this rule into the account, we have no evidence of disequilibrium between ^{230}Th and ^{234}U in the Uranium series, based on our measurement results. The estimation of the minimum age limit seems to be in the safest solution this situation. The minimum age limits have been estimated basing on measured activities ratios and their accuracy (measured activity ratios minus error). The corrected minimum age limit takes into the account detrital contamination and have been estimated assuming initial $^{230}Th/^{232}Th$ activity ratio in the detritus, equal 1.5 ± 0.5. The $^{234}U/^{238}U$ activity ratios, except in the samples with significant detrital contamination, are in equilibrium within the error range. This suggests ages >1.2 million years. This conclusion needs caution because of the low accuracy of the activity ratios. For the samples with significant detrital contamination we should take into account that not only Th, but U as well, may be mobilized at the time of dissolution of the sample. At the time of U mobilization, enrichment of ^{234}U is characteristic. Higher values of $^{234}U/^{238}U$ activity ratios in the samples with significant detrital contamination may suggest that not only Th but also U contamination must be assumed for these samples. It means that results of Th/U dating for these samples are not reliable.

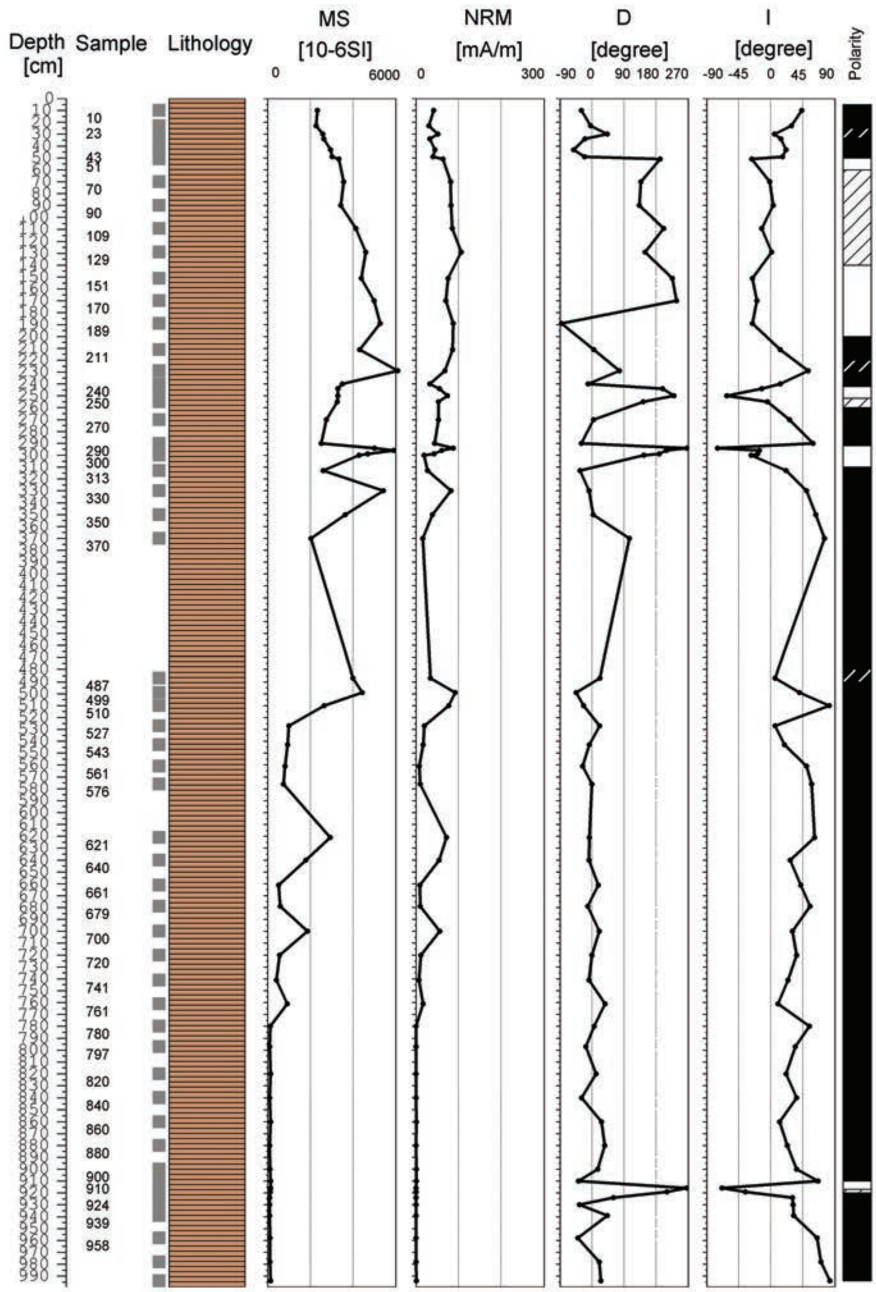

Figure 82 *Basic magnetic and palaeomagnetic properties, Jama pod Kalom. Legend: see Figure 37.*

Table 17 Th/U dating results using α-spectrometry from speleothems, Borehole No. S1, Jama pod Kalom

Sample	Lab. No.	U conc. [ppm]	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Age [ka]	Remarks
4.60–4.68 Upper	W 843	0.266±0.011	1.012±0.043	0.875±0.039	244	226^{+40}_{-29}	
4.60–4.58 Lower	W 842	0.239±0.010	1.026±0.045	0.927±0.041	221	284^{+90}_{-48}	
4.85–4.92 Upper	W 860	0.262±0.011	1.073±0.046	0.974±0.046	7.5	$393^{+\infty}_{-109}$	detrital contamination
4.85–4.92 Lower	W 861	0.263±0.011	0.994±0.048	1.008±0.049	14	>350	detrital contamination
6.20–6.30 Upper	W 863	0.046±0.031	1.113±0.236	1.035±0.086	4.1	>350	U leaching (?), detrital contamination
6.20–6.30 Lower	W 844	0.048±0.004	1.190±0.117	0.785±0.078	4.5	167^{+49}_{-34}	U leaching (?), detrital contamination

Note: The quoted errors are one standard deviation.

DISCUSSION OF RESULTS

The magnetostratigraphic data obtained from Jama pod Kalom (borehole S1) and Briščiki (borehole S3), appear very similar. In particular, the arrangement of the N and R polarized magnetozones (Figs. 62 and 82) can be judged as identical at first sight. Nevertheless the character of the J_n and K_n moduli differ, although the general character of both curves in both boreholes show similar trends. The J_n and k_n values for the lower part of the boreholes (7.80–9.94 m for S1 and 4.70–7.12 m for S3) differ substantially (Tab. 15). Similar differences can be detected also in the upper parts of borehole logs (0.10–7.61 m for S1 and 0.10–4.55 m for S3). Also detailed comparison of J_n and k_n curves shows differences in trends.

The J_n and k_n moduli reflects the major lithological boundaries detected in both boreholes, i.e. lithological change in transported material into the caves and/or some major climatic change. Such important boundaries are located at 7.65 m in the S1 log of Jama pod Kalom and at 4.37/4.65 m in the S3 borehole in Briščiki, respectively. Below both boundaries, the k_n values are 20 to 30 times lower than in the upper part and the J_n values are 20 to 100 times lower. It appears that the lower parts of both borehole logs represent re-deposited weathering residua of Eocene flysch, while the upper parts contain gradually increased proportions of re-deposited terrae calcis products (terra rossa from limestone areas). The reason for such change can be found in some kind of re-arrangement of source (catchment) areas of water streams feeding the karst and/or in climatic change. Climatic change is indicated especially by the magnetic susceptibility values (*cf.* Sroubek et al. 2001). The differences in rock magnetic properties can be traced also in the geochemical log of the sediments (especially changes in contents of Fe, Al, Cr), assemblages of heavy minerals, and in composition of clay mineral fractions (proportion of kaolinite, illite, smectite, chlorite, eventually also montmorillonite).

The dominant part of both profiles is represented by N magnetozones. There is one well-documented R polarized zone (0.51–1.89 m in the Jama pod Kalom; Fig. 82 and 0.90–1.50 m in the Briščiki; Fig. 62, respectively). There were also short R excursions of magnetic field. The position of these short-lived reversals differs in both borehole logs. In the Briščiki, two short reversals below a longer one are missing and the distance of the lower short reversal from the main one is shorter than in the Jama pod Kalom.

The Th/U dating yielded two acceptable results from the Jama pod Kalom (S1 borehole). The upper part of speleothem layer at 4.60–4.68 m indicate an age around 226 ka (+40, -29 ka), the lower part was dated to about 284 ka (+90, -48 ka). These dates indicate that before 194 to 332 ka there was a roofed cave as only a cave environment permits the formation of speleothem and flowstone layers on the top of the cave sediments.

The Th/U dates (226 to 284 ka), the lithostratigraphic situation (cave fill unconformably overlies fill of unroofed part), and recent palaeontological finds in Jama pod Kalom (cave bear about 50 ka old; G. Rabeder, pers. comm., 2003) may indicate that the longer reverse magnetozone in borehole S1 in Jama pod Kalom could represent the Blake event within the Brunhes chron. The Blake event is best dated in Chinese loess by Zhu et al. (1994) by thermoluminescence to 117.1 ±1.2 to 111.8 ±1.0 ka BP. Another short excursion of the polarity of geomagnetic field occurs in the Chinese loess (Zhu et al. 1999), i.e. Mono Lake excursion (27.1 to 26.0 ka BP) and Laschamp excursion (46.3 to 37.4 ka BP). Nevertheless, owing to the position of our reverse polarized magnetic zone they are younger and they eventually occur within the fossil-bearing fill of Jama pod Kalom.

The Briščiki log cannot be, probably, correlated with the situation in Jama pod Kalom. We expect that the log covers another climatic cycle with similar palaeogeographic situation.

The fills in Jama pod Kalom and in its unroofed continuation differ, as already mentioned by Mühldorfer (1907). In his section, cave fill unconformably overlies the fill of the unroofed part (*cf.* also Fig. 2 on p. 5 in Battaglia 1930). The fill of the unroofed cave consists of the red terra rossa-type of sediments in the upper part and yellow clays in the lower positions (*cf.* Battaglia 1930, fig. 25 on p. 30). Nevertheless, Battaglia (1930) expected that the yellow clays are younger member, Holocene in age, and terra rossa is older, Pleistocene in age (*cf.* his fig. 22 on p. 26).

The palaeomagnetic and Th/U dating of the borehole S1 from the unroofed part in front of the recent entrance to Jama pod Kalom indicates of a young geomorphic evolution of this part of the cave. The speleothem layers buried in the fill dated back to ca 194 and 332 ka represent the evidence of presence of the cave roof at that time. The roof had to be thick enough to prevent the collapse (i.e. as at the recent entrance to Jama pod Kalom, at least 3 to 4 m thick). The unroofing was younger than 194 ka. After unroofing, the younger sediments in Jama pod Kalom were deposited, disconformably overlying the fill of the unroofed part of the cave (*cf.* also Mühldorfer 1907). The excavation of older fill from the cave could represent the consequence of slope movement of sediments down to some yet unknown part of the cave and/or of backward erosion from hydrological active underground stream excavating the older fills in the depth. The erosion of the older fill occurred only after Blake event (ca 111–117 ka), i.e. after the Eemian interglacial, but before the deposition of bone-bearing beds dated back to ca 50 ka.

GROFOVA JAMA

SITE LOCATION AND CHARACTERISTICS

The entrance to Grofova jama (Reg. No. 6289; 45°47´54.61˝N; 13°37´40.87˝E; 265 m a.s.l.; Figs. 83 and 18) is located in a shallow doline. Outcrops of massive flowstones are exposed around the entrance, representing remnants of an old cave destroyed by denudation. The entrance and the cave itself are situated just below the top (275 m a.s.l.) of one of several small hills of Grmada (Fig. 84). Grmada is about 150 m above the levelled surface of the western part of the Kras (Fig. 5). The cave is only 4 km from the springs of Timavo on the coast of the Adriatic Sea.

The cave was formed in Lower Cretaceous limestone and dolomite (Buser, Pavlovec & Pleničar 1968), which alternate with rare limestone and dolomite breccia of the Brje Formation (Barremian–Aptian; Jurkovšek et al. 1996). It is about 300 m long and 46 m deep. Narrow passages from three entrances join at a depth of about 10 m into one larger, inclined passage up to 10 m wide and high and with phreatic forms. The cave was once completely filled by yellow clay-sized sediment as indicated by fill in niches on the walls. Speleothems of recent vadose percolation origin are not abundant. The entrance of the cave and the main passage were much reworked during the World War I, when the cave served as a shelter for soldiers.

There are two profiles in the sediments. One was exposed by military a works and another was preserved on the wall in the bottom part of the cave.

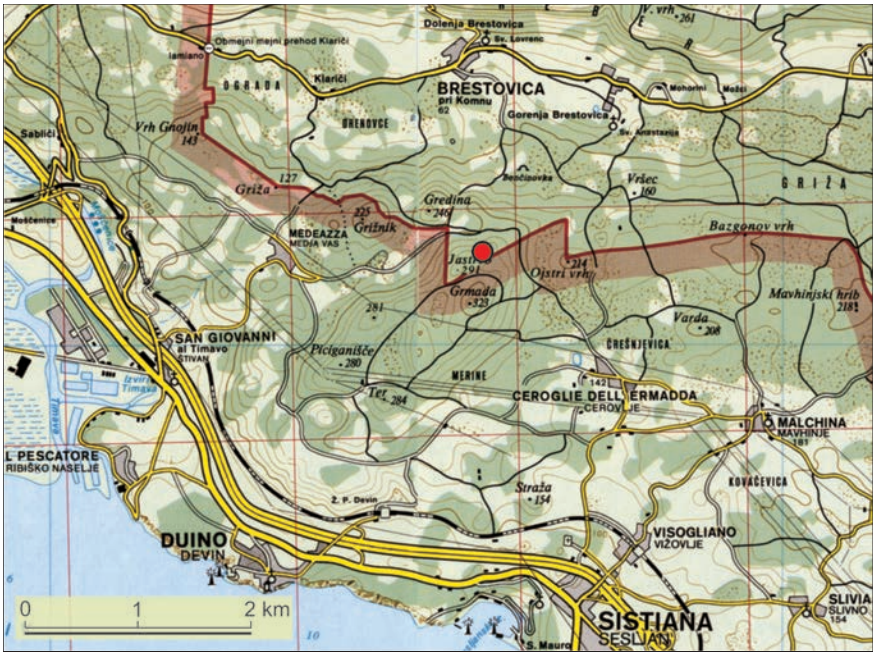

Figure 83 *Site location; Grofova jama (SW Slovenia).*

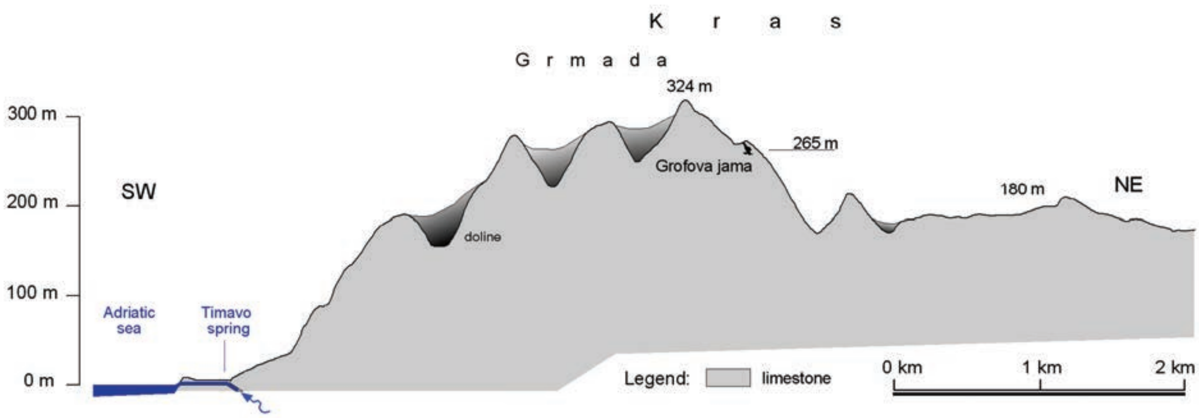

Figure 84 *Cross-section of Kras at Grofova jama.*

PROFILES

Two profiles were documented (Fig. 85). The first profile was situated on the side of an artificially levelled floor at survey point 18 (245 m a.s.l.). The second profile was situated above survey point 23 (238 m a.s.l.; Mikolic 1992).

LITHOLOGY

Profile I consisted of two parts, a red coloured upper part (77 cm) and a yellow-white lower part (92 cm; Fig. 86). The upper part was of red clays without any distinct sedimentary structures and textures (Fig. 87) Clasts of underlying sediments were present at the base. The base was relatively sharp, uneven and represents an important erosional event. Decomposed remains of thin flowstone occurred there. The lower part (Fig. 88) was composed of yellow and white montmorillonite clays with nearly horizontal lamination to banding (Fig. 89). The top (10–15 cm) sediments, below the erosion surface, were altered by ferruginization.

Profile II is situated on the wall of the bigger chamber at the termination of the cave (Fig. 90). The yellow-white sediments once filled the whole chamber. Also here the upper part consisted of red to brownish red clays; the lower part consisted of yellow clays. Between them there is a distinct erosional boundary.

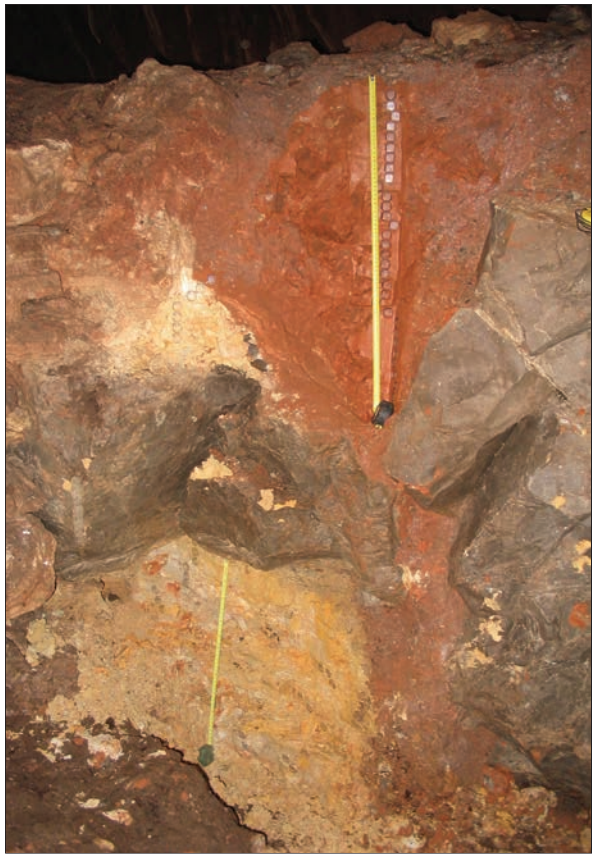

Figure 86 *Profile I in Grofova jama (the bottom part – yellow montmorillonite clays).*

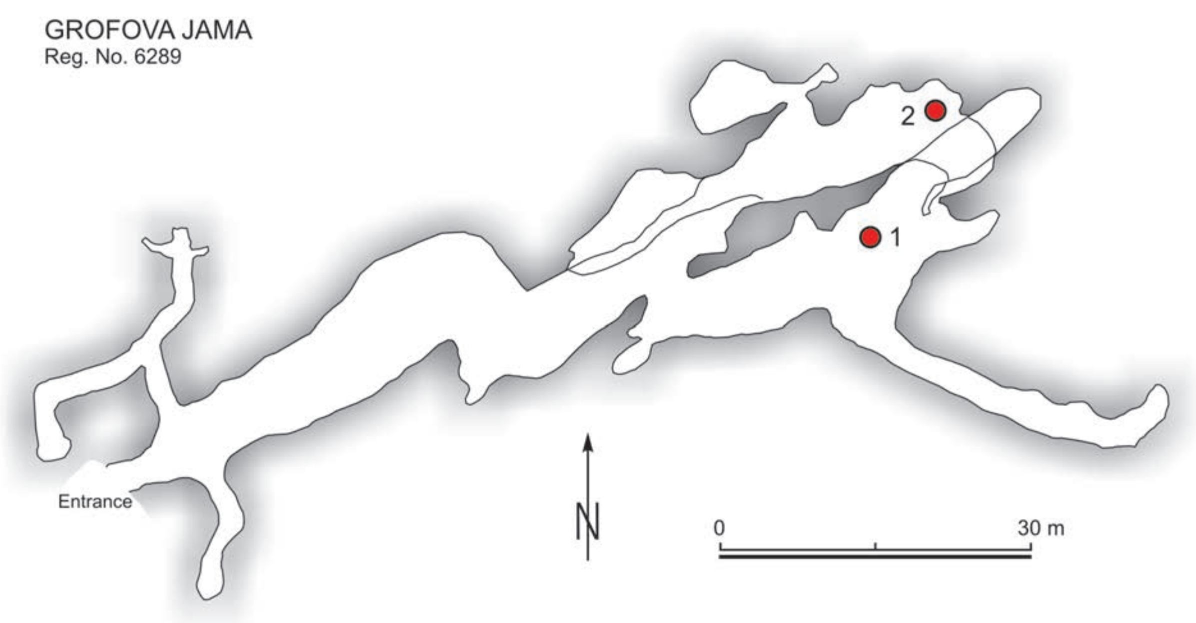

Figure 85 *Cave map and the profiles location (after Cave Register of IZRK ZRC SAZU and JZS). Legend: 1 – profile I (sampled for paleomagnetic analyses); 2 – profile II.*

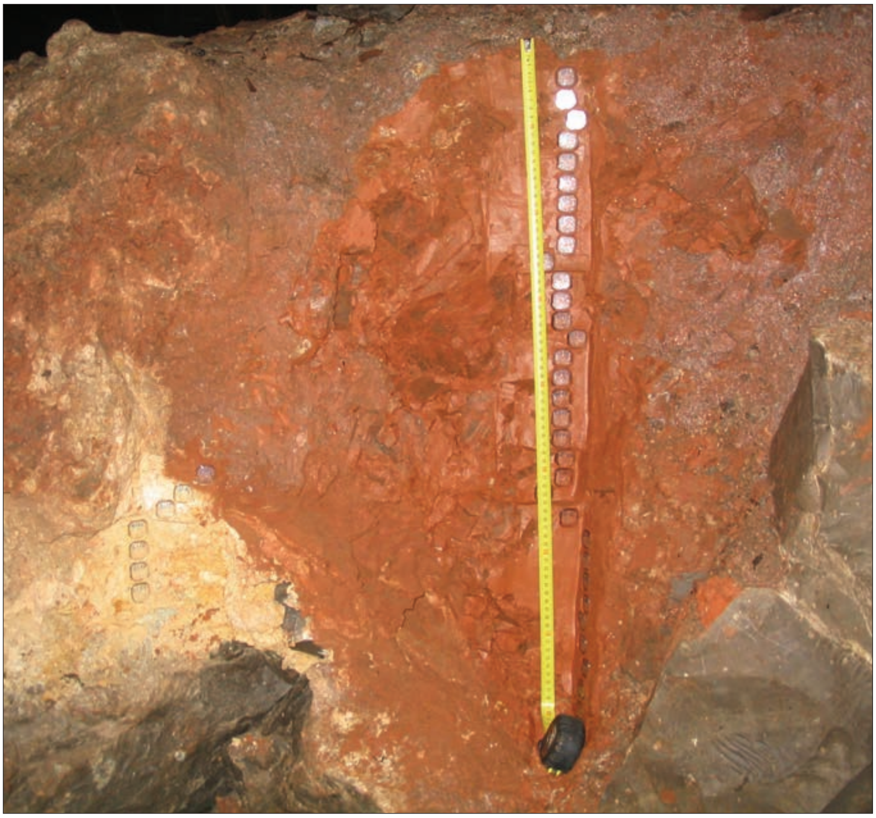

Figure 87 *Samples (boxes) in the red (upper) part of the profile I in Grofova jama.*

Figure 88 *Samples (boxes) in the yellow (lower) part of the profile I in Grofova jama.*

Columnar disintegration was developed in the upper part of the yellow clays. In places an irregular layer of sedimentary breccia was developed along the erosional contact. The clasts were composed of yellow/white clay and matrix was built of dark rosy clay. The upper part was irregularly altered by ferruginization (Liesegang features) and iron compounds filled joints between clay columns up to a depth of more than 1 m. Joints among columns were also filled by the dark rosy clay derived from the upper layer, and locally also by calcitic crusts covered by small triangular calcite crystals.

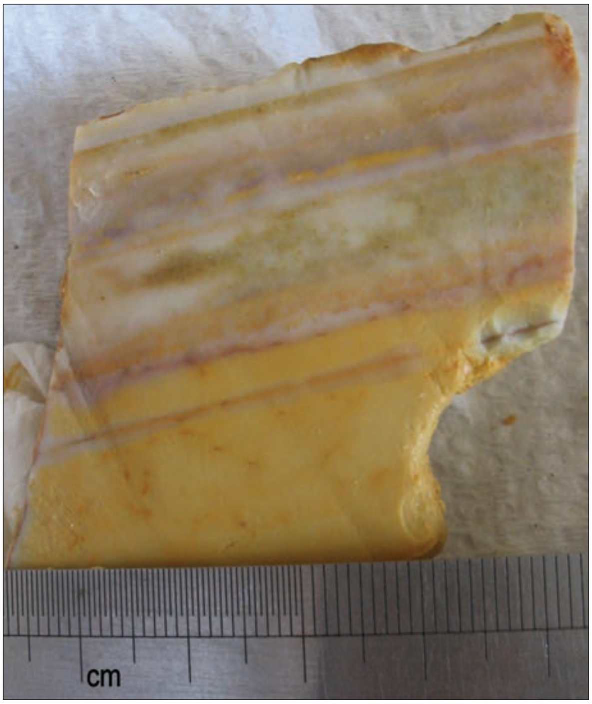

Figure 89 *Detail of laminated montmorillonite clays from the bottom of profile I, Grofova jama.*

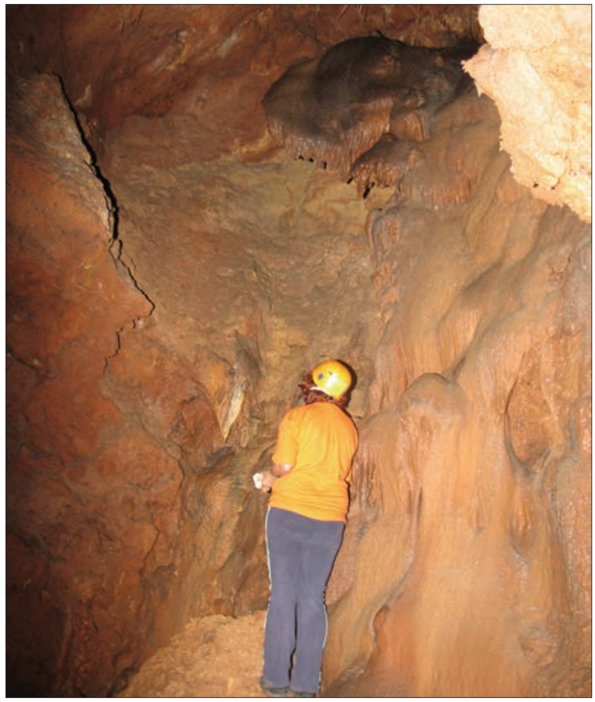

Figure 90 *Yellow clays from profile II are covered by red flowstones and clays, Grofova jama.*

MINERALOGY

Six samples were analysed by X-ray diffraction. Montmorillonite was the only mineral present in three samples of yellow and white clay from profile I (Zupan Hajna 2006). Red clay contained calcite, quartz, chlorite, hematite, mica, kaolinite and montmorillonite. Montmorillonite prevailed also in the sample of the yellow white clay from profile II; it was accompanied by kaolinite, mica and some quartz.

Two samples (25 and 60 kg) from profile II were decanted and different mineral fractions were separated. Detailed study is in progress. The light fraction was composed of quartz, clay minerals, plagioclases and K-feldspars. The heavy-mineral fraction contained some small grains of apatite, zircon, probably monazite and rare opaque ore minerals. Ferruginized clay minerals were common.

PALAEOMAGNETIC RESULTS

A total of 59 samples were studied for their palaeomagnetic properties from Profile I. Samples from the *upper part* (red in colour; 0–0.77 m) are characterized by an NRM intensity from 32 to 906 $mA.m^{-1}$ and the MS values from 1,426 to 1,874 x 10^{-6} SI units. Mean values of J_n and k_n moduli are documented in Table 18. According to the both values, the profile may be divided into three parts and categories. Samples are characterized by intermediate up to high J_n and k_n magnetic values.

Sediments from the *lower part* (yellow and white in colour; 0.48–1.69 m) are characterized by the NRM intensity from 1 to 54 $mA.m^{-1}$ and the MS values from 114 to 269 x 10^{-6} SI units. Mean values of J_n and k_n moduli are documented in Table 18. According to both values, the profile may be divided into three parts and categories. Samples are characterized by low up to intermediate J_n and k_n magnetic values.

All samples were subjected to detailed AF demagnetization in 14 steps. Multi-component analysis was applied to separate the respective RM components for each sample. Three components were isolated by AF demagnetization. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–2 up to 5 mT). The *B-LFC* is also secondary; they show harder magnetic properties and can be demagnetized in the AF (5–10 up to 15 mT). The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF field (ca 15–80 up to 100 mT). The characteristic *C-HFC* is not stable for specimens with extremely low J_n and k_n magnetic values, for which they cannot be isolated in the AF.

The stereographic projections of the C-component with N and R polarity from both part of profile are shown on Figures 91 and 92. Table 19 summarizes results of the mean direction of samples from red pro-

Table 18 Mean palaeomagnetic values and standard deviations, Grofova jama

Grofova jama	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m]
Mean value	59.965	1,563.0	Red profile 0.035–0.245
Standard deviation	15.092	61.2	
Number of samples	10	10	
Mean value	323.435	1,624.6	Red profile 0.27–0.36
Standard deviation	297.368	60.9	
Number of samples	5	5	
Mean value	68.126	1,645.0	Red profile 0.385–0.77
Standard deviation	8.542	114.2	
Number of samples	17	17	
Mean value	73.304	2,075.5	Yellow profile 0.48
Standard deviation	-	-	
Number of samples	1	1	
Mean value	1.110	32.9	Yellow profile 0.50–0.625
Standard deviation	0.461	9.9	
Number of samples	6	6	
Mean value	0.115	0.25	Yellow profile 1.14–1.69
Standard deviation	0.180	4.63	
Number of samples	20	20	

* from top to base

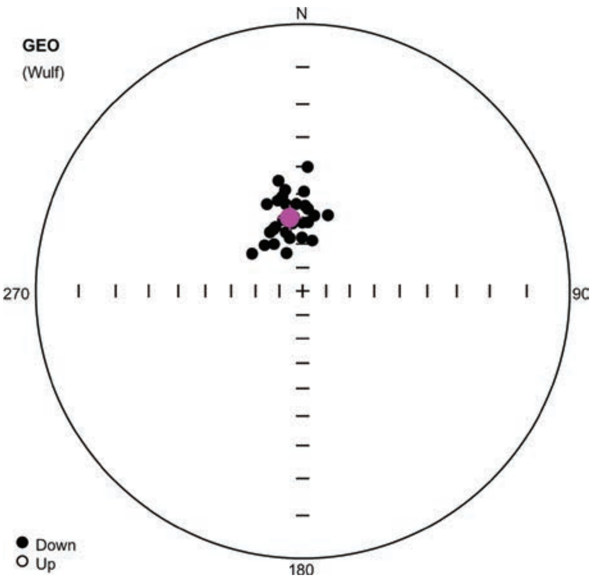

Figure 91 *Directions of C-components of remanence of samples with N polarity, Grofova jama. For detail description see Figure 34.*

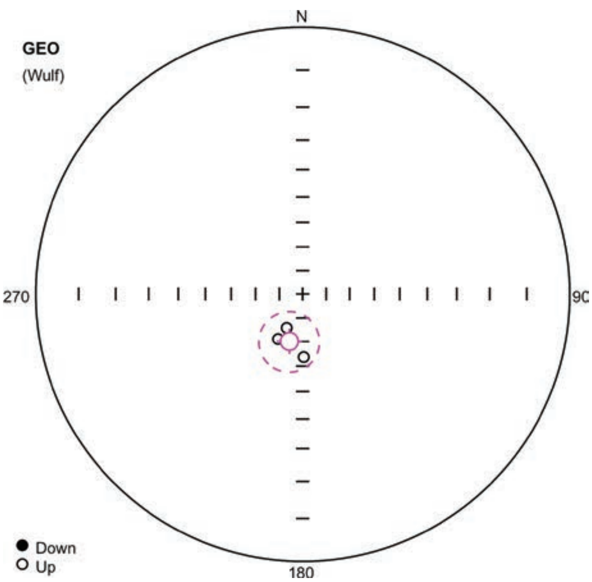

Figure 92 *Directions of C-components of remanence of samples with R polarity, Grofova jama. For detail description see Figure 34.*

Table 19 Mean palaeomagnetic directions, Grofova jama red profile

Grofova jama	**Polarity**	**Mean palaeomagnetic directions**		α_{95} [°]	**k**	**n**
		D [°]	I [°]			
	N	349.85	58.81	2.93	65.13	35
	R	195.91	-69.33	8.17	98.0	3

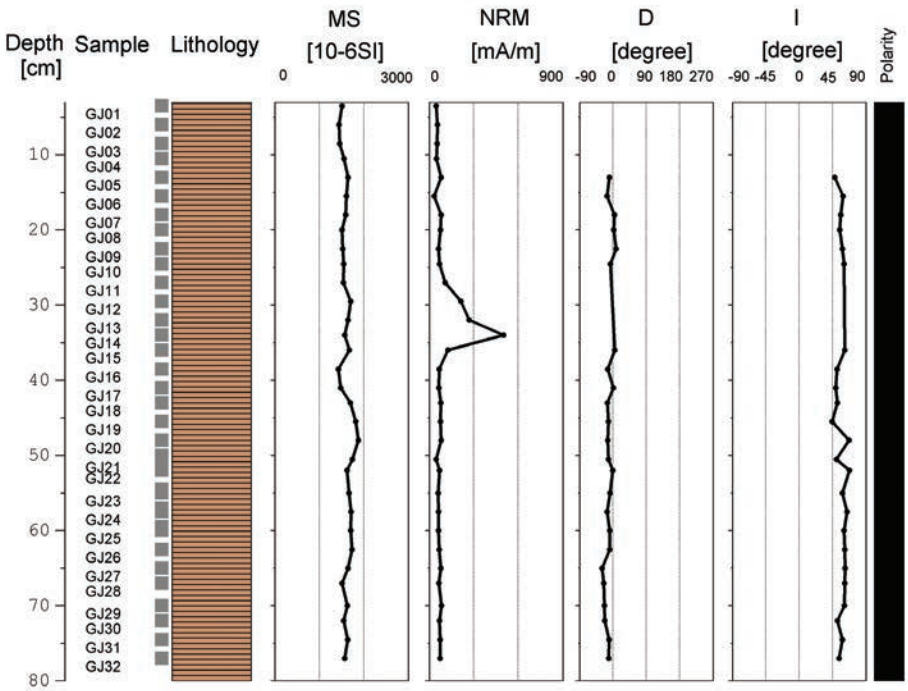

Figure 93 *Basic magnetic and palaeomagnetic properties, red part of profile I, Grofova jama. Legend: see Figure 37.*

file. The mean palaeomagnetic directions of C-components for the normal polarity are D = 350°, I = 59° and for the reverse polarity are D = 196°, I = -69°. Systematic acquisition of the palaeomagnetic data for the red part of the profile I allowed the construction of a detailed magnetostratigraphic profile (Fig. 93). The basic magnetic and palaeomagnetic properties of the yellow part of the profile I are presented in Figure 94.

DISCUSSION OF RESULTS

According to the morphology of the walls and passages of Grofova jama, the cave was formed in phreatic conditions. At one stage the entire cave was filled with montmorillonite clay. This sediment was later partly washed out and covered with red clay. Complete transition to the vadose zone is reflected in another erosion of nearly all sedimentary fill. There is modest flowstone deposition in the cave, but abundant flowstone remains occur when the part of the cave that was already destroyed by the denudation is considered.

The position of the cave at top of Grmada hill (Figs. 18 and 84) can be explained (1) by tectonic uplift of a small block above the general levelled surface of the Kras, or (2) the Grmada represents the residual hill. The second possibility is less probable since there is evidence of active tectonic movements in the area.

Montmorillonite is expected to be the product of volcanic ash weathering. The cave was filled by clay when it was situated at a much lower elevation. The montmorillonite does not occur in the other studied caves (Zupan Hajna 2006) in such amounts. The character and composition of cave fill clearly demonstrates that: (1) the yellow and white pure montmorillonitic clays represent weathering products or relatively pure and fine-grained volcaniclastic material (ash) in humid and warm climates of the tropical type. Such material should be products of intensive weathering of a quite thick volcaniclastic pile which completely covered the bedrock ; and (2) the red clays with frequent clastic impurities and mixture with iron compounds represents weathering products of flysch rocks (weathering on the surface in warm and periodically dry and wet climate) mixed with remains of the volcaniclastic material. Red clays were deposited only after the underlying montmorillonite clays were substantially eroded from the cave.

The montmorillonitic fill can represent either (1) *in situ* weathered volcanic ash or (2) weathering products of volcaniclastic rocks transported over the Kras by a river from the vicinity of the town of Idrija and washed into the cave. The principal problem with the second mechanism is the long distance between the source and the cave, and the grain size and purity of deposited material within the cave.

If montmorillonite represents more or less *in situ* weathering products of a layer of volcanic ash deposited over limestone, the source should be found

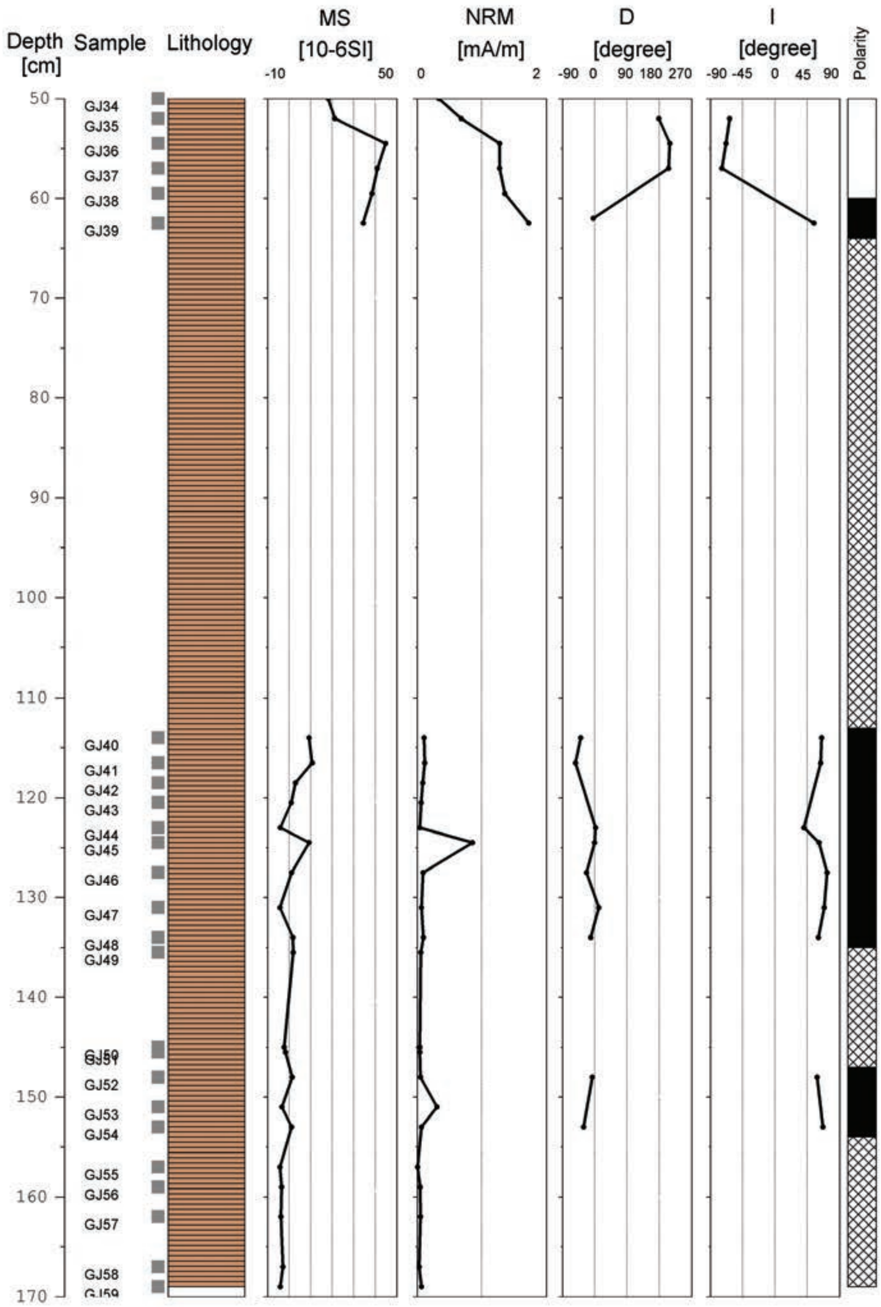

Figure 94 *Basic magnetic and palaeomagnetic properties, yellow part of profile I, Grofova jama. Legend: see Figure 37.*

in some of the volcanic centres around the Mediterranean (for review see Becalluva, Bianchini & Wilson 2007 and Lustrino & Wilson 2007). If westerly trade winds can be expected to dominate, the source of the volcanic material could be situated in region between Verona and Padova (northern Italy). Volcanic centres here were active from the Eocene to late Oligocene and the activity slowly shifted from west to east. Our source could be most probably found in the Coli Euganei (southwest of Padova, 170 km to the southwest from our site) or better in the Marostica Hills (near Bassano, 160 km to the west). Volcanism in Coli Euganei terminated in the late Oligocene, but activity in the Marostica Hills was limited only to Oligocene with the end during late Oligocene (Becalluca et al. 2007). So the activity in the expected source area ceased some 23 Ma ago.

If other directions of trade winds are hypothesized, there are several possibilities. Another relatively close and large volcanic region to the southwest is the Tuscany Magmatic Province (about 370 km to the southwest) in Italy, with activity younger than 7.5 Ma in its western part, Capraia Island, and younger than 4.1 Ma on the mainland (Conticelli et al. 2007). The Roman and Lucanian Magmatic provinces are situated farther to the south (410 km to the south-south-west, resp. 570 km to the south-south-east) with maximum volcanic activity from 0.8 to about 0.13 Ma, with some still active volcanism (e.g., Vesuvius; Conticelli et al. 2007).

Considering the alternative possibility of air transport of volcaniclastics from the northeast, its principal sources are of the Oligocene to Plio-Pleistocene ages (see review in Kovács et al. 2007). The nearest volcanism was in the Smrekovec, in the area of Periadriatic fault (Oligocene and Miocene andesites and andesitic tuffs), now situated about 100 km from our site. Other sources could be about 210 km (Styrian Basin), 330 km (Little Hungarian Plain and Transdanubian Range) and over 500 km (Central Slovakian volcanic field). These distances are recent; the original ones could be changed (prolonged) by movements especially along the Periadriatic fault.

View from the Grmada hill towards E on the Kras plateau.

DIVAŠKA JAMA

SITE LOCATION AND CHARACTERISTICS

Divaška jama (Reg. No. 741; 45°40´30.80˝N; 13°57´ 02.79˝E; 430 m a.s.l.; Figs. 18 and 95) is situated in the south-western part of the levelled surface of the Divaški kras (Fig. 20). Numerous dolines occur on the surface above the cave, but they are not directly connected to it. The cave is about 20 m below the surface. There are no flowing streams on the surface. Underground flow is accessible only in Kačna jama at 156 m a.s.l., which is situated about 1 km to the north-east of the site.

Divaška jama is developed in bedded limestone with rare rudist biostromes of the Sežana Formation (Senonian; Jurkovšek et al. 1996). Limestone beds dip south-westwards in the first half of the cave and southwards in the second (Gospodarič 1985). The accessible channels are transversal to the bedding, mostly following N–S-trending fractures.

The cave represents an approximately 700 m long relict of an originally larger cave system formed at about 350 to 410 m a.s.l. Both ends of the cave are choked by allogenic sediments and speleothems. Trhlovca cave, which is not connected with Divaška jama, is situated above the south-western end of the cave. A secondary entrance is situated in the north-

Figure 95 *Site location; Divaška jama (SW Slovenia).*

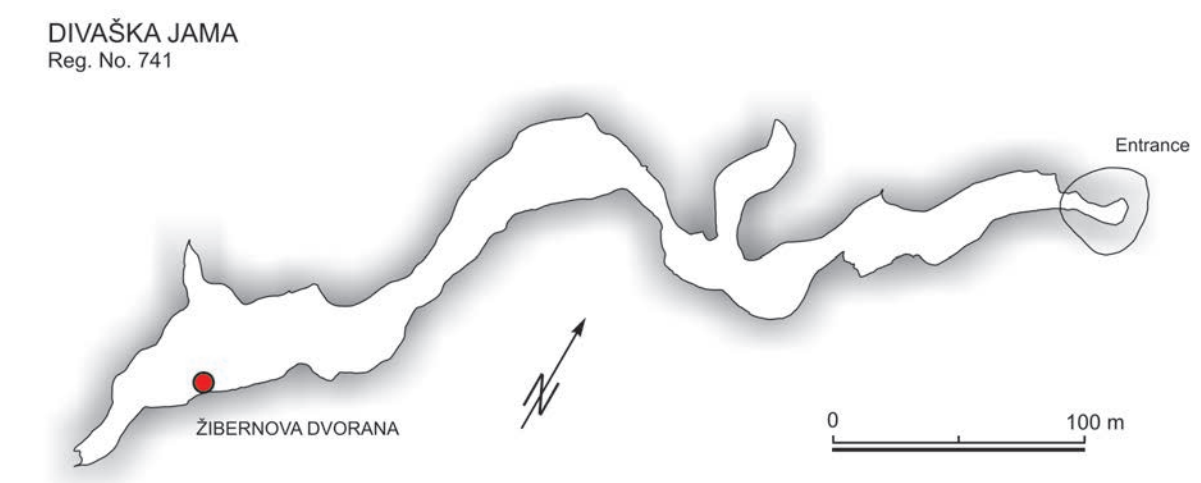

Figure 96 *Cave map and profile location (after Cave Register of IZRK ZRC SAZU and JZS).*

eastern part of Divaška jama. It was opened when the surface lowered and intercepted a chimney in the ceiling of large chamber.

The main part of the cave consists of large passage, up to >20 m high and 15 m wide. Sediments once filled completely the cave but were later mostly washed out.

Detailed study of the cave morphology, sediments and its relations to Trhlovca was undertaken by Gospodarič (1985). Mihevc (1997) dated speleothems and linked the cave with unroofed caves in the area and dated them by geomorphic methods (Mihevc 2001).

Divaška jama is filled by lithologically varied sediments and speleothems of different generations to the thickness of at least 30 m. A 2 m deep profile was excavated at the end of the cave in the Žibernova dvorana. Other individual samples were taken from yellow loams covering flowstone draperies in the same gallery.

PROFILE

The profile was on the wall of a shallow pit about 2 m deep (Fig. 96), at about 370 m a.s.l. Sampling was performed in three campaigns in 1997 (22 samples), 1998 (22 samples) and 2004 (60 samples).

LITHOLOGY

Four sequences can be distinguished in the profile (Fig. 97). The lower sequence is composed of brownish clays to silty clays with upward increased admixture of sandy fractions. Sediments are finely laminated. The second sequence starts with light-coloured sands only several centimetres thick above an erosional contact. These sands are overlain by a clay layer dissected by numerous small-scale fissures and slides. Next is a layer of sand. The whole sequence is terminated by clays. The third sequence is a flowstone crust with a 39 cm high stalagmite. The speleothem is covered by laminated brownish clays (fourth sequence; Fig. 98).

In the terminal part of the cave behind the excavated profile, clays and silty clays preserved on

Figure 98 *The profile of fluvial sediments from Divaška jama; yellow laminated sediments in the bottom part, flowstone layer with the stalagmite and on the top red laminated sediments.*

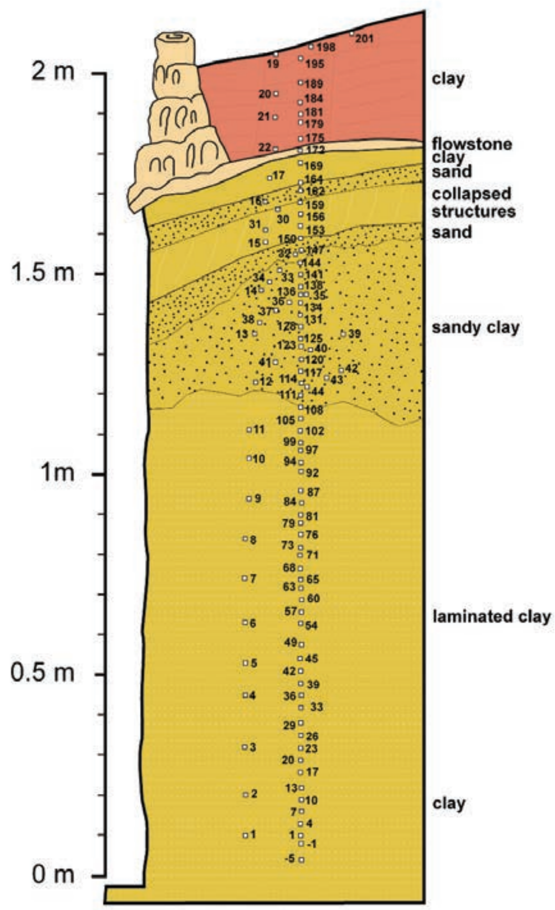

Figure 97 *Lithological log of profile in the Divaška jama with position of samples from 1997, 1998 and 2004 (based on drawing in Bosák, Pruner & Zupan Hajna 1998, with permission).*

Figure 99 *Yellow clay covers speleothems on the walls of Divaška jama; location of samples Nos. B and C.*

speleothem (draperies) coatings of cave walls were sampled (8 samples; A to H; Fig. 99). The clays were dominantly yellow, but two samples were red (D and F). Some parts of the clays were coated by thin speleothem crust.

MINERALOGY

Nine samples were taken from the excavated pit for mineralogical analyses. All samples contain: quartz (56–74 %), chlorite (13–28 %) and muscovite/illite (11–13 %). Plagioclase was found in two samples (about 2 %) and in traces in one sample. Hematite was found in one sample (4 %) and goethite was detected in traces in another sample. Apatite was determined in traces in three samples. Apatite was also indicated by chemical analysis in one sample (P_2O_5 content of 0.127 %).

Quartz, muscovite and plagioclase were derived from flysch rocks, illite and chlorite probably originated in weathered remains of flysch rocks. Hematite thinly coated individual particles in sediments, which were re-deposited from surface red soils. Apatite may

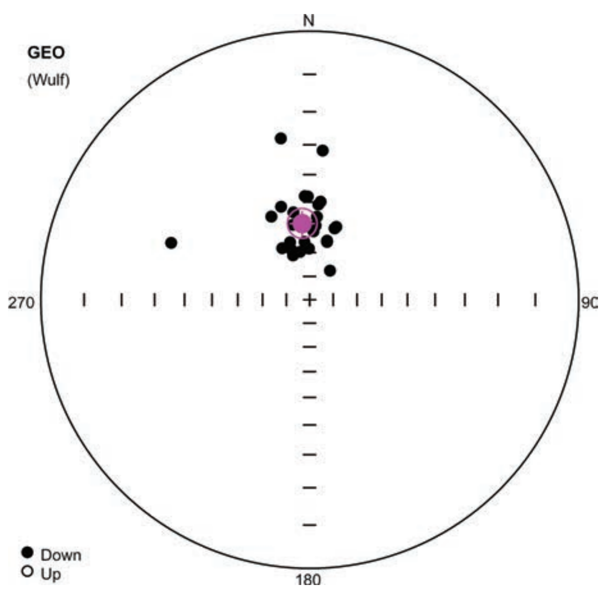

Figure 100 *Directions of C-components of remanence of samples with N polarity, Divaška jama. For detail description see Figure 34.*

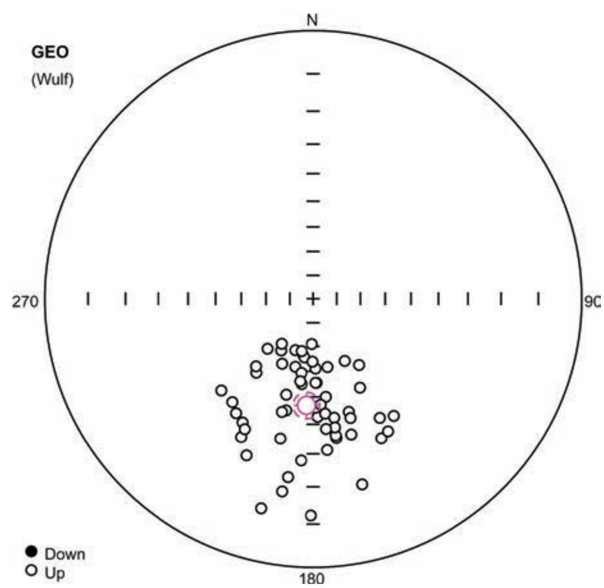

Figure 101 *Directions of C-components of remanence of samples with R polarity, Divaška jama. For detail description see Figure 34.*

indicate some organic material reacting with sediment.

PALAEOMAGNETIC RESULTS

All 104 samples were studied for their palaeomagnetic properties. Sediments are characterized by a large scatter of NRM intensities (0.7–301 mA.m^{-1}) and MS values (74–3,435 x 10^{-6} SI units). Mean values of J_n and k_n moduli are documented in Table 20 and show trend from low magnetic values in the base to high ones at the top of profile. From both ranges of values in the samples, the profile may be divided into five parts and categories. Samples are characterized by very low up to high J_n and k_n magnetic values.

Three components were isolated after AF demagnetization. The *A-components* are undoubtedly of viscous origin and can be demagnetized in the AF field (0–5 up to 10 mT). The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF field (ca 10–80 up to 100 mT).

The stereographic projections of the *C-component* with N and R polarity are shown in Figures 100 and 101. Table 21 summarizes results of the mean direction of the samples from this profile. The mean palaeomagnetic directions of C-components for the N polarity portion are D = 354°, I = 58° and for the R polarity portion are D = 184°, I = -47°. Only viscous components are interpreted for 16 samples. Basic magnetic parameters are documented for 104 samples in Figure 102.

Table 20 Mean palaeomagnetic values and standard deviations, Divaška jama

Divaška jama	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m]*
Mean value	162.534	2,107.0	2.05–1.81
Standard deviation	73.303	776.6	
Number of samples	9	9	
Mean value	50.505	818.1	1.80–1.68
Standard deviation	33.147	361.0	
Number of samples	7	7	
Mean value	18.407	381.7	1.66–1.31
Standard deviation	6.773	91.8	
Number of samples	26	26	
Mean value	6.599	236.8	1.30–0.19
Standard deviation	3.088	52.1	
Number of samples	52	52	
Mean value	1.466	111.8	0.17–(-0.05)
Standard deviation	0.578	31.7	
Number of samples	10	10	

* from top to base

Table 21 Mean palaeomagnetic directions, Divaška jama

Divaška jama	**Polarity**	**Mean palaeomagnetic directions**		α_{95} [°]	**k**	**n**
		D [°]	I [°]			
	N	354.36	58.15	5.57	24.26	26
	R	183.64	-46.78	4.7	15.3	58

Table 22: Th/U dating results using α-spectrometry, Divaška jama

Sample	**Lab. No.**	**U conc.** [ppm]	^{234}U/^{238}U	^{230}Th/^{234}U	^{230}Th/^{232}Th	**Min. age** [ka]	**Remarks**
DIVAILA	B 1242	0.250±0.004	1.0267±0.02016	1.0199±0.0.02648	10000	>350	≥ 1.2 Ma
DIVAILB	B 1505	0.210±0.004	1.279±0.057	0.9702±0.06532	292	303^{+273}_{-73}	
Divaca 1	W 1705	0.0456±0.0032	1.0934±0.0991	0.6353±0.0646	58±57	107^{+17}_{-15}	
Divaca 2	W 1703	0.0288±0.0040	0.9292±0.1742	*1.2133±0.2218*	52±60	>350	>1.2 Ma

TH/U DATING

Th/U dating was performed by Mihevc (1996) at the Department of Geology, Bergen University (Norway) using α-spectrometry (samples 1242 and 1505; analyses marked with B). The studied stalagmite was growing in the same position above yellow sediments and only few meters away from our profile. Results are in Table 22. The top of the stalagmite was dated near the limit of the method i.e. 303 ka, therefore the obtained time span is so broad (+237/- 73 ka) that the age can be from 270 to 540 ka. The stalagmite base is older than 350 ka and also than 1.2 Ma. Additional analyses were made in Warsaw (Poland; analyses marked with W) from the flowstone and stalagmite lying over yellow sediments in the studied profile. Samples B 1242 and W 1703 are identical, i.e. from the base of stalagmite and the continuing flowstone crust.

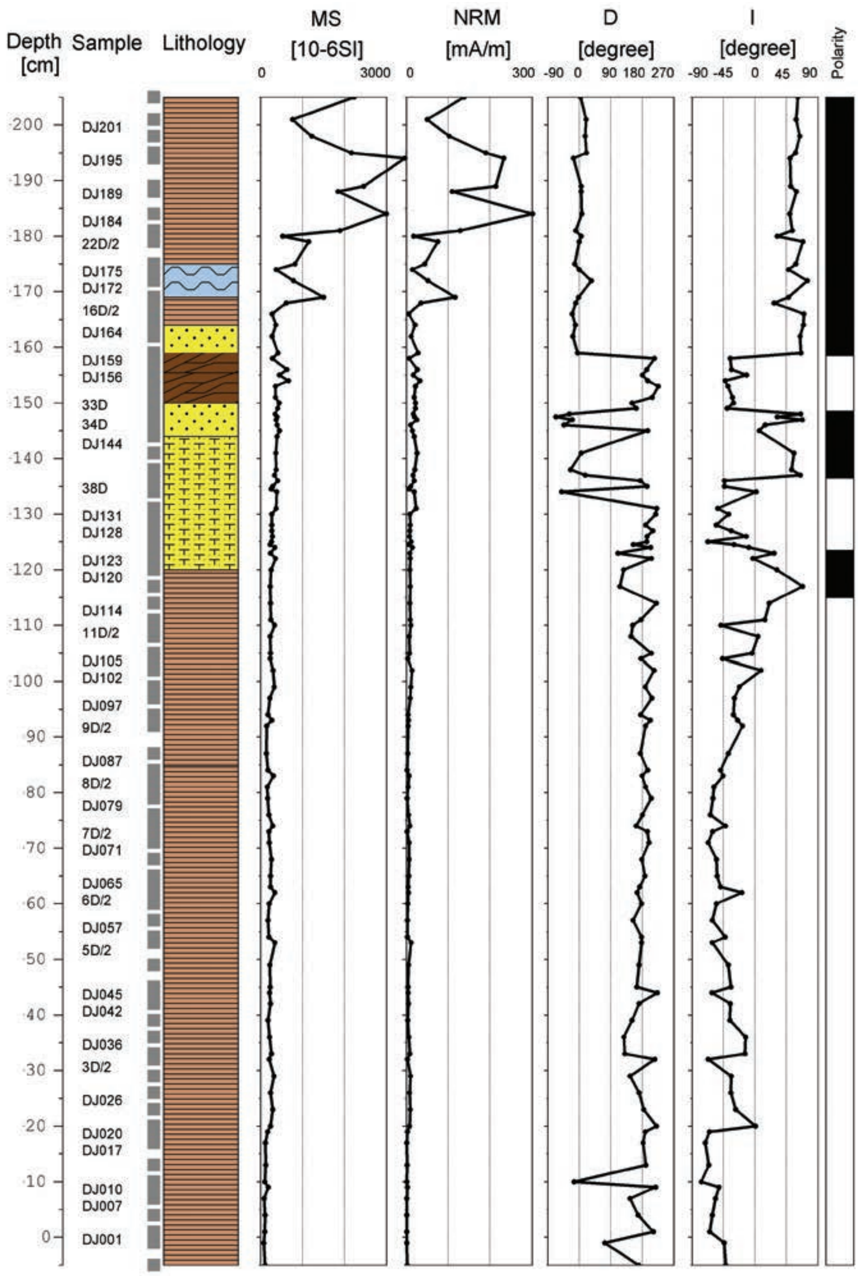

Figure 102 *Basic magnetic and palaeomagnetic properties, Divaška jama. Legend: see Figure 37.*

DISCUSSION OF RESULTS

Laminated sediments from Divaška jama were attributed to the Mindel (Gospodarič 1980 and 1988; Fig. 2) because they were expected to be younger than the Jaramillo N polarity event within the Matuyama R epoch. Preliminary results of palaeomagnetic research (Bosák, Pruner & Zupan Hajna 1998; Bosák et al. 200b) showed a substantially older age of sediments.

The palaeomagnetic sampling was carried out in three campaigns (1997, 1998 and 2004; see Fig. 274). The original analysis with relatively large distance between sampling points resulted in geometry of magnetozones which was interpreted as straddling the Brunhes/Matuyama boundary (0.78 Ma) and Jaramillo subzone (0.99–1.07 Ma; Bosák, Pruner & Zupan Hajna 1998). The magnetostratigraphic picture obtained from high-resolution analysis (2004) is more complicated than was detected by previous results (1997 and 1998). The upper part of the profile is N polarized but with two R polarized magnetozones, the lower part of the section is R polarized. The new high-resolution results offer quite uncertain interpretation. But there clearly exists the possibility of an age greater than 1.77 Ma (base of Olduvai subchron), i.e. identical to the Trhlovca cave – a part of the same cave system – and some other sites situated in the Kras.

The profile was lithologically relatively uniform, representing sediments of typical internal cave facies. Two general parts can be distinguished, separated by a speleothem horizon with a base more than 1.2 Ma, and top at the limit of the dating method with broad error bars. Both sedimentary sequences are more or less composed of lutitic laminites. Just below the speleothem, laminites alternate with sands. The lower sequence can be described as the sediment of a very calm sedimentary environment with gradually increased agitation (increased sandy input). Prior to deposition of speleothem, the environment changed abruptly. Laminites are overlain by two sandy layers separated by clay with „collapse“ structures. The contact of laminites and lower sandy layer is distinctly erosional. „Collapse“ structures indicate movement of fresh sediment, probably due to lateral erosion of channel.

The sequence of laminites above the speleothem can be interpreted as cave lacustrine deposits, as known from some other caves in the Kras. They resulted from water invasion of the cave and from calm deposition of fine-grained load in waters of cave streams. Laminites represent the remains of sediments which once filled the cave nearly completely. Remains of such fill are still preserved over speleothem wall coatings in the terminal hall of the cave. Palaeomagnetic analysis indicated a prevailing N polarization but some samples showed R polarity. The age of this deposition is not clear, but if the top of stalagmite in the profile in the Žibernova dvorana is dated to 270 to 540 ka, the sediments should be younger than those ages. Samples with R polarity then represent some of the short-lived excursions of the magnetic field within the Brunhes chron. The laminites are older than 16.4 ± 1.2 ka, which is the Th/U date from the base of the speleothem from the Pretnerjeva dvorana. A stalagmite covered thin layer of limestone clasts (collapsed from the cave roof) on eroded profile of the laminites (Mihevc 2001, p. 121).

The fill of Divaška jama represents one of the clear examples of temporary interruption of speleogenetic and cave-forming processes. After an infilling phase dated to more than 1.2 and/or 1.77 Ma, the cave was inactive for a long time. Deposition was renewed only after 540 ka, i.e. after a break lasting 0.7 to 1 Ma. This time-span is documented by erosion of old cave fill and by deposition of morphologically rich speleothems. The reason for the renewed filling of the cave by water is not clear, but it may be connected with a change of the hydrological system such as rise of the water table, blockage of outflow routes, etc.).

TRHLOVCA

SITE LOCATION AND CHARACTERISTICS

The cave Trhlovca (Reg. No. 67; 45°40´20,12˝N; 13°56´46,82˝E; 432 m a.s.l.; Figs. 18 and 103) is 142 m long and 22 deep, situated on the south-western side of the planed surface of Divaški kras (Fig. 20). The entrance to the cave is below vertical walls at the side of a doline. The doline probably represents the unroofed continuation of the cave, as the passage that connects the main passage with the cave entrance is a phreatic channel intercepted by the surface. About 40 m below the same doline there is also the south-western end of Divaška jama.

Trhlovca is developed in bedded limestone with rare rudist biostromes of Sežana Formation (Senonian; Jurkovšek et al. 1996) with a southerly dip of the strata (Gospodarič 1985).

The main part of the cave is an approximately 15

Figure 103 *Site location; Trhlovca (SW Slovenia).*

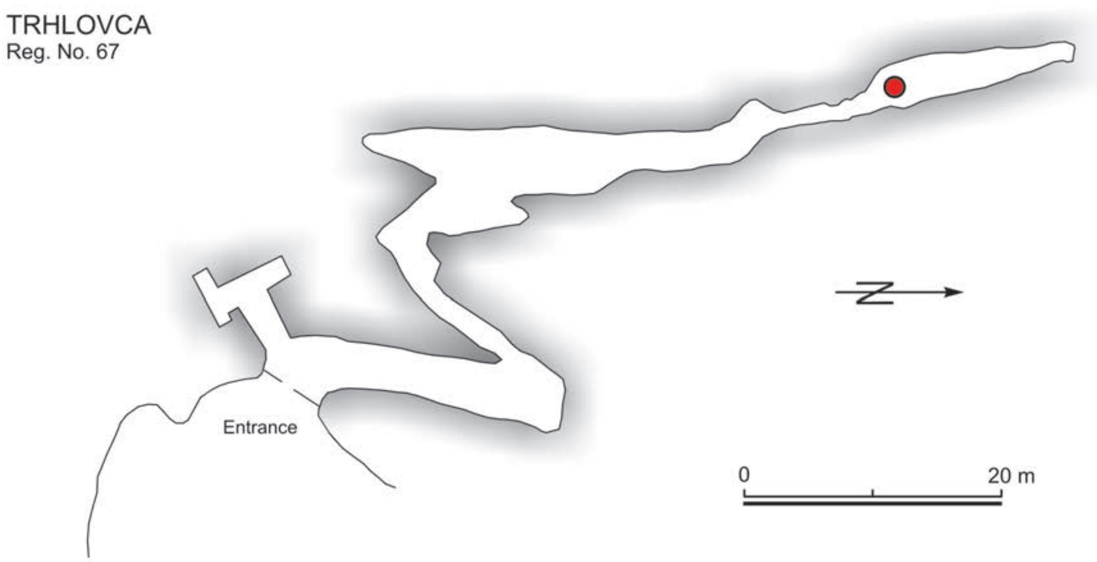

Figure 104 *Cave map and profile location (after Cave Register of IZRK ZRC SAZU and JZS).*

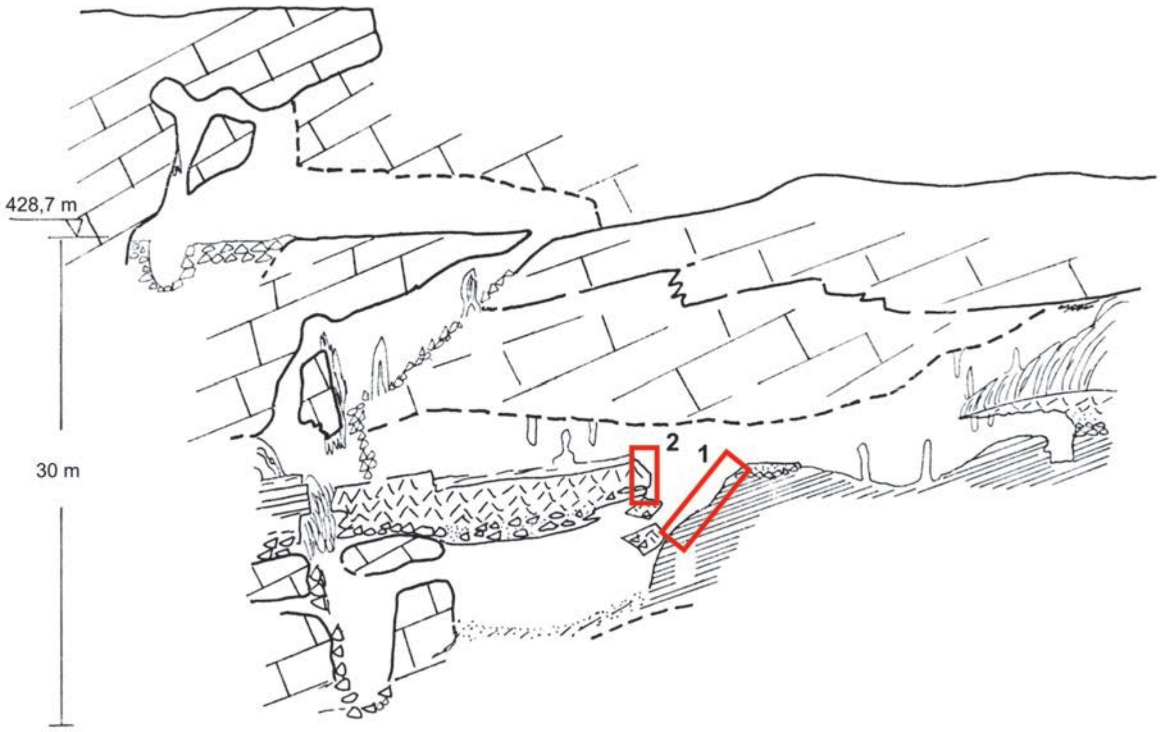

Figure 105 *Schematic cross-section of the Trhlovca, with the positions of sampled profiles. Legend: 1 – sediment profile; 2 – flowstone profile (drawing by Gospodarič 1985).*

m high, about 3 m wide and 60 m long meandering canyon following a N–S direction at 404–419 m a.s.l. Scallops and undulating notches are developed on walls, indicating evolution in phreatic and partly paragenetic conditions. The passage was completely filled with clastic fluvial sediments. The canyon continuations to the north and south are still blocked by allogenic deposits partly covered by flowstone. The cave is accessible due to washing out of the sediments.

PROFILE

We sampled from the sedimentary profile at 420 m a.s.l. and from overlying laminated flowstones (Figs. 104 and 105) several times (1997, 1998, 2004, 2005 and 2006), taking a total of 246 samples for paleomagnetic analyses.

LITHOLOGY

The sedimentary profile was about 4.5 m high. A 1.15 m thick flowstone was developed above sediments, but not directly lying on them. The sedimentary profile had very complicated internal structure (Fig. 106).

Figure 106 *Complicated sediment profile in the Trhlovca, sampling in 2005.*

Figure 107 *Upper part of the profile (E side), sampled in 2005, Trhlovca.*

Figure 108 *Lower part (E side) of the profile, sampled in 2006, Trhlovca.*

Figure 109 *Upper part of the profile (W side), sampled in November 2005, Trhlovca.*

Figure 110 *Profile in flowstone layers was sampled in 2006, Trhlovca.*

It was separated by fractures and fissures to individual blocks, sometimes slightly displaced and rotated. The centre was filled by less fractured, younger deposits. Sampling was performed in the left part of the profile close to the limestone wall in places, where fracturing was less intensive and the sedimentary sequence was complete.

The profile consisted mostly of clays (4.45 m). They were a multi-coloured (chocolate brown, light brown, yellowish brown, blackish brown, greyish yellow, light yellow, blackish grey, often reddish), commonly silty, sometimes very fine sandy, laminated and/or banded (with silty and/or sandy admixture and blackish grey, dark to light brown, chocolate brown, yellowish brown, whitish yellow colour). Convolute structures and Liesegang bands were developed in places (Fig.

107). Upward coarsening cycles were observed locally. One wedge-like layer contained reddish brown small circular concretions. Fine-grained sands with silty and clayey matrix formed two interbeds and the basal part (Fig. 108). They were yellowish brown with multi-coloured laminae and bands. The right part of the profile had less complicated stratigraphy and was composed of chocolate brown silty-sandy clays with small reddish brown concretions. They were overlain by light brown, clayey, very fine-grained sands with an increasing clay proportion in the lower part. Remains of older, eroded clays (comparable with those forming the left side of the profile) were preserved in wall niches. Dark-coloured (grey up to black) portions and lamination were enriched in Mn-compounds.

The central part of the section was composed of a well-stratified sequence (2.65 m, Fig. 107). It started with brownish red, clayey, very fine-grained sand with light greyish and yellowish brown bands at the top. The rest (about 2.2 m) was composed of clays (Fig. 109). They were a multi-coloured in the upper half (light brown, yellowish brown, orange, whitish yellow) and chocolate brown down. Silty to very fine-grained sandy admixtures occurred in bands and laminae, which were boudinaged in the basal layer. Well-rounded pebbles (mostly limestones) occur in the upper third of the profile.

Flowstones overlaying the sediments were mostly reddish brown, laminated, re-crystallized (Fig. 110). They are composed of several flowstone generations separated by clays with variable thickness. The basal plane contained cemented flat limestone gravel. We cut several trenches in the flowstone (Fig. 111) to get samples for the analyses.

Figure 111 *Trenches cut in the flowstone: upper cut – sample T I; lower cut – samples T II and T III; Trhlovca.*

MINERALOGY

Nine samples for mineralogical analyses were taken from the profile; samples were from yellow clays and silts. All samples contain quartz (40–90 %) and the muscovite/illite group of minerals (from traces to 5 %; Bosák et al. 1998, 2000b). Calcite is presented from 5 to 50 %. Montmorillonite, chlorite, goethite and

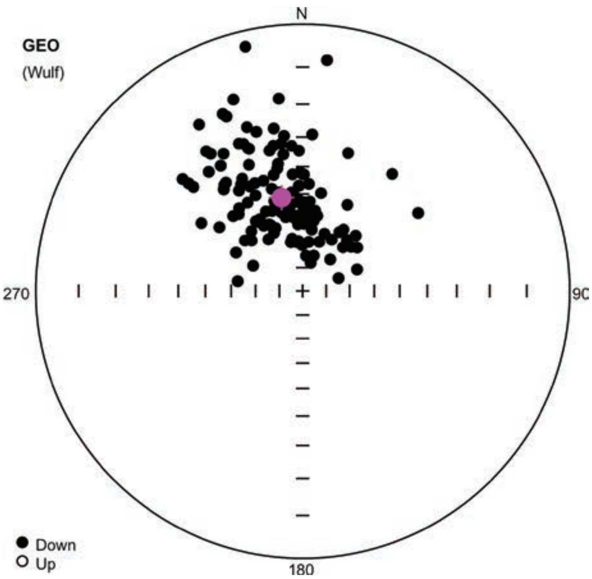

Figure 112 *Directions of C-components of remanence of samples with N polarity, Trhlovca. For detail description see Figure 34.*

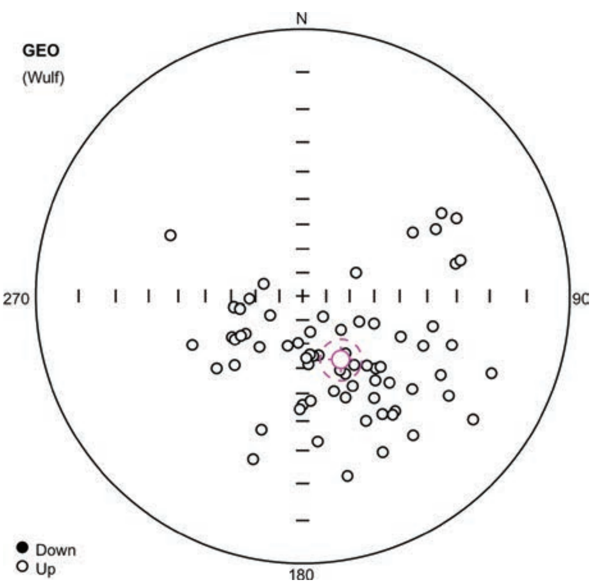

Figure 113 *Directions of C-components of remanence of samples with R polarity, Trhlovca. For detail description see Figure 34.*

microcline were found in several samples in small amounts. Gibbsite and hematite were present just in one sample.

PALAEOMAGNETIC RESULTS

A total of 246 samples were studied for their palaeomagnetic properties. The sediments are characterized by a large scatter of the NRM intensities (0.02–302 mA.m^{-1}) and MS values (-15–3,710 x 10^{-6} SI units). Samples are characterized by extremely low up to very high J_n and k_n magnetic values. Mean J_n and k_n moduli values are documented in Table 23. According to both values, the profile may be divided into seven parts and categories.

Table 23 Mean palaeomagnetic values and standard deviations, Trhlovca

Trhlovca	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m]*
Mean value	0.065	-11.4	8.49–8.42
Standard deviation	0.030	4.9	
Number of samples	3	4	
Mean value	47.334	202.4	8.37–7.31
Standard deviation	28.645	181.9	
Number of samples	37	40	
Mean value	184.768	2,541.5	7.22–6.44
Standard deviation	83.738	937.9	
Number of samples	17	17	
Mean value	49.701	699.9	6.41–5.79
Standard deviation	39.660	446.5	
Number of samples	15	15	
Mean value	11.3047	265.0	5.75–4.81
Standard deviation	8.190	269.4	
Number of samples	20	20	
Mean value	2.382	112.1	4.74–2.31
Standard deviation	1.688	51.6	
Number of samples	77	76	
Mean value	0.448	46.3	2.26–0
Standard deviation	0.492	19.0	
Number of samples	77	77	

* from top to base

Multi-component analysis of the remanence shows that the samples have a three-component RM. The *A-component* is undoubtedly of viscous (weathering) origin and can be demagnetized in a temperature range of 20 to (60) 120 °C or in the AF (0–5 up to 10 mT). The *B-component* also has a secondary origin but shows harder magnetic properties which can be demagnetized in a temperature range of about 120 to 360 °C or in the AF (10–20 mT). The *C-component* is the most stable, with demagnetization in a temperature range of about 400 to 560 °C or in the AF (20–80 up to 10 mT).

The stereographic projections of the C-component with N polarity and R polarity are shown on Figures 112 and 113. Table 24 summarizes results of the mean direction of samples from this profile. The mean palaeomagnetic directions of C-components for the N polarity are D = 346°, I = 51° and for R polarity part are D = 149°, I = -59°. Some of the samples are interpreted as transient polarity. The systematic acquisition of the palaeomagnetic data within the studied section allowed the construction of a detailed magnetostratigraphic profile (Fig. 114).

PALYNOLOGY

Two samples of flowstone were dissolved and studied for pollen content. Unfortunately, the pollen grains were highly damaged and the fossil material was not suitable for determination.

DISCUSSION OF RESULTS

The cave morphology shows clear paragenetic features indicating repeated complete and/or partial fill by sediments and their excavation. Some of the later phases are expressed by about 5 levels with remains of the red to reddish brown flowstone crusts and by a system of wall niches. Younger niches contour (more or less) flowstone crusts and sediments.

The evolution of the sampled profile and its closest surroundings was very complicated. The deposition of yellow clays and sands was interrupted by a number of unconformities (hiatuses), accompanied

Table 24 Mean palaeomagnetic directions, Trhlovca

Trhlovca	**Polarity**	**Mean palaeomagnetic directions**		α_{95} [°]	**k**	**n**
		D [°]	I [°]			
	N	346.4	51.15	3.18	14.86	130
	R	148.87	-59.19	7.37	5.31	68

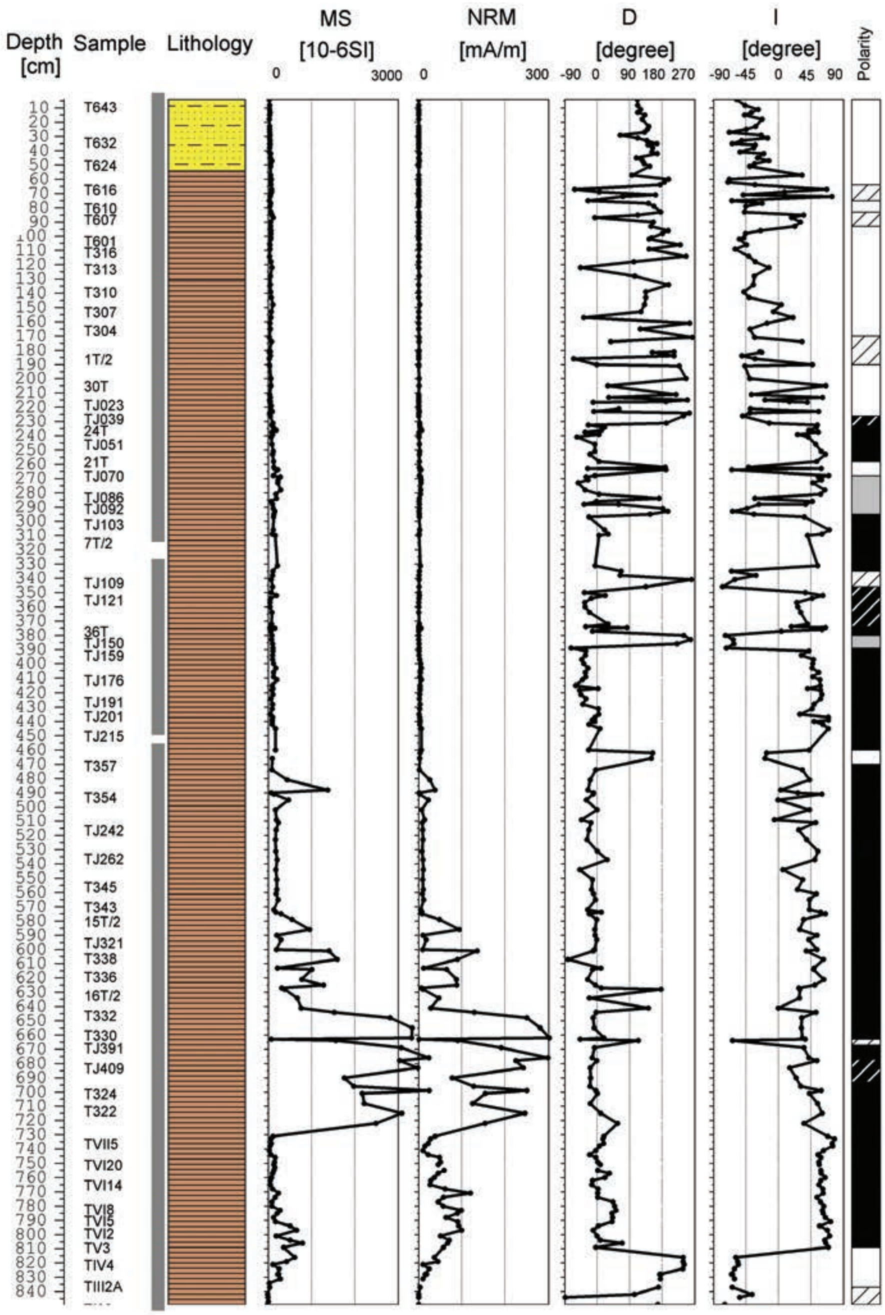

Figure 114 *Basic magnetic and palaeomagnetic properties, Trhlovca. Legend: see Figure 37.*

by erosion and some sediment alterations. Some of the sediments were preserved only in deeper irregularities in the sediment surfaces (like red gibbsite-rich concretions). After the deposition of the sandy-clayey sequence, the sediments were partly eroded (remains in wall niches on the east cave wall). Then the sequence of clays and sands was deposited there. Next, the central part of the section subsided, probably as a consequence of erosion beneath it. Both sides of the profile were affected by sliding and at the end of the motion the depression in the central part was filled by mostly clayey deposits.

Before the deposition of the first generation of the flowstone crust, sediments were partly eroded and gravels deposited. Thick flowstone crust developed in two principal periods interrupted by deposition of red clays. The next phase of erosion was very intensive. It partly destroyed the thick crust and partly was active below it. The next generation of the flowstone crust developed on the eroded surface, being nearly destroyed during the next erosion phase (only remains of the flowstone are on cave walls). The prominent collapse of the cave ceiling was the last extensive change in the passage. Erosional and depositional events resulted from oscillations of karst water level which is in this region still now very high (up to 100 m in Kačna jama).

The laminated sediments from Trhlovca were attributed to the Günz (Gospodarič 1980 and 1988; Fig. 2), and sediments were expected to be younger than Jaramillo normal polarity event within the Matuyama reverse epoch. Preliminary results of palaeomagnetic research (Bosák, Pruner & Zupan Hajna 1998; Bosák et al. 2000b) suggested a substantially older age for sediments in the cave. The arrangement of the detected magnetozones was interpreted as Brunhes/Matuyama boundary (0.78 Ma) and Jaramillo subchron (0.99–1.07 Ma). The high-resolution re-sampling of the whole profile has changed this interpretation. The arrangement of R and N polarized magnetozones, starting with the flowstone crust and continuing through the sedimentary profile is clearly older than 1.77 Ma (base of the Olduvai subchron). It is possible that the cave sediments may be the equivalent of the fill of the caves of Divača and Kozina profiles.

The Trhlovca profile shows the most heterogeneous mineral composition of all analyzed sections within the Divaški kras. Quartz, muscovite and microcline were derived again from the Eocene flysch and illite and chlorite were probably generated in weathered remains of them. Hematite is probably re-deposited from surface red soils (terrae calcis type). Gibbsite in red concretions and clasts represents mature products of weathering (surface paludal sediments, which underwent the initial bauxitization stage; *cf.* Bosák et al. 1999). Gibbsite was found only in this profile. Sediments were brought from the Eocene flysch rocks by allogenic streams entering the Kras. The degree of weathering of the source rocks differed as feldspars indicate low weathering of source rock and some clay minerals indicate higher degree of weathering or developments from weathering/soil profiles. The sediments represent, therefore, the admixture of materials derived from various source rocks and with different degrees of weathering.

The cave underwent a prolonged and complicated evolution. It cannot be excluded that Trhlovca represents an old fragment of a completely choked cave that was later rejuvenated as the consequence of the evolution of Divaška jama and its fill. Further, the lithification of the cave fill is distinctly higher in Trhlovca than it is in Divaška jama (much softer sediments).

Preparations for the sampling of the flowstone crust in Trhlovca.

RAČIŠKA PEČINA

SITE LOCATION AND CHARACTERISTICS

The Račiška pečina (Reg. No. 935; 45°30´12.10˝N; 14°09´00.83˝E; 590 m a.s.l.; Figs. 18 and 115) is situated in the south-eastern part of the Matarsko podolje (Fig. 21). The cave entrance is located at the foot of Martinov Stržen ridge (summit at 681 m a.s.l.). The rough and rocky slope surface and the plateau are dissected by numerous dolines above the cave.

The cave was formed in the Lower Cretaceous thick-bedded limestones and dolomite with limestone breccias and dolomitised limestones. Strata dip generally towards the north-east at an angle of 30° (Šikič et al. 1972).

The cave is 304 m long. It consists of a simple southwards dipping gallery, a relict of an old cave system, which was opened by denudation to the surface. The cave passage is mostly over 10 wide and 5–10 m high. On the southern side, it terminates with a collapse choke and sediment fill. Flood clays of unknown thickness covered by massive flowstone form the bottom of the cave. Some flowstones broke apart due to the unstable sediments on which they were deposited, exposing good profiles. There are remains of the extinct *Ursus spelaeus* on the cave floor (Mihevc 2003). Remains of Neolithic pottery were also found at cave entrance (Jamnik 2001). In the first half of 20th Century the cave was used as a military magazine. The floor was levelled and some large trenches were made through old massive flowstones. The studied profile is situated in one of cuts.

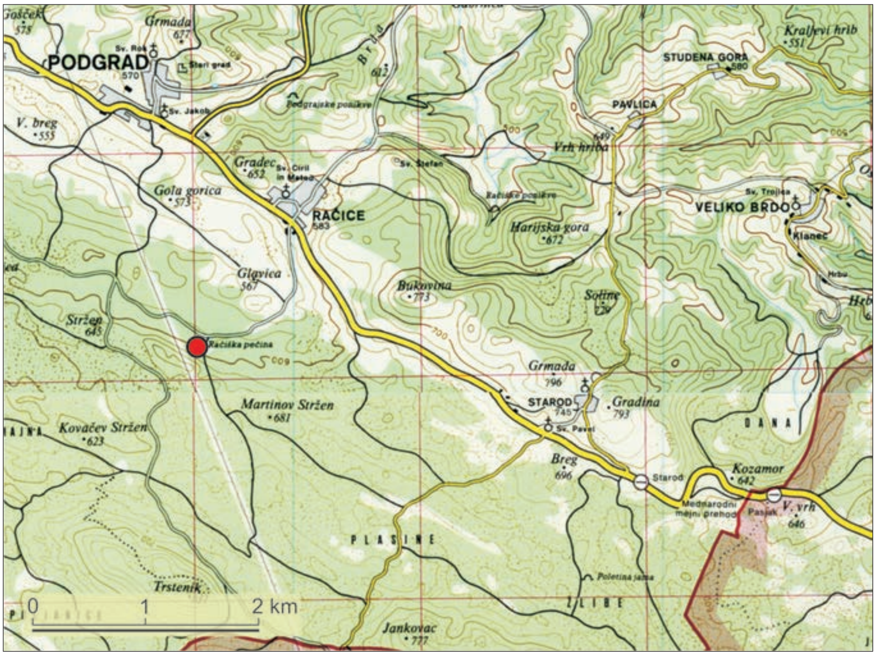

Figure 115 *Site location; Račiška pečina (SW Slovenia).*

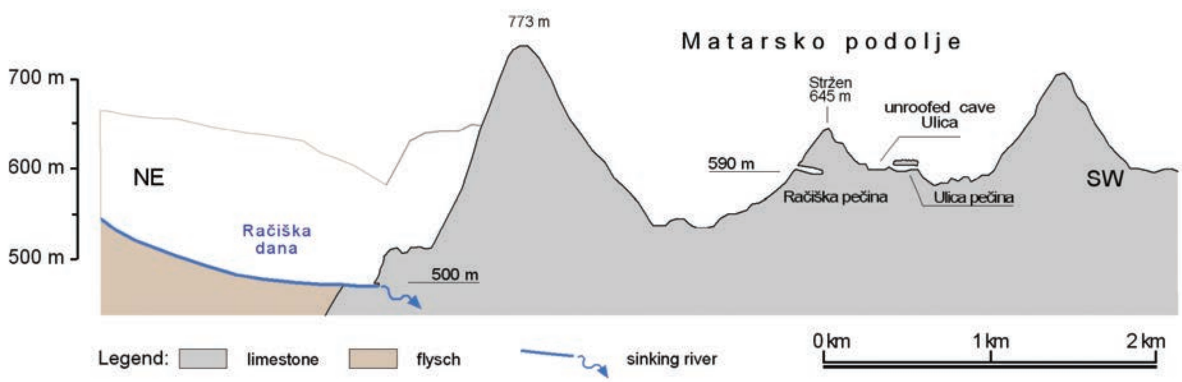

Figure 116 *Geological cross-section with the position of the caves Račiška pečina, Ulica pečina and unroofed Ulica cave.*

Several horizontal caves occur in the vicinity of the cave. The most important is Ulica pečina, about 1,200 m distant (Fig. 116). This is developed in the Lower Cretaceous thick-bedded limestone, with strata dipping north-east at an angle of 45°. The cave is 10–15 m wide, 120 m long and has two entrances. The ceiling of the cave is horizontal, levelled to same height, most likely the result of the paragenetic evolution while still in phreatic conditions. The thickness of the roof above the cave is less than 10 m. On the southern side the cave opens on to a hillside, while on the northern side it continues as an unroofed cave named Ulica. Ulica is local toponym for the elongated depression formed by the unroofed cave, which is about 10 m deep and 20–30 m wide. The walls of the unroofed cave are steep and its floor is composed of sediments and massive flowstones in places.

PROFILE

The largest cut through the banded flowstones is situated in the southern part of the cave; about 200 m from present entrance (Fig. 117). The studied section is about 13 m long (Fig. 118). The composite thickness of the sampled profile reaches 634 cm, but the true thickness exposed is only about 300 cm.

LITHOLOGY

Vertically the section is composed of three principal parts (Fig. 119): the lower part at bottom of the NW side of the profile; the second part is mainly in the middle of the profile; and the third part represents the top portion.

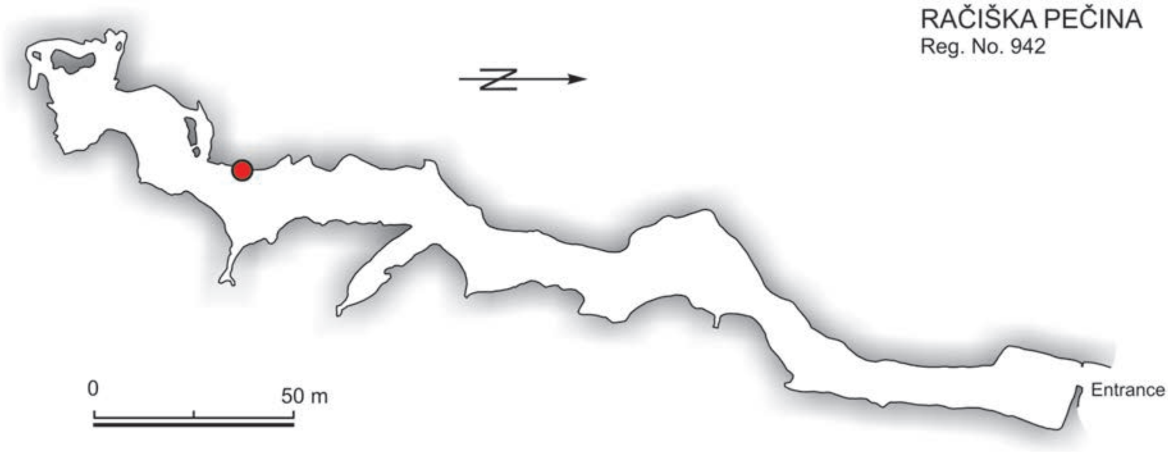

Figure 117 *Cave map and profile location (after Cave Register of IZRK ZRC SAZU and JZS).*

Figure 118 *The Račiška pečina profile; the best dated profile of all analysed sites.*

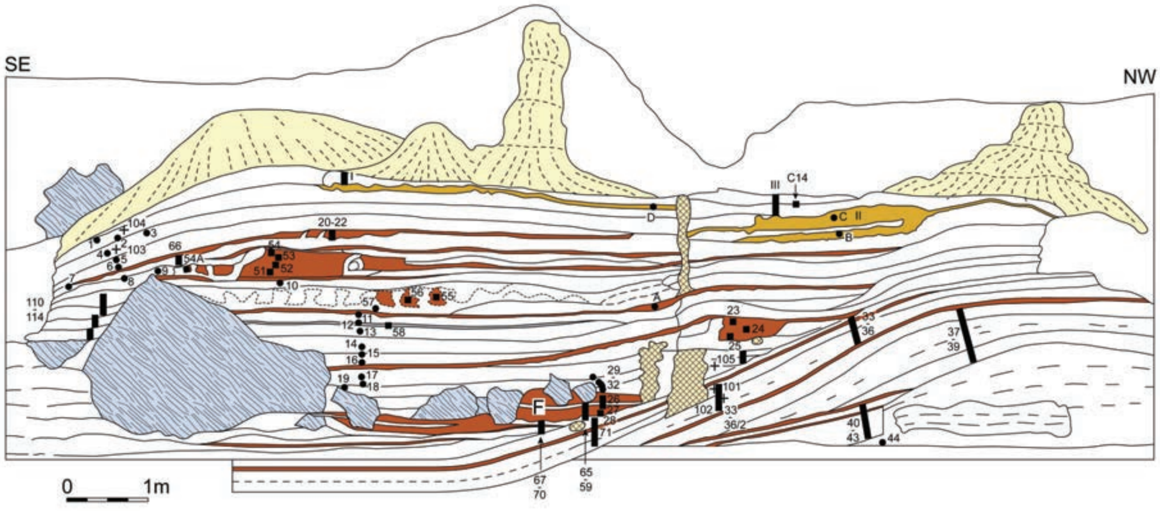

Figure 119 *Lithological log, Račiška pečina. Legend: red – red clays; ochre – brown clays with bones of cave bear; inclined shading (light blue) – collapsed limestone blocks; light yellow – speleothem cover of profile; black boxes – palaeomagnetic samples of speleothems; black circles – paleomagnetic samples of clays; numbers – numbers of the samples; F – Pliocene fauna.*

The lower part (180 cm) is composed of three sequences, representing the growth stages of a huge vaulted stalagmite (**sequences I to III**). They consist of brown to reddish brown massive but porous (corroded?) speleothems with some interbeds of red clays (1–2 cm) and two angular unconformities (Fig. 120). At the top of the sequences II and III broken remains of stalagmites are preserved.

The second part (**sequence IV**; 368 cm) consists of sub-horizontal laminated, mostly porous flowstones intercalated by a number of flowstone beds with gours and abundant red clays (1 mm to up to 10 cm thick); thin calcitized siltstones with flowstone fragments and iron-rich spherules occur in places. Collapsed blocks from the ceiling (Fig. 121) cover clays with finds of fauna (F) in the exposed lower part of the sequence.

The third part (96 cm) is represented by light-coloured, massive, mostly laminated speleothems with two lens-like interbeds of brownish grey loams with bone fragments. Some flowstone layers contain several series of distinct greyish black laminae enriched in organic carbon (soot). The top part consists of huge stalagmites, which were not studied.

MINERALOGY

Three samples were analysed by X-ray diffraction. The sample of red clay with Fe pisoids (palaeomagnetic samples RP 33–35; for location see Fig. 119) contained mainly quartz accompanied by hematite and magnetite; mica and chlorite were in traces. Quartz prevailed also in reddish-yellow laminated clay (palaeomagnetic samples RP 25–32) followed with some muscovite/illite and chlorite; there was some kaolinite and

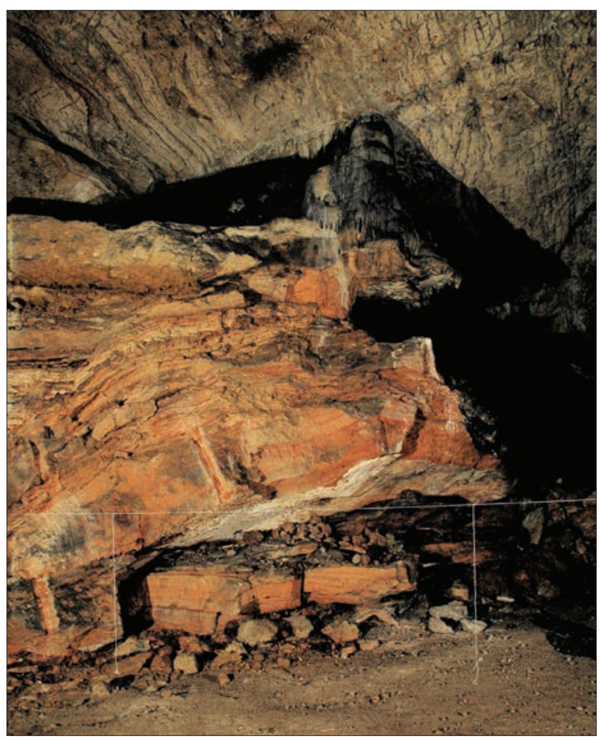

Figure 120 *The detail of the lower NW part of the Račiška pečina profile.*

Figure 121 *The detail of SE part of the Račiška pečina profile.*

feldspar. A red loam with white dots and black stains (palaeomagnetic samples RP 20–22) contained mainly quartz with some calcite (white dots were weathered limestone or flowstone rubble); feldspar, muscovite/illite and chlorite were detected in small amounts.

PALAEOMAGNETIC RESULTS

Standard analytical procedures for detection of palaeomagnetic properties were used: TD for solid samples; and AF demagnetisation for samples both for solid (speleothem) and unconsolidated samples (clays). The data are at high-resolution character with the distance

Table 25 Mean palaeomagnetic values and standard deviations, Račiška pečina

Račiška pečina	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	5.486	31.0	0.13–1.15
Standard deviation	4.375	49.0	
Number of samples	33	33	
Mean value	114.820	371.37	1.17–2.64
Standard deviation	312.817	451.29	
Number of samples	51	51	
Mean value	14.227	169.0	2.66–3.735
Standard deviation	7.887	165.6	
Number of samples	26	26	
Mean value	459.200	545.95	3.79–4.18
Standard deviation	682.320	496.03	
Number of samples	15	15	
Mean value	5.569	72.64	4.23–6.34
Standard deviation	3.668	57.96	
Number of samples	72	72	

* from top to base

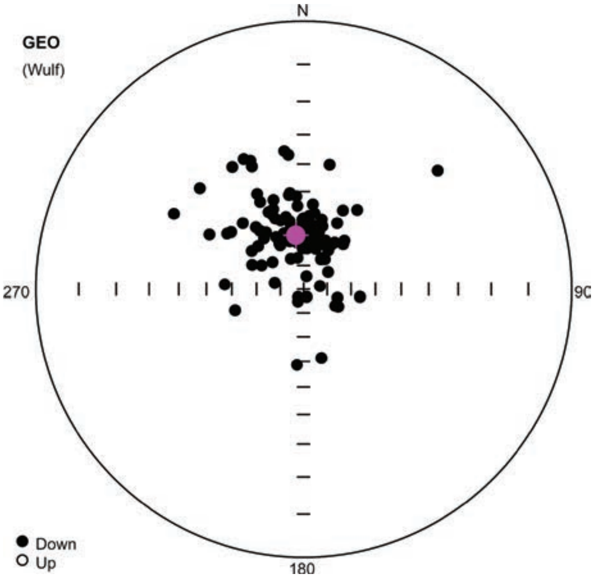

Figure 122 *Directions of C-components of remanence of samples with N polarity, Račiška pečina. For detail description see Figure 34.*

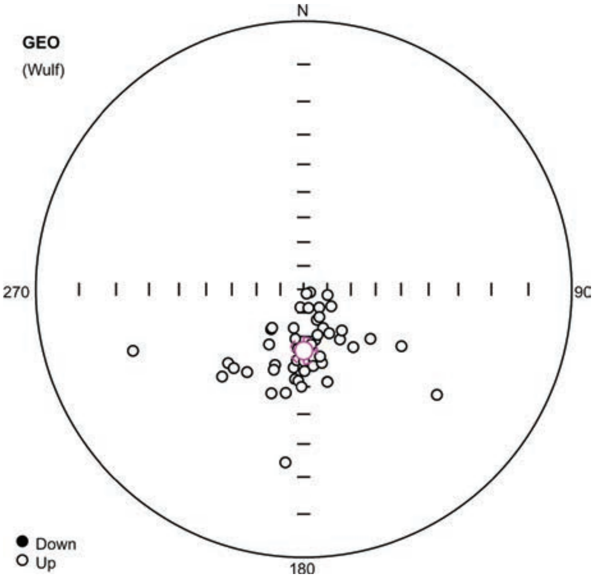

Figure 123 *Directions of C-components of remanence of samples with R polarity, Račiška pečina. For detail description see Figure 34.*

between samples only a few centimetres. The mean J_n and k_n moduli values are documented in Table 25. According to both values, the profile may be divided into five parts and categories. Sediments are characterized by a large scatter of NRM intensities (0.2–2,720 mA.m^{-1}) and the MS values (-9–2,140 x 10^{-6} SI units). Samples are characterized by very low up to very high J_n and k_n magnetic values.

Multi-component analysis of the remanence of 187 samples displays a three-component RM. The *A-component* is undoubtedly of viscous (weathering) origin and can be demagnetized in a temperature range of 20 to (60) 120 °C. The *B-component* also has a secondary origin but shows harder magnetic properties which can be demagnetized in a temperature range of about 120 to 360 °C. The *C-component* is the most stable, with demagnetization in a temperature range of about 400 to 560 °C.

The Fisher distribution displays two defined sets of the samples with N and R polarities. The stereographic projections of the C-component with N polarity and R polarity are shown on Figures 122 and

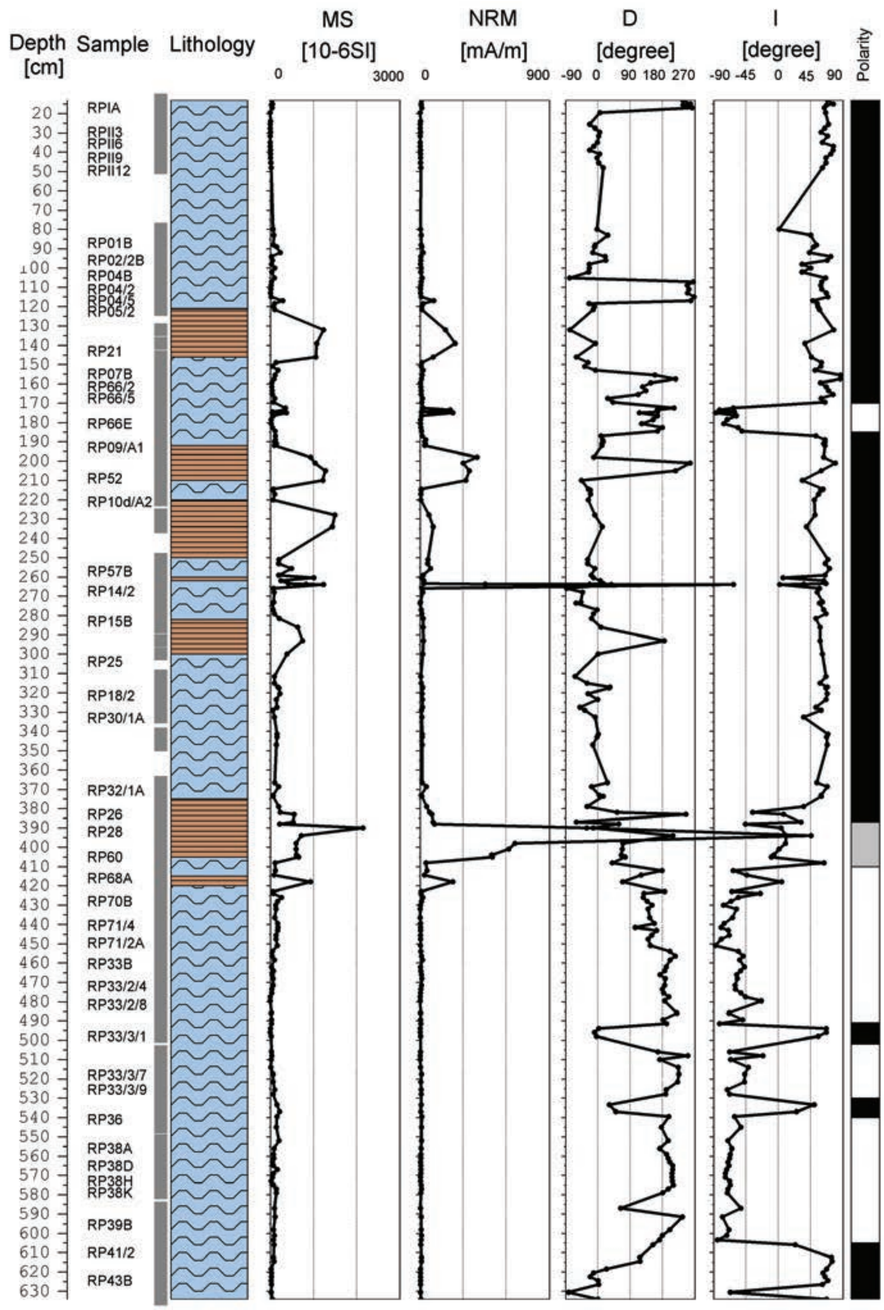

Figure 124 *Basic magnetic and palaeomagnetic properties, Račiška pečina. Legend: see Figure 37.*

Table 26 Mean palaeomagnetic directions, Račiška pečina

Račiška pečina	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	351.68	67.11	3.11	16.91	120
	R	179.94	-64.22	5.19	14.83	49

123. Table 26 summarizes mean direction of samples from this profile. The mean palaeomagnetic directions of C-components with normal polarity are D = 352°, I = 67° and for reverse polarity are D = 180°, I = -64°. Systematic acquisition of the palaeomagnetic data within the studied section allowed the construction of a detailed magnetostratigraphic profile (Fig. 124).

PALAEONTOLOGY

Samples from the principal clay accumulations were washed. Fossil remains were found in two layers. The upper (C on Fig. 119) contained broken bones and some small teeth of cave bear (Fig. 125) indicating a Pliocene age (det. I. Horáček). In the clay layer at the

Figure 125 *Fragments of the cave bear bones in loam (in the upper part of the profile drawing, marked as layer C in Figure 119), Račiška pečina.*

Figure 126 *Palaeontological finds, from red clays after selection from washed material (middle part of the profile drawing, marked as layer F in Figure 119); Račiška pečina.*

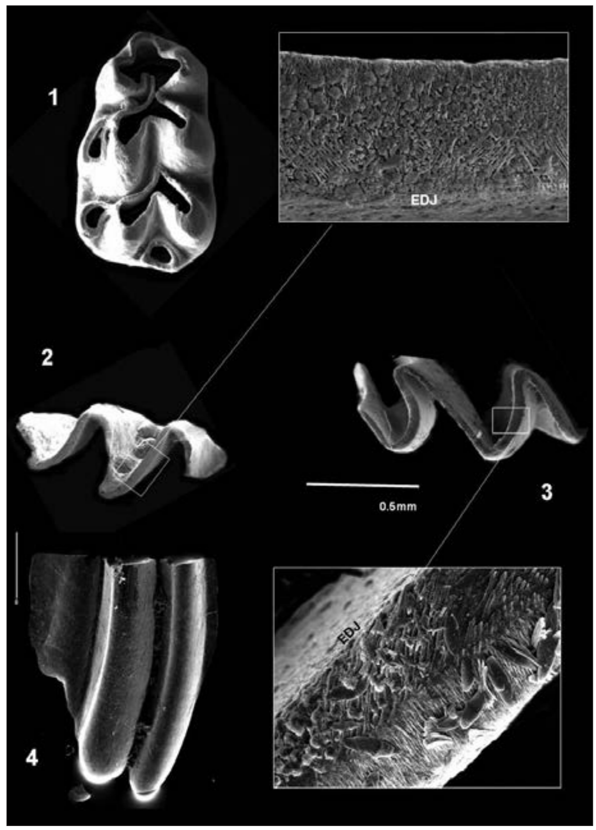

Figure 127 *Mammalian fossils from red clay (marked F in Figure 119) from profile Račiška pečina (from Horáček et al. 2007, with permission). Legend: 1 –* Apodemus (Sylvaemus) cf. atavus *Heller 1936, left M/1; 2 – Arvicolidae g.sp. indet., fragment of a lingual? wall of M/1, cf.* Borsodia *spp.; 3 – Arvicolidae g.sp. indet., fragment of a palatal wall of an upper molar (M1/ or M2/), cf.* Mimomys (Cseria) *sp.; 4 – Arvicolidae, g.sp. indet., lingual wall of the right M3/, cf.* Borsodia *sp.*

base of the sequence IV covered by collapsed blocks (F on Fig. 119) rodents and remains of probably fresh-water crabs were found (Fig. 126). A total of 74 items were obtained. They were mostly very poorly preserved, fragile, and composed particularly of small fragments of teeth enamel (max. 1 - 2 mm in size), corroded and without dentine. Non-mammalian remains (7 pieces) included: cf. *Potamon* (*Crustacea*), 2 tips of small conical teeth (not identified until now), and 3 pharyngeal pearl teeth of a *Cyprinid* fish, most probably *Barbus* sp. Mammalian remains were 67 in number: *Rodentia* (29 fragments of incisors, 2 fragments of metapodia, 35 fragments of molar enamel of arvicolids): at least 2 spp. (incl. cf. *Borsodia*), 1 M/1 (enamel): *Apodemus (Sylvaemus)* sp. – cf. *atavus* Heller 1936 (Fig. 127).

ESR DATING

On June 23 in 2004, some additional samples (parts of the stalagmite growing at the Pliocene fauna (marked with F) which probably are older than 2 Ma) were taken during an excursion of the 12th International Karstological School "Classical Karst" for ESR analyses (Dr. Bonnie A. B. Blackwell; Williams College, USA) but there were no results obtained due to a non-traditional signal from the samples.

DISCUSSION OF RESULTS

The caves Račiška pečina, Ulica pečina and the unroofed cave Ulica most likely represent remnants of the same cave system (Fig. 116). Even if they are not of the same system, they were most likely developed at the same time and at the same altitude. The possibility that they were displaced to the same altitude by tectonic movements is less probable.

The development of all caves was connected with the ponors of allogenic streams from Eocene flysch which at present lie only 2.5 km to the north of the caves. The recent streams sink at about 500 m a.s.l.; i.e. 90 m lower than the Račiška pečina.

The cave system still retains traces of paragenetic and epiphreatic speleogens, and phreatic features (large cupolas and scallops) are also preserved. Transition to the vadose zone caused exhumation and internal redistribution of cave fill and growth of massive speleothems (large domes and stalagmites) on allogenic deposits. The system was later dissected by erosion and denudation into the segments with more entrances and the cave roof was thinned or completely destroyed.

The studied profile in Račiška pečina consists of three parts. The lower one represents the upper part of huge vaulted stalagmite form. Its lower part is possible to reach below the sediment by a narrow passage at SE end of the profile. Unfortunately, the lithological correlation of this part with the uncovered section is not possible; we sampled this outcrop (Fig. 11) for another fold test, which is in process.

The overlying flowstone formation contains abundant intercalations of red clays (lutites). The character of the deposition and speleothems themselves, internal textures and structures and high porosity indicate growth in a warm and humid climate. High porosity, on the other hand, can also indicate post-depositional corrosion of speleothems. The lutitic intercalations represent results of floods bringing in allochthonous load. Clay material is well-sieved and represents the decantate from f the flowing water. Very fine-grained sand and silt laminae at the bottom or inside some clay layers are rare and occur only in clay beds of greater thickness, and indicate flood pulses within one lutitic depositional event. The character of allogenic lutites may indicate that deposition occurred when this position was far from any ponor and/or that the allogenic stream had to pass through a system of sumps. This observation is supported by the character of the faunal remains. But there is also another possibility that the allogenic clays were brought from a side passage or redeposited within the cave by vadose water. The number of alternations of flowstone and lutite layers (more than 40) evidences a periodical type of climate outside the cave with alternation of dry and wet periods. Clastic material was derived from flysch source rocks.

Collapsed blocks from the cave ceiling in the clay with fauna may indicate some tectonic unrest at about 1.9 Ma. It may be mentioned that the source of the collapse cannot be identified on the recent cave roof, which is smoothed by younger corrosion and perhaps a fluvial (phreatic/vadose) re-modelling, or the collapse blocks slid from the choked side passage behind the profile.

In the fauna the absence of the rootless molars in arvicolid material suggests that the communities do not belong to the Quaternary period because the Quaternary communities of small ground mammals since beginning of the Q1 are characterized by the overwhelming predominance of rootless voles. In Lagurini, the rooted forms (arranged in the genus Borsodia at the very beginning of Q1) disappeared. Therefore, we propose the MN17/Q1 boundary as the possible minimum age of the assemblage. The faunal assemblage is Pliocene in age; note the predominance of arvicolids and absence of any element suggesting the Miocene age.

For the first time, the magnetostratigraphic sequence can be correlated satisfactorily with the GPTS owing to the palaeontological data available. Based on fauna analysis (Quaternary age is excluded), the boundary of N and R polarized magnetozone within the layer with fauna (F) can be identified with the bottom of C2n Olduvai subchron (1.77–1.95 Ma). The short N chron just below the Olduvai base is correlated with the Reunion subchron (C2r.1n; 2.14–2.15 Ma). In the lower part of the profile, the following magnetozones are correlated: the base of Matuyama Chron (2.150–2.581 Ma) and the individual subchrons within the dominantly normal polarized Gauss Chron (2.581–3.58 Ma) = C2An.1n subchron (2.581–3.04 Ma), C2An.1r Keana subchron (3.04–3.11 Ma), C2An.2n subchron (3.11–3.22 Ma), C2An.2r Mammoth subchron (3.22–3.30 Ma) and the upper part of C2An.3n subchron (top at 3.33 Ma). The bottom flowstone layer at the NW side of the studied profile (Fig. 119) terminates at about 3.4 Ma.

The geometry of the palaeomagnetic subchrons is changed by numerous breaks in deposition, especially within the lower part of the profile. The subchron arrangement can assist estimation of the duration of individual breaks, being about 150–250 ka in the upper parts, and in sequences I to III probably substantially more. This fact can also explain the 36^{o} differences in declination values between upper and lower parts, indicating rotations of the tectonic block. In conclusion it may be emphasised that the roughly three m high profile was growing for more than 3 Ma years and that new speleothems on top of it are still growing.

The unroofed cave Ulica is continuing into the Ulica pečina cave.

PEČINA V BORŠTU

SITE LOCATION AND CHARACTERISTICS

Pečina v Borštu (Reg. No. 935; 45°33´07.25˝N; 14°04´44.28˝E; 566 m a.s.l.; Figs. 18 and 128) is a horizontal cave with its entrance in the Jezerina blind valley in Matarsko podolje (Fig. 21).

The blind valley is situated at the contact of well stratified Turonian limestone (Šikić et al. 1972) and Eocene flysch. Limestone strata dip towards the northeast. The valley is about one km long and over 100 m deep and was formed by two sinking rivers flowing from the flysch and sinking in small ponors in the valley bottom; the largest one is Ponikve v Jezerini (Slabe 1992; Mihevc 1994). There are several other caves, the largest one, Mitjina jama, being located about 15 m above the present valley bottom. Pečina v Borštu represents a part of the former cave system draining the blind valley. It opens in the steep western slope about 50 m above the valley bottom (Fig. 129).

The cave is approx. 250 m long and follows a N–S-trending fissure zone. The termination of the cave is choked by a fluvial fill composed mostly of quartz sands. The passage walls are extensively covered with speleothems. Speleogens indicate their formation in phreatic conditions. The considerable age of the speleothems was confirmed by Th/U dating (>200 ka; Mi-

Figure 128 *Site location; Pečina v Borštu (SW Slovenia).*

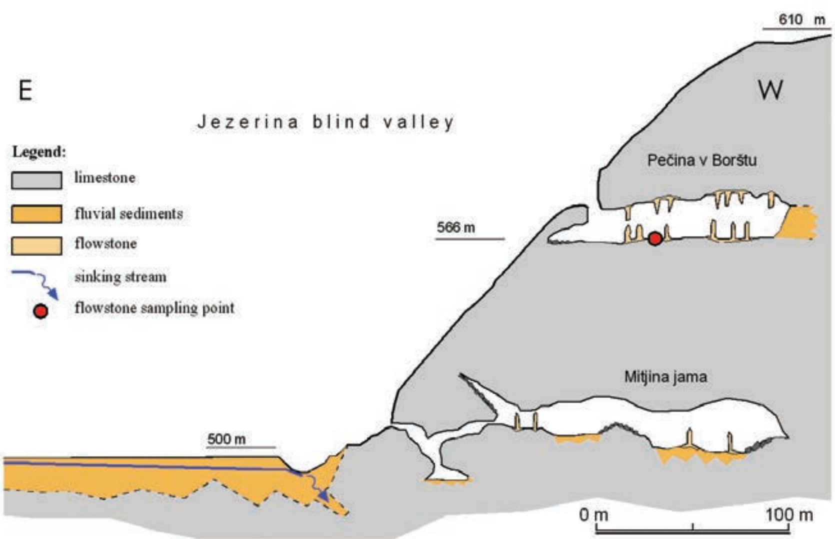

Figure 129 *Schematic cross-section of the edge of the Jezerina blind valley with caves and sampling point of the flowstone in Pečina v Borštu.*

Figure 130 *Location of the stalagmite in the cave (cave map after Cave Register of IZRK ZRC SAZU and JZS).*

hevc 2001). Spelothems in Mitjina jama which grow on collapsed material and fluvial deposits were dated to about 16 ka, indicating the end of river floods and the stabilisation of collapse (Mihevc 2001).

DOME-LIKE STALAGMITE

A small dome-like stalagmite was sampled for fold tests (Figs. 130 and 131). The dome was 65 x 55 x 16 cm with longer axis in direction of 145–325°. We cut two trenches from both sides: A (eastern wall; direction of cut 90/270°) and B (western wall; direction of cut 92/272°; Fig. 132).

Figure 131 *Stalagmite from Pečina v Borštu before cutting.*

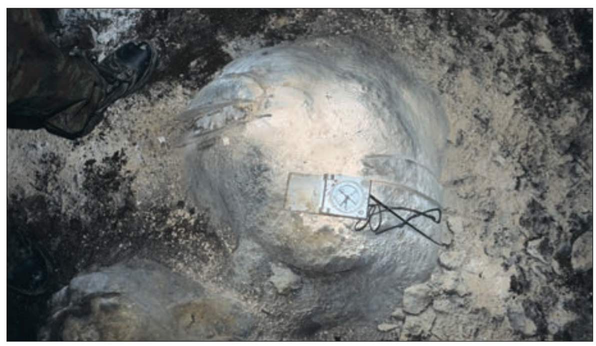

Figure 132 *Stalagmite with cuts for the fold test from Pečina v Borštu.*

PALAEOMAGNETIC RESULTS

All the samples cut from the speleothem trench were subjected to detailed AF demagnetization in 14 steps and/or TD method in 12–14 fields. Multi-component analysis was applied to separate respective RM component for each sample. Three components were isolated after TD (8 samples) or AF (31 samples) demagnetization. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–2 to 5 mT) and at temperature range of 20 to 60 (120) °C. The characteristic *C-HFC* and/or *C-HTC* are stable. They can be demagnetized or isolated in the AF (ca 15–80 to 100 mT) or at temperature range from 300 to 520 (550) °C. The unblocking temperatures (520 to 550 °C) indicate that magnetite represents the principal carrier of the RM in all studied samples. The mean J_n and k_n moduli values are documented in Table 27.

Table 27 Mean palaeomagnetic values and standard deviations, Pečina v Borštu

Pečina v Borštu	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m]
Mean value	4.398	18.7	-
Standard deviation	4.072	28.4	
Number of samples	39	39	

The mean NRM value is 4.4 ± 4.1 mA.m^{-1} and the respective MS value is 19 ± 28 x 10^{-6} SI units. The samples showed normal palaeomagnetic direction. Table 28 summarizes results of mean direction of samples corrected and not corrected for the bedding-tilt (*in situ* directions). The mean palaeomagnetic directions of normal polarized C-components for tilt- corrected samples are D = 347.1°, I = 69.2°, α_{95} = 9.45° and for samples not corrected to bedding-tilt (*in situ* directions) are D = 346.4°, I = 65.4°, α_{95} = 2.54°. In this case it is evidence of one of the criteria for negative fold test.

Fold test

The original clustering of directions of a primary magnetization is believed to deteriorate in the process of tectonic deformation. Let us suppose that these directions are expressed with the respect to the *in situ* (or geographic) coordinate system. In order to determine the age of the acquisition of a primary magnetization in relation to the deformation, the degree of clustering of directions is studied as a function of the relative amount of their untilting (the *in situ* directions and the bedding-tilt corrected ones correspond to the 0 % and 100 % untilting, respectively). The maximum of this function indicates the relative amount of folding that has occurred since the acquisition of the primary magnetization.

In the most widely used fold tests (McElhiny 1964; McFadden & Jones 1981) the directions are supposed to be Fisher distributed and the degree of their clustering is assessed by the precision parameter. On the other hand, as pointed out by Tauxe, Kylstra & Constable (1991), data used in a fold test are usually not Fisher distributed. Directions of the primary magnetization may reflect the alternating polarity of the ambient geomagnetic field; moreover, the Fisher distribution, presumably satisfied by these directions at the time of acquisition of the primary magnetization, is no longer obeyed by directions modified by folding. That is why Tauxe & Watson (1994) preferred a nonparametric technique (they do not pre-suppose any particular distribution of directions) and they assessed the degree of clustering by the normalized eigenvalues e_1,.., e_3 of the orientation matrix of directions (for its definition, see Fisher, Lewis & Embleton 1987). These eigenvalues, being positive numbers satisfying the inequality $e_1 \geq e_2 \geq e_3$, are associated with eigenvectors $\mathbf{v}_1$, $\mathbf{v}_2$, $\mathbf{v}_3$ that are orthogonal to one another. Let us introduce the quantities $\log(e_1/e_2)$ and $\log(e_2/e_3)$ (see Fig. 133). If the former quantity is large and the latter is close to zero, the cluster distribution is almost isotropic with respect to eigenvector $\mathbf{v}_1$ (referred to as a principal axis of the distribution). If, by contrast, the former quantity is close to zero and the latter is large, the distribution, called a girdle distribution, is almost isotropic with respect to eigenvector $\mathbf{v}_3$. The ratio of the above quantities, i.e., $\log(e_1/e_2)$ / $\log(e_2/e_3)$, termed the shape parameter (cf. Fisher, Lewis & Embleton 1987), seems to be a very sensitive indicator of clustering. As shown in Figure PB7, it achieves its maximum value (>>1) for a tight cluster of directions (see Fig. 134, associated with the -9% amount of relative untilting) and decreases under the value of 1 when the distribution tends to a girdle one (see Fig. 135, corresponding to the bedding-tilt corrected directions). The maximum of the shape parameter depends, however, on the particular sample set. If we considered another set from the same locality, we would find another position for this maximum. Moreover, the studied function need not be always unimodal. Due to the lack of other sample sets, the variability of the above maximum has been assessed by generating bootstrap samples (cf. Efron & Gong 1983). This way, following to Tauxe, Kylstra & Constable (1991), we found the 95% confidence interval (-19.8 %, 3.6 %) of the position of the shape parameter maximum. As far as this

Table 28 Mean palaeomagnetic directions, Pečina v Borštu

Pečina v Borštu	**Component of remanence**	**Polarity**	**Structural tilt correction**				**No structural tilt correction (in-situ directions)**				**n**
			Mean directions				**Mean directions**				
			D [°]	**I** [°]	α_{95} [°]	**k**	**D** [°]	**I** [°]	α_{95} [°]	**k**	
	C	N	347.06	59.21	9.45	5.62	346.41	65.36	2.54	78.14	39

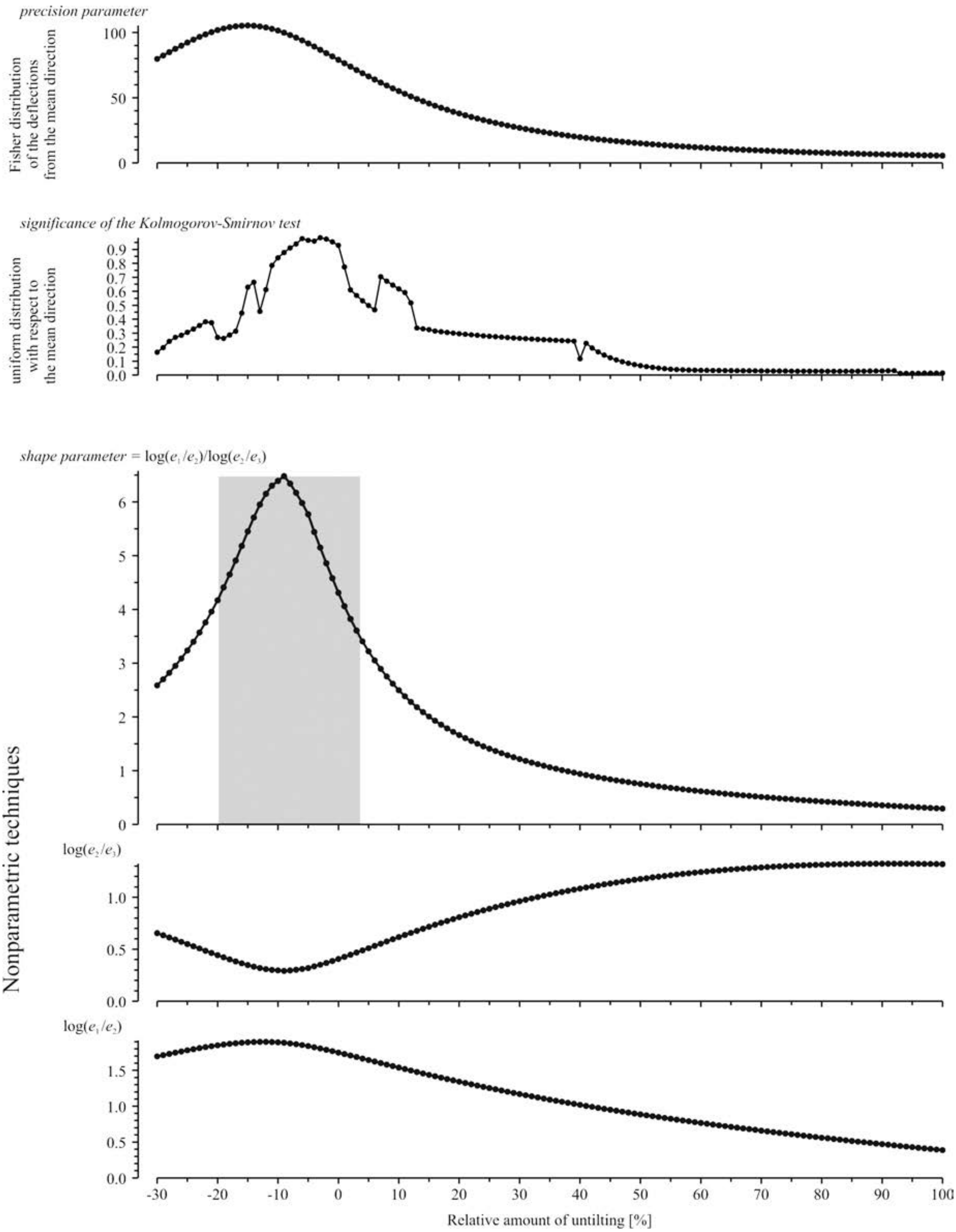

Figure 133 *Various criteria of clustering of primary magnetization directions plotted against the relative amount of untilting. From the bottom: quantities* $\log(e_1/e_2)$ *and* $\log(e_2/e_3)$ *and their ratio termed the shape parameter, significance of the hypothesis that the distribution of the deflections from the mean direction is isotropic, and the precision parameter of the assumed Fisher distribution of these deflections. The 95% confidence interval of the maximum of the shape parameter is shown by the shadow.*

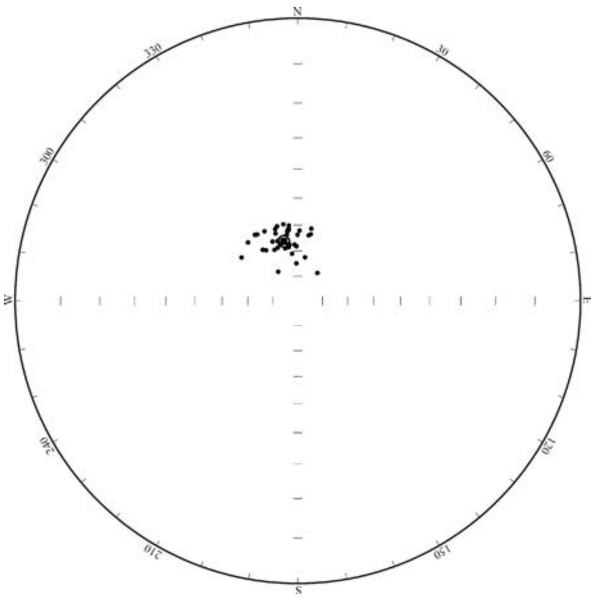

Figure 134 *Stereographic projections of directions of what is considered to be the primary magnetization, relative amount of untilting -9%, making the shape parameter to achieve its maximum value (cf. Fig. 133). The mean direction and its cone of 95% confidence are shown, as well.*

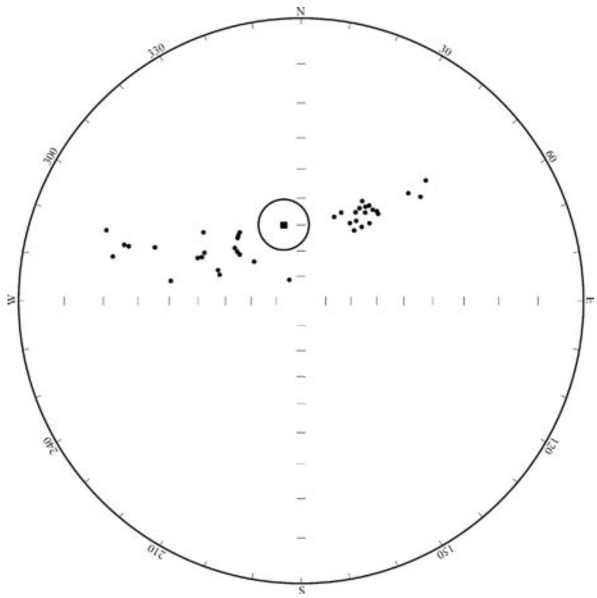

Figure 135 *Stereographic projections of directions of the primary magnetization, relative amount of untilting 100%. The distribution can be described as the girdle distribution.*

interval includes zero, we can conclude that the fold test has been negative – no deformation has occurred since the acquisition of the primary magnetization.

To compare this result with that obtained by a more traditional approach, we described the clustering of unfolded directions by the precision parameter of the Fisher distribution (see Fig. 133). In order to verify whether these directions really obey the Fisher distribution, we have, in fact, to test three hypotheses: (1) the distribution is isotropic with respect to the mean direction; (2) the deflection from the mean direction satisfies the Fisher distribution, and (3) these one-dimensional distributions are independent of one another. The significance of the Kolmogorov-Smirnov test (*cf.* Fisher, Lewis & Embleton 1987) of the first of these hypotheses is plotted in Figure 133 against the relative amount of unfolding.

TH/U DATING

The cave is extensively decorated by the speleothems. The central part of a stalagmite from the middle of the cave was dated to 211 +20/-17 ka (Mihevc 2001, p. 126).

DISCUSSION OF RESULTS

No reverse polarization was found. It seems that samples may be dated within the N polarized Brunhes chron, i.e. younger than 780 ka, which is in the accordance with the radiometric dating by Mihevc (2001).

KRIŽNA JAMA

SITE LOCATION AND CHARACTERISTICS

Križna jama (Reg. No. 65; 45°44´42.70˝N; 14°28´ 02.18˝E; 629 m a.s.l.; Fig. 18 and 136) is large river cave 8,273 m long. It is situated in the area between Loško, Bloško and Cerkniško poljes (Fig. 22). The relief above the cave is characterized by conical hills and closed depressions, dolines, uvalas and small, polje-like levelled surfaces. The entrance of the cave is located in an elongated karst depression to the east of Križna gora (856 m a.s.l.).

The cave is developed in the light grey micritic Liass/Dogger limestones, with lenses of dolomite (Gospodarič 1974; Buser, Grad & Pleničar 1967). Beds dip towards south to south-east at 20°. Passages are mainly developed along bedding planes and some of them follow N–S-trending tectonic structures (Gospodarič 1974). The cave was formed in rather stable conditions between the Cerkniško and Loško poljes, as indicated by the mostly epiphreatic conditions of passage evolution. A small river which sinks on Bloško polje, flows in the cave and continues through a deep terminal sump towards the west into the cave, Križna jama II, and to springs at Cerkniško polje.

The active water passages are located at about 610 m a.s.l. The older passages are slightly higher, between 620 and 640 m a.s.l. Remains of fluvial sediments are preserved throughout the entire cave, indicating that it was filled by more sediments in the past (Gospodarič 1974). The Medvedji rov (Bear Passage) represents one of such older passages. It is about 325 m long and about 15 m above the active stream. It was connected to the main passage at both ends but at present one entrance is blocked by speleothems. Different fluvial sediments and speleothems fill the passage almost to the ceiling in places. In some parts they have been eroded away.

The remains of *Ursus spelaeus* in clay inter-beds among flowstone sheets are important in the Medvedji rov. They were studied by Hochstetter (1881), Rabeder & Withalm (2001), Pohar et al. (2002) and the others. The most detailed study of fluvial sediments was done by Gospodarič (1974), who concluded that the cave was much more filled by sediment in the past and less open than it is at the present time.

Two profiles in the Medvedji rov were investigated (Figs. 137 and 138). The first, in 2003, was focused on sampling speleothems and sediments from the profile of Ford & Gospodarič (1989) in a small pit (profile Križna jama I) on the north side of the small chamber before Tetarata (Fig. 138), to confirm the results of Ford & Gospodarič (1989), Rabeder & Withalm (2001) and Pohar et al. (2002). In 2004 and 2005 we sampled another and much thicker sedimentary profile (profile Križna jama II) on the southern side of the same chamber, about 20–30 m away (Fig. 138).

Figure 136 *Site location; Križna jama (S Slovenia).*

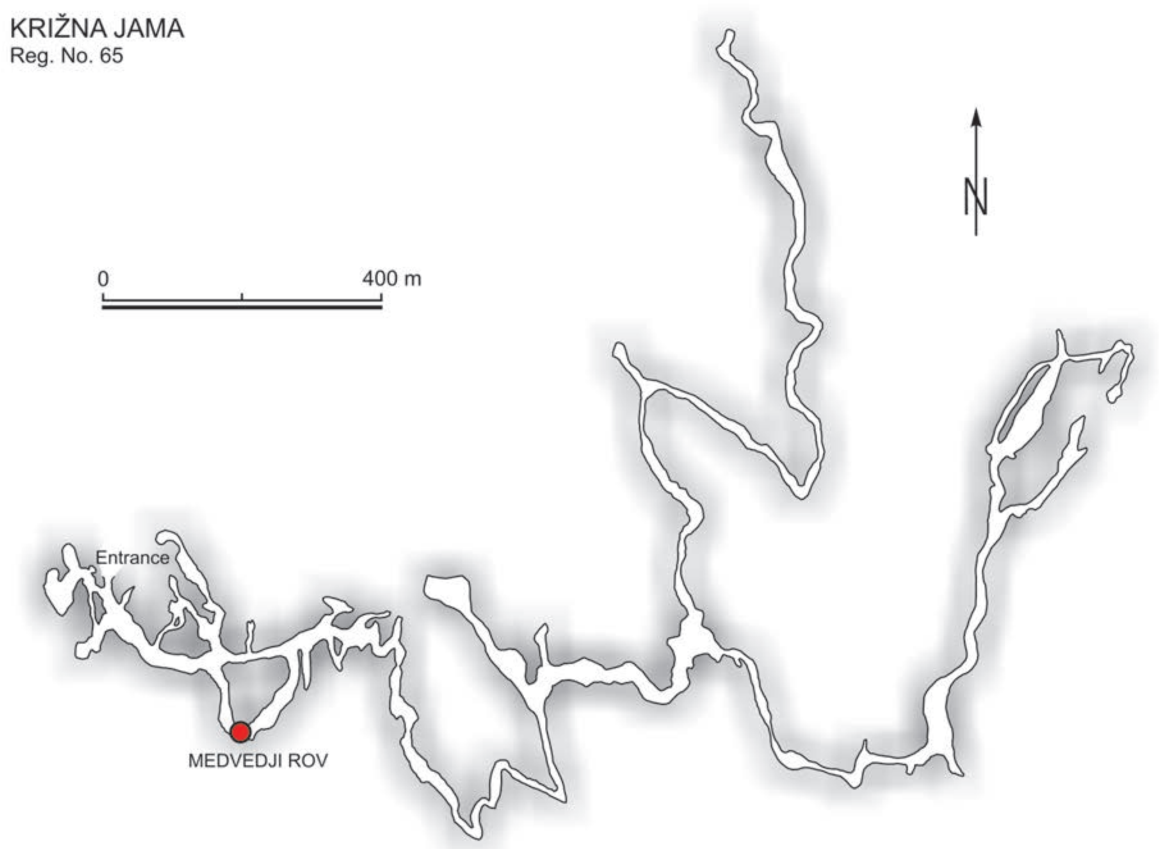

Figure 137 *The cave map with profiles location (after Cave Register of IZRK ZRC SAZU and JZS).*

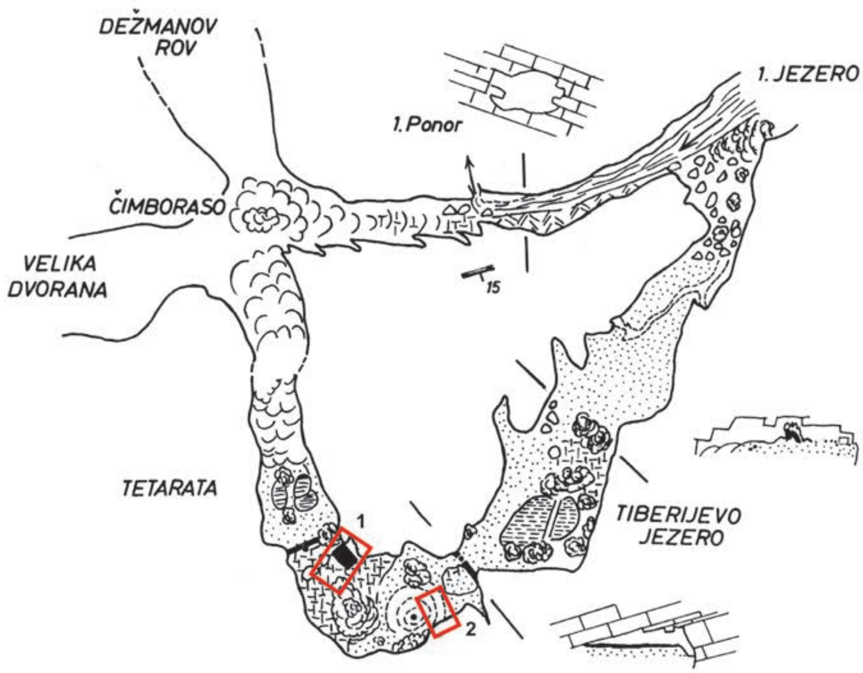

Figure 138 *Position of studied profiles in the Medvedji rov, Križna jama (passage map by Gospodarič 1973). Legend: 1 – Križna jama I profile ; 2 – Križna jama II profile.*

KRIŽNA JAMA I

PROFILE LOCATION

The Križna jama I profile (Fig. 139) was taken in the small pit dug out during archaeological and palaeontological studies in 1971 by Brodar and Gospodarič. For the first time they found *Ursus spelaeus* bones below flowstone layers (Brodar & Gospodarič 1973) in their excavated profile. Flowstones from the pit were later sampled by Ford & Gospodarič (1989) for Th/U dating.

LITHOLOGY

The excavated pit uncovered a sequence of flowstones with stalagmites alternating with clays and silts, underlain by further silts (Figs. 139 and 140; Tab. 29). The doc-

Figure 139 *The upper part of the profile Križna jama I; part with speleothems, state in 2003.*

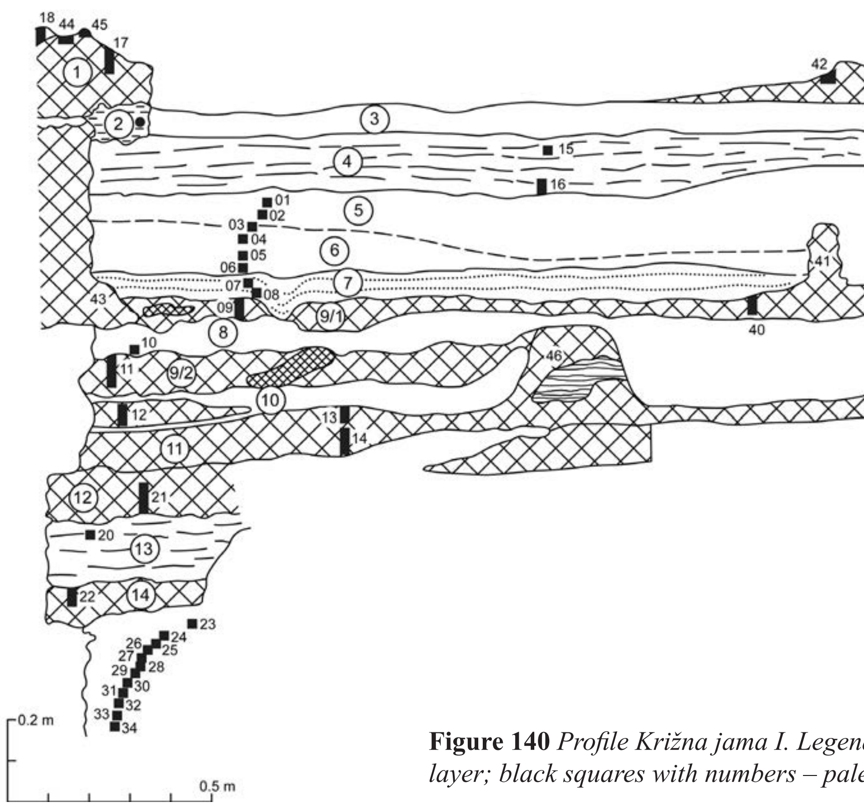

Figure 140 *Profile Križna jama I. Legend: number in circle – number of layer; black squares with numbers – paleomagnetic samples.*

umented profile differed from a drawing of Gospodarič from 1982 (published in Ford & Gospodarič 1989), the changes being caused by continued palaeontological excavations (*cf.* Rabeder & Withalm 2001; Pohar et al. 2002). Further changes were documented comparing the state of pit in 2003 and 2004, when flowstones with bear bones were missing and the shape of the pit changed substantially. Our layers No. 8 to 10 represent Ford & Gospodarič (1989) layer No. 3, which in 2003 was much thicker and uniform in lithology (reddish silt with bones of *Ursus spelaeus*) changed to alternation of clays and flowstones. Further, layers Nos. 9 and 10 contained bear bones in 2003 (Figs. 140 and 141). Snails reported in the bottom part of the profile (Ford & Gospodarič 1989) were not found. A comparison of the two stratigraphies is given in the Table 29.

MINERALOGY

The sterile clays (without *Ursus spelaeus* bones) below the bottom of the small pit were analysed by X-ray

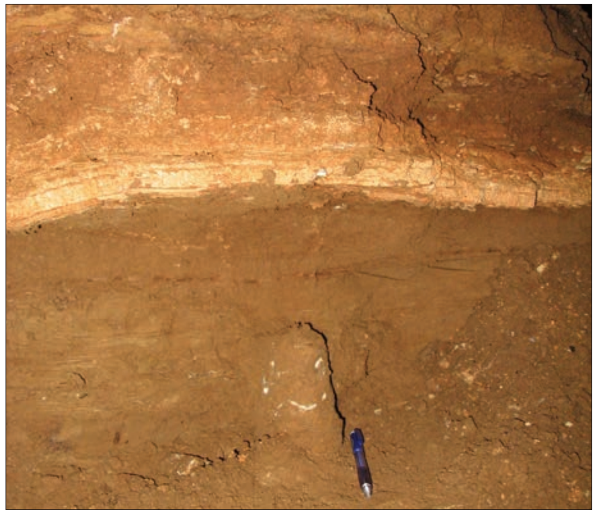

Figure 141 *The right side of the profile Križna jama I, state in 2004. Small stalagmite represents the top part of flowstone layer No. 9 (marked by number 41) on Figure 140.*

Table 29: Description of Križna jama I profile (from top to bottom; see Fig. 140)

Meters	Layer No.	Description	Layer No. after F/D*
0.00-0.17	1	Speleothem, white, crystalline, laminated	
0.17-0.28	2	Speleothem, brown, laminated, locally with laminas of clay	
0.79-1.18	3	Loam, redeposited/reworked by excavation	7
0.28-0.40	4	Speleothem, beige, laminated, hard laminas alternate with soft ones (moonmilk-like), bands of clay appear towards right	6
0.40-0.45	5	Clay, brown, laminated, with fine mica, with laminas to thin bands of chocolate brown clays	6
0.45-0.60	6	Loam, clayey, brown, locally with vario-coloured and dark stains	5
0.60-0.65	7	Clay, brown, laminated, slightly with fine mica, locally with manganese coatings on bedding planes	5
0.62-0.72	9/1	Speleothem with cave bear bones	4 (B)
0.65-0.75	8	Clay, yellowish to reddish brown, laminated, with fine mica, at middle breccia, ferruginized, locally carbonate cemented	3
0.75-0.89	9/2	Speleothem with cave bear bones	3
0.89-0.95	10	Clay, brown, irregularly cemented by carbonate	3
0.95-1.07	11	Speleothem, in upper part divided by clay lamina. Upper part thinning towards right. Lower part is laminated	2 (A)
1.07-1.25	12	Speleothem, rather brown, transition to carbonate-cemented loam	2 (A)
1.25-1.40	13	Loam, irregularly cemented by carbonate, with mud cracks, alternation with thin layers of flowstone	2 (A)
1.40-1.50	14	Speleothem, rather brown, transition to carbonate-cemented loam	
1.50-1.80	15	Clay, yellowish brown, irregularly columnar, with Mn+Fe-rich coatings on fissures	1

* F/D – Ford & Gospodarič (1989; Fig. 1 on p. 42)

diffraction. In yellow clay at the bottom of the profile (where Gospodarič found snails) quartz prevailed. Muscovite, chlorite, some kaolinite and mixed layered chlorite/montmorillonite were also present. Brown to red clays had almost the same mineral composition, except for plagioclase present there in the traces.

PALAEOMAGNETIC RESULTS

A total of 38 samples were studied for their palaeomagnetic properties from the Križna jama I profile. They are characterized by high scatter of the NRM intensities (0.45–56 mA.m^{-1}) and MS values (-4–414 x 10^{-6} SI units), and by very low up to intermediate J_n and k_n magnetic values. Mean J_n and k_n moduli values are documented in Table 30. Applying both values, the profile may be divided into three parts and categories.

Table 30 Mean palaeomagnetic values and standard deviations, profile Križna jama I

Križna jama I	**J_n** [mA.m^{-1}]	**k_n x 10^{-6}** [SI]	**Interval** [m]*
Mean value	7.001	174.3	0.02–1.01
Standard deviation	3.988	128.3	
Number of samples	20	20	
Mean value	30.368	290.5	1.07–1.42
Standard deviation	14.789	89.8	
Number of samples	6	6	
Mean value	8.954	243.8	1.46–1.72
Standard deviation	1.423	9.0	
Number of samples	12	12	

* from top to base

All samples were subjected to detailed AF and/or TD demagnetization. Multi-component analysis was applied to separate respective RM component for each sample. Three components were isolated after TD or the AF demagnetization. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–2 to 5 mT) and at temperature range of 20 to 60 (120) °C. The *B-LFC* and/or *B-LTC* are also secondary; they show harder magnetic properties and can be demagnetized in the AF (5–10 to 15 mT) or in a temperature range of 120 to (300) 400 °C. The characteristic *C-HFC* and/or *C-HTC* are stable. They can be demagnetized or isolated in the AF (ca 15–80 to 100 mT) or at a temperature range of 300 to 520 (550) °C. The unblocking temperatures (520 to 550 °C) indicate that magnetite is the principal carrier of RM.

The stereographic projections of the C-components with N and N-R polarity for profile Križna jama I are shown on Figures 142 and 143. Table 31 summarizes results of mean direction of samples from this profile. The mean palaeomagnetic directions of normal polarized C-components for profile I are D = 353°, I = 64° and of N-R polarized C-components are D = 229°, I = -11°. The basic magnetic parameters are documented in Figure 144. A short R polarized magnetozone (12 cm) was detected in the basal laminated clays below the principal speleothem layers. All the other samples show N polarization.

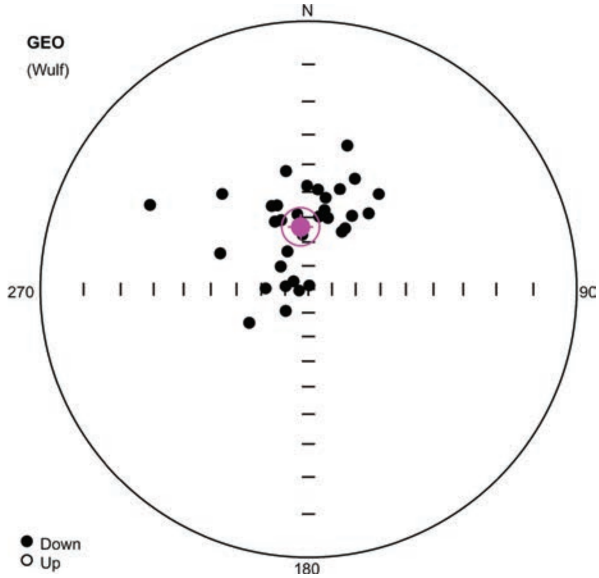

Figure 142 *Directions of C-components of remanence of samples with N polarity, profile Križna jama I. For detail description see Figure 34.*

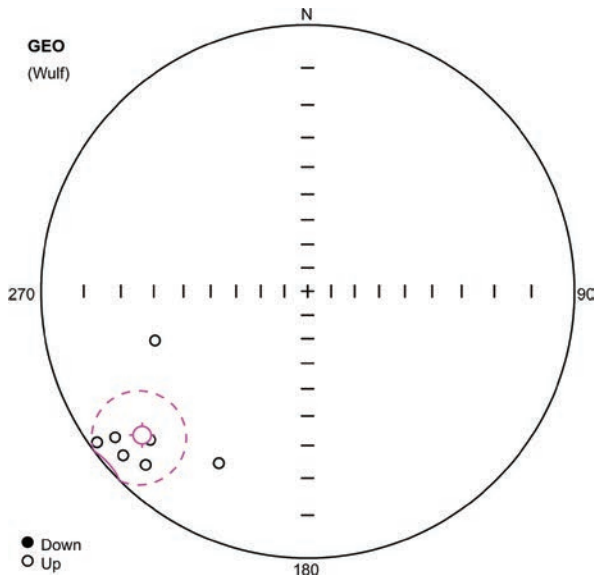

Figure 143 *Directions of C-components of remanence of samples with R polarity, profile Križna jama I. For detail description see Figure 34.*

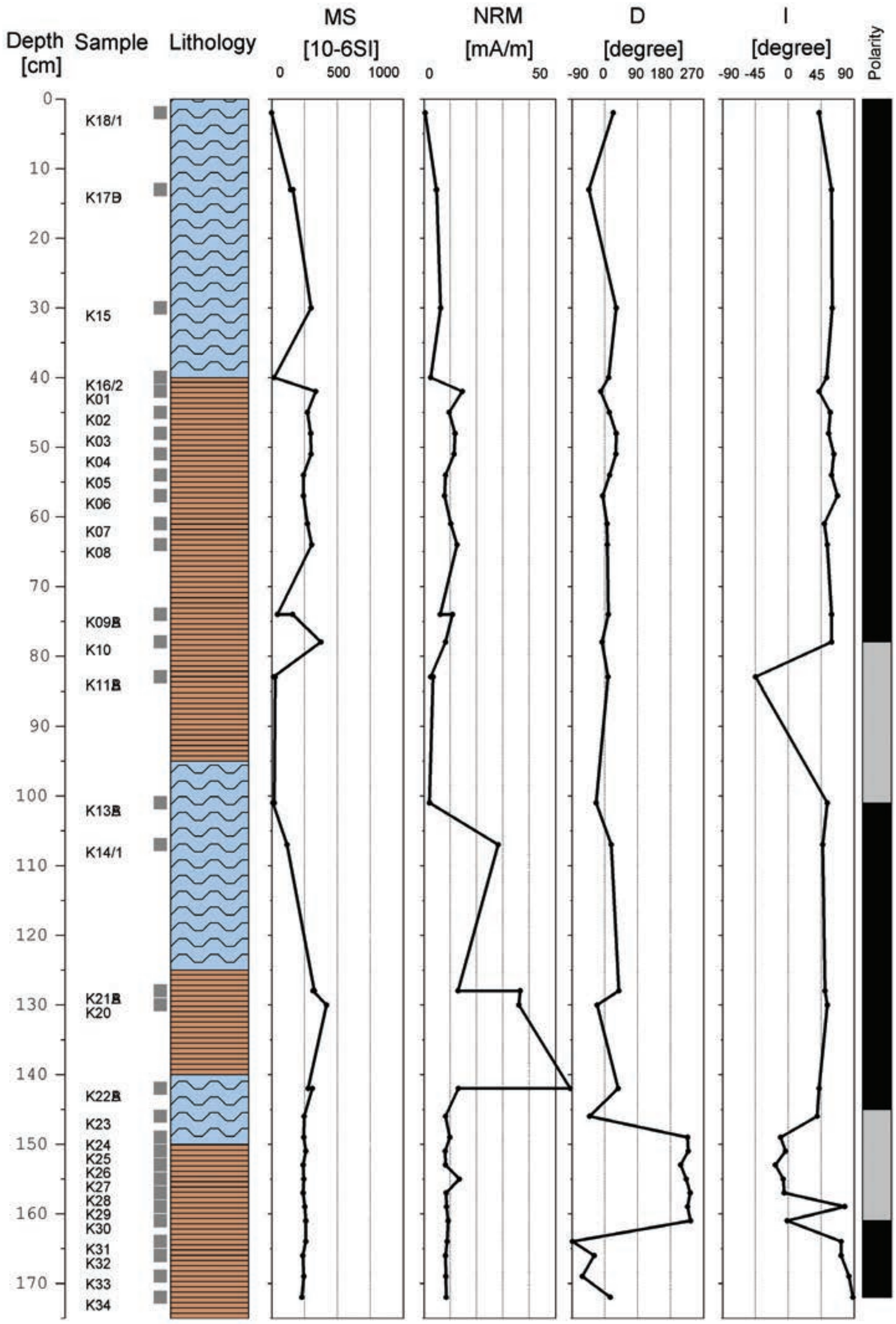

Figure 144 *Basic magnetic and palaeomagnetic properties, profile Križna jama I. Legend: see Figure 37.*

Table 31 Mean palaeomagnetic directions, profile Križna jama I

Križna jama I	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	352.81	63.66	7.16	11.24	34
	R	229.08	-11.17	10.29	26.42	7

Table 32 Th/U dating results using α-spectrometry from speleothems, profile Križna jama I

Sample*	Lab. No.	U content [ppm]	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Age [ka]	Remarks
K 45	W 1533	0.1262±0.0064	1.3466±0.0772	0.5969±0.0365	46±17	+8.3 93.8 -7.8	
K 42/1	W 1555	0.0787±0.0055	1.2320±0.1034	0.7831±0.0664	*3.7±0.5*		Detrital Th
K 43	W 1532	0.0460±0.0035	1.2165±0.1182	*1.1679±0.1040*	*2.4±0.3*		Detrital Th
K 41 middle	W 1615	0.0389±0.0026	1.2007±0.1039	0.7373±0.0662	22±8	+22 137 -19	
K 41 lower part	W 1616	0.4292±0.0145	0.9955±0.0270	0.0949±0.0062	20±6	+0.8 10.8 - 0.8	
K 46	W 1617	0.0266±0.0040	1.2252±0.2192	0.6829±0.1287	20±13	+39 118 -31	

* Samples are listed in stratigraphic order from top to bottom

TH/U DATING

Seven flowstones and stalagmites were sampled for Th/U dating in Warsaw (Poland). Results are given in Table 32.

With Th/U method we partly repeated samples measured by Ford (Ford & Gospodarič 1989), although he suggested halting the research if good results were obtained (p. 48). The reasons were as follows: (1) the pit has changed since December 1982, which caused a shift of its wall and (2) some changes in stratigraphy appeared, especially in layers Nos. 2 (A) to 4 (B; *cf.* Tab. 32), and (3) there have been discussions on the age of layer No. 3 of Ford & Gospodarič (1989). Data of Ford & Gospodarič (1989) are listed in Table 33; selected are data with $^{230}Th/^{234}U$ ratio close to 20 or above, i.e. those without detrital Th admixture (ratio above 20) or with only a small content of clastic impurities (only such dated are of acceptable quality).

DISCUSSION OF RESULTS

Gospodarič (1988) analysed snails for $^{18}O/^{16}O$. Stable isotopes indicated climatic conditions similar to the present. Therefore he expected that the sediment is of Mindel–Riss age. According to Gospodarič' interpretation (1974) the Medvedji rov was already inactive during the Late Würm. Flowstones were dated by the Th/U method (Gospodarič & Ford 1989) to Riss and Riss–Würm (between 200 and 104 ka).

Gospodarič & Ford (1989) stated that flowstone below the second horizon with *Ursus spelaeus* is older than 146 ka, and flowstone layer above it deposited between 146 and 126 ka. The upper layer with *Ursus spelaeus* is younger but contains re-deposited bones from the lower layer. Bones from the upper layer were dated by radiocarbon method by Rabeder & Withalm (2001) to more than 40 ka, which is much younger age than analysed by Gospodarič & Ford (1989).

Comparing our profile (Fig. 140) with that of Ford & Gospodarič (1989, fig. 1 on p. 42) there was only a slightly different lithostratigraphy. The upper parts are nearly identical (for correlation see Tab. 29). The middle parts slightly differ: layer with our sample No. K09 is equivalent to layer 4 or B and our layers Nos. 10 to 12 are equivalents to layer 2 or B of Ford & Gospodarič (1989). Nevertheless we detected a further layer No. 9/2 (flowstone with cave bear bones; palaeomagnetic sample K11), which is not marked within layer No. 3 of Ford & Gospodarič (1989). Also the lower part is lithologically more complicated than was simply drawn by Ford & Gospodarič (1989), i.e. alternation of flowstone, silts and carbonate-cemented silts. Remains of small snails reported from layer No. 1 of Ford & Gospodarič (1989) were not found by us. Cave bear bones occurred in our layers Nos. 5 to 10 (Fig. 140).

Table 33: Th/U dating results using α-spectrometry from speleothems, Križna jama I profile (selection from Ford & Gospodarič 1989)

Sample	U cont. [ppm]	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Age [ka]	Age corr.*	Layer No.
YUGK1A	0.11	1.089	0.763	31.4	+16 151 -15		4 (B)
YUGK4 Top	0.15	0.925	0.728	122	+44 146 -31		4 (B)
YUGKK4 Middle	0.10	1.133	0.816	36.1	+28 173 +22		4 (B)
YUGK4 Base	0.07	1.520	0.986	*15.7*	+54 251 -38	+55 244 -40	4 (B)
KYU4S Base	0.08	1.107	0.735	*15.5*	+33 139 -25	+36 133 -29	4 (B)
YUGK2R Top	0.12	1.189	0.703	37.4	+11 126 -10		2 (A)
YUGK2R Middle	0.11	1.232	0.725	42.7	+13 132 -12		2 (A)
YUGK2 Base	0.13	1.148	0.756	29.3	+14 146 -13		2 (A)
KYU2 Top	0.10	1.150	0.903	*17.4*	+54 224 -37	+55 218 -38	2 (A)
KYU2 Hiatus	0.10	1.191	0.801	*14.6*	+16 162 -14	+17 155 -15	2 (A)
KYU2 Base	0.10	1.107	0.735	*15.5*	+25 169 -21	+27 150 -23	2 (A)

* Corrected age in ka assuming initial ^{230}Th = 1.25

Prevailing N polarization of the whole profile indicates age younger than Brunhes/Matuyama boundary at 780 ka. The short R polarized magnetozone represents one of the short-lived excursions of the magnetic field within the Brunhes chron, which is older than about 146–160 ka.

Our sampling for radiometric dating resulted, in principle, from discrepancies which appeared in results and interpretations obtained by the radiocarbon dating (Rabeder & Withalm 2001; Pohar et al. 2002) and Th/U dating (Ford & Gospodarič 1989). Ford & Gospodarič (1989) dated speleothem layers (Th/U method) within the profile to about 126 ka and 146 ka. The base and top of the bone-bearing layer (their No. 3) dated to about 146 ka, expecting that the clastic deposit represents single-flood episode. Rabeder &

Withalm (2001) dated three samples of bones of Ursus spelaeus from 44.8 +1.8/-1.4 to 46.7 +2.4/-1.8 ka BP.

New radiometric dates have proved the results and interpretations of Ford & Gospodarič (1989). Our sample K41 Middle with age of 137 ka (Tab. 32) represents most probably the equivalent of Ford & Gospodarič (1989) samples YUGK1, YUGK4, YUGK4 and KYU4 dated to 173–146 ka (layer 4 or B; see Tab. 29) or represents flowstone layer somewhat younger than samples from layer 4 (B). Nevertheless $^{230}Th/^{234}U$ ratios can indicate some detrital Th admixture, i.e. a little bit younger age was obtained. Samples K41 Base and K46 contain some detrital admixture, thus the ages are younger than the true ones (especially sample No. K41; lower part). The top of stalagmite in the left part of our profile is dated to about 94 ka, indicating the termination of stalagmite growth just before the start of the last glacial. Sediments belonging to layers Nos. 7 to 4 are younger. Dates of Pohar et al. (2002) indicate ages between 43 and 49 ka. Nevertheless layers Nos. 9/1 to 10 containing remains of cave bear must be older than 125 ka, which is in full agreement with the interpretations of Ford (Ford & Gospodarič 1989, p. 46). Two hiatuses expected within the layer No. 2 (A), which lasted for 20 to 40 ka (Ford & Gospodarič 1989) were proven by the more complex lithology of their layer No. 3 later opened by excavations (our layers Nos. 10 and 9/2). Ford & Gospodarič (1989, p. 50) proposed an alternative explanation for discrepancies in age of cave bear bones by the intrusion of younger Layer 5 into the position of Layer 3. The detailed internal lithology reflected in the alternation of layers No. 10 to 9/1 and their low thicknesses exclude expected sandwiching of younger layers into eroded/washed spaces among flowstone layers No. 11, 10, 9/2 and 9/1. Remains of cave bears in Layers No. 4 (B) to 2 (B) are definitely older than 125 ka.

KRIŽNA JAMA II

PROFILE LOCATION

Profile Križna jama II, was located on the southern side of the same chamber as the Križna jama I profile (Fig. 138). There is a deep depression between the profiles, a result of sapping of sediments below the known passage bottom. The top of the profile is situated directly below cave ceiling; the rest was in the steep side of the depression (Fig. 145).

LITHOLOGY

The profile consisted of two parts. The upper one was situated directly below the cave ceiling, beginning some 18 cm below an overhanging wall. The lower part of the profile started on the edge of platform (an excavated palaeontological site) on the side of deep erosional hole (an underground dropout doline; Fig. 145). The lithology of the Križna jama II profile is presented in Figure 146.

The upper part of the profile (top 80 cm) consisted of an alternation of flowstone layers and silts to clays (Fig. 147). The flowstones were mostly laminated and intercalated by brown silt and clay laminae. The basal layer was brown and sponge-like, highly porous to vuggy. Silts to clays were finely laminated light grey and yellowish brown to brown and with fine-grained sandy admixture and small limestone clasts in places.

Figure 145 *Profile Križna jama II; middle and lower part of the profile are on the photo; and the upper top part of the profile is located directly below ceiling.*

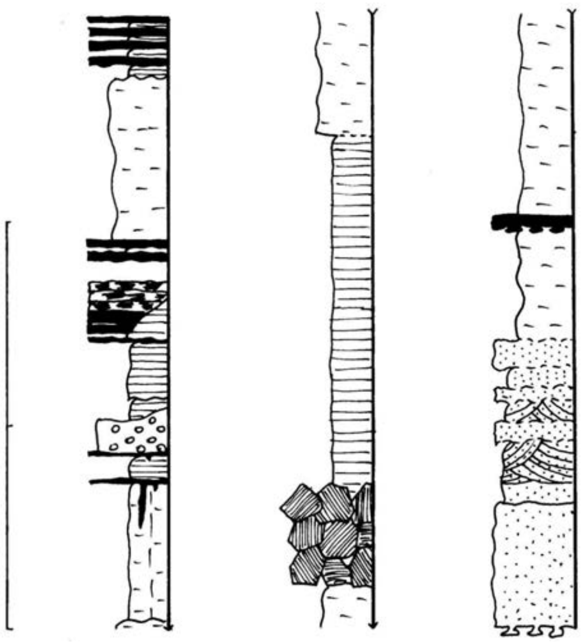

Figure 146 *Profile Križna jama II. Legend: bar – 1 m; black – massive, laminated flowstone; interrupted black – sponge-like flowstone; dotted – sand/ sandstone; shaded in different directions – collapsed limestone blocks; horizontal lines – clays; short lines – silt; vertical + horizontal lines – columnar clay; circles – microconglomerate.*

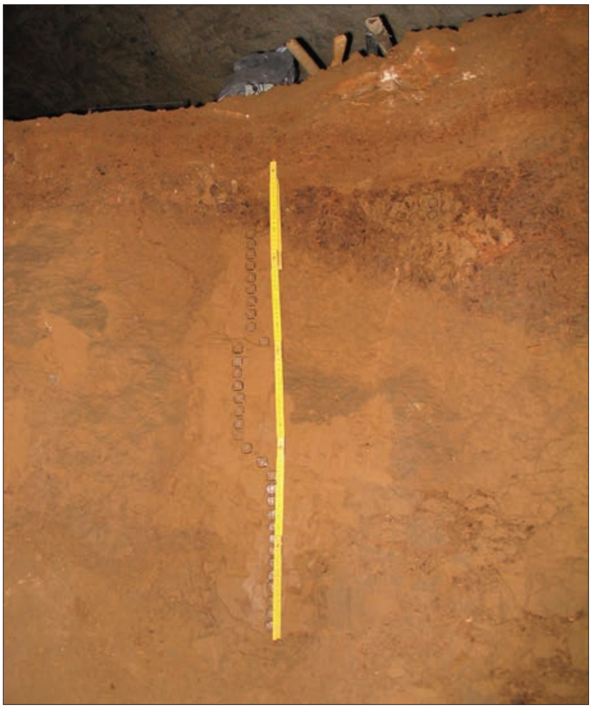

Figure 147 *The upper most part of the profile Križna jama II, sampled in 2004.*

The middle part of the profile (185 cm) was composed of yellowish brown to light brown clays and silty clays, with some layers of clayey silts (Fig. 148). In places, sediments were laminated with fine-grained sandy admixture, with thin laminae of flowstones, with small clay lithoclasts (2–3 cm in size), and with small fenestral structures along the lamination. Columnar disintegration was developed in two horizons. Fissures among the polygonal columns were coated by a dark grey to dark greyish violet film (Mn compounds?) and deeply infiltrated by calcite along fissures in the upper columnar layer. Thin calcite crusts and desiccation cracks marked the layer boundaries. About 5 cm below the top of this middle sequence, a lenticular layer of micro-conglomerate to breccia occurred (8 cm). It was composed of sub-angular to sub-oval clasts of compact clays derived from the underlying layer, with a light brown silty matrix and calcite-covered erosional base (Fig. 149). The silty clayey sequence was underlain by a 25 cm thick bed of blocky scree composed of angular limestone blocks (collapse) with yellow clayey matrix and 60 cm thick layer of light brown silt to clay.

The lower sequence (100 cm) is mostly sandy. It began with three cm of flowstone and orange to yellowish brown silt to clay, slightly sandy in lower half, with numerous small decomposed (pulverized) limestone clasts (up to 5 mm in size) in upper half and just above the base. Sands below were medium-grained, clayey, light brown, with abundant small clasts of fresh and decomposed limestone and brownish red Fe concretions (pellets 1–2 mm in size), with contact clayey cement, with small rounded clayey pellets (about 2 mm in size), locally cemented up to sandstone grade by crystalline carbonate, in upper half with distinct lenticular and cross-bedding. Cementation by calcite in the form of irregularly shaped rounded concretions was a typical feature of the whole lower sequence.

MINERALOGY

Quartz and calcite prevailed in the brown-yellow sandy sediment on the top of the profile. Muscovite, chlorite, and montmorillonite were also present and feldspar was detected in traces.

Pohar et al. (2002) studied sediments by X-ray analysis from Kittlovo brezno (a shaft in the entrance part of Križna jama). They detected calcite, hydroxylcarbonate apatite, fluorapatite, quartz, illite/muscovite, chlorite and clay fraction contained mixed layered illite/montmorillonite and chlorite/montmorillonite.

Figure 148 *Sampling of the profile Křižna jama II; top of the middle part of the profile.*

Figure 149 *The upper part of the middle sequence of profile Křižna jama II.*

PALAEOMAGNETIC RESULTS

A total of 110 oriented laboratory samples were studied for their palaeomagnetic properties. Studied sedi-

Table 34: Mean palaeomagnetic values and standard deviations, profile Křižna jama II

Křižna jama II	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	8.930	172.0	0.14–0.80
Standard deviation	2.604	95.4	
Number of samples	21	21	
Mean value	16.775	290.4	0.82–0.91
Standard deviation	8.902	39.4	
Number of samples	5	5	
Mean value	13.812	262.08	1.09–2. 22
Standard deviation	7.824	55.7	
Number of samples	38	38	
Mean value	7.331	190.6	2.245–3. 02
Standard deviation	2.784	19.1	
Number of samples	25	25	
Mean value	18.132	289.9	3.04–3.715
Standard deviation	3.441	28.2	
Number of samples	21	21	

* from top to base

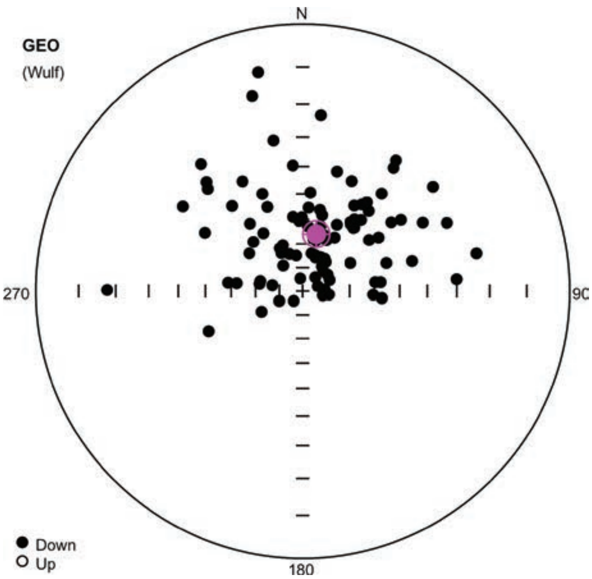

Figure 150 *Directions of C-components of remanence of samples with N polarity, profile Križna jama II. For detail description see Figure 34.*

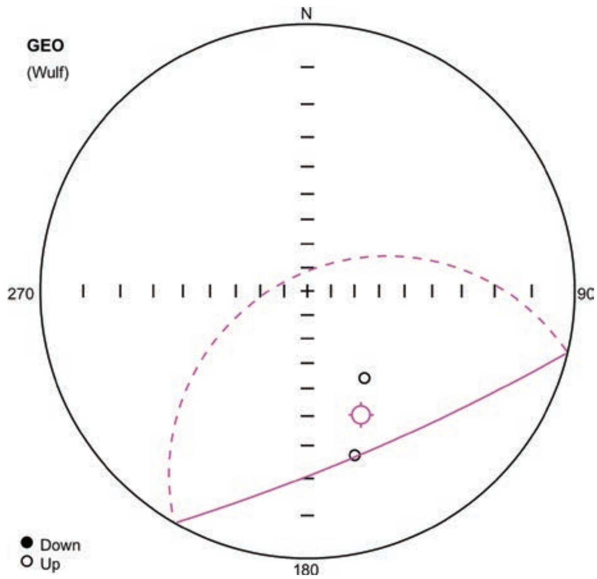

Figure 151 *Directions of C-components of remanence of samples with R polarity, profile Križna jama II. For detail description see Figure 34.*

Table 35: Mean palaeomagnetic directions, profile Križna jama II

Križna jama II	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	13.44	65.33	5.07	7.79	98
	R	156.53	-36.56	-	-	2

ments are characterized by a not too high scatter of the NRM intensities (1.2–37 mA.m^{-1}) and MS values (12–411 x 10^{-6} SI units). The samples are characterized by low up to intermediate J_n and k_n magnetic values. Mean J_n and k_n moduli values are documented for both profiles in Tables 34. Applying both values, the profile may be divided into five parts and categories.

All collected samples were subjected to detailed AF demagnetization in 14 steps in 12–14 fields. Multi-component analysis was applied to separate the respective RM components for each sample. Three components were isolated after the AF demagnetization. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–2 up to 5 mT). The *B-LFC* is secondary and can be demagnetized in the AF (5–10 up to 15 mT). The characteristic *C-HFC* is stable and can be demagnetized or isolated in the AF (ca 15–80 up to 100 mT).

The stereographic projections of the C-components with N and R polarity are shown on Figures 150 and 151. Table 35 summarizes results of the mean direction of samples from this profile.

The mean palaeomagnetic directions of the N polarity of C-components for this profile are D = 13°, I = 65° and of R polarity of C-components (for three samples only) are D = 156°, I = -37°. Except some transient zoning, three short R polarity magnetozones (excursions) were detected at 1.19, 1.675 and 3.02 m in the section. All other samples show N polarity. Systematic acquisition of palaeomagnetic data within the studied section allowed the construction of a detailed magnetostratigraphic profile (Fig. 152).

DISCUSSION OF RESULTS

The sediments were deposited in a cave fluvial environment. The upper part (0 to 3.95 m) resulted from slack water deposition in the little agitated environment of cave lakes, alluvial flats and crevasse splays. The sequence below it represents a fluvial deposit. Carbon-

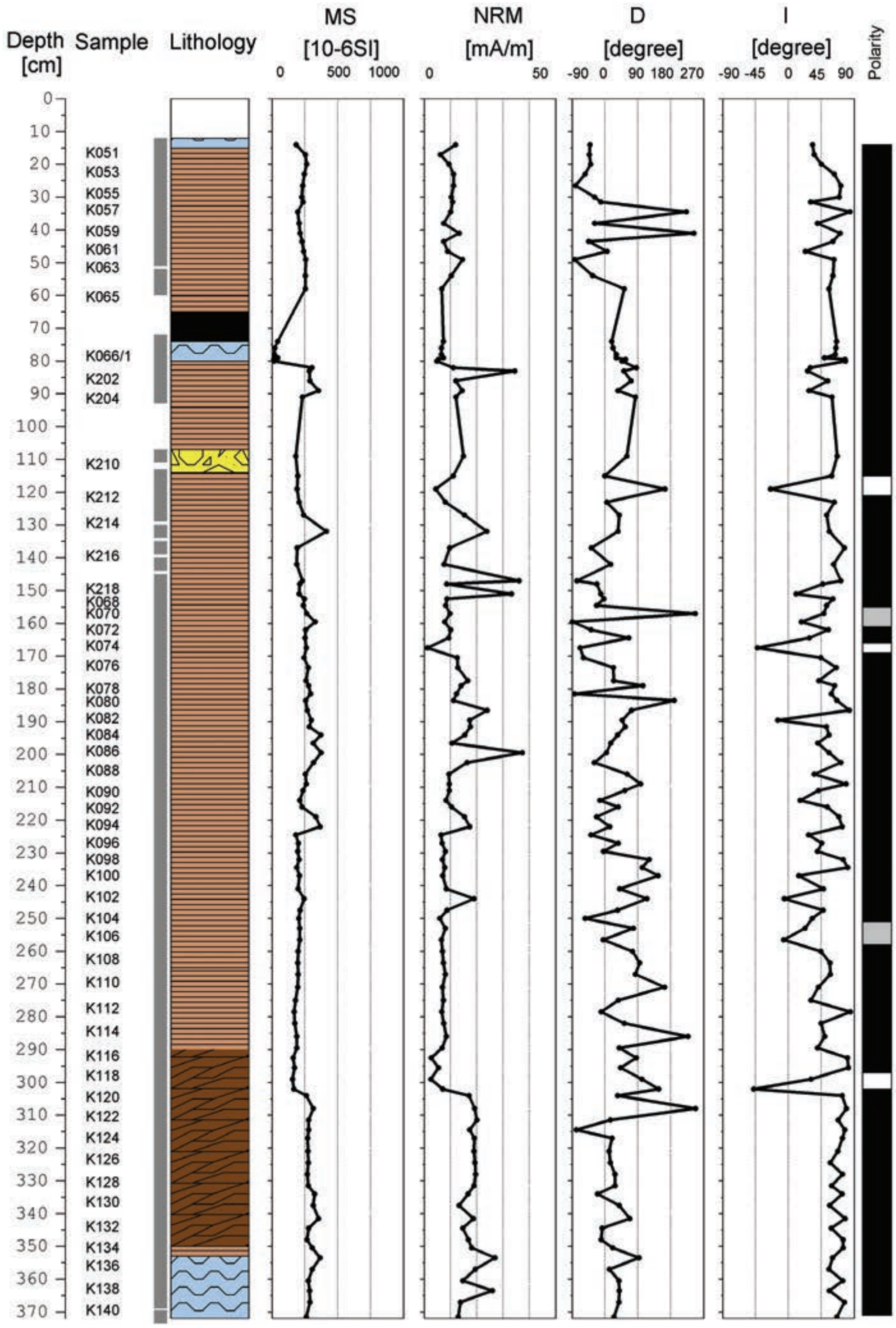

Figure 152 *Basic magnetic and palaeomagnetic properties, profile Křižna jama II. Legend: see Figure 37.*

ate cementation in the lower part of the profile (below 3.53 m) probably indicate warmer climatic conditions. The horizon between 1.14 and 1.48 m was probably disturbed by frost action and its upper bedding plane represents important hiatus in the deposition.

Gospodarič (1974) interpreted some sedimentological features from the clastic sediments of Križna jama. Angular limestone pebbles are interpreted as autochthonous and well-rounded as allochthonous. Pebbles of oolitic bauxite were derived from the surface above Križna jama where they were formed. An origin and redeposition from the Triassic bauxite was excluded. Different kinds of sands and silts contained quartz, limonite and bauxite grains. The quartz grains were interpreted as clastic (fluvial or eolian) re-deposited in the cave during the Pleistocene. Bauxites can be linked (Bosák et al. 1999) with surface paludal deposits, which underwent at least the initial stage of bauxitization.

The lithological correlation between the Križna jama II and Križna jama I profiles is clear. The upper part, an alternation of speleothems and silts to clays, is undoubtedly equivalent to layers No. 1 to 14 in Križna jama I site. Layer No. 15 (clays with columnar disintegration) can be compared with the similar layer in Križna jama II profile. Therefore, about 40 cm of sediments from the top of the middle sequence of Križna jama II profile are missing in the Križna jama I site.

According to the palaeomagnetic results (prevailing N polarization) and parameters we assume that deposition took place within the Brunhes chron (<780 ka). Three short R polarized magnetozones represent short-lived excursions within the Brunhes chron. They are older than 156 ka, which results from lithological correlation with the profile I.

Side passage in Križna jama.

PLANINSKA JAMA

SITE LOCATION AND CHARACTERISTICS

Planinska jama (Reg. No. 748; 45°49´11.62″N; 14°14´44.39″E; 453 m a.s.l.; Fig. 18 and 153) is situated on the southern edge of Planinsko polje, with its entrance at the end of a large pocket valley. The cave discharges the main spring of the Unica river, which flows through the polje (Fig. 22). The inner parts of the cave are at a slightly higher elevation than the entrance. A planed surface with many dolines occurs 50 m above the cave. The cave is one of the largest caves of the Postojnski kras (Fig. 23).

The cave entrance is situated in the Upper Cretaceous limestones and dolomites (Buser, Grad & Pleničar 1967). According to Gospodarič (1976), the entrance part and Rakov rokav are developed in Lower Cretaceous bedded limestones, limestones with chert and limestone breccia. Pivški rokav and Rudolfov rov (to the south of the Rakov rokav) are developed in Upper Cretaceous massive limestone and breccia with *Caprinidae* and *Chondrodontae*. Bedding dips northeastwards at 20° in the Rudolfov rov.

Planinska jama is a 6,656 m long cave with active stream passages. Only some small side passages at higher elevations are not active, such as Rudolfov rov. The passages are large, about 15 m wide and high. There are some collapse chambers and one of the passages terminates in a large collapse.

The confluence of the Pivka river, which arrives from Postojnska jama and the Rak river from Rakov Škocjan is situated within the cave. The two main passages were named after the tributaries: Pivški rokav and Rakov rokav. Both rivers flow into the cave via deep sumps.

Rudolfov rov is a side passage of Rakov rokav about 200 m long at ca 460–475 m a.s.l. The entrance to the passage is in the southern wall of Rakov rokav at 470 m a.s.l., i.e. about 16 m higher than the main passage floor. A small stream flows out of Rudolfov rov, eroding sediments away.

PROFILE

The profile base is situated at 45°48´50.49″N; 14°14´42.27″E and 468 m a.s.l. (Fig. 154). We sampled the same sediments as Gospodarič and Šebela (Šebela & Sasowsky 1999), but in a different place.

LITHOLOGY

The profile was composed of a sequence of light-coloured (yellowish brown and yellow) silty clays interlaminated by yellowish brown to whitish grey silts and fine-sandy silts to sands, locally with cross-bedding, in lower part with ferrugineous laminae, in all about 2.2 m thick (Fig. 155). Lamination was due to flood pulse, with sharp erosional bases to the sandy laminae. The profile represents remnants of fluvial deposits which once completely filled the passage and later were partly eroded.

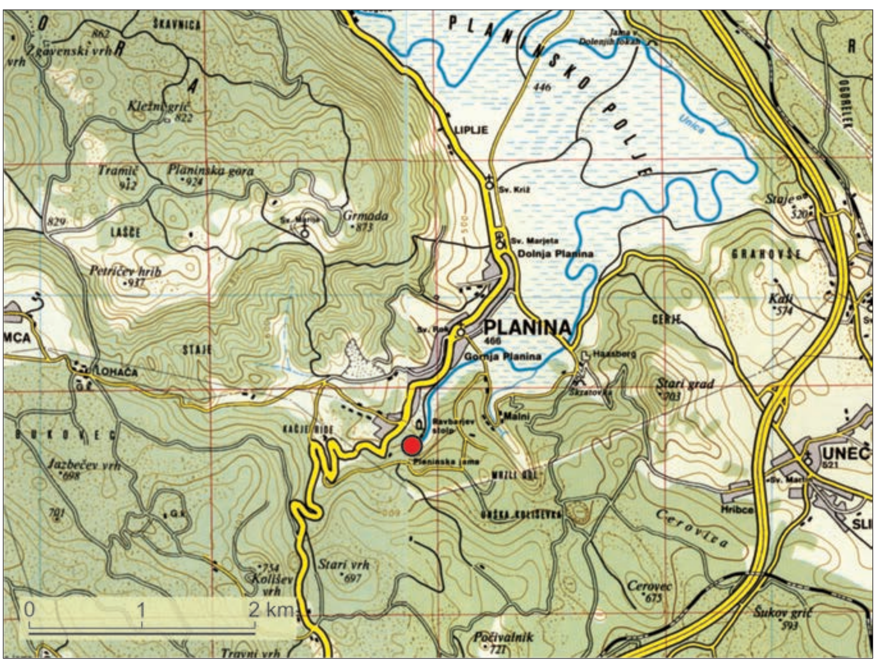

Figure 153 *Site location; Planinska jama (SW Slovenia).*

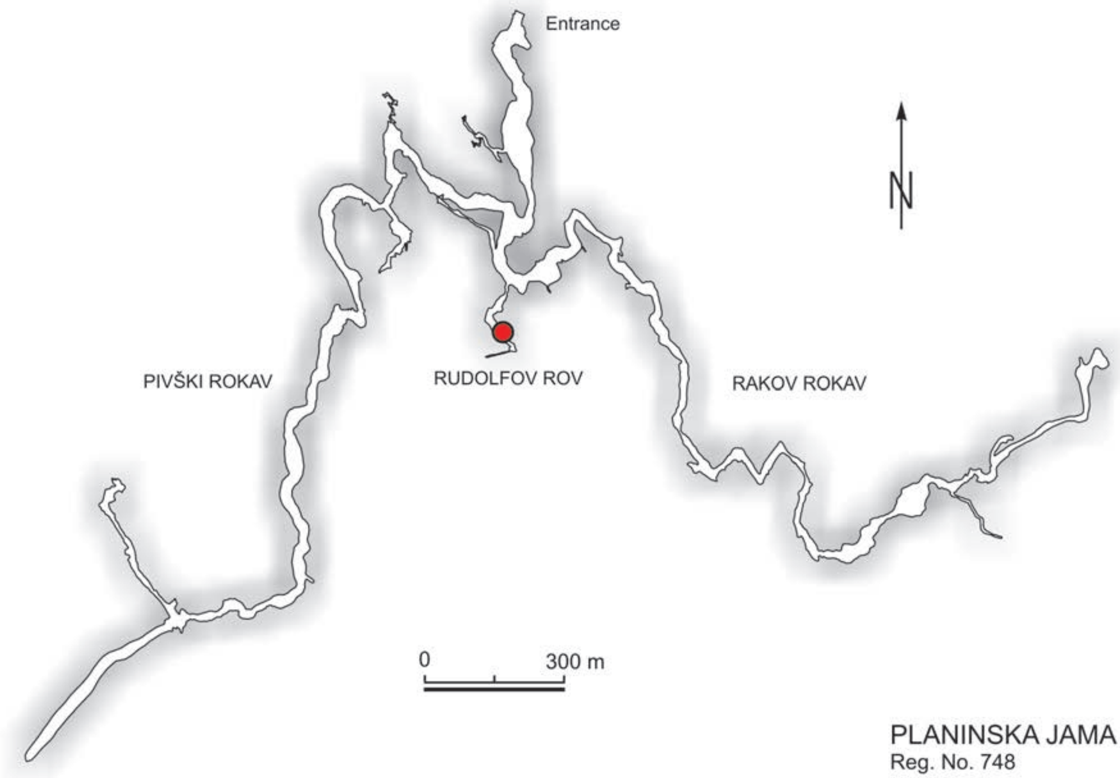

Figure 154 *Location of profile in the Rudolfov rov (after Cave Register of IZRK ZRC SAZU and JZS).*

MINERALOGY

The sample of laminated yellow loam contains quartz (40 %), muscovite (14 %), microcline (12 %), calcite (10 %), goethite (10 %), plagioclase (10 %) and chlorite (4 %; Zupan Hajna 1998).

PALAEOMAGNETIC RESULTS

All 85 samples were measured for their palaeomagnetic properties. The mean values of J_n and k_n moduli are documented in Table 36. From both values, the profile may be divided into three parts and categories. Detected NRM varied between 0.68 and 4.94 mA.m^{-1}, values of volume MS are from 82 to 233 x 10^{-6} SI. Samples are characterized by low to very low J_n and k_n magnetic values.

The samples were demagnetized by the AF up to 100 mT. Multi-component analysis was applied to separate respective RM component. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–2 to 5 mT). The *B-LFC* is also secondary but shows harder magnetic properties and can be demagnetized in the AF (5–10 to 15 mT). The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF (ca 15–80 to 100 mT).

Table 36 Mean palaeomagnetic values and standard deviations, Planinska jama

Planinska jama	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m]*
Mean value	1.619	114.6	0.02–0.41
Standard deviation	0.500	9.5	
Number of samples	20	20	
Mean value	1.929	130.5	0.45–1.98
Standard deviation	0.855	14.4	
Number of samples	55	55	
Mean value	3.387	193.3	2.00–2.23
Standard deviation	1.579	43.5	
Number of samples	9	9	

* from top to base

The stereographic projection of the C-compo-

Figure 155 *The Rudolfov rov profile in the Planinska jama.*

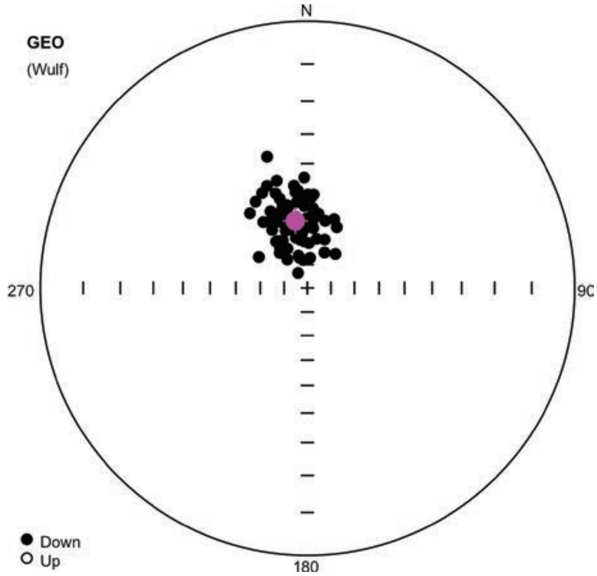

Figure 156 *Directions of C-components of remanence of samples with N polarity, Planinska jama. For detail description see Figure 34.*

Table 37 Mean palaeomagnetic directions, Planinska jama

Planinska jama	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	349.73	61.33	2.16	50.2	84

nent with the N polarity is shown in Figure 156. Table 37 summarizes results of mean direction of samples from this profile. Mean palaeomagnetic directions of normal polarized C-components for this profile are D = 349.7° and I = 61.3°. The basic magnetic parameters are documented in Figure 157.

DISCUSSION OF RESULTS

Gospodarič (1976) described sediments, which he found in the following stratigraphic succession: the oldest coloured chert gravels; older laminated loam (Middle Quaternary); white chert gravel (Riss); flowstone (80 ka, Riss–Würm); younger laminated loam (lower Würm); flowstone (Middle Würm); flood loam (Upper Würm); flowstone (Postglacial) and the youngest flowstone (Holocene). Erosion of the sediments was contemporaneous with the last phase of flowstone formation.

The Rudolfov rov was expected by Gospodarič (1976) to be filled by the older laminated loam, which rested upon the erosion bottom of the channel. This loam was expected to be overlain by white chert gravel. He expected that chert gravels of this colour were old and thus that the older laminated loam could be dated to about 350 ka, like all the oldest sediments in other caves of the region (Postojnska jama, Otoška jama, Risovec, Divaška jama and Križna jama). The mineral composition of sediments indicates that the waters depositing the clastic load in the cave arrived from the Pivka basin where Eocene flysch rocks were eroded (Gospodarič 1976; Zupan Hajna 1992). However, modern water in Rudolfov rov flows from Javorniki mountain and Cerknica polje. This water eroded the sediments that once completely filled the passage.

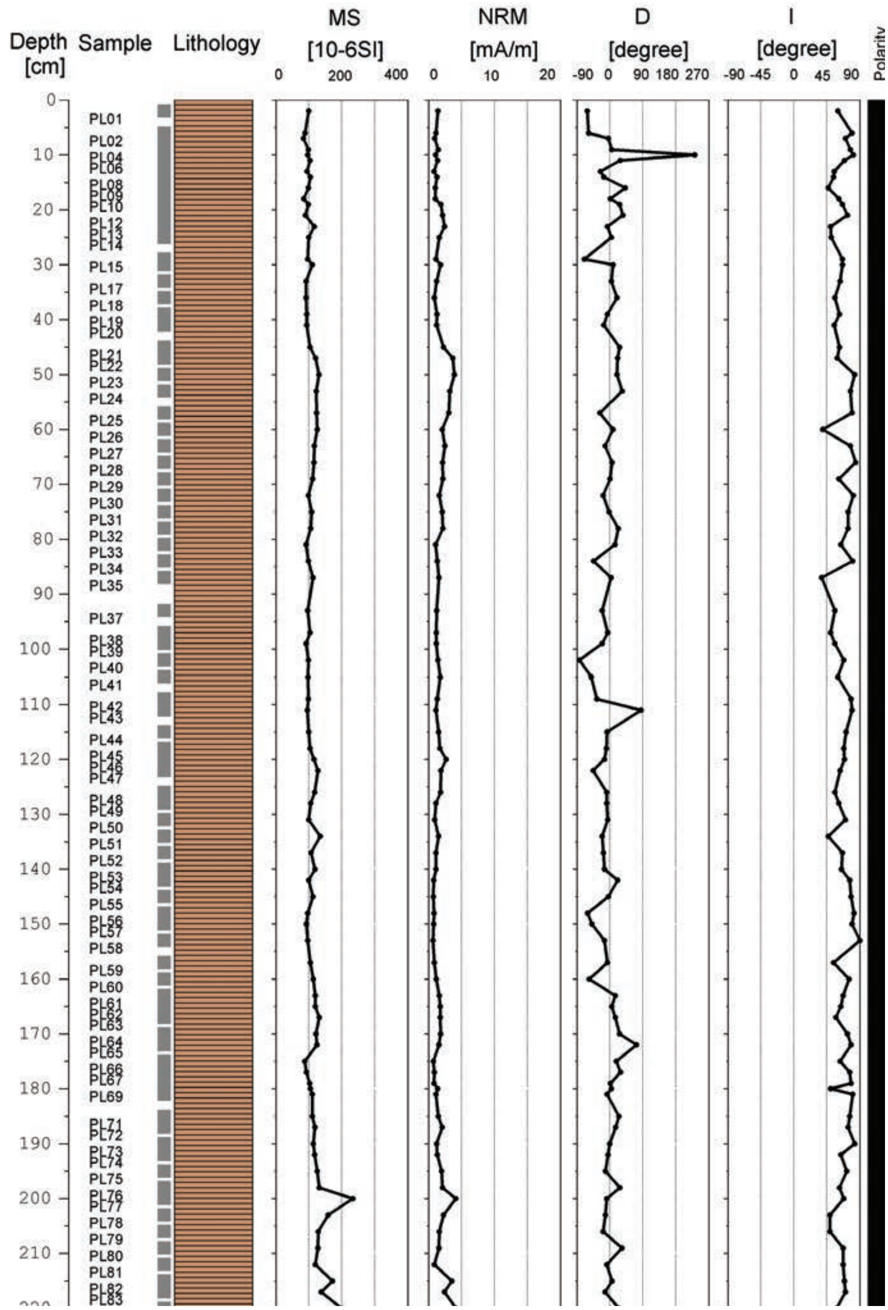

Figure 157 *Basic magnetic and palaeomagnetic properties, Planinska jama. Legend: see Figure 37.*

Šušteršič et al. (2003) re-interpreted stratigraphy of Gospodarič and his evolution phases of the Planinska jama, but added no new data. They considered the development in Planinska jama during the last 100 ka to be very "vigorous". The possibility cannot be excluded that their proposed succession of events is correct, but the amount of time proposed for such dynamics of infilling and erosion phases is unrealistic in our view (too short). Our contention is based not only on all the radiometric and relative dating (including archaeology; *cf.* Brodar 1969) referred to or described in this book, but also from general knowledge of dynamics of filling and erosion phases in the Postojnska jama system (e.g., Pruner et al. 2004) and other caves in this part of Slovenia.

The sequence of fine-grained sediments studied was deposited from pulsed floods or from suspension in the calm sedimentary environment of cave lakes. The prevalence of a lutitic clastic component indicates rather great distances from the catchment area and/or the fact that the coarse-grained load was already deposited or sieved (e.g., in sumps and semi-sumps), which is in close accordance with data obtained by Gospodarič (1976) and Zupan Hajna (1992).

The older laminated loam of Gospodarič (1976) was sampled for palaeomagnetic analyses from Rudolfov rov by Gospodarič and Šebela (Šebela & Sasowsky 1999). Šebela & Sasowsky (1999) published results from an approximately 4 m thick profile of yellowish brown laminated loams at about 460 m a.s.l. Palaeomagnetic properties were studied on 12 samples (6 duplicates). Normal polarization of all samples was interpreted as younger than 0.73 Ma. They suggested that the palaeomagnetic results are in good accordance with Mindel age (0.35–0.59 Ma) proposed by Gospodarič (1981).

Our results confirmed a N polarization without any R polarized samples. It appears that the profile can be placed within the Brunhes chron, i.e. the sediments are most probably younger than 0.78 Ma, as expected by Šebela & Sasowsky (1999). But without any comparative data (Th/U dating, fossils) we cannot be certain.

Entrance of Planinska jama; the spring of Unica river.

POSTOJNSKA JAMA

SITE LOCATION AND CHARACTERISTICS

Postojnska jama (Reg. No. 747; 45°46´57.79˝N; 14°12´13.18˝E; Fig. 158) developed in Postojnski kras (Fig. 23) where the surface is at 600 to 650 m a.s.l. The evolution of the Pivka basin (flysch rocks) is defined by the altitudes of the ponors of Pivka river that drain into this cave. The gentle fluvial surface of the basin itself stands out in sharp contrast to the karst lands above the cave and to other higher karst plateaus, where there are no traces of fluvial valleys or other elements of the early fluvial relief today. These surfaces are dissected with numerous dolines. Sixteen large collapse dolines developed above some parts of Postojnska jama, blocking certain passages. The thickness of bedrock overburden above the cave is 60 to 120 m.

The cave was formed by the Pivka river. Its modern ponor is at 511 m a.s.l. and the terminal sump in Pivka jama is at 477 m a.s.l. There are still more than

Figure 158 *Site location; Postojnska jama (SW Slovenia).*

Figure 159 *Speleothems in Postojnska jama deposited in different phases; stalagmites in the Pisani rov.*

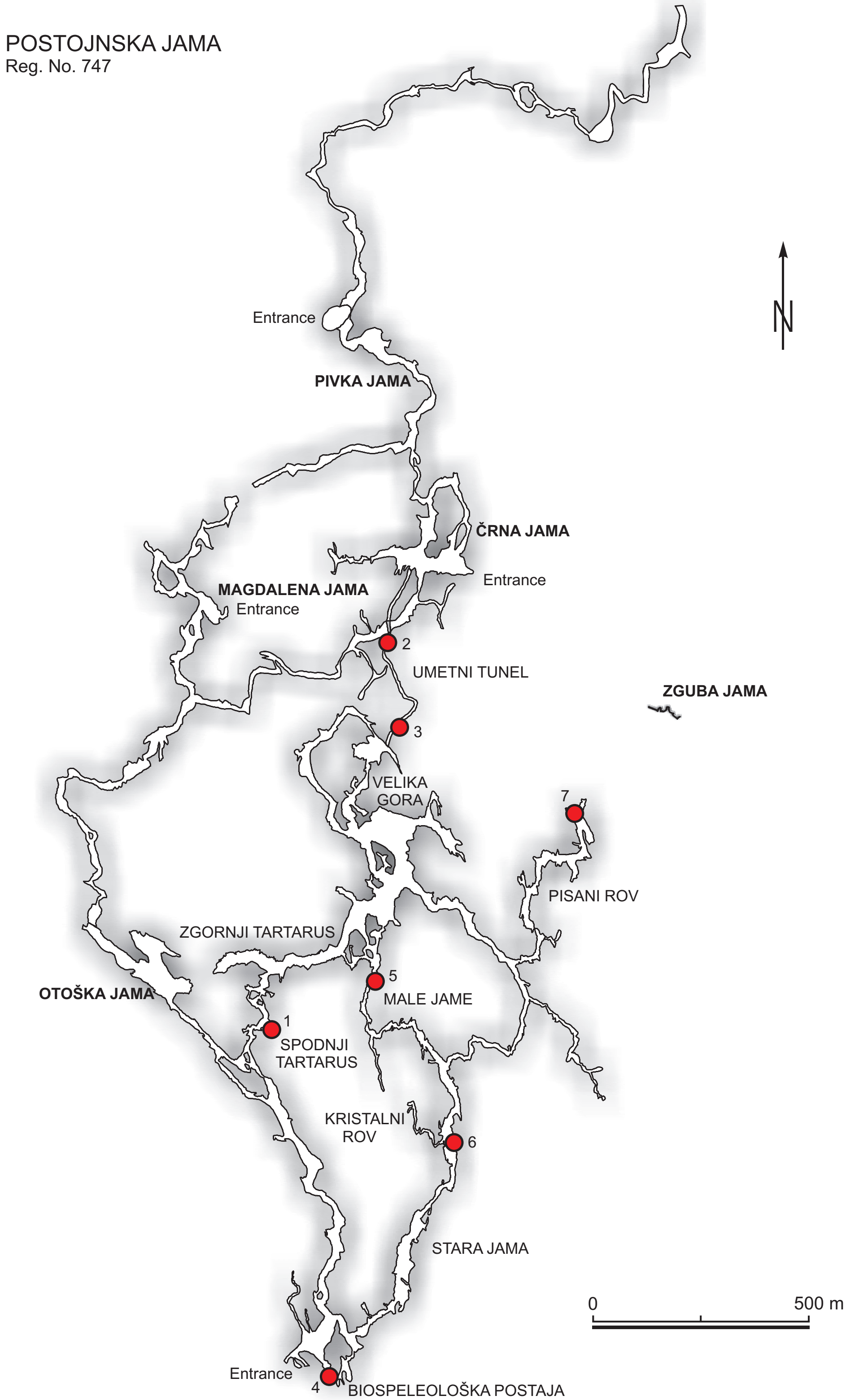

Figure 160 *Profile locations in the cave map of Postojnska jama (cave map after Cave Register of IZRK ZRC SAZU and ZRC). Legend: 1 – profiles in Spodnji Tartarus; 2 – profile Umetni tunel I; 3 – Umetni tunel II; 4 – profile in Biospeleološka postaja; 5 – profile in Male jam; 6 – profile in Stara jama; 7 – profile in Pisani rov.*

2,200 m of unexplored galleries before the river re-appears in Planinska jama at 460 m a.s.l.

The historical entrance at 529 m a.s.l. is located above the modern ponor. Other entrances and parts of the system, i.e. Otoška jama, Magdalena jama, Črna jama and Pivka jama, are scattered on the surface above the cave. All these caves are interconnected and form a cave system 20.5 km in length, the longest in Slovenia.

The entrance to Postojnska jama is situated near the contact between the Eocene flysch and the Upper Cretaceous limestones (Buser, Grad & Pleničar 1967). The entire cave system is developed in an 800 m thick sequence of the Upper Cenomanian and Turonian to Senonian limestones. The Upper Cenomanian limestones are bedded and contain cherts, and white limestone with *Chondrodontae* (Rižnar 1997). The Turonian limestone contains radiolitid fauna. The transition from Turonian to Senonian limestone is gradual. The lower part of Senonian consists of thick-bedded limestone with numerous *Keramospherina tergestina*. The youngest beds belong to Maastrichtian, with some *Hippurites giordanni Pirona*.

The cave passages are formed in the Postojna anticline, which is oriented NW–SE (Gospodarič 1976), most of channels being in its steeper south-western flank. The cave system is in the tectonic block confined by two distinctive dextral strike-slip fault zones in the Dinaric trend, the Idrija and Predjama faults (Buser, Grad & Pleničar 1967; Placer 1996). Habič (1982a) explained different features, such as collapses and sumps in the cave, as the results of neotectonic movements. A geological survey of the cave passages was made by Gospodarič (1964, 1976) and Šebela (1994, 1998a, b) added structural mapping in detail. The cave and the Pivka underground river have a general N–S trend.

The known passages were formed at two main levels. The upper level is between 529 m a.s.l., at the main entrance to the cave and 520 m a.s.l. in the Črna jama. This level is composed of large passages, generally up to 10 m high and wide. Their profiles are more rounded and show also traces of paragenesis (levelled ceilings, side notches on the walls and scallops on the walls and ceiling). There are also remnants of cave fills indicating repeated fillings of the cave and successive erosion of the sediments. Speleothems were deposited in different phases above clastic sediments (Fig. 159). The natural floor of the cave was modified for the construction of a railway during opening for tourists.

The second level is about 18 m below the upper one, where the modern underground Pivka river flows from its entrance. The river bed has a low gradient and, except for some collapses and sumps, there are no natural barriers. It leaves the system through a terminal sump. The active river passages are mostly smaller than the higher ones. The river bed is composed mostly of gravels derived from the Eocene flysch. The mean annual discharge of the river is 5.2 $m^3 \cdot s^{-1}$. The water level can rise 10 m during floods.

The cave is filled by several kinds of alluvial deposits characteristic of the internal cave facies, such as silts, sands, gravels, covered and/or intercalated by rich speleothems. The entrance cave facies consists of slope-derived debris mixed with the fluvial deposits. Pleistocene large mammal fauna such as hippopotamus, cave lion and cave bear, were found here (Rakovec 1954) as well as Palaeolithic stone tools from the last glacial (Brodar 1969).

In Postojnska jama we took samples from a total of nine profiles (Fig. 160) including three in Spodnji Tartarus, two in Umetni tunel, and one each in Male jame, Pisani rov, Stara jama and Biospeleološka postaja.

SPODNJI TARTARUS NORTH

Spodnji Tartarus passage connects the upper cave level to the lower active one. Its floor is in the lower part covered with young grey fluvial sediments and may be temporarily flooded. There is a small side passage, Rov koalicije, in the southern part of Spodnji Tartarus. It is about 50 m long, a 2 m wide and up to 17 m high canyon-like side passages developed in the thick-bedded Senonian rudist limestones dipping SW. Inclined and undulating notches on the walls show that it evolved under phreatic and paragenetic conditions. This passage was almost filled with sediments, leaving only a two m empty space below the flat paragenetic ceiling (Fig. 161). The sediments were later partly washed out, leaving a 13 m long pile of sediments remaining in the central part of the passage, terminated on the north and south ends by two large vertical profiles. We sampled sediments from both ends of the sediment fill.

PROFILE LOCATION

The Spodnji Tartarus North profile is at the entrance to Rov koalicje (45°47´23.16˝N; 14°12´09.72˝E, 526–533 m a.s.l.; Figs. 160 and 161). The profile was sampled in 2003, 2004 and 2005 to have enough samples for good statistical results.

LITHOLOGY

The profile consisted of two parts (Fig. 162). The lower part termed the red profile. The upper yellow part overlies it, with a distinct erosion surface between

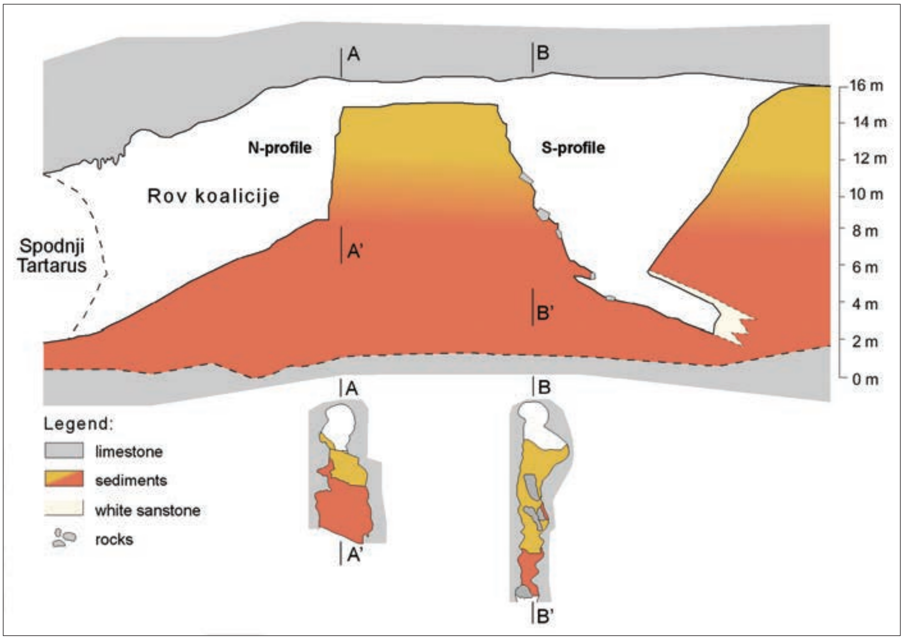

Figure 161 *Cross-section of the passage Rov koalicije with the location of the profiles Spodnji Tartarus North (A–A'), Spodnji Tartarus South (B–B') and white sandstone.*

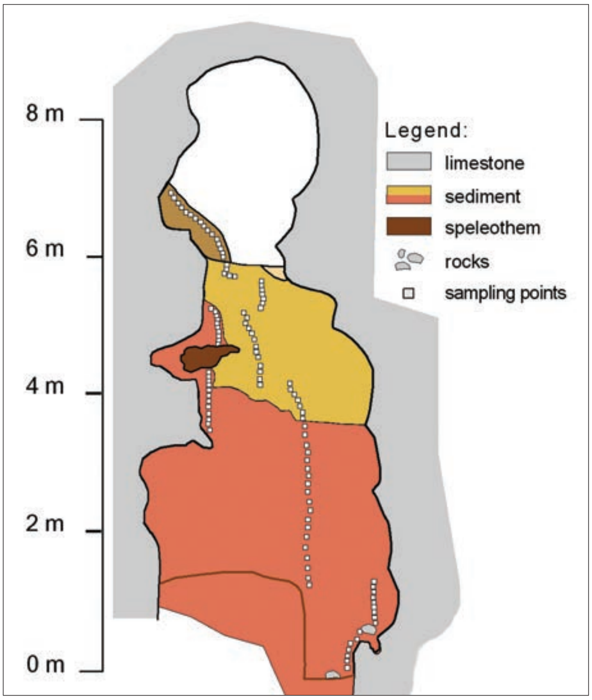

Figure162 *Sediment profile Spodnji Tartarus N with marked location of the samples.*

Figure 163 *Profile Spodnji Tartarus North. The lower part consists of red clays with some yellow laminae; the upper part consists of yellow clays and some sandy layers.*

them (Fig. 163). The base of the yellow profile is at 3.40 m above base on the left side and rises step-like to 3.85 m along the left side and up to 5.05 m at the left corridor wall. The lower part (Fig. 164) consisted of red to reddish brown clays overlying large limestone blocks (collapse). The limestone debris were covered by thin black manganese coatings over weathered limestone

Figure 164 *The yellow laminas between red clays in the bottom of the profile Spodnji Tartarus North.*

Figure 165 *The upper brown part of the profile Spodnji Tartarus North.*

surfaces (pulverized, bleached). The clays were silty, commonly laminated, yellowish in colour indicating a sandy admixture (at the base, in the middle and close to the top), sandy bands contained small clasts formed of clay, some horizons had brecciated texture, small erosional features at layer boundaries were commonly developed and locally associated with slight ferruginization. Clasts of corroded limestones (up to 2 cm) occurred close to the top.

The upper part of the profile (Fig. 165) was of yellowish brown and light brown laminated and banded clays. Flat clasts derived from the red lower part marked the erosional base. Some laminae and bands were reddish brown and composed of sets of thinner laminae.

MINERALOGY

Six samples were taken for X-ray diffraction analyses. Yellow clay in the bottom of the profile (between limestone blocks) consisted predominantly of quartz, with some muscovite, chlorite, kaolinite and montmorillonite. Quartz prevailed in the overlying red clay with yellow laminae and chlorite, kaolinite, muscovite and chlorite/muscovite were also detected. Red clay at the erosion base contained quartz, muscovite, chlorite and some feldspar. Yellow clay (upper part of the profile) above the erosion base consisted of quartz, calcite, chlorite, muscovite, feldspar, montmorillonite and kaolinite. Yellow clay at the top of the profile (at palaeomagnetic sample 155) was composed mainly of quartz with some chlorite, muscovite montmorillonite and kaolinite. Brown clay on the top of the profile contained quartz, muscovite, chlorite and feldspar with some montmorillonite and kaolinite. All samples indicate that the origin of the minerals was the Eocene flysch rocks of Pivka basin, weathered to different degrees.

PALAEOMAGNETIC RESULTS

Red profile

All 101 samples from the red part of the Spodnji Tartarus North profile were studied for their palaeomagnetic properties. They are characterized by NRM intensities between 7 and 398 $mA.m^{-1}$ and MS values from 228 to 3,180 x 10^{-6} SI units. The mean values J_n and k_n moduli are documented in Table 38. Applying both sets of values, the profile may be divided into three parts and categories. Samples are characterized by low up to high J_n and k_n magnetic values.

Multi-component analysis was applied to separate respective RM components after detailed AF demagnetization of each sample. Three components

Table 38 Mean palaeomagnetic values and standard deviations, Spodnji Tartarus North, red

Spodnji Tartarus North red	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	37.104	439.2	4.835–3.895
Standard deviation	15.326	99.6	
Number of samples	26	26	
Mean value	34.875	731.1	3.85–2.47
Standard deviation	19.399	325.6	
Number of samples	24	24	
Mean value	141.814	1,935.0	2.35–0.03
Standard deviation	83.794	639.6	
Number of samples	51	51	

* from top to base

were isolated: the *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (2 up to 5 mT). The *B-LFC* is also secondary; it shows harder magnetic properties and can be demagnetized in the AF (5–10 up to 15 mT). The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF (ca 15–80 up to 100 mT).

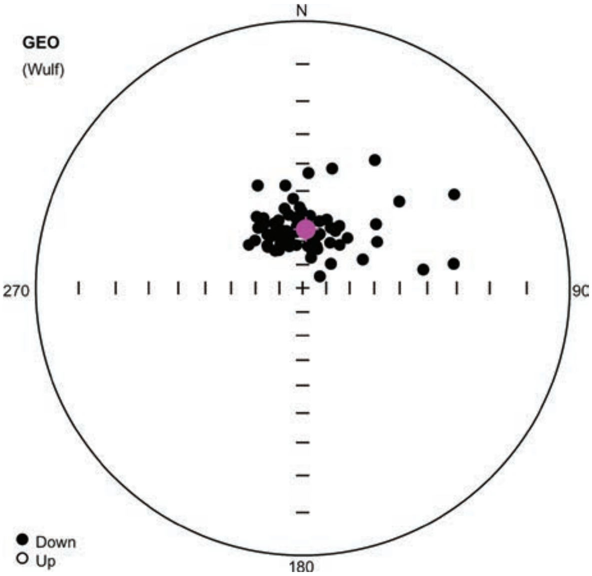

Figure 166 *Directions of C-components of remanence of samples with N polarity, Spodnji Tartarus North, red part of the profile. For detail description see Figure 34.*

Table 39 Mean palaeomagnetic directions, Spodnji Tartarus North, red

Spodnji Tartarus North red	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	3.11	65.17	3.52	20.55	77

The stereographic projection of the C-component with N polarity is shown in Figure 166. Table 39 summarises results of mean direction of samples. The mean palaeomagnetic directions of C-components for the N polarity are D = 3°, I = 65°. Systematic acquisition of palaeomagnetic data within the studied section allowed the construction of a detailed magnetostratigraphic profile (Fig. 167). The profile showed a N palaeomagnetic direction.

Yellow profile

A total of 88 samples were studied for their palaeomagnetic properties from the yellow portion of the Spodnji Tartarus North profile. The sediments are characterized by NRM intensities between 1 and 63 mA.m^{-1} and MS values from 89 to 551 x 10^{-6} SI units. The mean values of J_n and k_n moduli are documented in Table 40. From both sets of values, the profile may be divided into two parts and categories. Samples are characterized by low up to intermediate J_n and k_n magnetic values.

Multi-component analysis was applied to separate the respective RM components after detailed AF demagnetization of each sample. Three components were isolated: the *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (2 up to 5 mT). The *B-LFC* is also secondary and can be demagnetized in the AF (5–10 up to 15 mT). The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF (ca 15–80 up to 100 mT).

The stereographic projections of the C-component with N and R polarities are shown on Figures

Table 40 Mean palaeomagnetic values and standard deviations, Spodnji Tartarus North, yellow

Spodnji Tartarus North yellow	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	21.949	265.6	7.445–4.465
Standard deviation	11.919	67,1	
Number of samples	70	70	
Mean value	2.894	108.3	4.415–3.05
Standard deviation	1.536	11.1	
Number of samples	18	18	

* from top to base

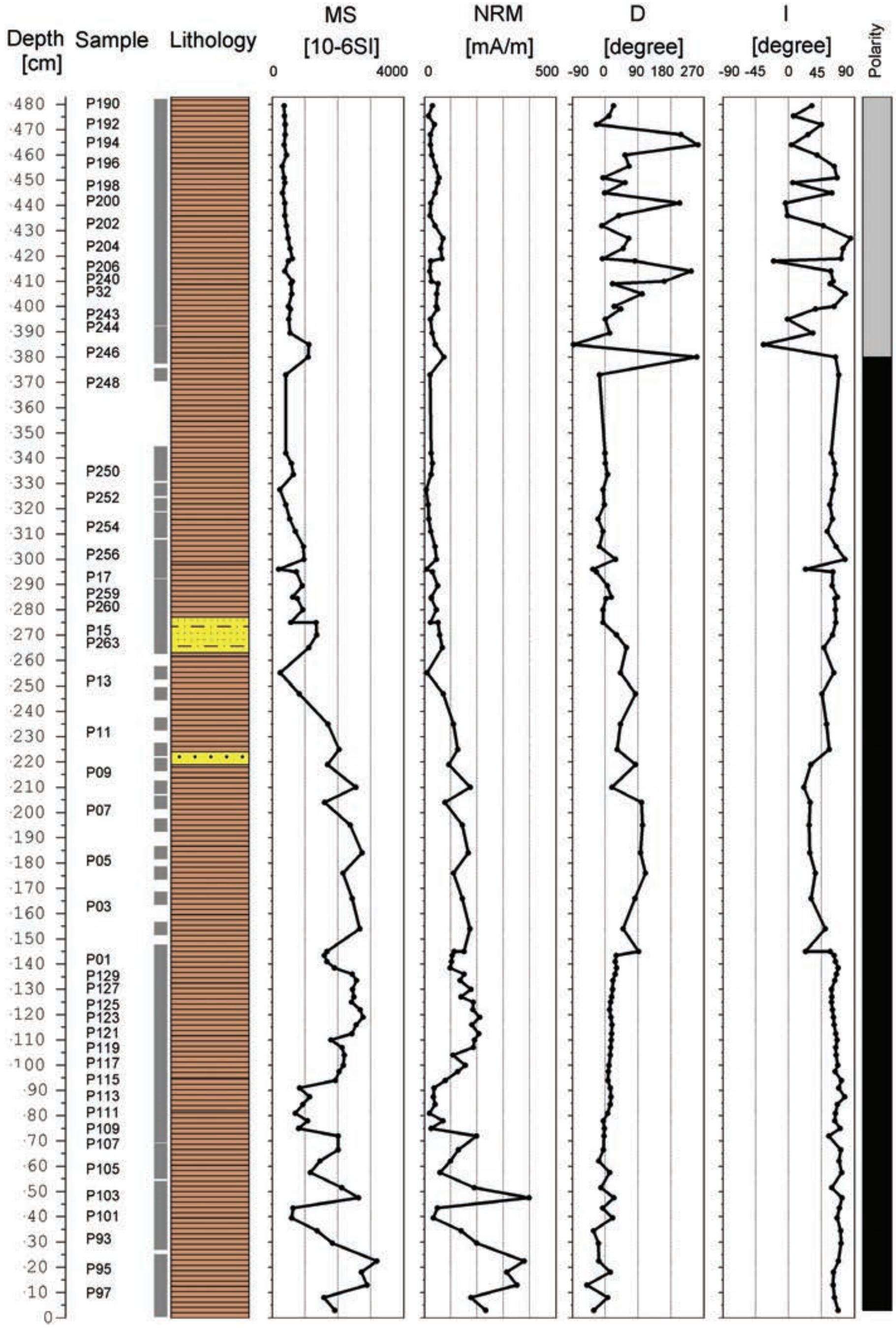

Figure 167 *Basic magnetic and palaeomagnetic properties, Spodnji Tartarus North, red part of the profile. Legend: see Figure 37.*

Table 41: Mean palaeomagnetic directions, Spodnji Tartarus North, yellow

Spodnji Tartarus North yellow	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	355.18	63.05	4.35	16.41	63
	R	190.13	-52.25	14.23	24.19	

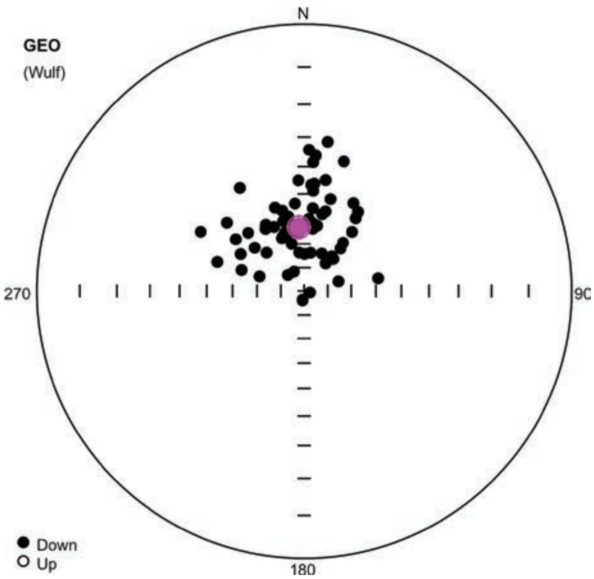

Figure 168 *Directions of C-components of remanence of samples with N polarity, Spodnji Tartarus North, yellow part of the profile. For detail description see Figure 34.*

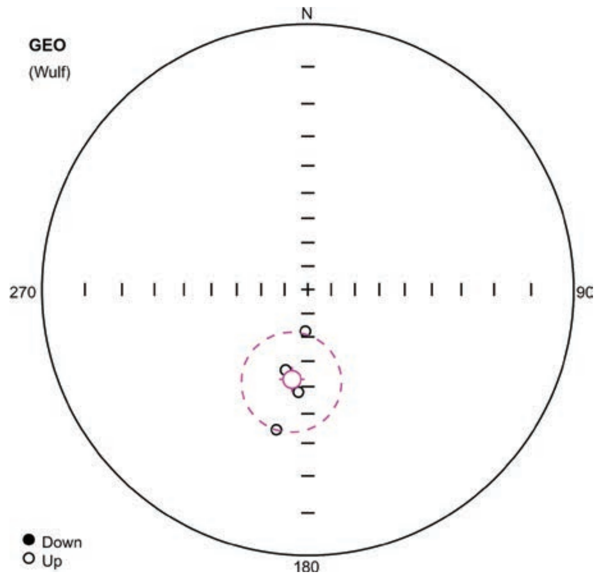

Figure 169 *Directions of C-components of remanence of samples with R polarity, Spodnji Tartarus North, yellow part of the profile. For detail description see Figure 34.*

Table 42: Th/U dating results using α-spectrometry, Spodnji Tartarus North

Sample	Lab. No.	U content [ppm]	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$
Tartarus 3/2	W 1624	0.0638±0.0040	1.0419±0.0886	0.1611±0.0259	*2.8±0.8*
Tartarus 3/1	W 1637	0.0862±0.0044	1.0339±0.0691	0.0943±0.0157	*12±8*

168 and 169. Table 41 summarizes results of the mean direction of samples from this profile. The mean palaeomagnetic directions of C-components for the N polarity are D = 355°, I = 63° and for reverse polarity are D = 190°, I = -52°. Systematic acquisition of palaeomagnetic data within the studied section allowed the construction of a detailed magnetostratigraphic profile (Fig. 170). The yellow profile showed N palaeomagnetic direction and two narrow R zones including a few transient zones.

TH/U DATING

One sample was taken for radiometric dating (Warsaw, Poland). It was a small stalagmite on an inclined surface below the profile (sample No. 3). Unfortunately the analyzed portion contained high proportion of detrital admixture (Tab. 42).

DISCUSSION OF RESULTS

The petromagnetic results from the upper part (4.5 to 7.8 m) of the yellow profile, show changed RM and MS values when compared with both values of lower part of the profile. Palaeomagnetic results from the yellow profile also show two short R polarized excursions in the middle of the section. The upper part (3.85 to 4.84 m) of the red profile has no defined polarity because of the coarse magnetic grains there. Palaeomagnetic results from the rest of the red profile show a N polarization only. Thus far we may assume that deposition of the entire northern profile occurred within the Brunhes chron (< 780 Ka). For mode details see discussion in the Spodnji Tartarus South subchapter.

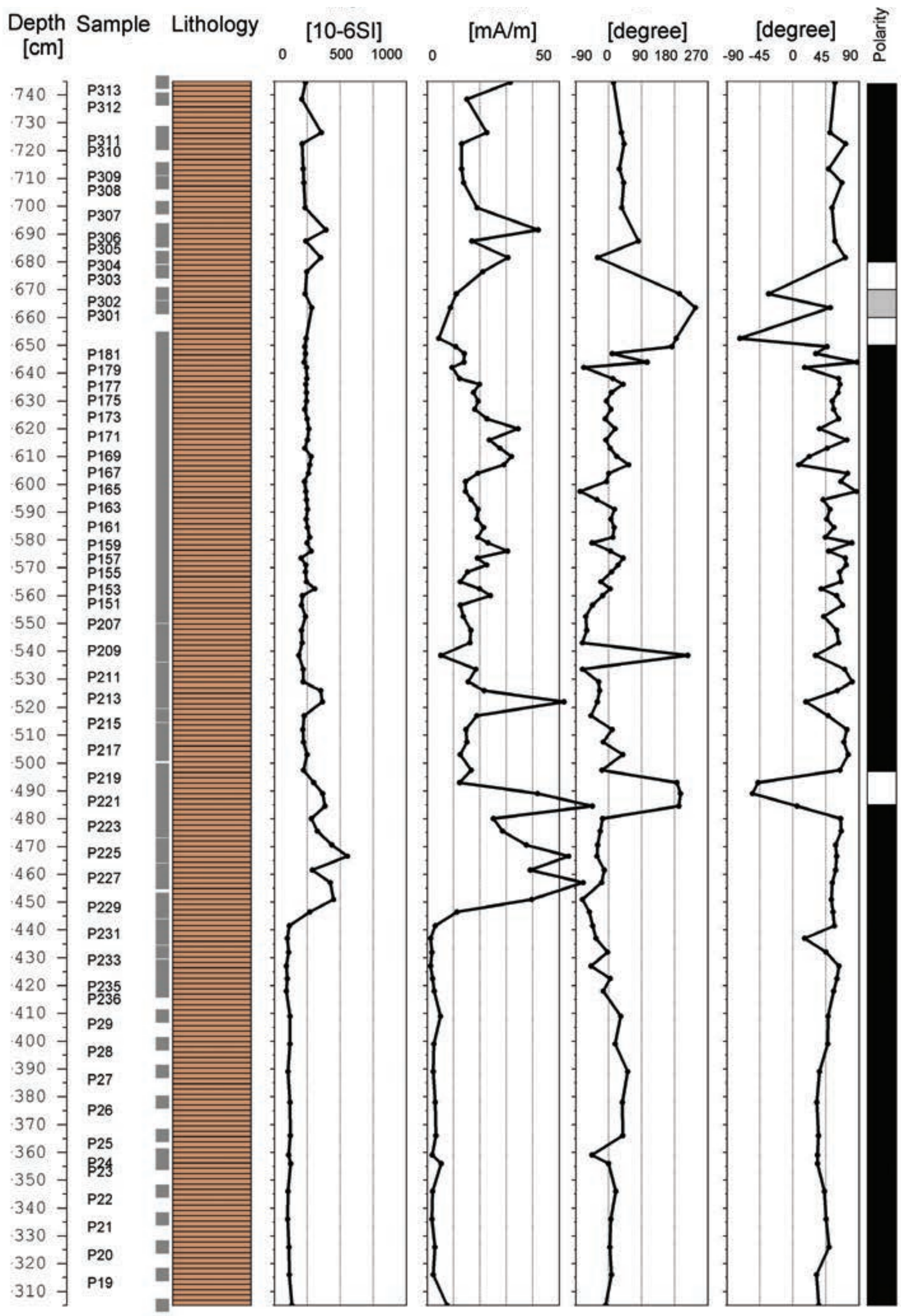

Figure 170 *Basic magnetic and palaeomagnetic properties, Spodnji Tartarus North, yellow part of the profile. Legend: see Figure 37.*

SPODNJI TARTARUS SOUTH

PROFILE LOCATION

The Spodnji Tartarus South profile is located in Rov koalicije about 13 meters to the south of the northern profile (profile 45°47´22.58˝N; 14°12´10.19˝E; 522–534 m a.s.l.; Figs. 160 and 161).

LITHOLOGY

The profile limited the sedimentary choke of Spodnji Tartarus from the south. The profile started on blocky scree and continued with about 10 m of clays and silty clays (Figs. 171 and 172). Colour in the lower part was rather reddish brown (Fig. 173), sometimes with yellowish schlieren, laminae and bands. The upper part was dominantly yellow or yellowish brown. The distinct, but not sharply erosional, boundary associated

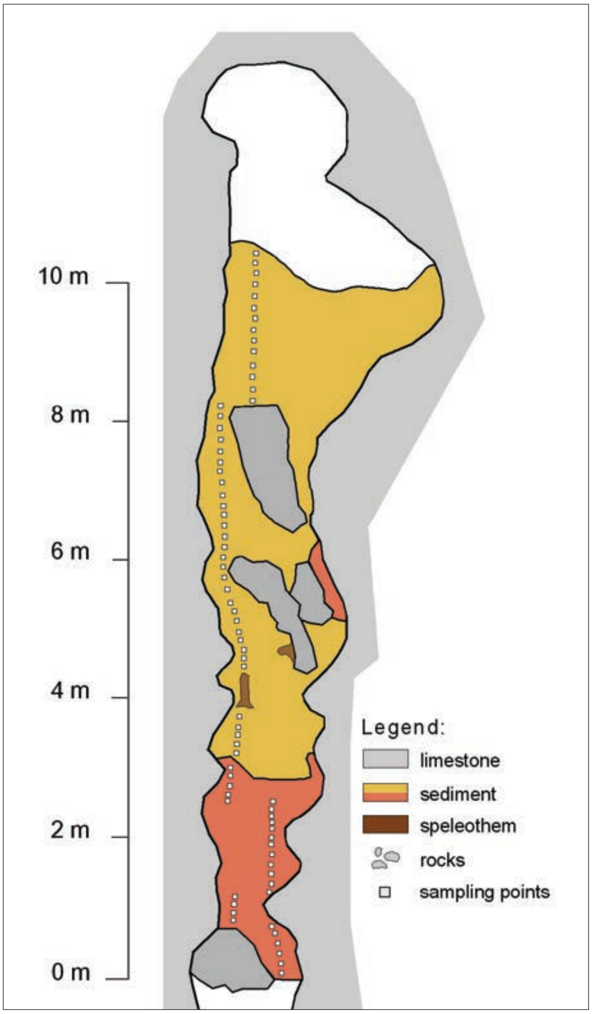

Figure 171 *Sketch of the profile Spodnji Tartarus South.*

Figure 172 *The profile Spodnji Tartarus South.*

Figure 173 *Detail from sampling of red clays, Spodnji Tartarus South.*

with the colour change was at about 2.40 m above the lowest sample. Collapsed blocks were included also within the profile, some with small stalagmites in rotated positions. The profile was covered by thin calcite crusts, sometimes with candlestick stalagmites up to about 20 cm high. Numerous traces of cave bear (*Ursus spelaeus*) were discovered at the top of sediments (Fig. 174) and on the passage walls.

PALAEOMAGNETIC RESULTS

A total of 176 samples from the Spodnji Tartarus South profile were analysed for their palaeomagnetic properties. They are characterized by NRM intensities between 0.6 and 211 mA.m^{-1} and MS values from 80 to 2,610 x 10^{-6} SI units. The mean values of J_n and k_n moduli are documented in Table 43. From both sets of values, the profile may be divided into four parts and

Figure 174 *Scratches made by extinct cave bear claws (between ladder and metre) on profile wall, Spodnji Tartarus South.*

categories. The samples are characterized by very low up to high J_n and k_n magnetic values.

Table 43 Mean palaeomagnetic values and standard deviations, Spodnji Tartarus South

Spodnji Tartarus South	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m] *
Mean value	55.114	459.3	9.41–9.11
Standard deviation	20.448	193.4	
Number of samples	7	7	
Mean value	3.733	105.0	9.06–6.26
Standard deviation	2.564	25.7	
Number of samples	57	57	
Mean value	83.429	1,346.4	6.21–5.55
Standard deviation	54.789	856.6	
Number of samples	14	14	
Mean value	28.654	678.5	5.49–0.02
Standard deviation	25.567	394.4	
Number of samples	101	101	

* from top to base

All samples were subjected to detailed AF demagnetization in 14 steps. Multi-component analysis was applied to separate the respective RM components of each sample. Three components were isolated after the AF demagnetization. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–2 up to 5 mT). The *B-LFC* is also secondary; they show harder magnetic properties and can be demagnetized in the AF (5–10 up to 15 mT). The characteris-

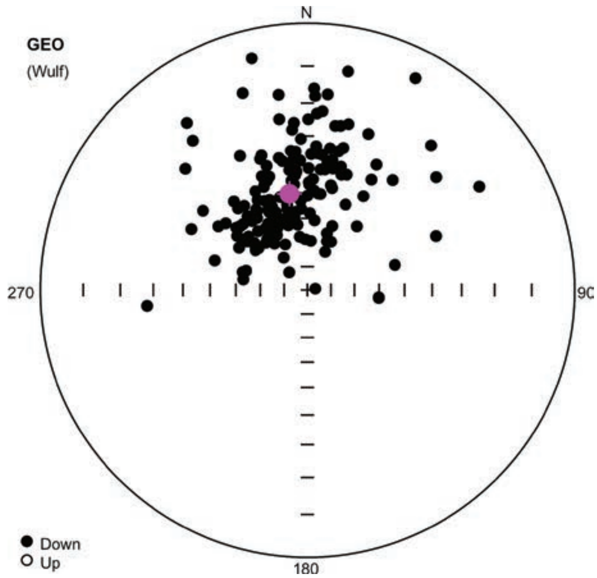

Figure 175 *Directions of C-components of remanence of samples with N polarity, Spodnji Tartarus South. For detail description see Figure 34.*

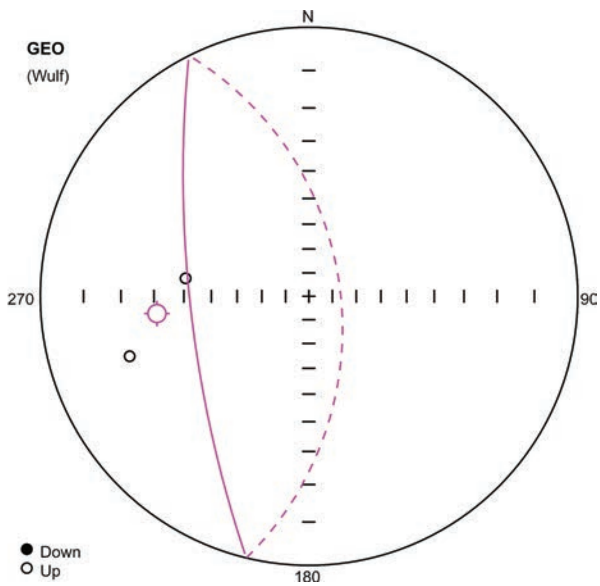

Figure 176 *Directions of C-components of remanence of samples with R polarity, Spodnji Tartarus South. For detail description see Figure 34.*

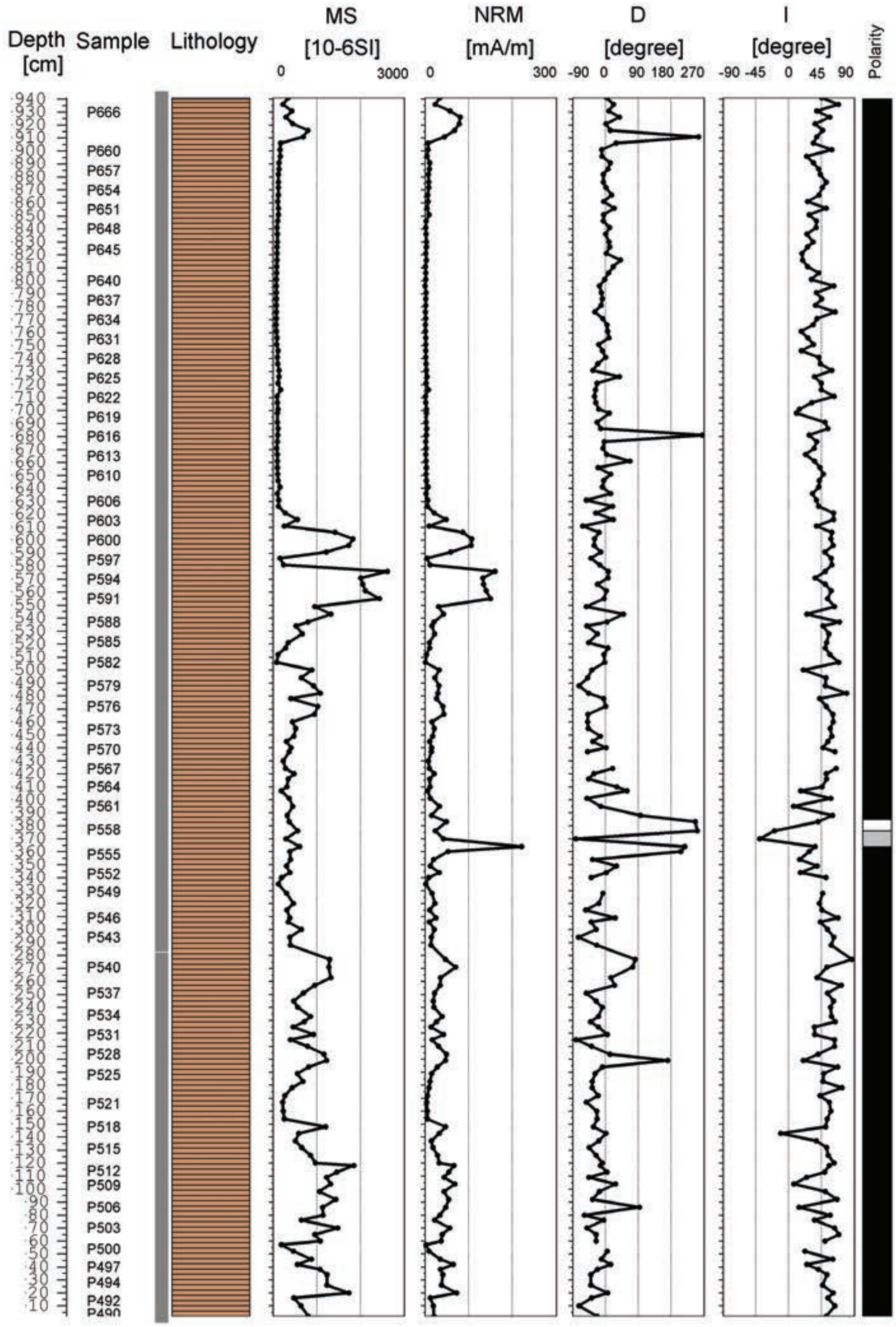

Figure 177 *Basic magnetic and palaeomagnetic properties, Spodnji Tartarus South. Legend: see Figure 37.*

tic *C-HFC* is stable. It can be demagnetized or isolated in the AF (ca 15–80 up to 100 mT).

The stereographic projections of the C-component with N and R polarity are shown on Figures 175 and 176. Table 44 summarises results of the mean direction of samples from this profile. The mean palaeomagnetic directions of C-components for the N polarity are D = 349°, I = 50° and for reverse polarity are D = 263°, I = -31° (two samples only). Systematic acquisition of palaeomagnetic data within the studied section allowed the construction of a detailed magnetostratigraphic profile (Fig. 177). The profile showed a N palaeomagnetic direction, one narrow R zone and a few transient zones.

TH/U DATING

Four samples of speleothems were taken from the profile: No. 1, a stalagmite about 25 cm high with thin calcite crust at the base (with base at about 344 cm above

Table 44 Mean palaeomagnetic directions, Spodnji Tartarus South

Spodnji Tartarus South	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	349.34	49.72	3.2	11.49	167
	R	263.48	-30.63	-	-	2

Figure 178 *Stalagmite in the profile with base at about 344 cm, Spodnji Tartarus South.*

Figure 179 *Small stalagmite on rotated collapse block was dated by Th/U method, Spodnji Tartarus South.*

the base of profile; Fig. 178); No. 2, a small stalagmite on a rotated, collapsed limestone block (Fig. 179), Nos. 4 and 5, thin calcite crusts covering the profile. Results of Th/U analyses are in Table 45. Unfortunately, except for two analyses, the samples contained too high a proportion of detrital admixture (detrital Th, see low ^{230}Th/^{232}Th ratio). The crust covering the eroded sediments is 143 +26/-22 ka old and the rotated stalagmite on a limestone block is 108 +19/-22 ka old.

Table 45 Th/U dating results using α-spectrometry, Spodnji Tartarus South

Sample	Lab. No.	U content [ppm]	^{234}U/^{238}U	^{230}Th/^{234}U	^{230}Th/^{232}Th	Age [ka]
Tartarus 5	W 1639	0.0249±0.0020	0.9732±0.1045	0.4016±0.0587	*1±0.2*	
Tartarus 4	W 1638	0.0489±0.0032	1.0552±0.0934	0.7397±0.0701	*>1000*	+ 26 143 - 22
Tartarus 2/2	W 1623	0.2988±0.0094	1.2166±0.0461	0.9452±0.0345	*2,9±0.2*	
Tartarus 2/1	W 1636	0.0486±0.0031	0.9054±0.0825	0.6219±0.0664	25±12	+ 19 108 - 17
Tartarus 1/2	W 1625	0.0523±0.0030	0.8276±0.0670	0.4304±0.0472	*3.4±0.7*	
Tartarus 1/1	W 1635	0.0367±0.0028	0.7570±0.0838	0.5312±0.0764	*4.5±1.2*	

DISCUSSION OF RESULTS

The palaeomagnetic results from the Spodnji Tartarus South profile show a short R polarized excursion in the middle part of the section. To date we assume that deposition was within the Brunhes chron (<780 Ka), as in the northern profile. Detailed correlation between the two Spodnji Tartarus profiles is not easy because the erosional boundary between red and yellow parts of the profile is not distinct in the southern section. In addition, the correlation of the short reversals that were found is not simple and will need further detailed study and interpretation based on palaeomagnetic parameters.

The profile was eroded at some time before 143 +26/-22 ka, as the Th/U-dated calcite crust covering the already eroded profile. The relation of the profile to the collapsed limestone block on the right side of the profile is not completely clear. Collapse occurred before 127–91 ka as indicated by age of the rotated small stalagmite on one of the blocks. Most probably, collapse occurred only after the part of sedimentary profile was eroded away. Distinct and perfectly preserved scratches of *Ursus spelaeus* on the profile (top and incline) indicates that, since the time when the cave bear was "climbing" it, there have been no substantial changes in the morphology of the profile.

Figure 180 *White sandstone fills the upper part of the passage; termination of passage Rov Koalicije in Spodnji Tartarus.*

SPODNJI TARTARUS, "WHITE SANDSTONE"

PROFILE LOCATION

White sandstone is preserved at the bottom part of the sediment fill of Rov koalicje at about 520 m a.s.l. (Figs. 160 and 161).

LITHOLOGY

The profile was situated below the level of the profile Spodnji Tartarus South and farther to the southwest. It was represented by cemented crusts with the appearance of "white sandstone" and a thickness more than 2 m. The fill was later eroded into an arch-like structure within the passage and was present also on the ceiling and the walls at the bottom part of the passage (Fig. 180).

MINERALOGY

The X- ray diffraction analyse indicated that the white 'sandstone' consisted predominantly of calcite. There is also some quartz with muscovite and chlorite in traces. This type of clastic sediment was not found in any other part of the Postojna cave system. It has to be very old sediment with calcite particles probably originating from incomplete weathering of cave walls, brought and deposited here by flowing water. Quartz grains may origin from Eocene Flysch or from cherts in the Cenomanian limestones.

PALAEOMAGNETIC RESULTS

From the top of the profile eight solid rock samples were taken as pilot samples and cut up into 22 laboratory specimens for TD demagnetization. The specimens are currently subject to laboratory analyses.

DISCUSSION OF RESULTS

The fill represent, without any doubt, the oldest fill in Spodnji Tartarus. Its nature can be identified only by future and more detailed research.

UMETNI TUNEL I

PROFILE LOCATION

Approximately in the middle of the artificial tunnel between Postojnska jama and Črna jama another passage filled by fluvial sediments is intercepted (45°47´51.20˝N; 14°12´21.22˝E; 520 m a.s.l.; Fig. 160). The passage is formed in limestone with cherts, beds dip towards north-west along a cross-Dinaric fault, which was active also after the fill was deposited (Gospodarič 1964; Sasowsky, Šebela & Harbert 2002). The profile was sampled twice, in 2003 and 2007.

LITHOLOGY

The fill of the old conduit was exposed by the tunnel in several profiles, all composed dominantly of sands. The bedding was not entirely horizontal, sometimes being slightly inclined, in other profiles gently arched. Sediments in one of the profiles were disturbed by undulating slickenslides with lustrous surfaces and striations (first mentioned by Gospodarič 1964).

The profile Umetni tunnel I was 130 cm high and terminated by the limestone ceiling (Figs. 181 and 182). The lower part terminated on the excavated bottom of the tunnel. From the top, the sequence was composed of: clay, yellowish brown, sometimes reddish, with thin laminae with sandy admixture to laminated sand (9 cm); sand, dominantly medium-grained, with a coarse-grained admixture, with slightly clayey matrix, slightly arcosic, indistinctly laminated, with oriented elongated mineral grains (11 cm); weathered surface of clays enriched in Fe+Mn compounds (ferricrete; 1 cm); clay, locally silty, yellowish brown, finely sandy in laminae and bands, at the top distinctly sandy with cross-bedding (20 cm), sand, medium to coarse-grained, grey, slightly with clayey matrix, with flat clasts of clays making cross-bedding more distinct (17 cm), and alternation of fine- to medium- and medium- to coarse-grained sands in bands, grey, laminated, slightly arcosic, cross-bedded, locally with chaotic texture (72 cm).

MINERALOGY

X- ray diffraction analysis indicated that the sediment consisted predominantly of quartz; there were also chlorite, muscovite and feldspar.

PALAEOMAGNETIC RESULTS

The profile was already studied by Šebela & Sasowsky (1999) and Sasowsky, Šebela & Harbert (2003), for paleomagnetic analyses but their sampling was widely spaced and the results showed distinct scatter. The profile was sampled by us to compare with the results from our other sampled profiles from Postojnska jama. In 2003 palaeomagnetic and magnetostratigraphic investigations were carried out on 14 samples. Values of the NRM (J_n) and MS (k_n) moduli in their natural state show small scatter. The mean values of J_n and k_n moduli are documented in Table 46. The sediments are characterized by a NRM intensity from 1.1 to 15 mA.m^{-1} and the MS values from 154 to 734 x 10^{-6} SI units. From both sets of values, the profile may

Figure 181 *Photo of the profile Umetni tunel I; sampling in 2007.*

Figure182 *Detail of sedimentary structures in the upper part of the profile Umetni tunel I; sampling in 2007.*

be divided into two parts and categories. Samples are characterized by low up to intermediate J_n and k_n magnetic values.

Table 46 Mean palaeomagnetic values and standard deviations, Umetni tunel I

Umetni tunel I	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	1.830	191.2	0.04–0.34
Standard deviation	0.614	40.5	
Number of samples	8	8	
Mean value	5.966	397.3	0.35–0.40
Standard deviation	4.609	175.5	
Number of samples	5	5	

* from top to base

The RM directions inferred by the above procedures were tested using a multi-component analysis. *A-components* of remanence are mostly of viscous origin and can be demagnetized in an AF of 5 to 10 mT. The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF (ca 10–80 to 100 mT).

The stereographic projection of the C-component with N and R polarity is shown on Figures 183 and 184. Table 47 summarizes results of the mean direction of samples from this profile. Mean palaeomagnetic directions of C-components for the N polarity are D = 288° and I = 50° and for R polarity are D = 166° and I = -56°. Systematic acquisition of palaeomagnetic data within the studied section allowed the construction of a detailed magnetostratigraphic profile (Fig. 185). The profile showed an R direction – Matuyama chron. There is also a shorter N polarized zone in the long R one.

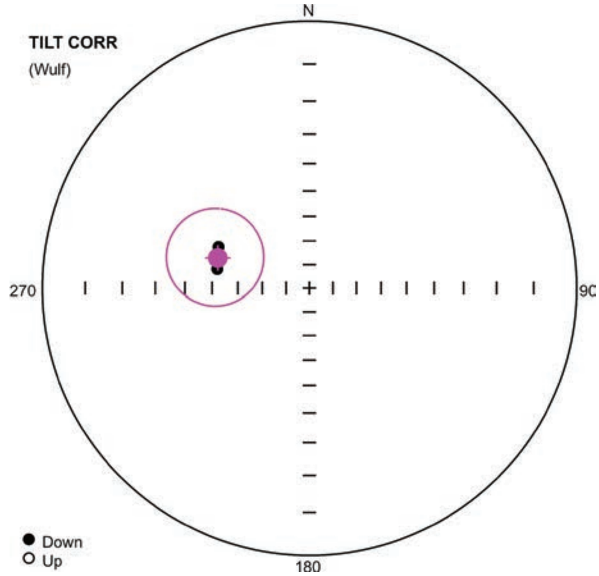

Figure 183 *Directions of C-components of remanence of samples with N polarity, Umetni tunel I. For detail description see Figure 34.*

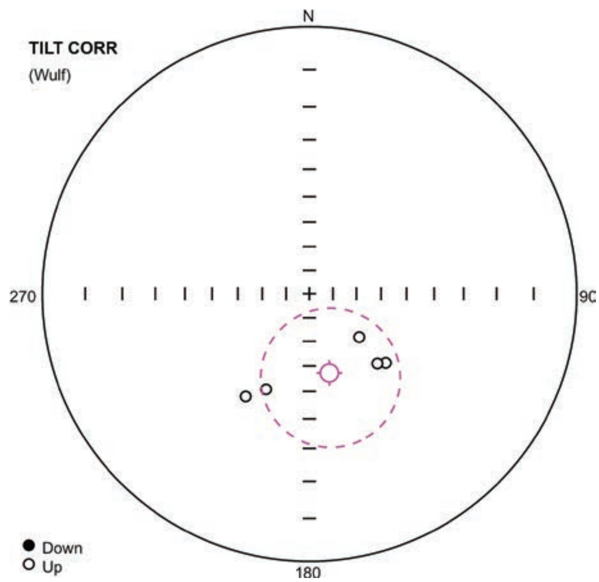

Figure 184 *Directions of C-components of remanence of samples with R polarity, Umetni tunel I. For detail description see Figure 34.*

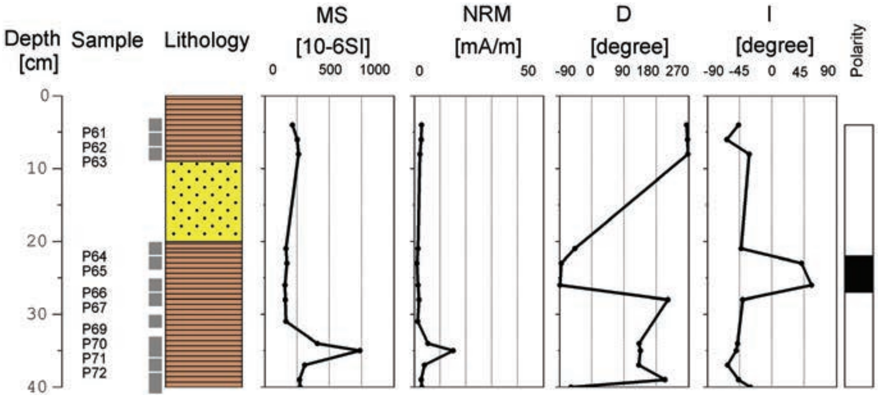

Figure 185 *Basic magnetic and palaeomagnetic properties, Umetni tunel I. Legend: see Figure 37.*

Table 47 Mean palaeomagnetic directions, Umetni tunel I

Umetni tunel I	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	288.14	50.32	-	-	2
	R	165.86	-56.22	20.7	9.15	5

DISCUSSION OF RESULTS

The sequence (130 cm) of fine- to medium-grained sands, sometimes with clayey matrix and flat clasts of clays and distinct cross-bedding, are overlain by clays and sands. At 21 cm from the top, a plane of unconformity is clearly marked by a surface enriched in Fe- and Mn-rich compounds. Sediments are disturbed by slickenslides. Our data showed R magnetic polarity with a short N polarized magnetozone at the top of clay below the stained surface. This N polarized magnetozone was not detected by Šebela & Sasowsky (1999) and Sasowsky, Šebela & Harbert (2003) due to their lesser number of samples. Sasowsky, Šebela & Harbert (2003) interpreted the age of profile from 0.99 to 0.78 Ma (top of the Matuyama chron). The declination values of the normal vectors (in the A-component) represent a counter-clockwise rotation of about 23.5°. The average declination in the B-component is of about 180°. This value represents two different groups (two and two samples from the same level only) with declinations of about 201° and 138°. Based on four samples of the reverse polarity group, the calculated value of α_{95} is very high. These values indicate clockwise rotation of 19° and counter-clockwise rotation of 43°. Nevertheless, according to magnitudes they concluded that these variations represent palaeo-secular variation rather than significant rotation. Sasowsky, Šebela & Harbert (2003) calculated palaeo-rotations, but the distribution of directions from only several samples cannot be used for Fisher statistics (1953).

Our high-resolution magnetostratigraphy in the fine-grained deposits indicated a N polarized zone within the R polarized. This fact may shift the age of sediments studied below the expected limit of 0.99 Ma. The N polarized zone could represent the Jaramillo subchron (0.99–1.07 Ma) as well as other N polarized subchrons within the Matuyama (e.g., Reunion dated to 2.14 to 2.15 Ma) or older chrons. To obtain better results (lower value of α_{95}) in 2007 we sampled the profile again (45 new samples) and the specimens are currently undergoing laboratory analyses.

UMETNI TUNEL II

PROFILE LOCATION

Profile Umetni tunel II is near the entrance from Postojnska jama (45°47´47.82˝N; 14°12´24. 79˝E; 521 m a.s.l.; Fig. 160). The host Cenomanian limestones contain cherts. The bedding is almost horizontal. The profile was originally presented by Zupan (1990).

LITHOLOGY

The section was composed of yellowish brown clays, laminated to banded, locally with finely sandy laminae, with yellowish brown fine- to medium-grained sands at the base containing varied proportions of clayey matrix (Figs. 186 and 187). In the central part of the section, cross-bedding (205/33°) with lenticu-

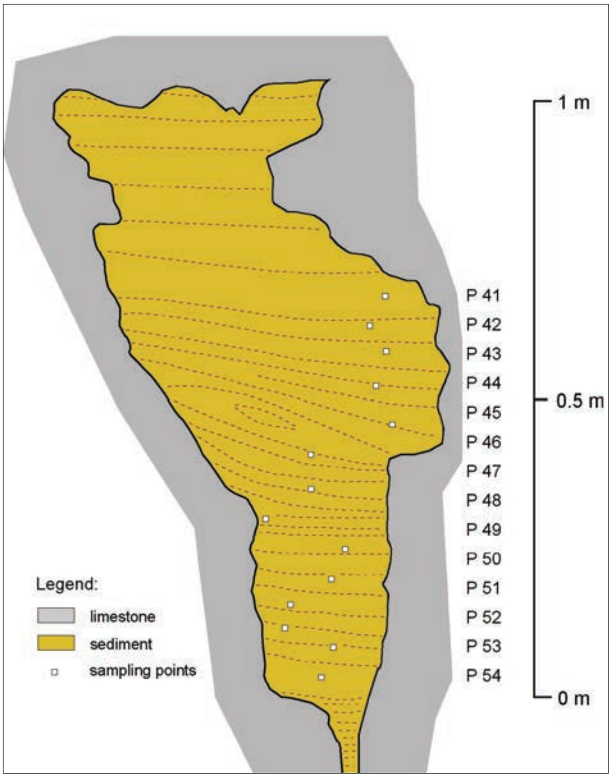

Figure 186 *Drawing of the profile Umetni tunel II with marked locations of the samples.*

Figure 187 *Filled passage with yellow fluvial sediments - profile Umetni tunel II.*

lar and continuous sandy laminae and bands could be observed. The upper part consisted of homogeneous clays, silty light yellowish brown in colour with an indistinct erosional base. The top was composed of light yellowish brown clays, laminated to banded with fine-grained sandy admixture.

MINERALOGY

Samples of the yellow sand and loam profile consisted mainly of quartz (85 %), some calcite, muscovite, and microcline. Chlorite, kaolinite, plagioclase and goethite were present in traces (Zupan Hajna 1998).

PALAEOMAGNETIC RESULTS

We took 14 samples in the profile for their palaeomagnetic properties. The sediments are characterized by the low scatter of NRM intensities (0.2–1 mA.m-1) and MS values (50–112 x 10-6 SI units). Mean values of J_n and kn moduli are documented in Table 48. Samples are characterized by very low J_n and of k_n magnetic values.

Table 48 Mean palaeomagnetic values and standard deviations, Umetni tunel II

Umetni tunel II	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m]*
Mean value	0.540	90.1	0.54–0.04
Standard deviation	0.220	17.3	
Number of samples	14	14	

* from top to base

All 14 samples were subjected to detailed AF demagnetization in 14 steps. Multi-component analysis was applied to separate the respective RM component for each sample. Two components were isolated after the AF (14 samples) demagnetization. The *A-component* is undoubtedly of viscous origin and can be demagnetized in an AF field of 0–2 to 5 mT. The characteristic *C-HFC* is not stable and it cannot be isolated in the AF.

DISCUSSION OF RESULTS

The samples we studied are not suitable for palaeomagnetic investigation. The characteristic component is not stable and cannot be isolated in the AF.

BIOSPELEOLOŠKA POSTAJA

PROFILE LOCATION

The profile (45°46´56.97˝N; 14°12´16.80˝E; 530 m a.s.l.; Fig. 160) is situated at the entrance to the Rov novih podpisov (Passage of New Signatures), where the speleobiological laboratory was originally situated. This part of the cave is now known as Biospeleološka postaja (the Speleobiological Station). The passage represents one of the old entrances to the cave. It is developed in the thick-bedded Upper Senonian limestones with dips towards south-west.

The passage is now without any hydrological function. Two profiles with an approximately 7 m thick sequence of sediments were cut during the adaptation of the gallery for tourists. One is situated in the railway tunnel and the other is exposed along the tourist path to inner part of the passage.

There are three types of sediment in the passage (Figure 188). The bottom of exposed profile is composed of silts, sands and gravels with clastic components derived from flysch source rocks. Above them, gravels composed of angular clasts of flowstones and limestones are deposited. Limestone clasts form the upper part of this layer. Palaeolithic tools (Mousterian, about 40 ka old) were found there (Brodar 1969). Reddish loam covered with flowstone terminated the profile.

LITHOLOGY

The top of profile is covered by flowstone with stalagmites. It is underlain by a sequence of clays (about 65 cm), reddish dark brown, laminated, in places with columnar disintegration, and one interbed of flowstone (Fig. 189). The lower part consists of a complicated sequence of scree (about 140 cm). At the top it contained some clayey matrix, in the lower part a layer with carbonate cement. Individual scree layers differ in grain-size of the limestone clasts. Clasts were most-

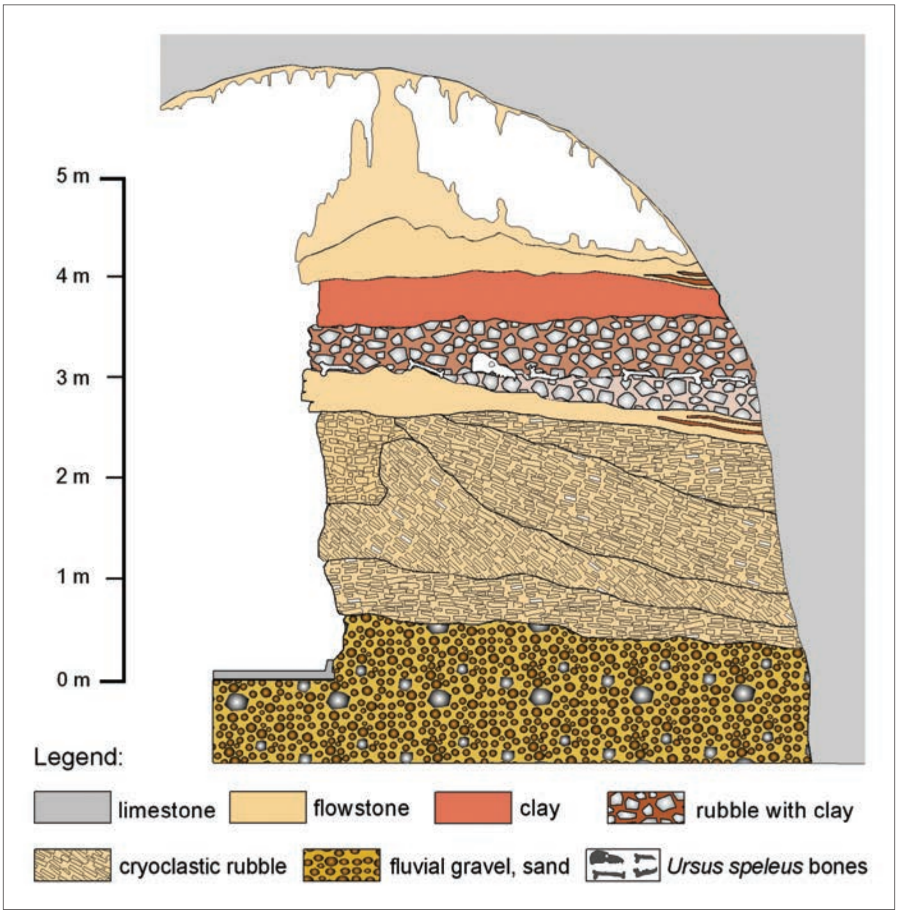

Figure 188 *Schematic cross-section of the sediment profile at the entrance part in Biospeleološka postaja.*

Figure 189 *The red clay from upper part of the profile in Biospeleološka postaja was sampled for paleomagnetic analyses – to prove the method.*

ly angular, rounded limestone pebbles being present only in the middle part. The layer boundaries were often sharp. There was a thin layer of reddish dark brown clay in the middle of scree sequence.

PALAEOMAGNETIC RESULTS

A total of 15 samples were studied for their palaeomagnetic properties. They were subjected to detailed AF demagnetization in 14 steps. The mean values of the J_n and k_n moduli are documented in Table 49. From both sets of values, the profile may be divided into two

Table 49 Mean palaeomagnetic values and standard deviations, Biospeleološka postaja

Biospeleološka postaja	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m]*
Mean value	128.000	2,772.3	Upper part 0.31–0.64
Standard deviation	15.857	316.8	
Number of samples	11	11	
Mean value	100.500	2,820.9	Lower part 0.955–1.04
Standard deviation	4.509	149.5	
Number of samples	4	4	

* from top to base

parts and categories. Sediments are characterized by a large scatter of NRM intensities (97–158 mA.m^{-1}) and the MS values (1,960–2,720 x 10^{-6} SI units). Samples are characterized by intermediate up to high J_n and k_n magnetic values.

Multi-component analysis was applied to separate the respective RM component for each sample. The *A-component* is undoubtedly of viscous origin and can be demagnetized in an AF of 0–to 5 mT. The *B-LFC* is also secondary; they show harder magnetic properties and

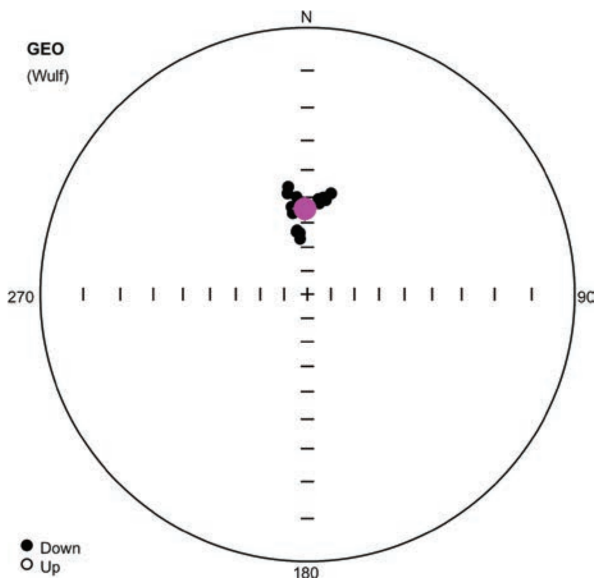

Figure 190 *Directions of C-components of remanence of samples with N polarity, Biospeleološka postaja. For detail description see Figure 34.*

Table 50 Mean palaeomagnetic directions, Biospeleološka postaja

Biospeleološka postaja	**Polarity**	**Mean palaeomagnetic directions**		α_{95} [°]	**k**	**n**
		D [°]	I [°]			
	N	358.34	54.47	3.86	87.52	15

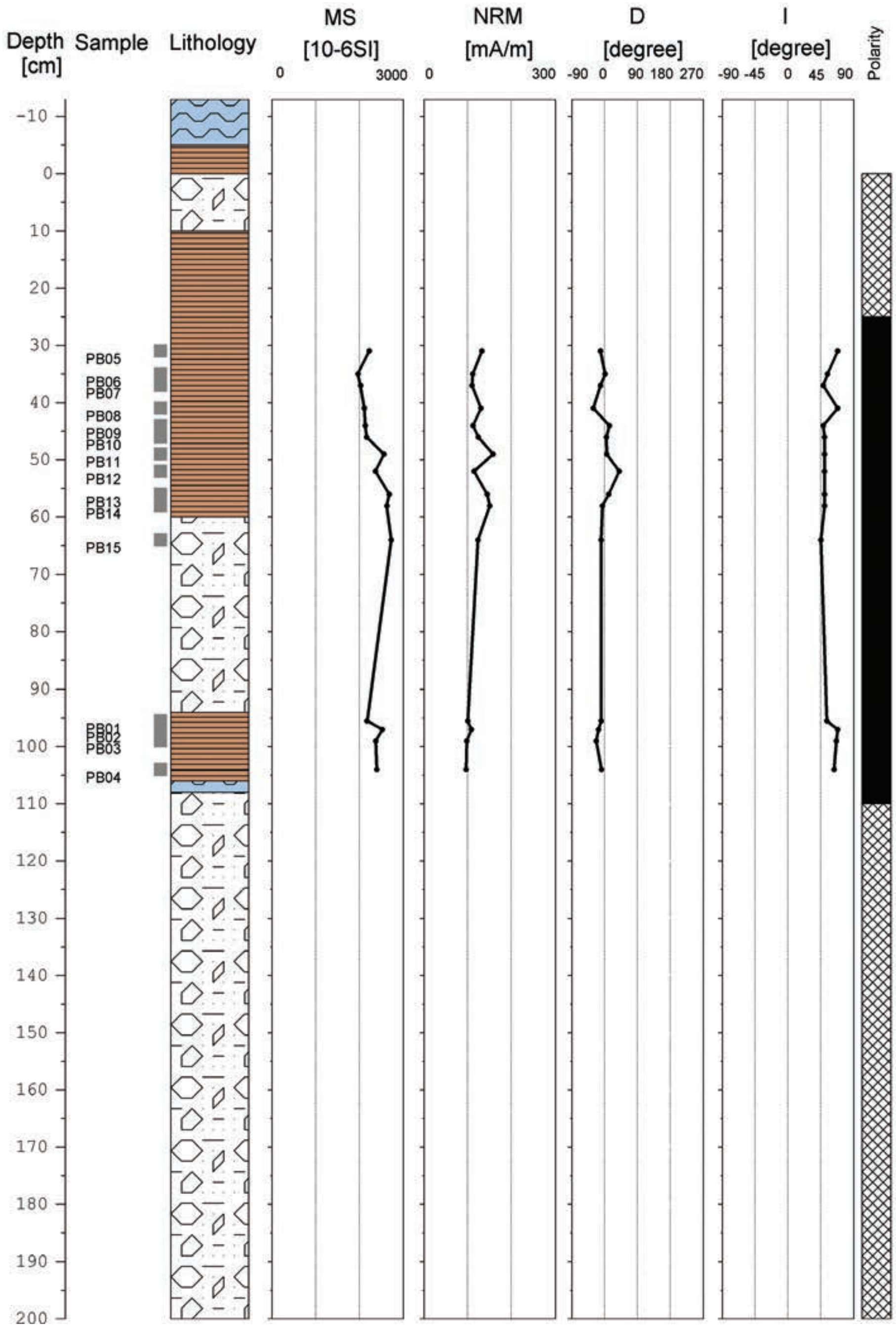

Figure 191 *Basic magnetic and palaeomagnetic properties, Biospeleološka postaja. Legend: see Figure 37.*

can be demagnetized in the AF (5–10 to 15 mT). The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF (ca 15–80 to 100 mT).

The stereographic projection of the C-component with N polarity is shown in Figure 190. Table 50 summarizes results of mean directions of samples from this profile. Mean palaeomagnetic directions of normal polarized C-components for this profile are D = 358° and I = 54°. The basic magnetic parameters are documented in Figure 191.

DISCUSSION OF RESULTS

We were aware that sediments of the Biospeleološka postaja profile are very young but we wanted to test the method in these kinds of deposits. The bottom consisted of sediments derived from flysch source rocks mixed with angular limestone fragments. They represent remains of the oldest sediments deposited in the cave by the Pivka underground stream. The upper part of the sediment was eroded away. After an important erosion phase, rubble and breccias composed of limestone and flowstone clasts was deposited. The breccia was cemented in places. The clasts were created by freezing and disintegration of the ceiling and walls in the entrance section of the cave. Fragments of white microcrystalline flowstone indicate the summer deposition of calcite in warmer humid conditions and winter destruction of the flowstone due to cold air inflow. This stratum was probably formed at the beginning of the Würm glaciation. The upper part of breccia mixed with clay contained rock fragments showing subcutaneous corrosion features. The origin of the rubble is the slope above the cave. The lower part of the stratum contains the bones of a cave bear. In similar strata in the other profile within the passage, stone tools from the early Stone Age were found. The layer formed between 40 to 20 ka years BP in the last cold phase of the Würm glaciation. The top clay was washed into the cave from the surface. Most probably it developed when the cave entrance was blocked and the passage was no longer exposed to intrusions of cold winter air and freezing. The stalagmites and the flowstones which cover the floor are Holocene.

The profile showed only N polarized magnetization and a palaeomagnetic direction very close to the present magnetic field. Therefore we assume deposition within the Brunhes chron (<780 Ka), which is in accordance with the expected age of deposits and archaeological finds.

Figure 192 *The profile of fluvial sediments in Male jame.*

MALE JAME

PROFILE LOCATION

Male jame is a smaller passage which developed in epiphreatic conditions at 515–527 m a.s.l. It connects passages of Stara jama and Zgornji Tartarus. It is developed in thick-bedded rudist Turonian limestone with strata dipping south-west.

The sample profile in Male jame (45°47´28.49˝N; 14°12´20.89˝E; 520 m a.s.l.; Fig. 160) is situated in the northern part of the passage where there was a quarry for sand during the construction of the tourist path (Fig. 192). The profile was earlier sampled by Šebela (Šebela & Sasowsky 1999).

LITHOLOGY

The top 60 cm consisted of greenish grey, clayey-silty-sandy gravels with fine-grained laminae and bands. They were underlain by 120 cm of quite well lithified, brownish grey to reddish brown and red, fine to medium-grained, highly-micaceous sands (muscovite) with clayey-silty matrix and well-rounded pebbles of flysch sandstones (mostly up to 1 cm, locally up to 4 cm in size) strongly decomposed *in situ* and with Mn-enriched coatings, with angular clasts coated by ferrugineous crusts (maybe lateritized sandstones), with schlieren enriched in Mn compounds, and with small clasts of highly decomposed white cherts. Brecciated and laminated/banded textures were poorly visible. The lower part of the profile (90 cm) was composed of soft yellowish brown clays, in its upper part with brown bands and laminae, in the lower part homogeneous (Fig. 193).

PALAEOMAGNETIC RESULTS

All 33 samples from the Male jame profile were analysed for their palaeomagnetic properties. The mean values of the J_n and k_n moduli are documented in Table 51. According to both sets of values, the profile may be divided into four parts and categories. The sediments are characterized by the wide scatter of NRM intensities from 0.8 to 14 $mA.m^{-1}$ and the MS values from

Figure 193 *Yellow clays in the lower part of the Male jame profile.*

96 to 309 x 10^{-6} SI units. Samples are characterized by very low up to intermediate J_n and k_n magnetic values.

Multi-component analysis of the remanence shows that the samples have a three-component RM. Two components were isolated after AF demagnetization. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF field (0–5 up to 10 mT). The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF (ca 15–80 up to 100 mT).

The stereographic projection of the C-component with N polarity is shown in Figure 194. Table 52 summarizes results of the mean direction of samples from this profile. The mean palaeomagnetic directions of C-components for the N polarity part are D = 324° and I = 72°. Systematic acquisition of the palaeomagnetic data within the studied section allowed the construction of a detailed magnetostratigraphic profile (Fig. 195). The profile showed a N palaeomagnetic direction.

Table 51 Mean palaeomagnetic values and standard deviations, Male jame

Male jame	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	1.593	146.6	0.95–0.74
Standard deviation	0.464	13.4	
Number of samples	9	9	
Mean value	6.404	251.2	0.71–0.65
Standard deviation	2.204	42.3	
Number of samples	3	3	
Mean value	2.079	163.8	0.63–0.42
Standard deviation	0.998	25.8	
Number of samples	8	8	
Mean value	0.970	121.8	0.39–0.03
Standard deviation	0.388	14.9	
Number of samples	13	13	

* from top to base

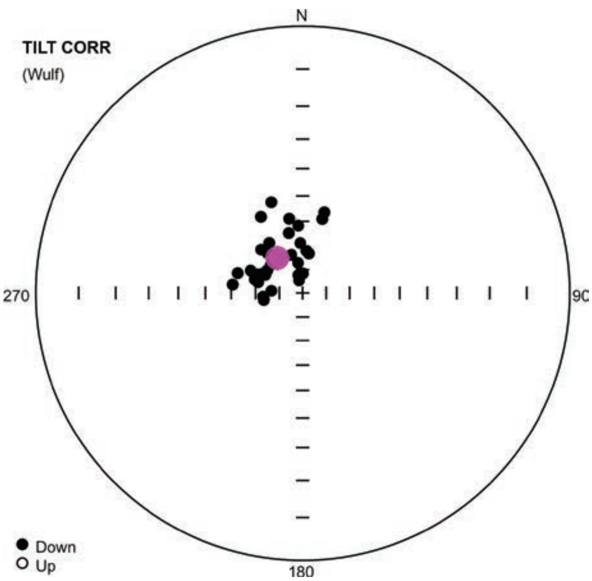

Figure194 *Directions of C-components of remanence of samples with N polarity, Male jame. For detail description see Figure 34.*

Table 52: Mean palaeomagnetic directions, Male jame

Male jame	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	323.93	71.67	4.37	32.08	32

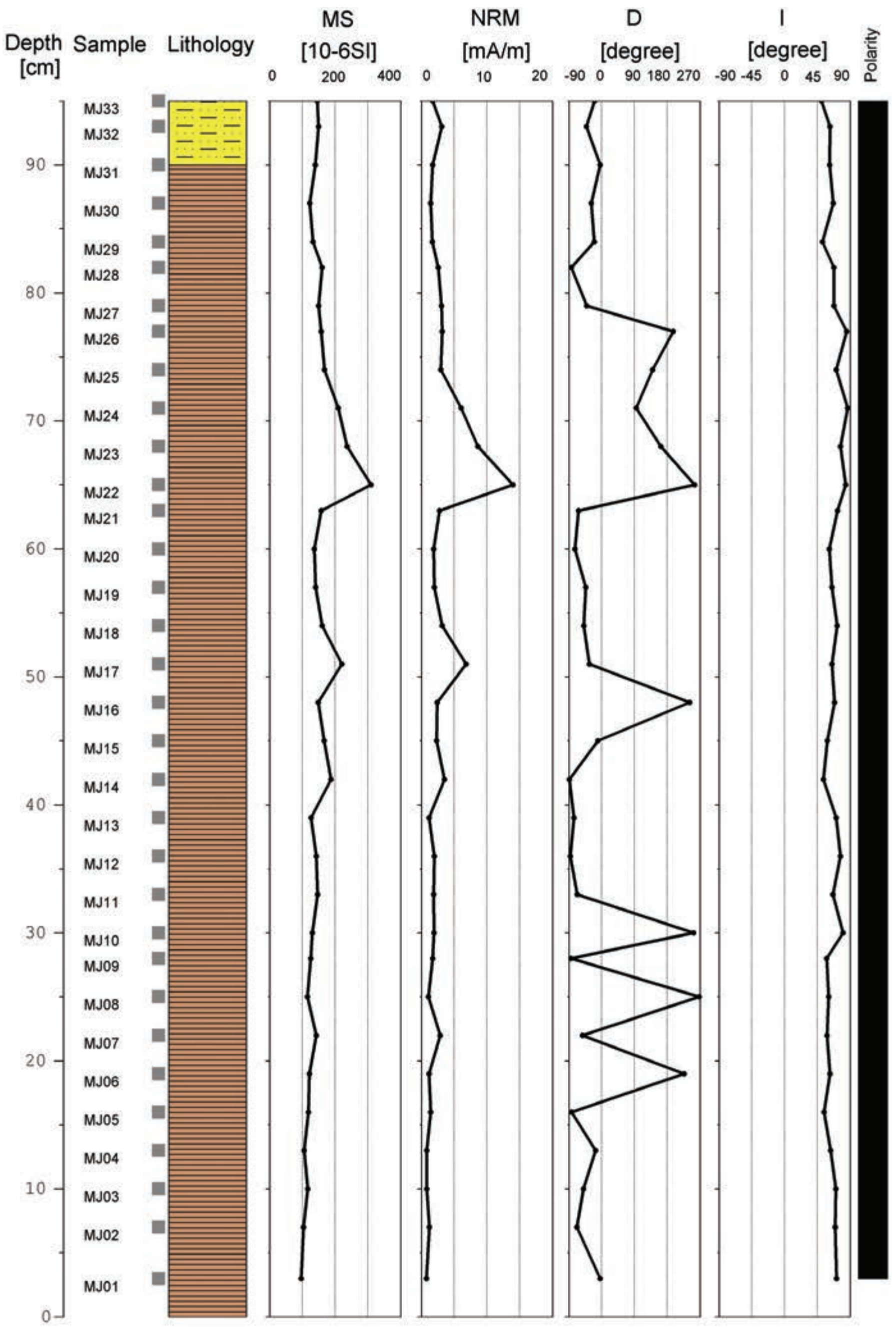

Figure 195 *Basic magnetic and palaeomagnetic properties, Male jame. Legend: see Figure 37.*

DISCUSSION OF RESULTS

From the N polarization of all samples from the Male jame profile, all deposition could have occurred within the Brunhes chron (<780 ka) as far as can be determined. The same results were obtained by Šebela & Sasowsky (1999) from eight samples from the uppermost and lower parts of the profile.

Nevertheless, the lithological character of gravel-sandy overburden of clays with flysch-derived sandstone pebbles strongly weathered *in situ* and quite strong lithification could indicate a substantial age for the deposits, although clays in the lower part of the profile are quite soft and without any traces of the alterations seen in the overlying sediments. *In situ* weathering inside the cave demands quite prolonged time and a quite different external climate than there has been recently. Very similar deposits containing *in situ* weathered flysch (Lower Carboniferous) pebbles were dated by Kadlec et al. (2001) from the fluvial sequence of ponor Nezaměstnaných Cave in the northern part of the Moravian Karst by cosmogenic nuclides to ages of 0.8–1.2 Ma. It cannot be completely excluded, therefore, that the soft and very slightly lithified clays may represent a younger fill of the passage (<780 ka) deposited on or inside (sandwiching; Osborne 1984) the already eroded sandy-gravely profile, which could easily be much older (>780 ka?).

STARA JAMA

SITE LOCATION AND CHARACTERISTICS

Stara jama is the main passage of the upper level of the cave, gently dipping to the north. It is developed in the thick-bedded rudist Turonian limestone, with stratal dip south-west. The passage was formed in epiphreatic conditions and there are traces of paragenesis on the ceiling. Relicts of the sedimentary fill are still preserved in some parts where protected by flowstones or collapse.

Our profile of the sediments is located in Stara jama at Križ (in front of the Kristalni rov; bottom: 45°47´15.26˝N; 14°12´28.81˝E; 528 m a.s.l.; Fig. 160). It was exposed by quarrying for sand during the construction of tourist pathways (Fig. 196).

Figure 196 *Location of sedimentary profile in Stara jama.*

LITHOLOGY

The approximately 220 cm profile was sampled in the left portion of the outcrop, where it was covered by flowstone (Fig. 197). Grey clayey-sandy gravels with sub-angular to sub-rounded flat pebbles up to 3 cm in size, with some bands and lenses of clayey-silty fine-grained sand, constituted the lower 118 cm of the profile. They were overlain by greyish light brown silty clays; finely light micaceous, with laminae and bands with sandy admixture (6 cm). The clays were succeeded by a sequence of sands (28 cm) composed of greyish light brown, highly clayey very fine- to fine-grained texture, up to medium-grained just at the base with dark-coloured schlieren and laminae, with clasts of clay in the upper part. The next 10 cm were of yellowish to light brown and silty clays, finely light micaceous, finely indistinctly laminated, with sandy admixture increasing to the top, at the top up to clayey, fine-grained sand which passed up to highly clayey, unsorted sands (9 cm) with single flat pebbles up to 1.3 cm in size. The top part (Fig. 198) of the clastic sediments was represented by light brown, at the base up to olive green, silty clays with flaky disintegration, with small clasts of limestone at the top. The flowstone was about 20 cm thick; light brown, laminated and crystalline. The upper clays

Figure 197 *The sedimentary profile Stara jama.*

Figure 198 *Detailed of sample sections, profile Stara jama.*

Table 53 Mean palaeomagnetic values and standard deviations, Stara jama

Stara jama	**J_n** [mA.m^{-1}]	**k_n x 10^{-6}** [SI]	**Interval** [m]*
Mean value	6.705	378.3	1.35–0.01
Standard deviation	2.627	106.7	
Number of samples	20	26	

* from top to base

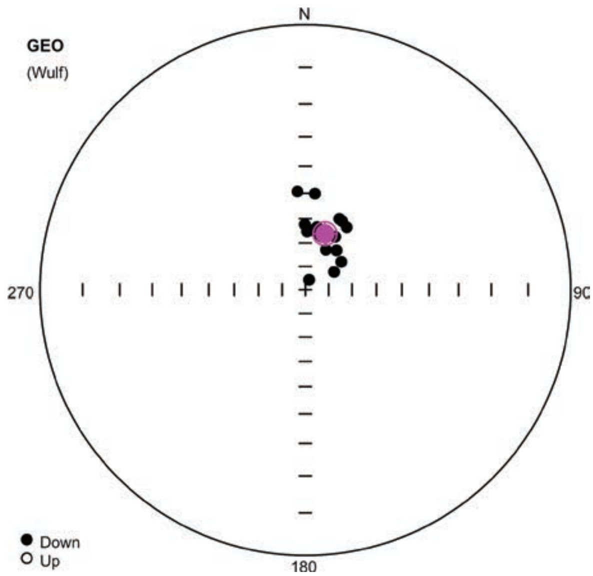

Figure 199 *Directions of C-components of remanence of samples with N polarity, Stara jama. For detail description see Figure 34.*

and sands became substantially thicker in the right part of the outcrop.

PALAEOMAGNETIC RESULTS

A total of 26 samples were investigated from the Stara jama profile. They were subjected to detailed AF demagnetization in 14 steps. The mean values of the J_n and k_n moduli are documented in Table 53. The sediments are characterized by a low scatter of NRM intensities (2.7–10.6 mA.m^{-1}) and the MS values (225–561 x 10^{-6} SI units). Samples are characterized by low up to intermediate J_n and k_n magnetic values.

Multi-component analysis was applied to separate the respective RM component for each sample. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–to 5 mT). The *B-LFC* is also secondary and can be demagnetized in the AF (5–10 mT). The characteristic *C-HFC* is stable and can be demagnetized or isolated in the AF (ca 10–80 mT).

The stereographic projection of the C-component with N polarity is shown in Figure 199. Table 54 summarizes results of mean direction of samples from this profile. Mean palaeomagnetic directions of N polarized C-components for this profile are D = 19° and I = 65°. The basic magnetic parameters are documented in Figure 200.

Table 54 Mean palaeomagnetic directions, Stara jama

Stara jama	**Polarity**	**Mean palaeomagnetic directions**		**α_{95}** [°]	**k**	**n**
		D [°]	I [°]			
	N	19.19	64.84	4.59	51.61	18

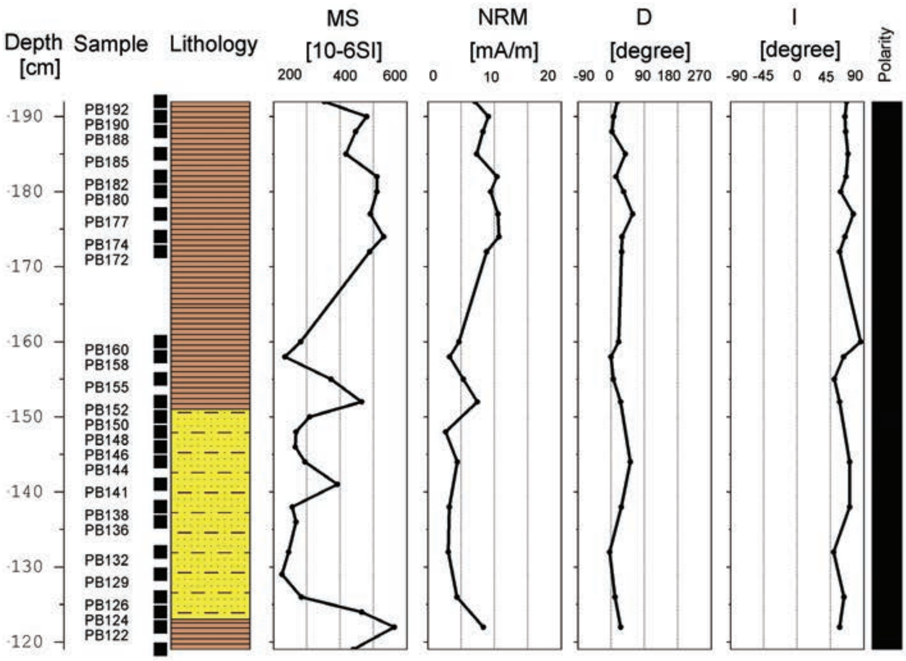

Figure 200 *Basic magnetic and palaeomagnetic properties, Stara jame. Legend: see Figure 37.*

PALAEONTOLOGY

Fragments of bones (probably *Ursus spelaeus*; det. I. Horáček 2007) were found in silty clays between sands in the right part of the outcrop.

DISCUSSION OF RESULTS

As far as can be said the palaeomagnetic results indicate the age of sediments is younger than 0.78 Ma in the Stara jama profile. This interpretation is also supported by Pleistocene bear bones occurring on the top of the profile. The top part of the profile showing flaky disintegration could be disturbed by freezing, as this kind of texture is typical for cryoturbation processes.

PISANI ROV

SITE LOCATION AND CHARACTERISTICS

Pisani rov is the passage which deviates to the north from the main passage of the Stara jama (Fig. 160). It terminates below the slopes of the collapse doline of Velika Jeršanova where the bottom is filled by sediments at 535 m a.s.l. The passage was formed in the thick-bedded Turonian limestones with the stratal dip towards west.

The profile studied was situated at the end of the Pisani rov (bottom: 45°47´39.90″N; 14°12´41.66″E; 529 m a.s.l.; Fig. 160), where the collapse boulders and massive flowstone are covered with fine-grained sediment.

LITHOLOGY

The roughly 145 cm thick Pisani rov profile (Fig. 201) was composed of yellowish brown silts to clays with dark stains and schlieren, with an olive-green horizon in the lower third, finely laminated in the lower part. The upper part of lutites showed cubic to columnar disintegration with Fe stains on the fractures. The profile was covered by two layers of flowstone (Fig. 202). The lower one contained broken stalagmite, which remain was lying on flowstone surface. The second layer was developed only in places and was covered by limestone clasts. Samples of flowstone were delivered for Th/U dating to Warsaw (Poland).

PALAEOMAGNETIC RESULTS

A total of 65 samples have been investigated for their palaeomagnetic properties. The mean J_n and k_n moduli values are documented in Table 55. According to both sets of values, the profile may be divided into two parts and categories. One of them is flowstone and the second is clays. The sediments are characterized by a low scatter of NRM intensities (6.8–45 mA.m^{-1}) and MS values (27–785 x 10^{-6} SI units). Samples are characterized by low up to intermediate J_n and k_n magnetic values.

Multi-component analysis of the remanence shows

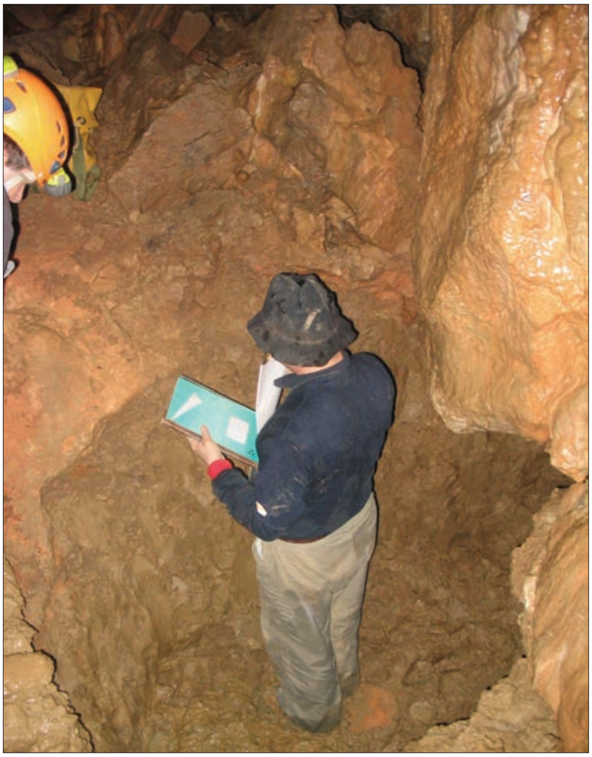

Figure 201 *Sedimentary profile at the end of the Pisani rov passage.*

Figure 202 *Top part of the Pisani rov profile.*

Table 55 Mean palaeomagnetic values and standard deviations, Pisani rov

Pisani rov	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	11.258	249.3	1.92–1.19
Standard deviation	2.889	24.3	
Number of samples	52	52	
Mean value	10.880	49.1	flowstone 1.46–1.37
Standard deviation	2.191	13.2	
Number of samples	13	13	

* from top to base

that the samples have a three-component RM. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–5 mT). The *B-LFC* is also secondary; they show harder magnetic properties and can be demagnetized in the AF (5–10 to 15 mT). The

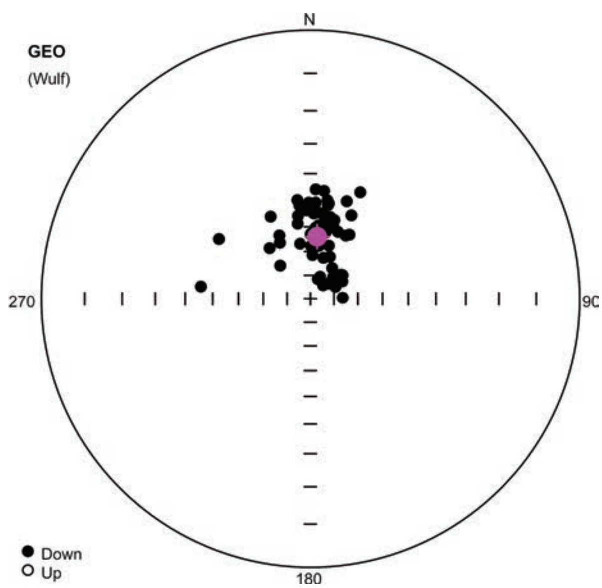

Figure 203 *Directions of C-components of remanence of samples with N polarity, Pisani rov. For detail description see Figure 34.*

Table 56: Mean palaeomagnetic directions, Pisani rov

Pisani rov	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	6.19	63.79	3.31	27.16	66

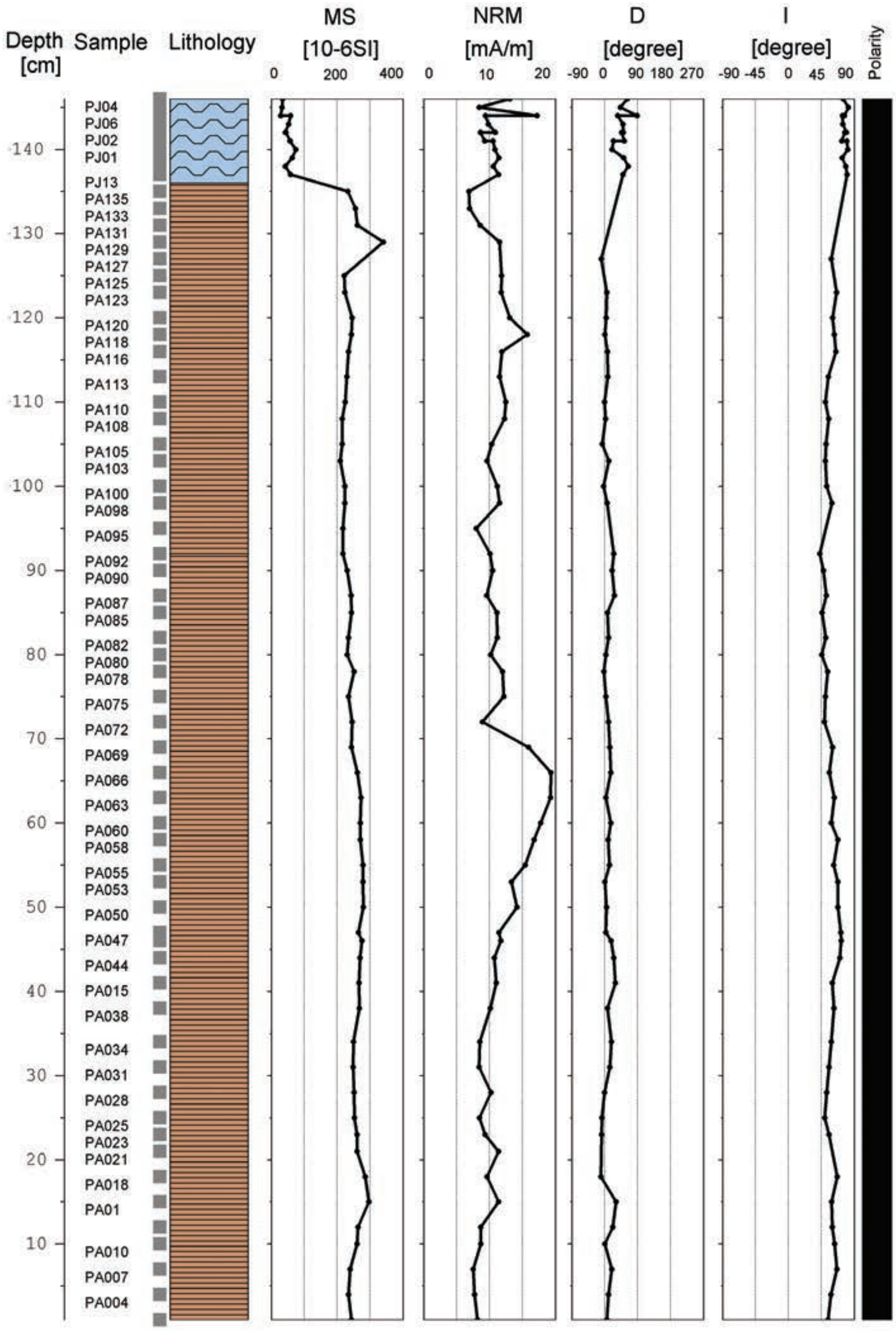

Figure 204 *Basic magnetic and palaeomagnetic properties of the Pisani rov profile. Legend: see Figure 37.*

characteristic *C-HFC* is stable and can be demagnetized or isolated in the AF (ca 15–80 to 100 mT).

The stereographic projection of the C-component with N polarity is shown in Figure 203. Table 56 summarizes results of mean direction of samples from this profile. Mean palaeomagnetic directions of N polarized C-components for this profile are D = 6° and I = 64°. The basic magnetic parameters are documented in Figure 204.

DISCUSSION OF RESULTS

The profile showed only N polarized magnetization and a palaeomagnetic direction very close to the present magnetic field; therefore we assume that deposition occurred within the Brunhes chron (<780 ka).

DISCUSSION OF RESULTS FROM POSTOJNSKA JAMA

Cave sediments in this large system were studied at first by archaeologists and palaeontologists. Rakovec (1954) described remains of Pleistocene hippopotamus found in the cave at the beginning of the 19th Century. Younger sediments, mostly from the last glacial, were described by archaeologists (Brodar 1969).

Older sediments were systematically studied by Gospodarič (1976), who compiled a stratigraphy of the cave sediments, from the oldest to the youngest, as follows: (1) coloured chert gravel, (2) rubble and white chert gravel, (3) speleothems and red loam, (4) younger laminated loam and flysch sand, (5) speleothems, (6) breakdown rocks and flood loam and sand, (7) speleothems. This stratigraphy differs from that of Planinska jama, where old laminated loam was deposited on the coloured chert gravel. The old laminated loam is missing entirely in Postojnska jama (Gospodarič 1976). This fact is very important for the dating of cave sediments in this cave. Another important factor to take into account is that the depositional processes within the cave at the same time, but in different hydraulic conditions, may deposit different sediments in different passages or even erode them in one cave segment to accumulate them in the other. Gospodarič (1976) suspected that the oldest sediments from Postojnska jama were not older than Middle Quaternary (i.e. about 400 ka; see Fig. 2).

The mineral composition of the studied fluvial sediments from Postojnska jama indicate that the catchment area of allogenic streams was situated on weathered flysch rocks in the Pivka basin (Gospodarič 1976; Zupan Hajna 1998) for a very long time and there are no perceived differences in mineral composition of eroded flysch beds (beds are not in horizontal position and in their mineral composition is no big variation – the cave reach its eroded average).

From the Postojnska jama different samples were analysed by radiometric dating (^{14}C, Th/U and ESR). Ages obtained by the ^{14}C method range from 7.5 to 39.5 ka (Franke & Geyh 1971; Gospodarič 1972, 1977). The ESR method dated samples to 125–530 ka (Ikeya, Miki & Gospodarič 1983) and Th/U method yielded dates from 6 ka to more than 350 ka (Zupan 1991; Mihevc 2002). Stalactite from the Pisani rov was dated by the ESR method (Ikeya et al. 1983) and by Th/U (Zupan 1991). Red flowstone in the nucleus was older than 350 ka; the next two rings, separated by lamina of flood loam, were dated to about 270 ka and to about 75 ka, respectively. Two other samples from the Podorna dvorana in Pisani rov were dated by the Th/U method. The base of a stalactite under a collapse block yielded age of about 75 ka and the base of a stalagmite which grew on the block was established to be about 20 ka old. Mihevc (2002) recorded three periods of flowstone growth on the Velika gora and in the Pisani rov (excluding recent flowstones). The oldest flowstone was dated at the foot of collapse at the railway station. Flowstone was deposited above collapse boulders at 152 $\pm$ 40 ka. A flowstone dome at the top of the Kalvaria was 70 $\pm$ 26 ka old. An important growth period of flowstone was documented in five samples from Pisani rov. The sampled stalagmites here fell because clayey substratum was washed away and afterwards they were covered by big boulders or they were found broken and covered with scree. The stalagmites were growing on clays (41 $\pm$ 3 ka, 43 $\pm$ 10 ka), on collapse boulders (37 $\pm$ 7 ka) and on rubble (47 $\pm$ 7 ka). The youngest phase of flowstone deposition is recorded in samples of grey crystalline flowstone and stalagmite (12 $\pm$ 5 ka and 6 $\pm$ 4 ka) covering all collapse blocks. The intensity of rock fall is low under the present conditions. These data, in spite of some errors, helped to distinguish some clear phases of collapse alternating with flowstone deposition. Collapses have been usually connected with colder climate, flowstone deposition with the warmer one.

Šebela & Sasowsky (1999) did the first palaeomagnetic research on fluvial sediments from Postojnska jama (Male jame, Otoška jama, Partizanski rov = Umetni tunel). They analysed yellowish-brown fluvial sediments from the Otoška jama (8 samples – 4 duplicates) and Male jame (8 samples – 4 duplicates). All samples showed N orientation. They concluded that sediments are younger than 0.73 Ma. Nevertheless, reddish-brown sandy loams from the Otoška jama and Male jame were misinterpreted by them as an older laminated loam (*sensu* Gospodarič 1976), which exists only in Planinska jama (Gospodarič 1976). Palaeomagnetic measurement of four samples (2 duplicates) from the natural passage in the Umetni tunnel showed R polarity and an age of at least 0.73–0.90 Ma was expected. They deduced that reddish-brown sandy loams in Umetni tunnel are older than the coloured chert gravel (*sensu* Gospodarič 1976) and older laminated loam (which Gospodarič 1976 contended are not present in Postojnska jama at all!), is also because of the more sandy character of those sediments. The sediments were disturbed by younger movement on a cross-Dinaric fault situated in this part of the Umetni tunel (Gospodarič 1964; Sasowsky, Harbert & Šebela 2003).

Palaeomagnetic and magnetostratigraphy data obtained by our research partly confirmed the findings of Šebela & Sasowsky (1999), but indicated a different age interpretation than was offered by Sasowsky, Harbert & Šebela (2003) and produced some new evidences. Samples from most profiles were N polarized. Short R magnetozones (excursions) were detected only in places (Spodnji Tartarus North and South). Therefore we interpreted most of the studied sediments as younger than 780 ka, so belonging to the Brunhes chron. Nevertheless this preliminary age estimation is not final, as detailed statistical analyses of palaeomagnetic parameters we obtained are in progress. The possibility cannot be completely excluded that the N polarization in some profiles can be linked with older N polarized subchrons than 0.78 Ma, as in the Umetni tunel I site. The lithological situation in Male jame is questionable; unfortunately most of the sediments here are not suitable for palaeomagnetic analysis, so it will be problematic to interpret this site.

The dominant N polarization in the sediments and lack of more common R polarized excursions can also be take to indicate that the deposition of most of sediment sections we studied was relatively rapid, occurring in short time-spans. Some sections may even represent single flood events or deposition lasting at most a few thousand years.

Several new Th/U data placed the erosion of the profile in Spodnji Tartarus before 169 ka and the collapse after the erosion took place during the Eemian (around 106 ka).

Data obtained from sedimentological analyses, palaeontological and quantitative dating indicate that several depositional and erosion phases alternated in Postojnska jama. It is quite possible that individual cave segments or passages were filled and exhumed several times during the quite prolonged evolution of the cave as indicated, for example, by remains of cemented sediments on walls and ceiling in the main passage of Stara jama and in other places. The general stabilization of the hydrological system of the Pivka basin – Postojnska jama – Planinska jama – Planinsko polje for a long time-span (presumably even as old as 2 Ma; Pruner et al. 2004) led to the formation of a long and complex cave system. Proposals for a very young evolutionary history for Planinsko and Cerkniško poljes and the related cave systems (developed within the last approximately 30–100 ka) presented in a number of papers by F. Šušteršič and his colleagues (a.o. Šušteršič, Šušteršič & Stepišnik 2003) must be rejected as they are not in accordance with the data summarized here.

The alternation of depositional and erosion phases could be connected with conditions within the cave system, function of the resurgence area, collapses, climatic changes, tectonic movements and the intrinsic mechanisms of the contact karst. Fluvial sediments derived from flysch can be found in entrance parts of Postojnska jama as high as 530 m a.s.l., in cave fillings in the bottom of collapse dolines at above 535 m a.s.l. (Stepišnik 2004) and in Zguba jama at 560 m a.s.l. It can be expected that the deposition was not uniform throughout the entire cave at a given time; more likely there was active erosion in one part of it while deposition predominated in another. Repeated reworking and re-deposition of the same sedimentary material can be also expected within such a long, voluminous and complicated cave system. The uniformity of the allogenic clastic material dominantly derived only from one source (Eocene siliciclastics) was enhanced by mixing of reworked older sedimentary cave fill. Small differences in mineral composition between different sediments we studied, mostly attributable to different degrees of weathering in the catchment area, support this mechanism.

ZGUBA JAMA

SITE LOCATION AND CHARACTERISTICS

Zguba jama (Reg. No. 6290; 45°47´47.50˝N; 14°12´49.57˝E; 561 m a.s.l.; Fig. 205) is situated on the karst surface above Postojnska jama. The surface (600–650 m a.s.l.) is dissected with numerous dolines, and several large collapse dolines above passages of Postojnska jama itself (Fig. 23). The cave entrance opened to the surface east of Mala Jeršanova dolina due to karst lowering.

The cave is formed in Upper Cretaceous limestones (Buser, Grad & Pleničar 1967) with the general strata dip to the north and north-east. The geological survey of the cave was performed by Šebela (1994, 1998a, b).

The 122 m long cave is a simple SW–NE-trending channel no more than 2 m wide, 2 m high and 4 m deep. It was later filled with allogenic fluvial sediments. The cave is situated above passages of Postojnska jama (about 510 m a.s.l.) – Pisani rov is the closest part, only 265 m from Zguba jama (see Fig. 160).

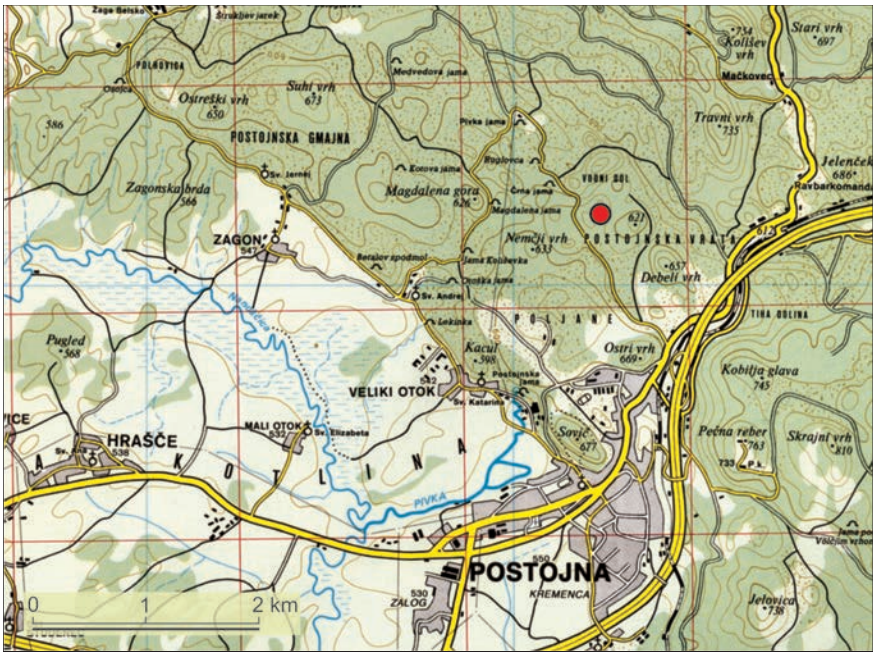

Figure 205 *Site location; Zguba jama (SW Slovenia).*

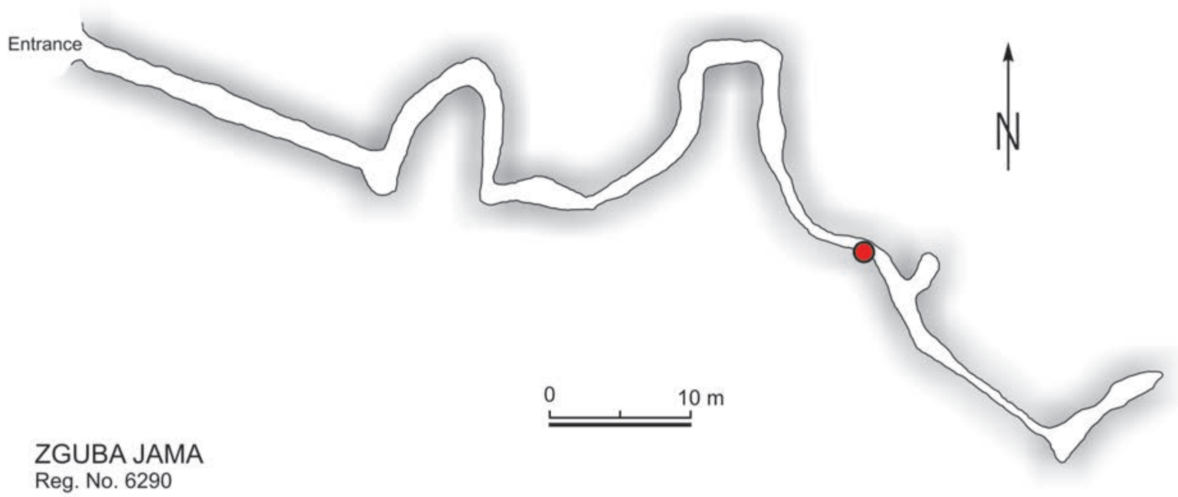

Figure 206 *Position of the profile on the cave map, Zguba jama (after Cave Register of IZRK ZRC SAZU and JZS).*

PROFILE

The profile is in the interior of the cave close to its end (45°47´47.10˝N; 14°12´52.26˝E; 563 m a.s.l.; Fig. 206). A small excavation on the north-eastern side of the channel was sampled to a depth of about 121 cm (Fig. 207).

Figure 207 *Sampling of the fluvial sediments in Zguba jama.*

Figure 208 *The upper part of the profile – Zguba jama, profile I.*

LITHOLOGY

The upper part (Fig. 208) consisted from silt to clay, reddish brown with indistinct yellowish brown stains, bioturbated at the top, in the lower part very fine sand with fine flakes of muscovite and small irregular cementations (concretions). The boundary with the underlying layer was marked by a carbonate-cemented horizon about 3 cm thick. The lower 70 cm was of orange and yellowish brown up to multicoloured, with reddish dots, silty-clayey, very fine-grained sand with fine flakes of muscovite, with light to dark grey bands and some clay laminae near the base (Fig. 209). The basal part (about 20 cm) contained desiccation cracks filled by red silt to clay in places.

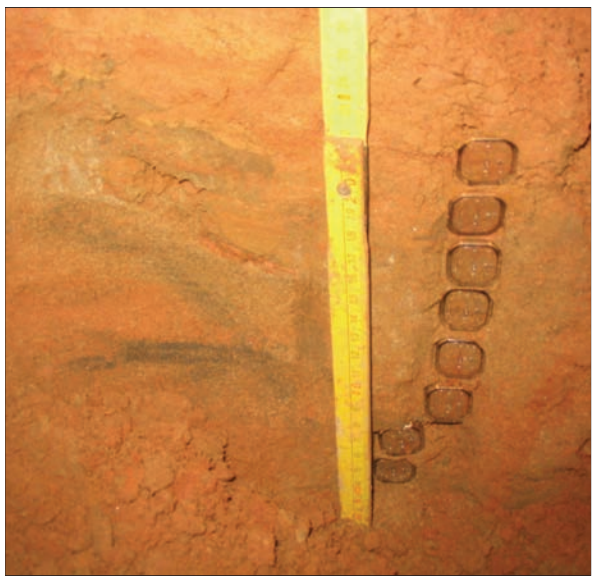

Figure 209 *The lower part of the profile – Zguba jama, profile II.*

PALAEOMAGNETIC RESULTS

A total of 45 samples were studied for their palaeomagnetic properties from both parts of the profile in Zguba jama. It was divided into two slightly overlapping palaeomagnetic sub-profiles. Sediments from **profile I** (1.04 m thick upper part) are characterized by an NRM intensity from 2 to 35 mA.m^{-1} and MS values from 114 to 1,119 x 10^{-6} SI units. Mean J_n and k_n moduli values are documented in Table 57. From the values of both sets of samples, the profile may be divided into three parts and categories. Samples are characterized by low up to intermediate magnetic values of J_n and k_n.

Table 57 Mean palaeomagnetic values and standard deviations, Zguba jama, profile I

Zguba jama I	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m]
Mean value	26.393	698.9	1.04–0.78
Standard deviation	5.764	169.4	
Number of samples	8	11	
Mean value	13.838	341.4	0.75–0.19
Standard deviation	5.437	129.0	
Number of samples	23	23	
Mean value	4.117	144.7	0.16–0.01
Standard deviation	1.699	33.0	
Number of samples	6	6	

* from top to base

All samples were subjected to detailed AF demagnetization in 14 steps. Multi-component analysis was applied to separate the respective RM components for each sample. Three components were isolated after the AF demagnetization. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–2 up to 5 mT). The *B-LFC* is also secondary; they show harder magnetic properties and can be demagnetized in the AF (5–10 up to 15 mT). The characteristic *C-HFC* is stable and can be demagnetized or isolated in the AF (ca 15–80 up to 100 mT).

The stereographic projections of the C-component with N and R polarity are shown on Figures 210 and 211. Table 58 summarizes results of the mean direction of the samples from this profile. The mean palaeomagnetic directions of C-components for the N polarity are D = 340°, I = 70° and for R polarity are D = 217°, I = -31° (two samples only). The upper part of profile showed an N palaeomagnetic direction. There are very short R excursions and transient polarised zones (N-R) within the long N magnetozone (Fig. 212).

Sediments from **profile II** (21 cm thick basal part) are characterized by an NRM intensity from 1 to 54 mA.m^{-1} and the MS values from 114 to 269 x 10^{-6} SI units. Mean J_n and k_n moduli values are documented in Table 59.

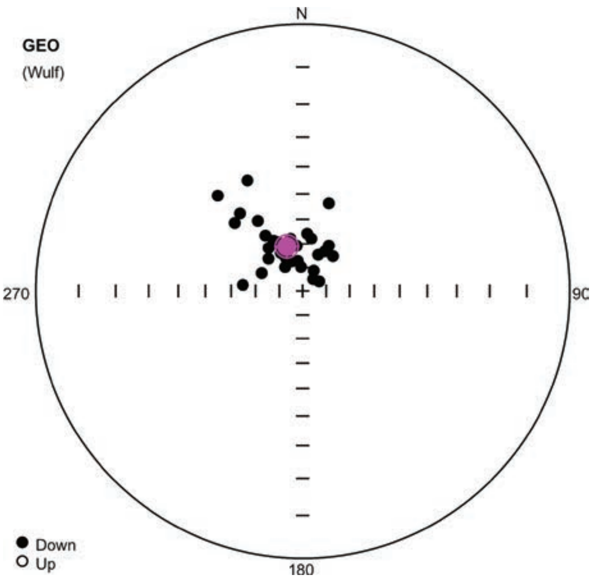

Figure 210 *Directions of C-components of remanence of samples with N polarity, Zguba jama, profile I. For detail description see Figure 34.*

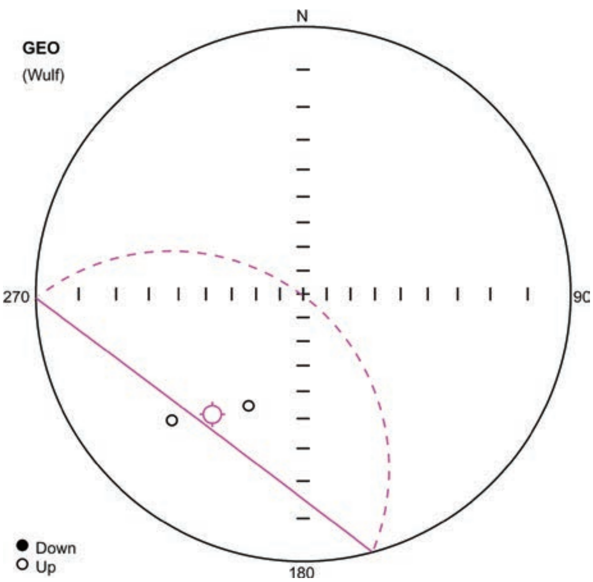

Figure 211 *Directions of C-components of remanence of samples with R polarity, Zguba jama, profile I. For detail description see Figure 34.*

Table 58: Mean palaeomagnetic directions, Zguba jama, profile I

	Polarity	**Mean palaeomagnetic directions**		**α$_{95}$** [°]	**k**	**n**
		D [°]	I [°]			
Zguba jama I	N	340.38	69.93	4.62	27.81	33
	R	217.04	-31.14	-	-	2

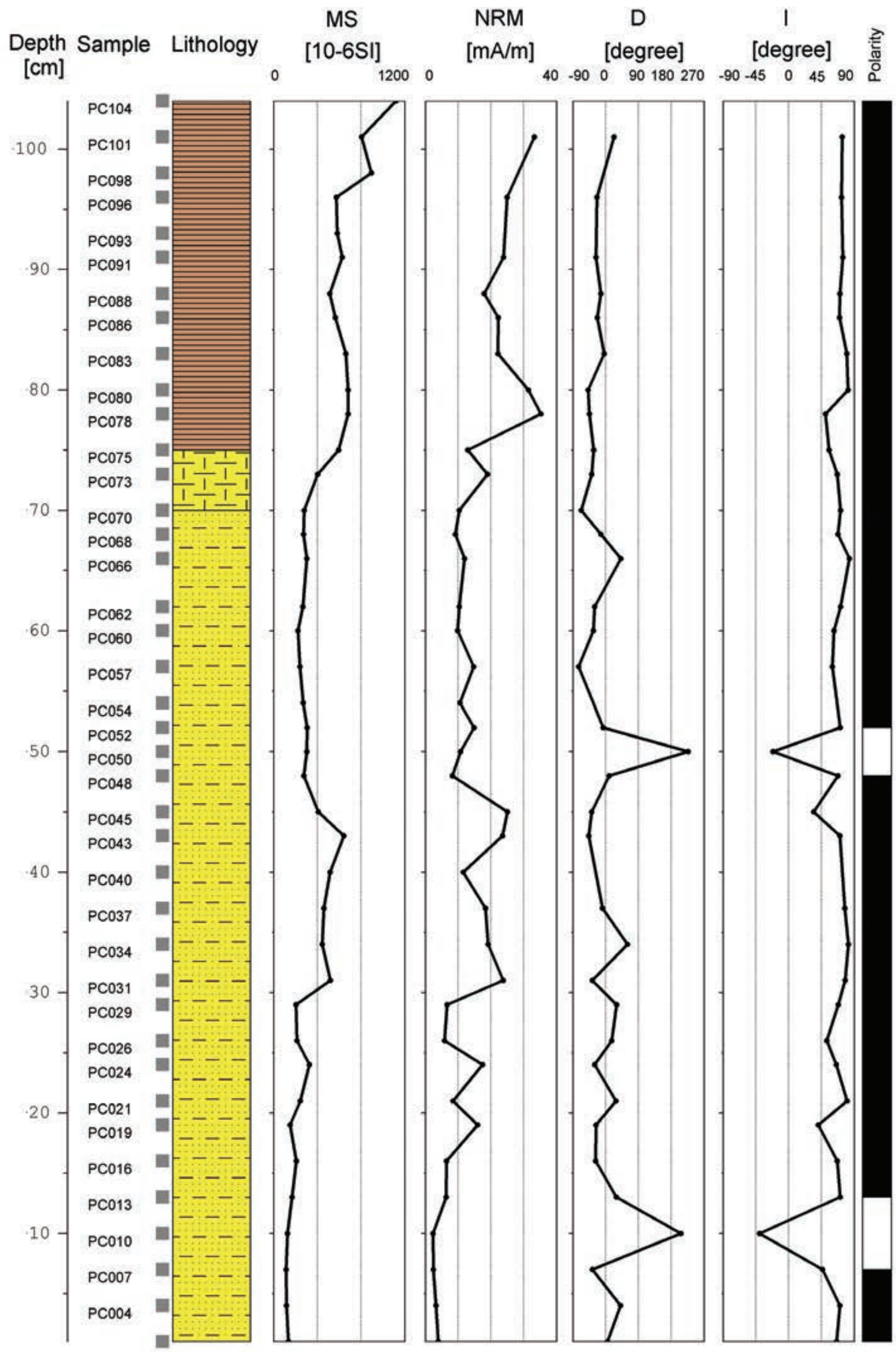

Figure 212 *Basic magnetic and palaeomagnetic properties, Zguba jama, profile I. Legend: see Figure 37.*

According to both values, the profile may be divided into two parts and categories. Samples are characterized by low up to intermediate J_n and k_n magnetic values. The stereographic projection of the C-component (HFC) with N polarity is shown in Figure 213. Table 60 summarises results of the mean direction of samples from this profile. The mean palaeomagnetic directions of C-components for the normal polarity are D = 19°, I = 75°.

Systematic acquisition of palaeomagnetic data within the both studied profiles allowed the construction of a detailed magnetostratigraphic profiles (Figs. 212 and 214). The lower part of profile showed only N palaeomagnetic direction.

Table 59 Mean palaeomagnetic values and standard deviations, Zguba jama, profile II

Zguba jama II	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	**Interval** [m] *
Mean value	5.256	178.1	0.21–0.03
Standard deviation	3.323	58.9	
Number of samples	7	7	
Mean value	53.915	162.7	0.03
Standard deviation	-		
Number of samples	1	1	

* from top to base

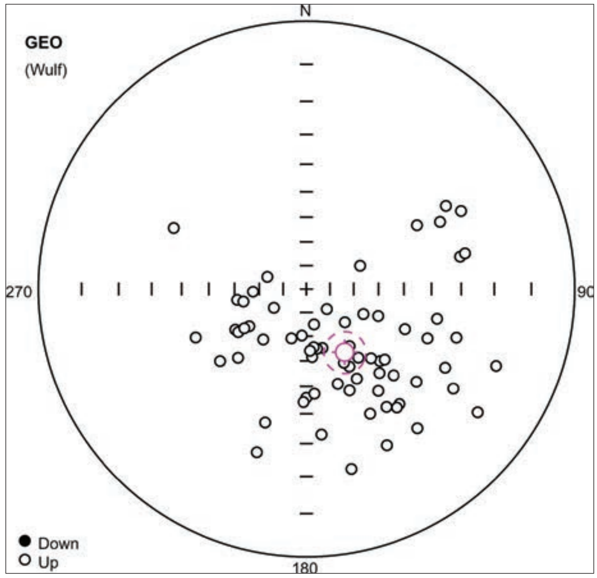

Figure 213 *Directions of C-components of remanence of samples with N polarity, Zguba jama, profile II. For detail description see Figure 34.*

DISCUSSION OF RESULTS

Šebela (1994) interpreted the cave as a probably fossil phreatic channel developed at higher level than Pisani rov in Postojnska jama. The cave was completely filled by sediments, of which the upper part was derived from flysch, which were later partly or entirely removed.

The palaeomagnetic data showed prevailing N polarity for nearly all samples in the profile, except very short R or transient excursions. Upper and lower parts of the profile differ in principal palaeomagnetic parameters (D and I). Although data could support quite young ages, D and I parameters indicate that the N polarization could belong to an older chron/subchron than Brunhes and therefore sediments could be older than 0.78 Ma.

Table 60 Mean palaeomagnetic directions, Zguba jama, profile II

Zguba jama II	**Polarity**	**Mean palaeomagnetic directions**		α_{95} [°]	**k**	**n**
		D [°]	I [°]			
	N	19.27	75.25	12.99	19.37	6

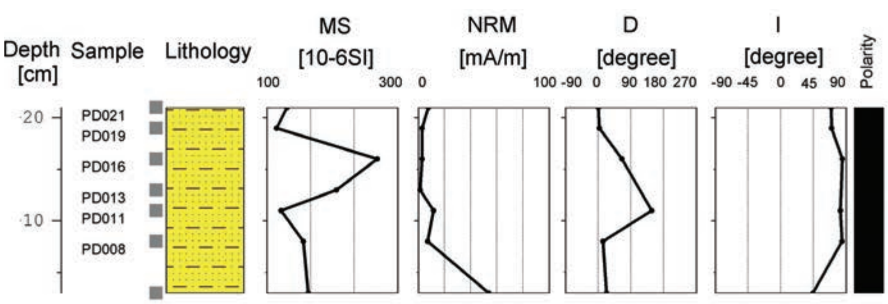

Figure 214 *Basic magnetic and palaeomagnetic properties, Zguba jama, profile II. Legend: see Figure 37.*

MARKOV SPODMOL

SITE LOCATION AND CHARACTERISTICS

Markov spodmol (Reg. No. 878; 45°44´04.78″N; 14°06´18.52″E; 555 m a.s.l., Fig. 22) is a horizontal cave 868 m long and 12 m deep. The entrance lies on the southern edge of a blind valley opening into the Pivka basin (Fig. 215). The cave serves as an intermittent ponor for the Sajevščica brook, which drains a catchment of about 2.4 km² on Eocene flysch. The brook sinks in ponors several hundreds meters in front of the cave, but during heavier precipitation several times a year it still flows into the cave entrance. Water tracing test confirmed that the cave belongs to the catchment area of the Reka river. The cave was connected to 6 km long cave system of Vodna jama v Lozi by diving in the terminal sump (Cave Register of IZRK ZRC SAZU and JZS).

The cave entrance is situated in the Palaeocene

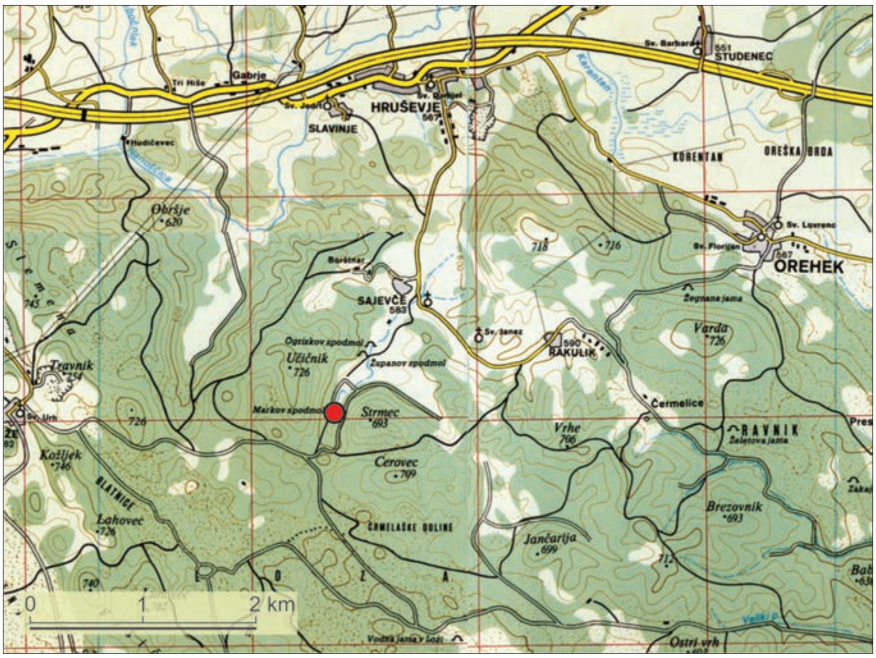

Figure 215 *Site location; Markov spodmol (SW Slovenia; W from Postojna).*

Figure 216 *Main passage in Markov spodmol; analyzed profile is situated on the right side of the passage, just behind the photographer.*

(Danian) limestones with cherts (Buser, Grad & Pleničar 1967) and the inner part is in the Upper Cretaceous limestones with dolomite (Gospodarič, Habe & Habič 1970).

The main part of the cave consist of horizontal passage several meters high and wide with some widened small chambers in the middle part. A series of small cascades lead to a terminal sump more than 30 m deep at the end of the cave (Habe & Hribar 1964). The sump connects the cave with Vodna jama v Lozi, as noted. There are also few short remnants of side passages, which are mostly filled by sediments. Several sedimentary profiles are exposed.

PROFILE

The profile studied in Markov spodmol was situated in a side passage or large niche of the main passage (Fig. 216) about 150 m from the entrance (Fig. 217).

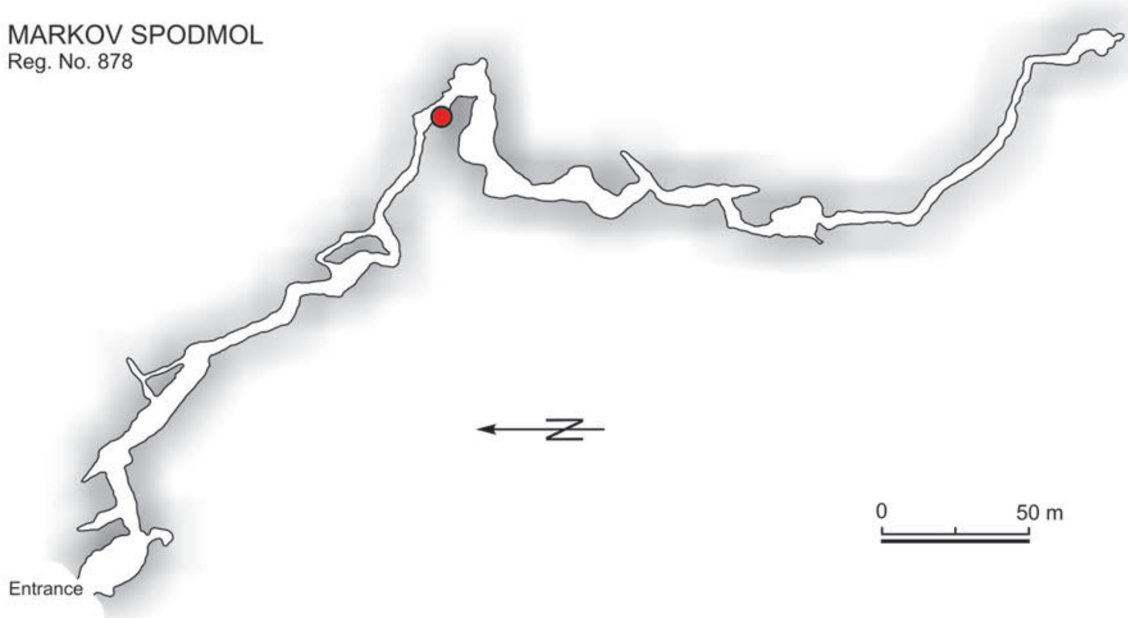

Figure 217 *Profile location in the cave map, Markov spodmol (after Cave Register of IZRK ZRC SAZU and JZS).*

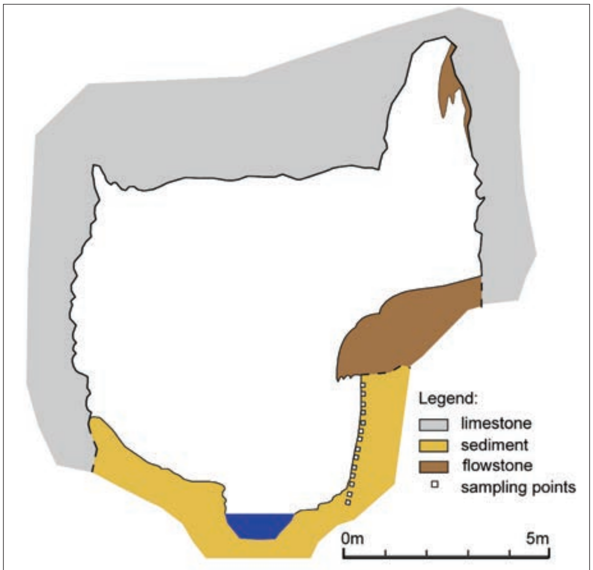

Figure 218 *The cross-section of the cave passage with the Markov spodmol profile.*

The section of fluvial sediments studied is about 4 m thick (Fig. 218); the true depth is greater but the lower part is below the level of the permanent lake. The site was sampled in several different visits (2004, 2005, 2007), resulting in completion of two palaeomagnetic profiles. Palaeomagnetic profile B overlaps the lower part of the profile A (Fig. 219 and 220).

LITHOLOGY

The profile is covered by a layer of flowstones about 1 m thick with cemented well-rounded pebbles of flysch sandstones (**sequence I**). About 5 cm of homogeneous yellow clay was directly below the flowstone. The sampled profile consisted of laminated to banded clays and silts, sometimes with sandy admixture with yellowish brown, yellow and sometimes grey colour (**sequence II = profile B**; Fig. 220) and with a thickness of nearly 200 cm. Reddish brown laminae (thin ferricrust) continue as a pinching out wedge of sediment

Figure 219 *The profile in Markov spodmol: flowstone (sequence I) covers yellow fluvial sediments (sequences II, III, IV; divided for paleomagnetic analyses in profiles A and B).*

Figure 220 *Markov spodmolprofile; upper part in the middle of the photo is profile A and lower part is profile B (at their ends profiles overlap).*

with high sandy admixture to a depth of 69 cm below the flowstone. Similar laminae (ferricrust) covering an erosional channel at a depth of 110 cm marked a change of lamination dip to 23°. Sediments of this segment were penetrated by vertical to subvertical veins of darker, probably ferrugineous material. Curved Liesegang ferruginous bands both sub-parallel with the left cave wall and sediment lamination occur near the cave wall up to a distance of about 80 cm; due to the alteration, the entire zone has developed a multicoloured character. Lamination dip at the bottom was 20 to 51° (channel fill). With a distinct erosional boundary and strata dip change the laminated/banded section overlies multicoloured sandy clays with intercalations of fine- to medium-grained sands (**sequence III = profile A – upper part**; thickness of about 40 cm; Fig. 221). Lamination dip here is 11 to 31°. The last sequence (**sequence IV = profile A – lower part**; thickness more than 1 m) begins with rather greenish grey sands to fine-grained gravels, composed of rounded flat clasts of clay representing the fill of erosion cut in yellowish brown silty clays similar to sequence II. The upper part of clays is not laminated, the lower part showed traces of lamination or banding. The upper contact is distinctly erosional. The lowermost part (about 25 cm) was sampled by penetration with a plastic tube to sediment below the level of lake in front of the profile (Fig. 219).

Figure 221 *Detail of laminated upper part of the profile A; Markov spodmol.*

The cave passage above the flowstone layer was filled with light grey laminated clays to silts of unclear stratigraphic position – these lutites can represent either the direct, higher continuation of sampled sedimentary profile or deposits above the flowstone.

PALAEOMAGNETIC RESULTS

A total of 80 oriented laboratory samples were studied for their palaeomagnetic properties from both profiles (A and B). Sediments from **profile A** (0.075–2.865 m) are characterized by an NRM intensity from 0.5 to 167 $mA.m^{-1}$ and MS values from 79 to $1,070x10^{-6}$ SI units. Mean values of J_n and k_n moduli are documented in Table 61.

Table 61 Mean palaeomagnetic values and standard deviations, Markov spodmol profile A

Markov spodmol profile A	J_n [$mA.m^{-1}$]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	2.072	95.2	0.075–2.075
Standard deviation	1.508	14.4	
Number of samples	41	41	
Mean value	71.434	463.3	2.125–2.225
Standard deviation	67.816	329.7	
Number of samples	3	3	
Mean value	3.916	173.2	2.275–2.475
Standard deviation	1.410	42.2	
Number of samples	5	5	
Mean value	27.559	672.4	2.525–2.865
Standard deviation	16.138	330.4	
Number of samples	9	9	

* from top to base

From both sets of values, the profile may be divided into four parts and categories. Samples are characterized by very low up to high J_n and k_n magnetic values. All samples were subjected to detailed AF demagnetization in 14 steps. Multi-component analysis was applied to separate the respective RM components for each sample. Three components were isolated. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–2 up to 5 mT). The *B- LFC* is also secondary; they show harder magnetic properties and can be demagnetized in the AF (5–10 up to15 mT). The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF (ca 15–80 up to 100 mT).

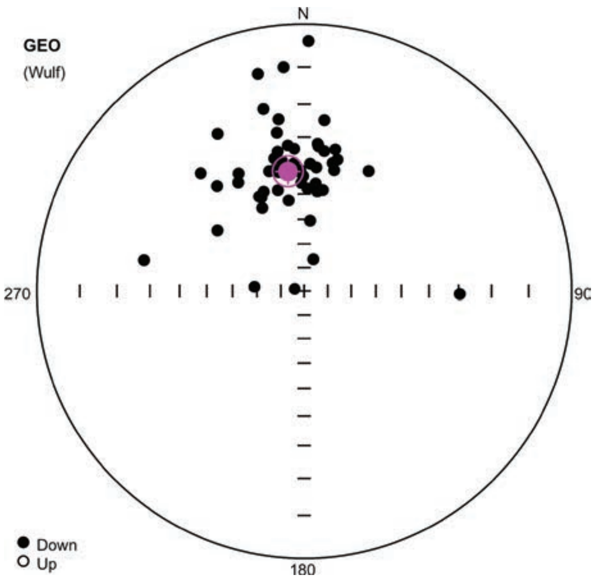

Figure 222 *Directions of C-components of remanence of samples with N polarity of profile A, Markov spodmol. For detail description see Figure 34.*

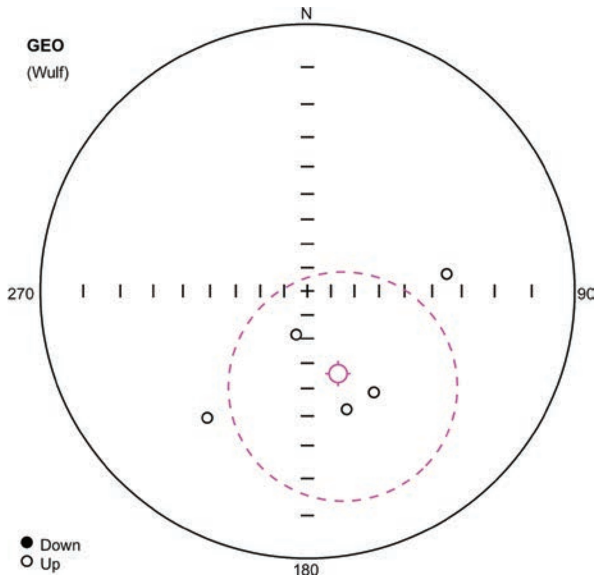

Figure 223 *Directions of C-components of remanence of samples with R polarity of profile A, Markov spodmol. For detail description see Figure 34.*

Table 62: Mean palaeomagnetic directions, Markov spodmol profile A

Markov spodmol profile A	**Polarity**	**Mean palaeomagnetic directions**		**α_{95} [°]**	**k**	**n**
		D [°]	I [°]			
	N	352.26	41.38	5.17	13.12	56
	R	159.63	-53.72	30.12	4.32	5

The stereographic projections of the C-component (HFC) with N and R polarity are shown in Figures 222 and 223. Table 62 summarizes results of the mean direction of samples from this profile. The mean palaeomagnetic directions of C-components for the N

Table 63: Mean palaeomagnetic values and standard deviations, Markov spodmol profile B

Markov Spodmol profile B	***J_n*** [mA.m^{-1}]	***k_n* x 10^{-6}** [SI]	**Interval** [m]*
Mean value	6.353	203.0	2.5
Standard deviation	-	-	
Number of samples	1	1	
Mean value	0.904	78.9	2.54–3.16
Standard deviation	0.392	13.6	
Number of samples	17	17	
Mean value	4.973	189.8	3.20–3.30
Standard deviation	1.647	43.2	
Number of samples	4	4	

* from top to base

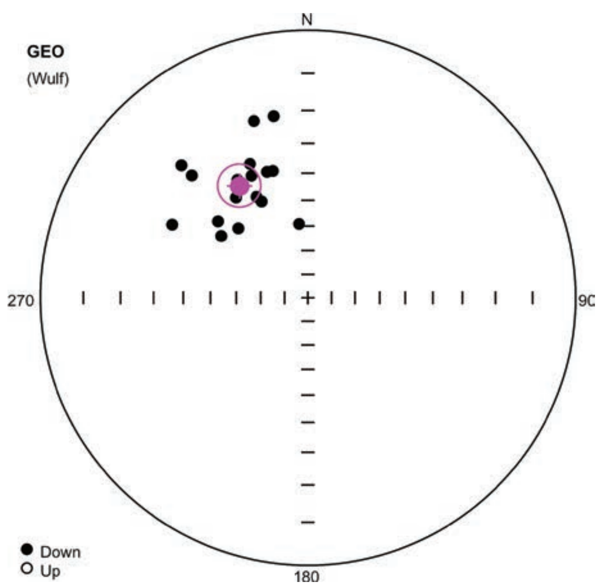

Figure 224 *Directions of C-components of remanence of samples with N polarity of profile B, Markov spodmol. For detail description see Figure 34.*

polarity are D = 352°, I = 41° and for R polarity are D = 160°, I = -54°.

Sediments from **profile B** (2.5–3.3 m) are characterized by an NRM intensity from 0.3 to 7 mA.m^{-1} and MS values from 63 to 247 x 10^{-6} SI units. Mean values of J_n and k_n moduli are documented in Table 63.

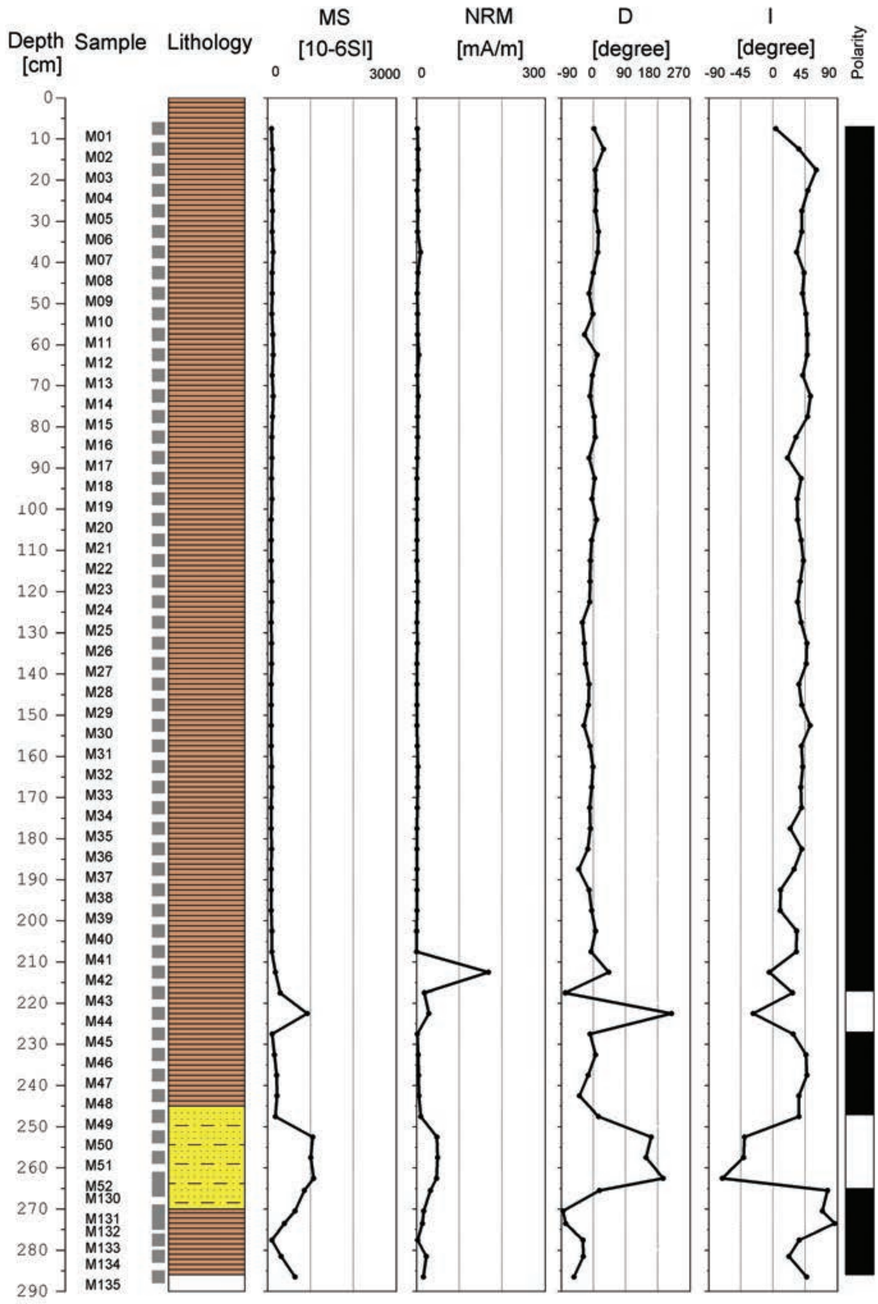

Figure 225 *Basic magnetic and palaeomagnetic properties of profile A, Markov spodmol. Legend: see Figure 37.*

Table 64: Mean palaeomagnetic directions, Markov spodmol profile B

Markov spodmol profile B	**Polarity**	**Mean palaeomagnetic directions**		**α_{95} [°]**	**k**	**n**
		D [°]	I [°]			
	N	328.53	37.87	6.94	23.97	17

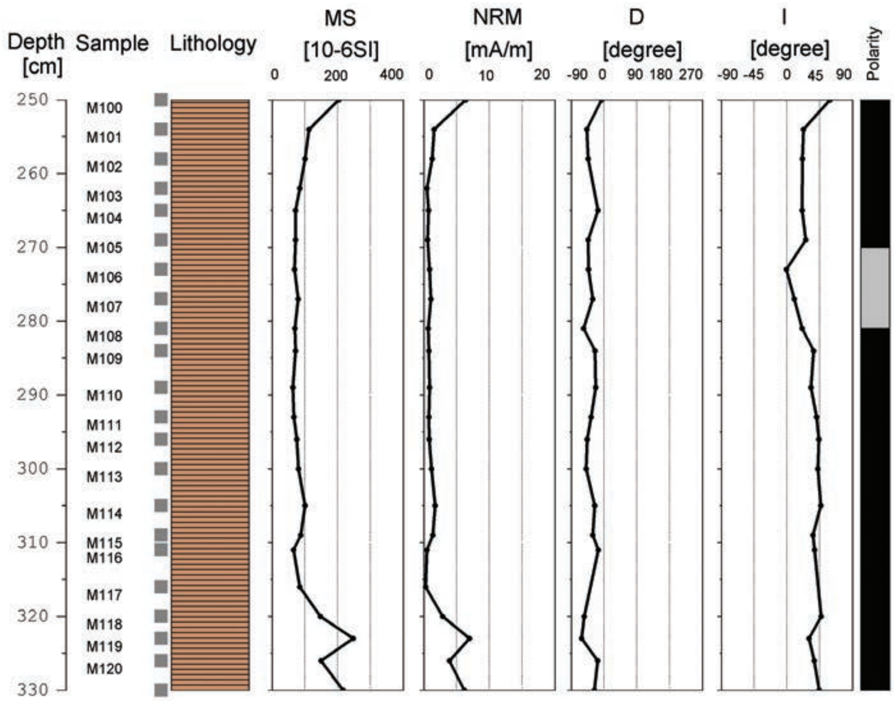

Figure 226 *Basic magnetic and palaeomagnetic properties of profile B, Markov spodmol. Legend: see Figure 37.*

From the values of both sets, the profile may be divided into three parts and categories. Samples are characterized by very low up to low magnetic values of J_n and k_n. The stereographic projection of the *C-HFC* with N polarity is shown on Figure 224. Table 64 summarises results of the mean direction of samples from this profile. The mean palaeomagnetic directions of C-components for the N polarity are D = 329°, I = 38°.

Systematic acquisition of palaeomagnetic data within both studied profiles allowed the construction of detailed magnetostratigraphic profiles (Figs. 225 and 226). The profile A showed N palaeomagnetic direction. There are also shorter excursions (R) or transient polarized zones (N–R) in the long N magnetozone. **The profile B** showed only N palaeomagnetic direction.

DISCUSSION OF RESULTS

The palaeomagnetic and magnetostratigraphy results we obtained showed that the profile in Markov spodmol is composed at least of three different sequences. Interpretation of palaeomagnetic and lithological features indicates, that:

There are 4 different lithological units: (a) upper laminated clays (sequence I), (b) multi-coloured clays with grey band at the top with sandy band above the base (sequence III), (c) sand to gravel (sequence IV), (d) lower laminated clays (sequence IV). There are two prominent unconformities: at samples No. M 40 and M 49 and at the base of layer c. The boundary at M 40 is expressed by a two cm thick multi-coloured zone and was most probably *in situ* weathered before the deposition of upper laminated sequence, so may represent prominent break in the deposition.

The profile contains several unconformities, which can be detected also by the changes in bedding inclination and/or distinct erosion features (channels with cross-bedded arrangement of basal sediments).

In the upper part, the profile A show N magnetic polarization, but in the lower part there are three strongly expressed R magnetozones. The profile B shows only N magnetic polarization. R polarized zones occur in the section of abrupt lithological change from uniformly laminated silty clays to multi-coloured clays and sands with gravel fill of erosion channel in yellowish brown clays. The age of the fill can be interpreted as follows: the upper laminated clay was deposited within the normal Brunhes chron, the multi-coloured clays and sands/gravels were deposited in Matuyama or Gauss chrons, and the lower laminated clay is older than the middle sequence. Traces of *in situ* weathering in the lower part of the profile indicate a quite prolonged hiatus in deposition. The creation of a weathered zone under subsurface conditions needs prolonged time and warm/humid external climate. The weathering supports a rather higher age of the profile.

Post-depositional changes of the profile were quite strong. The principal change was represented by percolation of fluids which caused alteration and deposition of iron-containing compounds in the form of Liesegang features. The alteration is exceptionally strong at the left cave wall. The sediment continued its compaction after the deposition of top flowstone cap. Immediately below it, there is yellow plastic clay (about 5 cm) resulting from deposition from younger floods (sandwiching). The remains of cemented pebbles at the base of the flowstone cap indicate that (a) the profile was much thicker, continued by a new cycle of gravel deposition, and/or (b) sandwiching could occur not only in the phase depositing yellow clays.

The situation in the cave indicates that it was filled with coarse-grained gravels and fine-grained sediments in the past. The old fill was partly or entirely eroded away. Coarse-grained sediments with well-rounded pebbles up to 5 cm in size are still present in places. Thick flowstone domes were deposited on the preserved sediments in some places. Sedimentary material was derived from flysch source rocks.

Main channel in the Markov spodmol. Remains of the yellow allogenic sediments are seen below the younger limestone pebbles.

HRASTJE

SITE LOCATION AND CHARACTERISTICS

A sediment profile was taken at Profile No. 207 (45°50´46.02˝N; 15°08´59.01˝E; 360 m a.s.l.) of highway construction in the section, Hrastje-Lešnica, on the pass between Karteljevo and Novo mesto in the Dolenjska region (Figs. 24, 227 and 228).

The carbonates belong to the Upper Jurassic white to grey limestones, oolitic limestones and thin-bedded limestones with chert, with stratal dip to the east/north-east (Pleničar, Premru & Herak 1977). Karstified limestones are covered by several meters of grey, yellowish-brown to red laminated sediments.

Figure 227 *Site location; Hrastje (SE Slovenia).*

Figure 228 *Construction of the highway north of Novo mesto has exposed profile of the laminated grey sediments, which were covered by red soil. The profile lies behind the drilling machine in the middle of the photo.*

Figure 229 *Grey laminated sediments of the Hrastje profile.*

PROFILE

LITHOLOGY

The profile of laminated sediments 383 cm thick (Fig. 229) was composed mostly of clays and silty clays with interbeds and bands to laminas of clayey-sandy and clayey silts. The colour of the sediments was dominantly grey, sometimes brown and beige mottled and with yellowish brown lamination (Fig. 230). Finds of gastropod shells, plant remains and plant roots were concentrated in the lower half of the profile (Fig. 231). Structures of protopalaeosols (mottled zone with plant roots and iron rich geodes – ferruginized plant roots) occurred in the same section.

PALAEOMAGNETIC RESULTS

A total of 34 samples from Hrastje profile were studied for their palaeomagnetic properties (Tab. 65). They are characterized by NRM intensities between 3 and 27 $mA.m^{-1}$ and MS values from 101 to 494 x 10^{-6} SI units. Based on both sets of values, the profile may be divided into two parts and categories. Samples are characterized by low up to intermediate J_n and k_n magnetic values. Only one sample with R polarization is

Figure 230 *The upper part of the Hrastje profile.*

Figure 231 *The lower part of the Hrastje profile.*

characterized by a high NRM (1,973 $mA.m^{-1}$) and MS (5,060 $x10^{-6}$ SI units).

Three components were isolated after AF demagnetization. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–5 up to 10 mT). The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF (ca 15–80 up to 100 mT). The stereographic projection of the C-components with N polarity is shown in Figure 232. Table 66 summarizes results of the mean direction of samples from this profile.

The mean palaeomagnetic directions of C-components for the normal polarity are D = 7°, I = 49°. Palaeomagnetic directions for one sample of R polarity are D = 212°, I = - 40°, but statistical parameters of α_{95} and *k* can be calculated for one sample only. The systematic acquisition of palaeomagnetic data within the studied section allowed the construction of a detailed magnetostratigraphic profile (Fig. 233).

Table 65: Mean palaeomagnetic values and standard deviations, Hrastje

Hrastje	J_n [$mA.m^{-1}$]	k_n x 10^{-6} [SI]	Interval [m] *
Mean value	7.745	183.5	0–3.707
Standard deviation	5.005	77.2	
Number of samples	33	33	
Mean value	1,972.87	5,060.0	3.827
Standard deviation	-	-	
Number of samples	1	1	

* from top to base

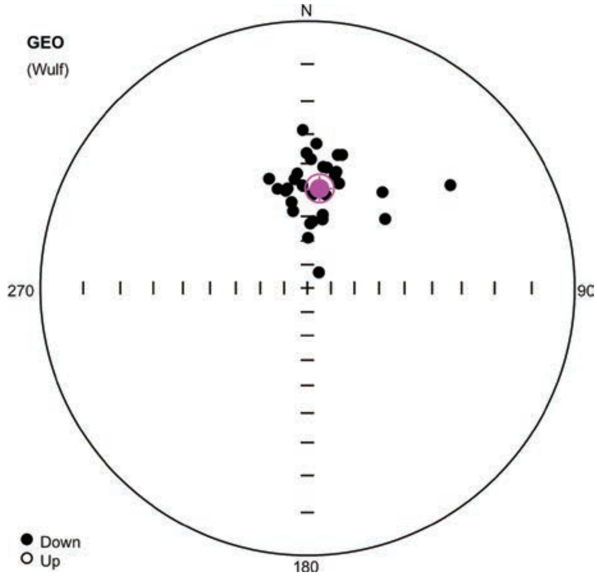

Figure 232 *Directions of C-components of remanence of samples with N polarity, Hrastje profile. For detail description see Figure 34.*

Table 66 Mean palaeomagnetic directions, Hrastje

Hrastje	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	6.93	48.9	5.11	23.46	32
	R	212.4	-39.7	-	-	1

DISCUSSION OF RESULTS

The laminated clays and silts were deposited in a very calm sedimentary environment. The whole profile is N polarized except the last sample, which is R. The uniformity of palaeomagnetic parameters indicates quite rapid deposition. Without results of palaeozoological (gastropods) and palaeobotanical (plant remains) determinations, there can be three possible interpretations of the age: (1) the deposition took place within the Brunhes chron (< 780 ka), or at the Brunhes/Matuyama boundary (780 ka), which then must be placed between 3.71 and 3.8 m; (2) the R polarization represents some of the excursions within the N polarized magnetozone, and (3) the profile can be older than the Brunhes chron.

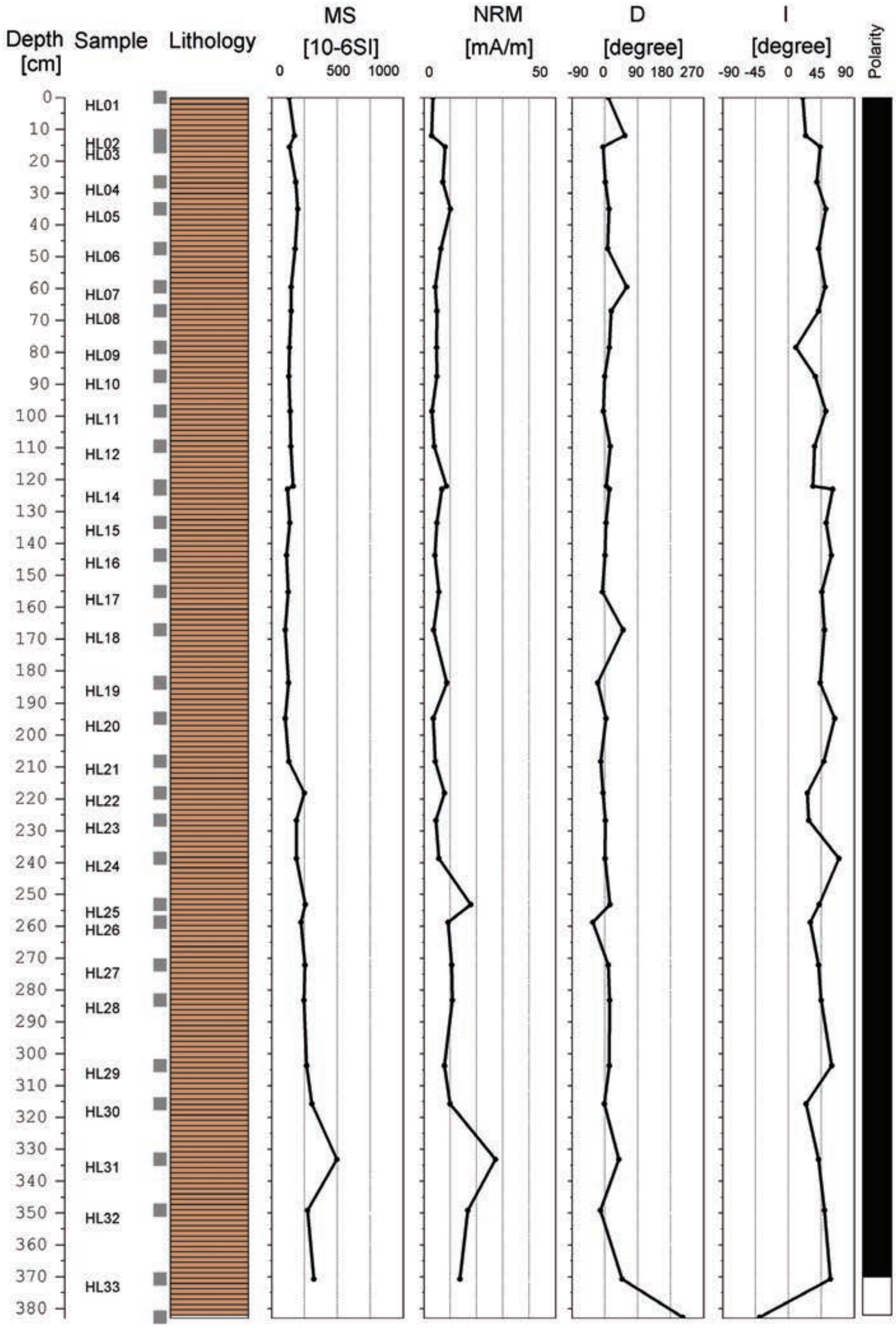

Figure 233 *Basic magnetic and palaeomagnetic properties, Hrastje profile. Legend: see Figure 37.*

JAMA POD BABJIM ZOBOM

SITE LOCATION AND CHARACTERISTICS

Jama pod Babjim zobom (Reg. No. 129; 46°19´33.12˝N; 14°04´20.84˝E; 860 m a.s.l.; Fig. 234) is situated in the valley of the Sava river on the western slope of the Jelovica plateau (Fig. 235). The valley is a karst canyon between two high karst plateaus with numerous dolines and altitudes above 1000 m a.s.l., Pokljuka on the north-west and Jelovica on the south-east (Fig. 25). The valley was glaciated and modified by a glacier from Bohinj valley.

The cave entrance lies under the vertical walls of the upper part of the Jelovica plateau. Below the entrance of the cave scree slopes descend to the valley bottom, where the Sava river flows at 460 m a.s.l.

The cave was formed in the Upper Triassic limestones with dolomites and with a strata dip at 20° towards the south (Grad & Ferjančič 1974).

Jama pod Babjim zobom is 360 m long and 50 m deep. It consists of a horizontal passage and younger vadose shafts which pass through it. The mainly horizontal gallery extends eastwards along the strike with an average width of about 15 m. There are abundant speleothems (Gams 1962). Several types of calcite crystals cover walls and fill wall niches and ceiling pockets. There are no traces of Pleistocene glacial sediments or inflow to the cave, although the entire Sava valley was filled with the Bohinj glacier.

PROFILE

The analysed flowstone profile is situated on the wall at the end of the cave (Fig. 236).

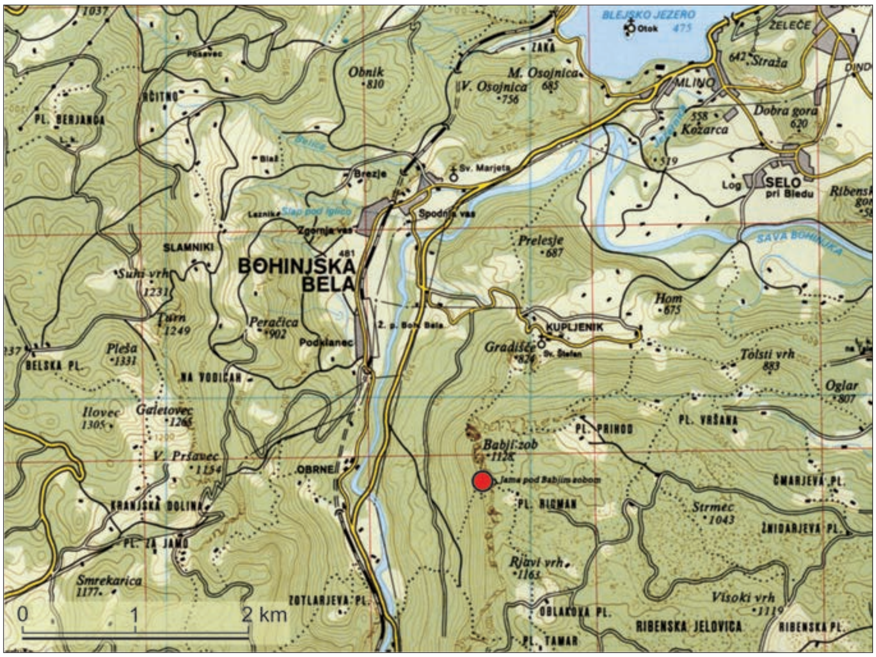

Figure 234 *Site location; Jama pod Babjim zobom (NW Slovenia).*

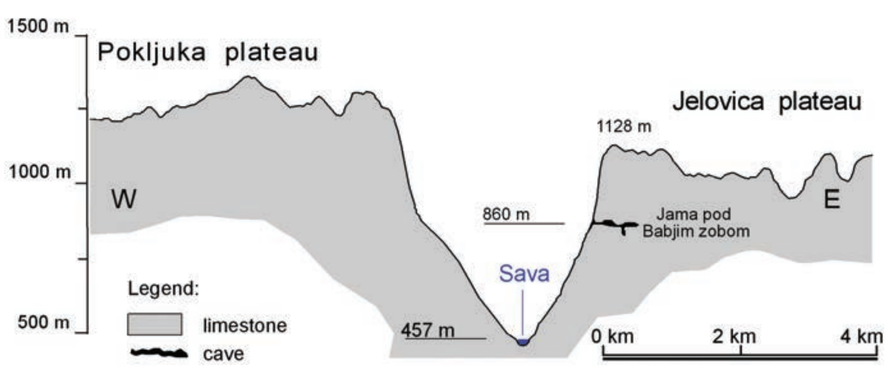

Figure 235 *Position of Jama pod Babjim zobom on the Jelovica plateau.*

Figure 236 *Position of the profile on the cave map, Jama pod Babjim zobom (after Cave Register IZRK ZRC SAZU and JZS).*

Figure 237 *The flowstone profile in Jama pod Babjim zobom.*

LITHOLOGY

The section of flowstones and speleothems, about 2.2 m high (Fig. 237), was composed of: (1) flowstone and stalagmite, white, yellowish in lower part, coarse-

Figure 238 *Drilling for the speleothem samples, Jama pod Babjim zobom.*

crystalline, laminated, (2) flowstone, white, yellowish in lower part, coarse-crystalline, laminated; (3) flowstone, brown, medium-crystalline, laminated, and (4) flowstone, massive, crystalline, columnar. Samples were mostly drilled out as solid cores (Fig. 238).

PALAEOMAGNETIC RESULTS

All samples from the Jama pod Babjim zobom profile were subjected to detailed AF demagnetization in 14 steps. Multi-component analysis was applied to separate the respective RM component for each sample. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–2 to 5 mT). The characteristic *C-HFC* is stable and can be demagnetized or isolated in the AF (ca 15–80 to100 mT). The mean values of J_n and k_n moduli are documented in Table 67.

Table 67 Mean palaeomagnetic values and standard deviations, Jama pod Babjim zobom

Jama pod Babjim zobom	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	2.200	32.7	0.01–0.22
Standard deviation	1.060	36.8	
Number of samples	5	5	
Mean value	1.675	64.5	0.96–1.26
Standard deviation	1.180	61.2	
Number of samples	12	12	

* from top to base

The mean value of the NRM is 0.0017 ± 0.0011 A.m^{-1} and the respective MS value is 52 ± 55 x 10^{-6} SI units. Stereographic projections of the C-component with N and R polarity are shown in Figures 239 and 240. Table 68 summarizes results of mean direction of samples from this profile. Mean palaeomagnetic directions of N polarized C-components for this profile are D = 343°, I = 51° and of R polarized C-components are D = 204°, I = -54°. The basic magnetic parameters are documented for 19 samples in Figure 241.

The flowstone profile consists of two parts. The upper one contains an N polarized magnetozone and the lower one has R polarization.

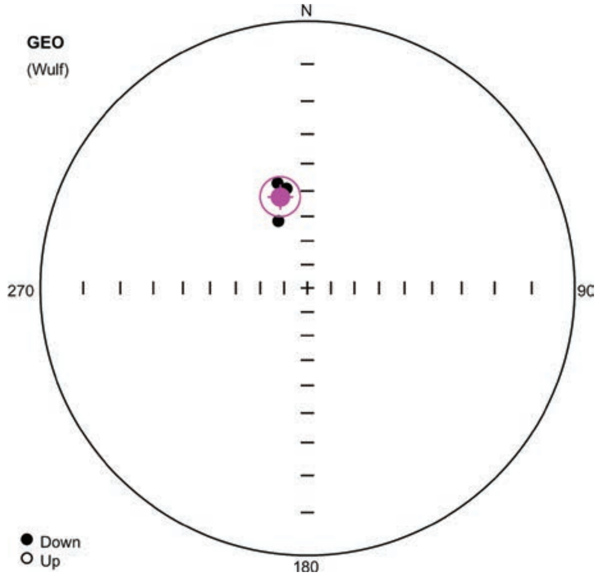

Figure 239 *Directions of C-components of remanence of samples with N polarity, Jama pod Babjim zobom. For detail description see Figure 34.*

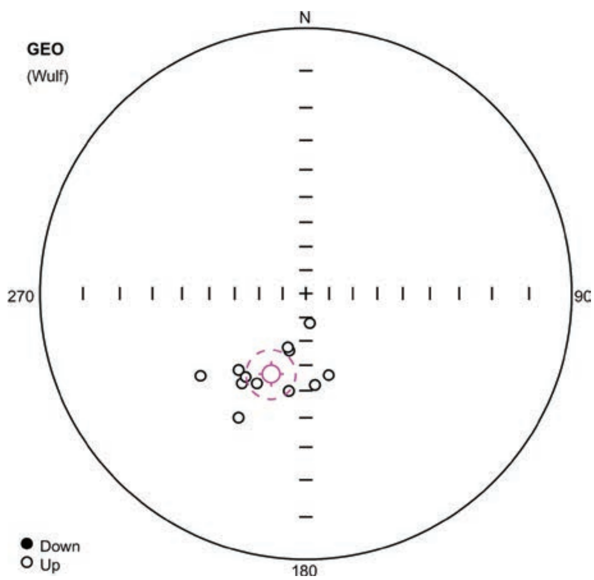

Figure 240 *Directions of C-components of remanence of samples with R polarity, Jama pod Babjim zobom. For detail description see Figure 34.*

Table 68 Mean palaeomagnetic directions, Jama pod Babjim zobom

Jama pod Babjim zobom	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	343.39	50.86	5.76	147.45	4
	R	203.54	-53.67	8.73	21.45	12

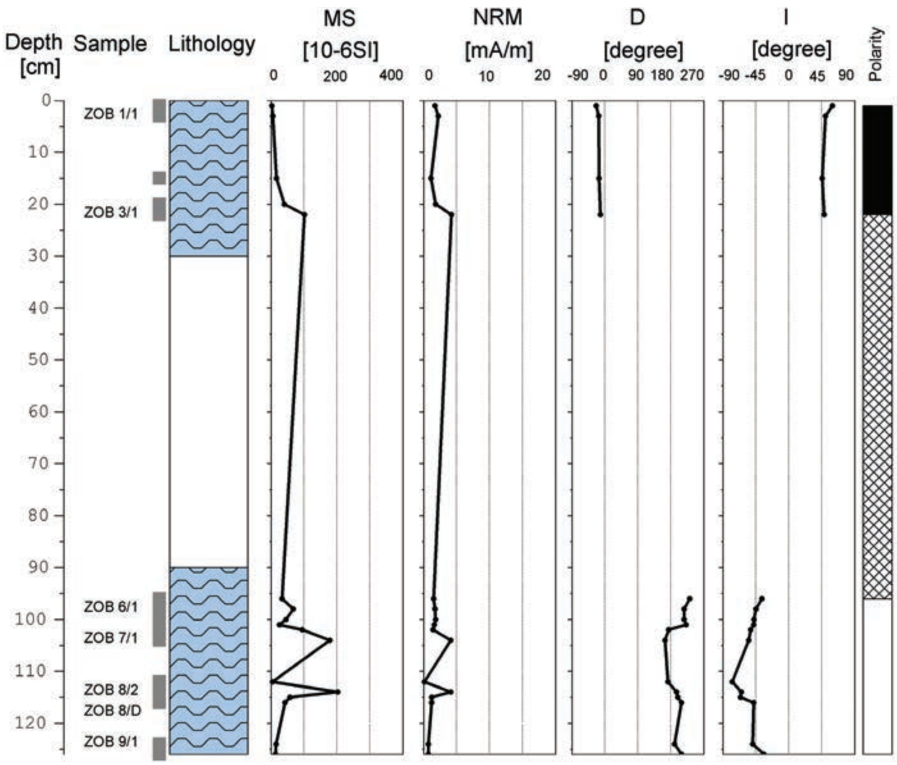

Figure 241 *Basic magnetic and palaeomagnetic properties, Jama pod Babjim zobom. Legend: see Figure 37.*

DISCUSSION OF RESULTS

The origin of the cave is complex. It was probably formed before the Sava river entrenched some 650 m and separated the Jelovica plateau from the Pokljuka plateau, i.e. probably around the Miocene/Pliocene boundary. The cave could have been genetically connected with some stage in the evolution of surface on the Jelovica plateau, probably along a zone of mixing of meteoric and hypogene (hydrothermal) waters. The hypogene waters came from below, like some of the recent thermal springs existing in this general region. It is possible that the earliest stage was entirely hypogenic. The large calcite crystals (scalenohedrons) on walls of some copula-like niches in walls and cave roof and special features of some other speleogens support this idea (Fig. 242). Crystallization of large scalenohedrons and deposition of some other speleothem types probably originated from degassing of up-welling thermal waters. Nevertheless, not all scalenohedral calcite crystals are thermal in origin. Smaller scalenohedrons were developed in cave pools and gours during later cave evolution, which resulted from cold water speleogenesis in epiphreatic conditions. This phase contributed to some remodelling of the cave, especially of vertical shafts, although hypogenic speleothems have been preserved. Fine-grained cave sediments were also deposited. The massive speleothems and some vadose shafts were formed in vadose conditions. Evolution of the vadose elements was connected with the entrenchment of the Sava river-bed. Deposition of the massive vadose speleothems cannot be correlated with the recent climatic conditions at their present elevations (Gams 1962).

The interpretation of palaeomagnetic data can easily support ages greater than 780 ka in spite of quite high degree of speleothem recrystallization.

Figure 242 *Big calcite crystals in niches, which were later exposed by formation of younger passage, belong to older (hypogenic) stage of the cave development.*

SPODMOL NAD PLANINO JEZERO

SITE LOCATION AND CHARACTERISTICS

Spodmol nad Planino Jezero (Reg. No. 9057; 46°18´39.02˝N; 13°49´22.55˝E, 1535 m a.s.l.; Figs. 25 and 243) is a remnant of a presumably old cave system that was breached by a small Pleistocene glacial valley. The karst depression is filled with glacial till, and a small lake (Jezero) is situated below cave entrance (Jamnik 1999).

The cave was formed in Upper Triassic Dachstein limestones with dolomites. Strata dip towards southwest (Buser 1987).

The entrance to the cave is in a four m high overhang on a narrow ledge in the cliffs about 50 m above dry bottom of the valley (Fig. 244). The cave has a simple horizontal passage about 2 m high, 1.5–2

Figure 243 *Site location; Spodmol nad Planino Jezero (NW Slovenia).*

Figure 244 *Entrance to the cave Spodmol nad Planino Jezero (left entrance).*

m wide and 15 m long. Passage walls in the entrance show traces of frost action, generating gravel on the bottom. A well-developed roof channel is preserved in the cave ceiling. The passage terminates in sedimentary fill (Fig. 245).

PROFILE

The profile of sediments in the terminal choke of the cave was sampled (Fig. 246); it was about 1.7 m high and 1.5 m wide, situated on the southern side of the passage.

LITHOLOGY

The studied profile consisted of three distinctly different sets of sediments: **(1) quartz sands** with bands of darker and lighter colour filled the lower part of the profile. Sand grains were smaller than 1 mm. Some cemented layers occurred in the lower left part of the profile. Cemented gravel with some clay interbeds were below sands on the contact with the western wall. There were plastic deformations, possibly during the compaction; **(2)** a **mixture of sands and clays** overlain sands with a probable erosional contact. Clayey bands were thinner than sandy ones. Strata showed some distinct sedimentary structures (sand-filled erosion channels in laminated sediment, sandy intercalations, etc.), and **(3) a top clay**, which filled both the roof channel and space between sands and the wall.

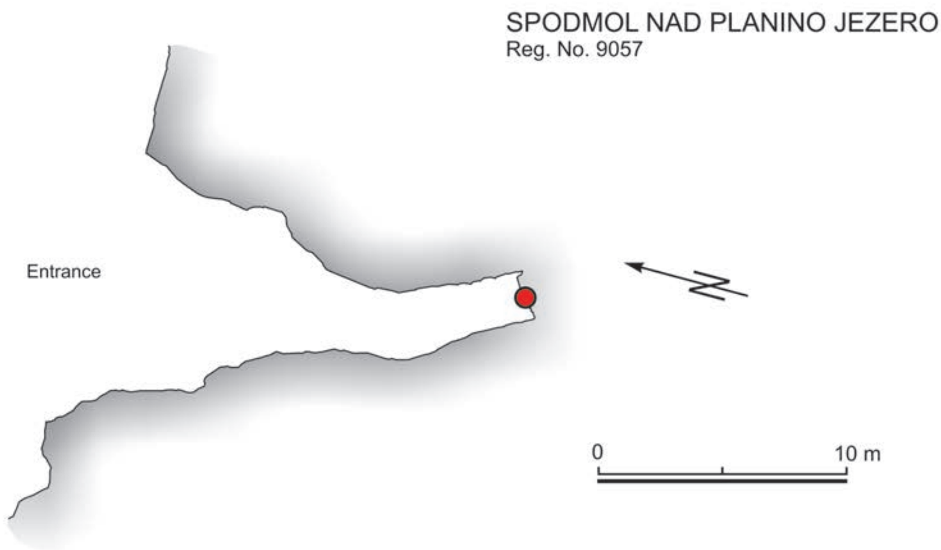

Figure 245 *Position of the profile on the cave map, Spodmol nad Planino Jezero (after Cave Register of IZRK ZRC SAZU and JZS).*

Figure 246 *Profile of sediments in Spodmol nad Planino Jezero.*

PALAEOMAGNETIC RESULTS

A total of six samples (Fig. 247) were studied for their palaeomagnetic properties. The NRM (J_n) and MS (k_n) values in their natural state show small scatter. The mean values J_n and k_n moduli are documented in Table 69.

The sediments are characterized by very low NRM intensities between 0.5 and 1 mA.m^{-1} and MS

Table 69 Mean palaeomagnetic values and standard deviations, Spodmol nad Planino Jezero

Spodmol nad Planino Jezero	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	0.775	-10.95	0.09–0.60
Standard deviation	0.20	0.64	
Number of samples	6	6	

* from top to base

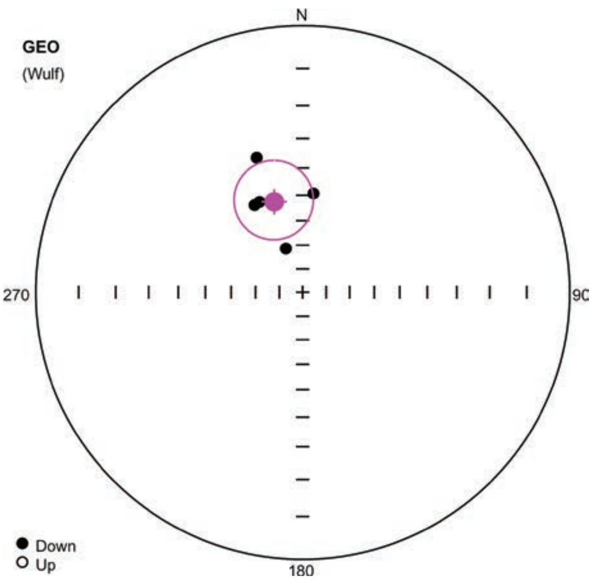

Figure 248 *Directions of C-components of remanence of samples with N polarity, Spodmol nad Planino Jezero. For detail description see Figure 34.*

Figure 247 *Detail of sediments with the samples for paleomagnetic analyses, Spodmol nad Planino Jezero.*

Table 70 Mean palaeomagnetic directions, Spodmol nad Planino Jezero

Spodmol nad Planino Jezero	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	342.54	50.87	12.06	26.94	5

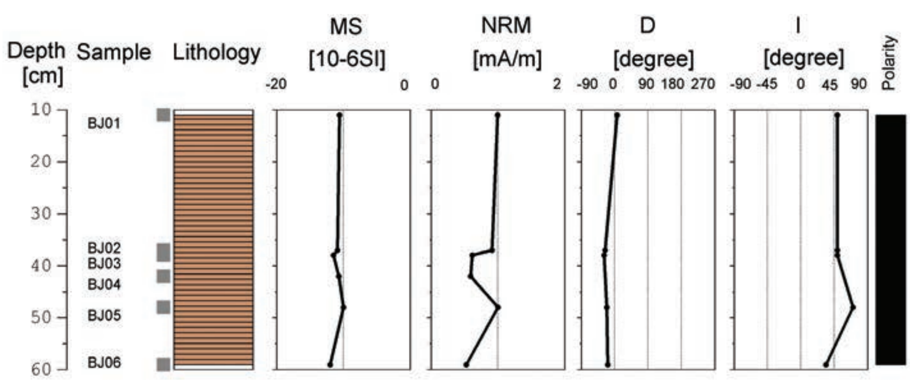

Figure 249 *Basic magnetic and palaeomagnetic properties, Spodmol nad Planino Jezero. Legend: see Figure 37.*

values from -12 to -9 x 10^{-6} SI units (paramagnetic mineral). All samples were subjected to detailed AF demagnetization in 14 steps. Multi-component analysis was applied to separate the respective RM components for each sample. Two components were isolated after the AF demagnetization. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–5 mT). The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF (ca 10–65 up to 80 mT).

The stereographic projection of the C-component with N polarity is shown in Figure 248. Table 70 summarizes results of the mean direction of samples from this profile. The basic magnetic parameters are documented for the six samples in Figure 249. The mean palaeomagnetic directions of C-components give normal polarity (five samples) are D = 343°, I = 51°, the characteristic C-component of one sample could not been determined.

All samples were subjected to detailed AF demagnetization in 14 steps. Multi-component analysis was applied to separate the respective RM components for each sample. Two components were isolated after the AF demagnetization. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–5 mT). The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF (ca 10–65 up to 80 mT).

DISCUSSION OF RESULTS

The cave is too short to offer a good understanding of the hydrologic system to which it belonged. It was formed under phreatic conditions and later was completely filled with clastic sediments. Sediments were finer-grained towards the end of filling, forming a typical upwards-fining sedimentary cycle. Because the top clay filled narrow openings between the already at least partially compacted sediment and cave walls and roof channel, it seems that the top clay deposited when the passage was almost completely filled. When the cave was completely filled, a paragenetic roof channel 30 cm wide and about 50 cm high developed, which was later filled by clay.

Opening of the passage in the side of the glaciated dry valley occurred probably in the last glacial cycle, when the glacier deepened the valley and eroded its walls. Following that the cave fill was washed out or slid out, making passage accessible.

The entire profile (0.6 m) is N polarized: no R polarization was found. Although the samples could be dated within the N polarized Brunhes chron, (i.e. younger than 780 ka), they are probably much older, and belonging to some other N polarized subchron or chron. This interpretation is supported by the substantial lithification of the sediment and the geomorphic position of cave in the landscape.

Scree on the W slope of Ograda (1928 m) in Julian Alps.

SNEŽNA JAMA

SITE LOCATION AND CHARACTERISTICS

Snežna jama (Reg. No. 1254; 46°23´55.94″N; 14°44´ 29.78″E; 1556 m a.s.l.; Figs. 26 and 250) is a horizontal cave 1,600 m long, situated in the southern slopes of the Raduha ridge to the south of the highest summit (Velika Raduha, 2062 m a.s.l.). The Raduha represents the north-eastern part of the Kamnik–Savinja Alps, but is separated from the main massive by the deep valley of the Savinja river. The cave entrance is on the south-western slope of the Raduha (Fig. 251) about 900 m above the Savinja river (Naraglav & Ramšak 1990).

The cave was formed in the Upper Triassic massive and thick-bedded limestones with stratal dip towards south/south-west (Mioč et al. 1983).

The main part of the cave consists of a large, mostly horizontal, gallery at 1500 to 1600 m a.s.l., which is penetrated by four large invasion vadose shafts. The cave is entered through one of them. The shafts are important features because strong airflow brings cold air into the cave. Therefore, permanent ice can form and stay in the entrance part of the cave. A collapse terminates the cave close to the vertical northern edge of the Raduha massif (Fig. 251).

Fluvial sediments and large flowstone masses were deposited in the main gallery of the cave. In one part of it a profile of fluvial sediments more than 10 m in height is preserved. The deposits consist of laminated clays and sands with well-rounded pebbles up to 30 mm in size. Allochthonous pebbles mostly composed of andesite tuffs and tuffites prevail, while poorly-rounded autochthonous limestone pebbles are less frequent. The allochthonous deposits possibly came from Smrekovec mountain east of the Raduha. At the present time, the contact of volcanic and volcaniclas-

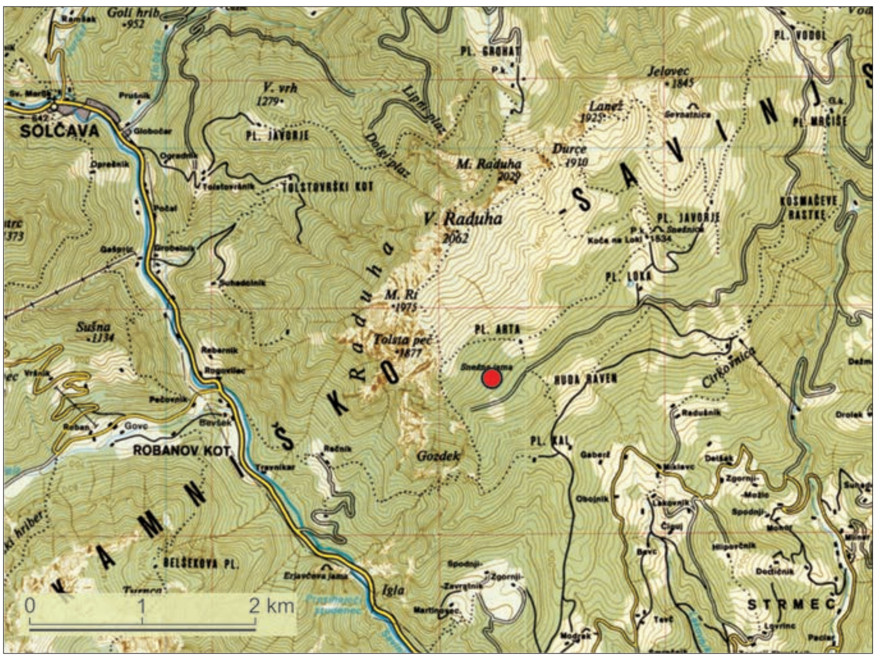

Figure 250 *Site location; Snežna jama (N – central part of Slovenia).*

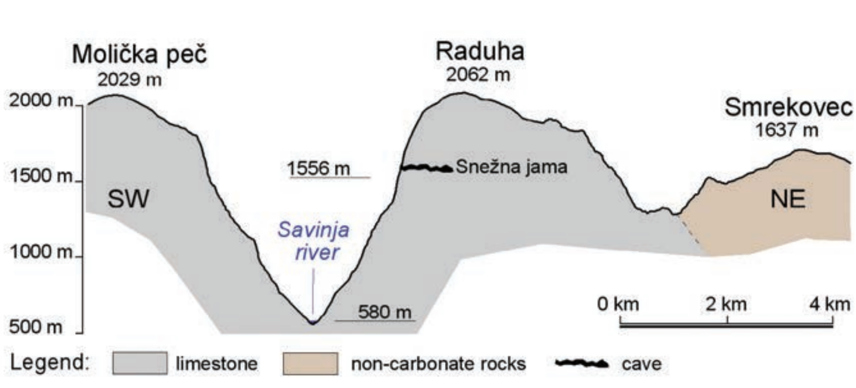

Figure 251 *Schematic cross-section of the Raduha Massif with the position of the Snežna jama (after Bosák et al. 2002b, with permission).*

tic rocks with limestones lies one km southeast of the cave, but at elevation of 350 m below it.

In the main gallery of the cave, large flowstone masses were deposited over the older sediments. Speleothems, large flowstone domes and massive stalagmites covered nearly the entire surface. Massive flowstone was deposited also in some of the vadose shafts, and was later corroded away, leaving some traces only. There is no deposition of flowstone in the present climatic conditions in the cave or in other caves at the same altitude. The flowstone is severely damaged by frost activity in the entrance section of the cave due to the strong and cold airflow from vadose shafts. Speleothems were broken away and displaced by cryoturbation. The influence of frost and cryogenic damage on speleothems and cave walls in the past can be seen throughout the whole cave. In the cave average the annual temperature today is about 4.5 °C. Speleothems are absent in the terminal part of the cave, where the gallery was interrupted by an extensive collapse. A skeleton of *Ursus spelaeus* was found here. The cave bear could not enter the cave through the current entrance, so there had to be another entrance in the terminal part of the cave, which also permitted air movements and cooling of the cave.

PROFILE

The speleothem profile is situated in the inner part of the chamber, Ledena dvorana, about 90 m from the entrance to the cave and at a depth of about 45 m (Figs. 252 and 253).

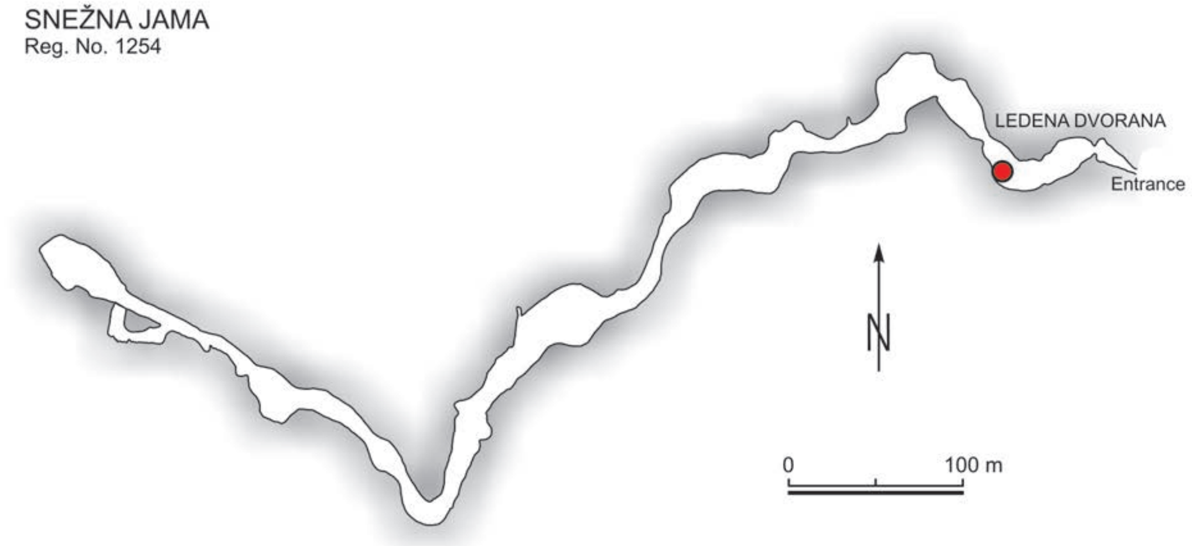

Figure 252 *Profile position on the cave plan, Snežna jama (after Cave Register of IZRK ZRC SAZU and JZS)*

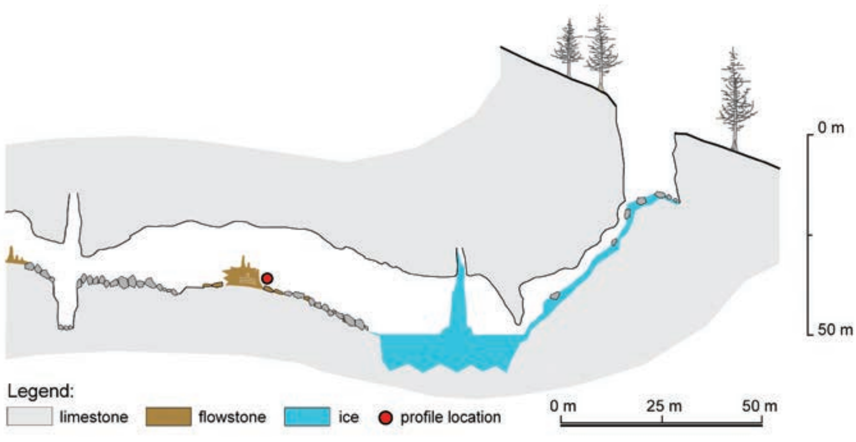

Figure 253 *Cross-section of the entrance part of the Snežna jama with the position of studied profile (after Bosák et al. 2002b, with permission).*

LITHOLOGY

Speleothems were deposited in a complex sequence of flowstones with numerous breaks in deposition; there are six principal flowstone layers. The lower part of the profile contains abundant terrigeneous components (most probably clay of terra rossa-type). Stalagmites developed in several of the older periods were completely buried by nearly horizontal younger sequences of flowstone. Some stalagmites were buried even after breakage. Approximately 2.4 m of flowstone were sampled continuously in three successive profiles (Figs. 254 and 255). Profile No. 3 was situated in a basal part of the sequence (4–52 cm). Profile No. 2 was situated in the lower part of the sequence (42–85 cm) terminating on an important unconformity plane within the speleothems and overlapping 10 cm with the previous profile. Profile No. 3 was composed of three individual sections in the middle and upper parts of the sequence. Above the main wall, there were several layers of speleothems representing the top of the sequence, which are not shown on the drawing in Figure 254.

The lower part of the profile (0–85 cm) was composed of mostly reddish brown to brownish red, sometime light brown, flowstone with some grey bands and reddish brown lamination. It was mostly fine-crystalline and often fenestral (porous to vuggy). Porous bands alternated with massive beds in some sections of the profile. Fenestral structures were coated by fine-crystalline and 1–2 mm thick palisade calcite. The remaining profile was composed of light-coloured flowstones (beige, light ochre, light grey, honey-coloured), laminated to banded, partly re-crystallized with bands composed of columnar calcite crystals. Regular alternation of laminated bands, bands with columnar structure, and highly porous bands occurs in places. The porous bands resembled lithified moonmilk layers. Some layers were corroded, especially in the upper part of the profile, and vugs were coated or filled with fine hedgehog-like wall coatings or hedgehog crystal aggregates. Some bands had a chalky appearance and others were pseudo-oolitic at their bases. One thin intercalation of light brown, fine-grained clayey-silty sand was detected at 145 cm.

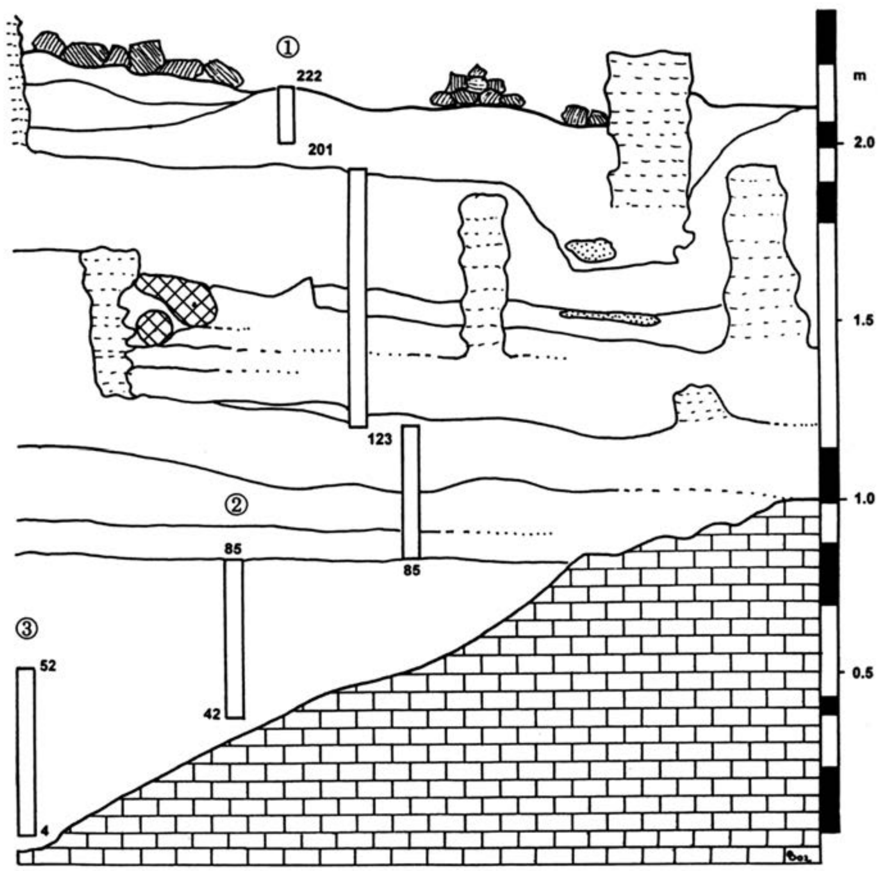

Figure 254 *Snežna jama, schematic sketch of the flowstone profile (after Bosák et al. 2002b, with permission). Legend: dashed – stalagmites; cross shading – broken stalagmites; dotted – cavities;← to → – sampling profiles, numbers refer to the height in cm above the profile base; magnetostratigraphy log on the right side: white – reverse magnetic polarity, black – normal magnetic polarity).*

Figure 255 *The flowstone profile in Snežna jama.*

PALAEOMAGNETIC RESULTS

The Snežna jama flowstone profile was the first example of a high-resolution magnetostratigraphic profile sampled in Slovenia. Continuous columns of flowstone cut by circular saw were divided in the lab into continuous sets of laboratory specimens (cubes). A total of 98 samples were studied for their palaeomagnetic properties. Values of the NRM moduli (J_n) and those of the MS (k_n) show a large scatter. The flowstones are characterized by very low up to high J_n and k_n magnetic values. The NRM intensities are between 0.2 and 523 mA.m-1, and the MS values between -13 and 324 SI units (Tab. 71). Based on both sets of values, the profile may be divided into four parts.

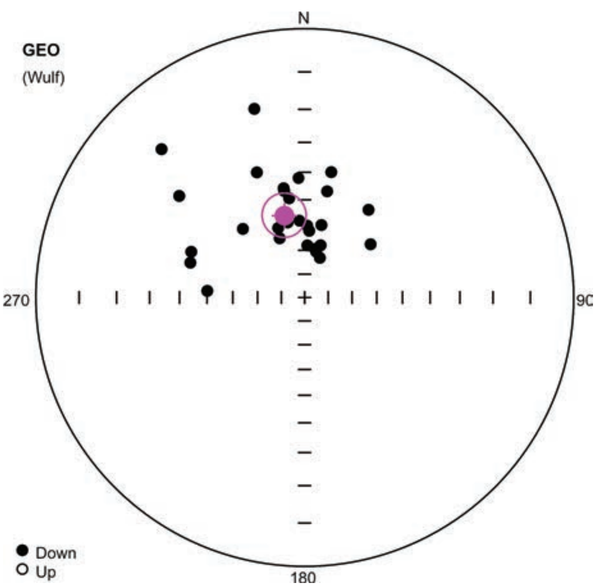

Figure 256 *Directions of C-components of remanence of samples with N polarity, Snežna jama. For detail description see Figure 34.*

Table 71: Mean palaeomagnetic values and standard deviations, Snežna jama

Snežna jama	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	1.318	-3.75	2.38–1.07
Standard deviation	1.740	11.14	
Number of samples	61	61	
Mean value	62.677	10.08	1.03–0.91
Standard deviation	35.513	13.29	
Number of samples	5	5	
Mean value	241.020	215.38	0.83–0.37
Standard deviation	111.792	47.25	
Number of samples	24	24	
Mean value	79.307	187.95	0.27–0.07
Standard deviation	20.693	21.86	
Number of samples	10		

* from top to base

The RM directions were tested using a multi-component analysis. A-components of remanence are mostly of viscous or chemoremanent (weathering) origin; they can be removed by AF demagnetisation with an intensity of 1–5 mT. The *B-LFC* is secondary but shows harder magnetic properties and can be demagnetized in the AF (5–10 to15 mT). The characteristic *C-HFC* is stable. It can be isolated in the AF (ca 15–65 to 80 mT).

N and R C-component directions are documented on Figures 256 and 257. The Fisher distribution displays two well-defined sets of samples with N and R polarities (Tab. 72). Magnetostratigraphic results of the samples show both N and R polarity magnetozones (Fig. 258). The top of the profile displays a N magnetozone (227–238 cm). Two narrow N magnetozones (201–205 cm and 179–182 cm) are detected in the long R zone at 115–225 cm). The middle and lower parts of the profile from 7 to 113 cm display two narrow (91–96 cm, 21–37 cm) and one longer (45–70 cm) R polarity zones.

TH/U DATING

Th/U dating was carried out in the Geochronology Laboratory of the Institute of Geological Sciences, Polish Academy of Sciences in Warsaw (Helena Hercman and the lab staff). Results are on Table 73.

All samples are characterized by low U content. As a result the accuracy of analyses is rather low. In addition there was significant contamination by detrital Th in samples W809 and W806 ($^{230}Th/^{232}Th<20$). $^{230}Th/^{234}U$ activity ratios are in equilibrium within the error range (1 standard deviation). $^{234}U/^{238}U$ activity ratios, except the samples with significant detrital contamination, are also in equilibrium within the error range. This suggests ages >1.2 Ma. This conclusion must be accepted with caution, however because low accuracy of the activity ratios. Further proof is needed.

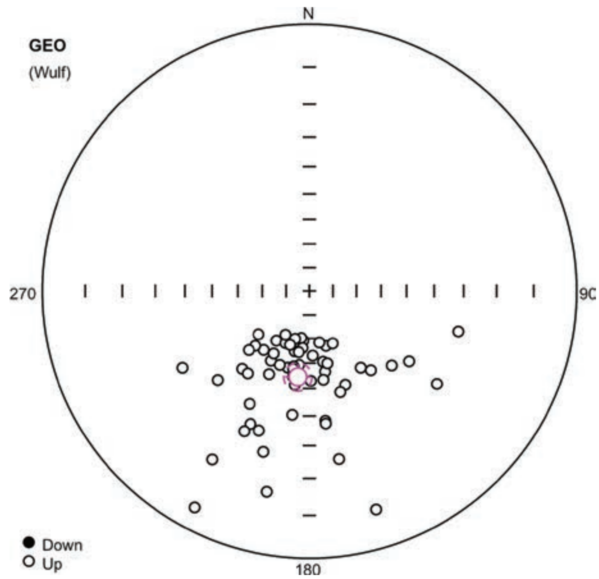

Figure 257 *Directions of C-components of remanence of samples with R polarity, Snežna jama. For detail description see Figure 34.*

Table 72: Mean palaeomagnetic directions, Snežna jama

Snežna jama	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	345.93	55.13	7.94	11.1	28
	R	187.7	-54.27	5.18	11.8	62

Table 73: Th/U dating results using α-spectrometry, Snežna jama

Sample [cm]	Lab. No.	U conc. [ppm]	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Min. age* [ka]	Remarks
117	W 813	0.037±0.019	1.087±0.555	0.976±0.108	23	>300	
121	W 809	0.052±0.009	1.142±0.190	1.042±0.071	10		Significant detrital contamination
125	W 810	0.057±0.006	1.063±0.106	0.969±0.051	60	>300	
129	W 814	0.040±0.010	0.994±0.239	0.913±0.104	40	>200	
131	W 811	0.070±0.010	0.971±0.144	0.987±0.064	72	>300	
147	W 806	0.031±0.007	1.403±0.323	0.926±0.072	6		Significant detrital contamination

* Minimum age calculated basing on activity ratios and their accuracy

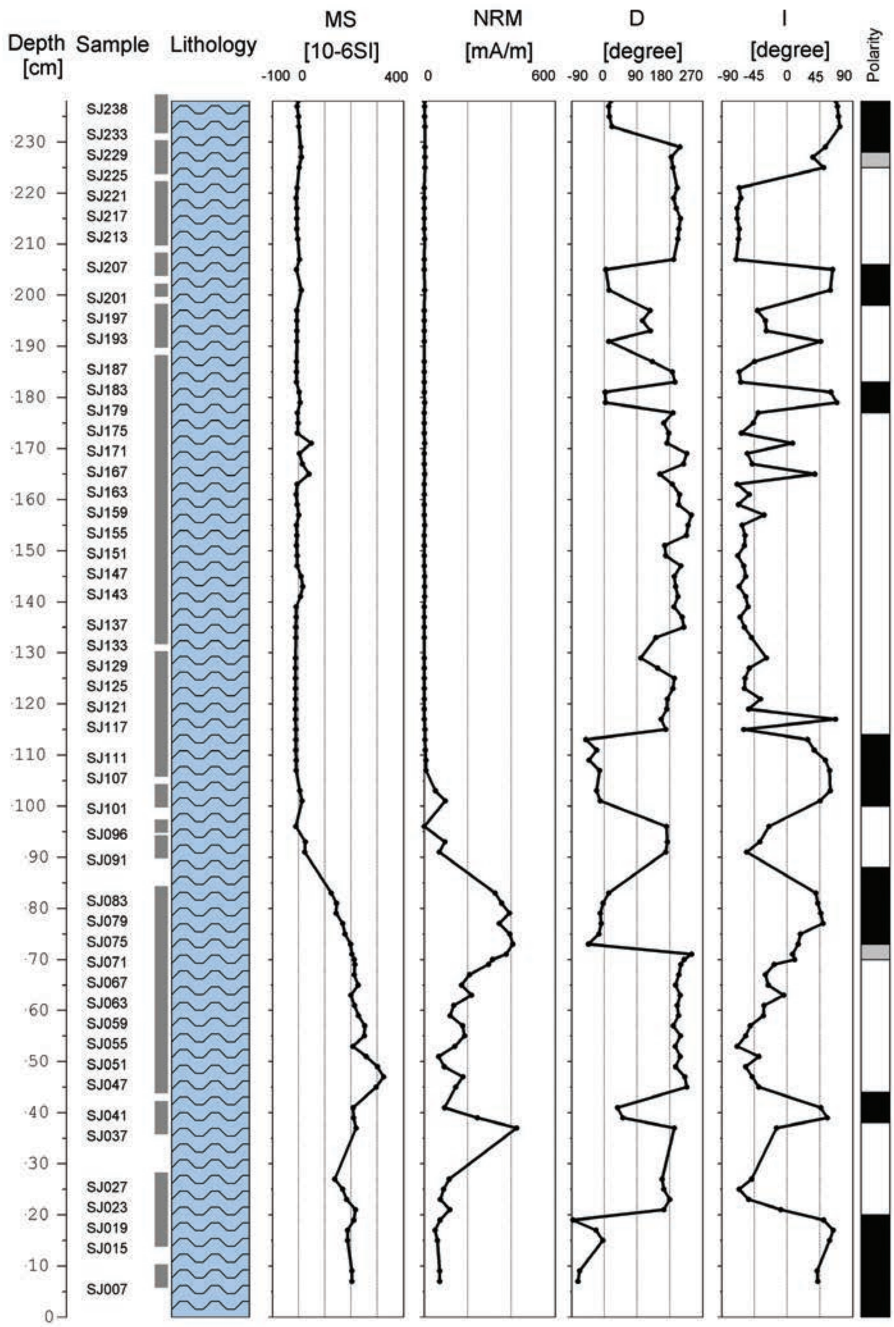

Figure 258 *Basic magnetic and magnetostratigraphic parameters, Snežna jama. Legend: see Figure 37.*

One sample was dated by Stein-Erik Lauritzen (University of Bergen, Norway, alpha spectroscopy, pers. comm. 2000). The detected age was over the limit of the method (i.e. >350 ka).

DISCUSSION OF RESULTS

Snežna jama in the Kamnik–Savinja Alps represents a highly important site from the point of view of cave evolution. A huge and nearly horizontal cave at a substantial altitude represents, without any doubts, a relict of an ancient karstification related to some completely different arrangement of morphology in the Slovenian Alps.

A complex magnetostratigraphic picture was obtained by the high-resolution palaeomagnetic analysis. Dense sampling contributed to the precision of detection of individual subchron boundaries. A total of seven normal polarised zones are separated by six reverse polarised zones. All samples studied are older than 350 or 200 ka according to Th/U dating. Uranium isotopic equilibrium indicates the substantial age of samples, clearly over 1.2 Ma. Any correlation with the GPTS for the Cenozoic (Cande & Kent, 1995) is highly risky especially owing to the fact that there are several unconformities within the profile that could hide substantial periods of time (*cf.* Bosák et al. 2000b). Some of magnetozones detected terminate or start on such unconformities (85, 201 and 222 cm). Some unconformities are expressed by the renewed stalagmite growth on them. The height of the stalagmites (about 50 cm) suggests that the time necessary for the growth of each of them did not exceed several 10^1 ka. Further stalagmites will be collected in 2008 to obtain additional samples for palaeomagnetic and stable isotope analyses. It may be supposed that the profile represents a time sequence not younger than the Matuyama chron (1.77 Ma, Olduvai subchron). The profile can be rather more satisfactorily correlated with the Gauss and Gilbert chrons (about 2.6 to 5 Ma). The geometry of individual magnetozones and their arrangement, taking into account also hidden time on unconformities, indicates that the most probable correlation is with subchrons at 3.0 to 5.0 Ma; another acceptable correlation could be 1.8 to 3.6 Ma. Both possibilities indicate that the growth of the speleothems took place over an approximately equal time span of 1.8 to 2.0 Ma, which gives mean speleothem growth rates of about 1.1 to1.3 m per 1 Ma.

The distribution of the NRM (J_n) and total MS (k_n) indicates deposition of the sequence in two distinct parts (Fig. 258). The lower part of the profile has substantially higher NRM values. This unit is composed of banded brown speleothem with high content of terrigeneous-derived material resembling reworked and re-deposited terra rossa-like soil. The upper part, above approx. 103 cm, composed of typical light-coloured banded flowstone sequence, shows negligible NRM values (max. 4 $mA.m^{-1}$). The complete MS curve shows a similar trend. The interpretation of the NRM and κ curves is highly problematic without a final stable isotope curve. If the κ curve represents the reflection not only of the iron content in the terrigeneous influx to the cave, but also the climatic conditions (*cf.* e.g., Sroubek et al. 2001), then we can expect the different palaeo-environmental conditions during the deposition of the two parts of the profile. More detailed evaluation will be possible only after stable isotope analyses are available.

A rough reconstruction of the cave development can be deduced both from the cave morphology and fills and our preliminary results. The main part of the cave was formed as a phreatic/epiphreatic cave containing water table elements with some vadose re-modelling connected mostly with bypassing (e.g., paragenesis). The subterranean flow had an estimated recharge of several cubic meters per second. Both the dimensions and shape of the main cave gallery indicate the stabilization of the karst water level here for a prolonged time period. According to the pebble composition, the catchment area was situated to the southeast of the cave on the Upper Oligocene volcanogenic rocks. The altitude differences of the relief at the time of cave formation can be estimated to 600 m at least, but the hydraulic head in the karst was small.

Pebbles of Miocene rocks were found in the Potočka zijalka (Mihevc 2001a) at a similar elevation about 10 km to the north of the Raduha. The possibility cannot be excluded that both caves were formed in the same prolonged stable period during the Upper Miocene and Pliocene.

Fluvial sediments deposited in Snežna jama were covered by thick speleothems, indicating warm, wet climate and a low altitude for the cave. Flowstones, which can be said to have a low altitude circum-Mediterranean appearance, were deposited in different climatic conditions and/or before the main uplift of the mountain. The deposition of speleothems ceased due to climate change caused by the mountain uplift and/or some other general reasons (climate cycles).

The change of depositional environment that is reflected well in the palaeomagnetic parameters between 85 and 103 cm in the profile represents an important turning point in the evolution of the cave, i.e. the gradual decrease in influx of terrigeneous material from the surface. It seems most probable, that this interval marks the start of entrenchment of the valley system that was initiated by the start of more accelerated uplift of mountains in that part of Kamnik–Savinja Alps, resulting in the detachment of the subterranean river system from its catchment area.

Rapid mountain uplift caused surface river entrenchment and cut off the subterranean karst drainage. Fall of the karst water level for about 900 m created conditions favourable for vertical drainage and origin of invasion vadose shafts most probably connected with melt of glaciers (proglacial caves *sensu* Głazek, Rudnicki & Szynkiewicz 1977). Karst drainage was reorganized and the cave finally became dry (fossilised) and has experienced very little change since. Some vertical shafts simply penetrate the cave, leaving the main passage unchanged, which is comparable with other high mountainous areas, e.g., the Northern Limestone Alps in Austria (Bauer & Zötl 1972; Zötl 1989), Western Tatra Mts. in Poland (Kicińska 2002), Karzhantau Ridge in southern Kazakhstan (Bosák et al. 1985; Bosák 1989a).

The morphological conditions of the Kamnik–Savinja Alps are comparable with another part of the Alpine chain – the Northern Calcareous Alps. As early as 1956 Schauberger discussed the concentration of caves at certain elevations in the Tennengebirge, the Dachstein Massif and the Totes Gebirge. Zötl (1989) reported that the main cave systems in the Dachstein area are found at 1300 to 1500 m a.s.l., i.e. 900 m above the modern local base levels of erosione. Also, caves in the Hegengebirge and the Hochschwab Massif are concentrated at 1300 to 1700 m a.s.l., and 1400 to 1600 m a.s.l., respectively.

In the upper Pleistocene, the denudation of the slopes reached the cave and probably created two entrances. Cave bears could enter the cave through a yet unknown one on the north-western side of the ridge. Cold Pleistocene climate or simply two entrances with strong air circulation caused freezing throughout the entire cave. Recently these processes have been limited to the entrance part only, where there is a subterranean glacier. The frost processes displaced or destroyed thick layers of speleothems.

The time of detachment of Snežna jama from its original hydrological system can be compared with some of other caves in Slovenia, especially with unroofed caves uncovered in the Karst of south-western Slovenia. Magnetostratigraphic data from the Divača profile (Bosák, Pruner & Zupan Hajna 1998), Kozina profile (Bosák et al. 2000a), Črnotiče I (Bosák et al. 1999) and Črnotiče II (Bosák, Mihevc & Pruner 2004) and recent palaeontological finds (Horáček et al. 2007) indicate that the age of all those cave fills is older than 1.77 Ma, with likely ages ranging from about 2.6/3.8 to about 5.23 Ma by matching obtained magnetostratigraphy logs with the GPSR for Cenozoic (Cande & Kent 1995). Although now found at completely different altitudes, the host caves could represent the result of the same speleogenetic epoch. In the Northern Calcareous Alps, the main phase of subterranean flow connected with the last stage of origin of huge horizontal cave systems is believed to be in the Miocene (Frisch et al. 2000, 2001, 2002) and Pliocene (e.g., Zötl 1989). The difference of altitudes can be easily attributed to the later uplift of Alpine mountain chain during Pliocene-Quaternary, which hydrologically separated karst massifs from their respective catchment areas. This palaeogeographic change is well-recorded in the palaeomagnetic properties of speleothems in the Snežna jama.

Old speleothems were precipitated on the allogenic sediments in Snežna jama.

TAJNA JAMA

SITE LOCATION AND CHARACTERISTICS

Tajna jama 1 (Reg. No. 527; 46°18´04.14˝N; 15°04´53.26˝E; 309 m a.s.l.; Figs. 26 and 259) is situated in small isolated karst area north of Celjska kotlina (Celje Basin). The surface of the area is undulating with altitudinal differences of about 150 m. Shallow dolines covered with thick soils are the chief landforms on limestones. Fluvial relief is developed on non-carbonate areas, with flat-floored main valleys. Several brooks sink in small blind valleys along the boundary of the carbonate rocks. The entrance to Tajna jama is at the end of a blind valley (Fig. 260). The limestone ridge above the cave collects water from infiltration and other sinking streams, feeding springs situated several kilometres to the south.

The cave was formed at the contact between Upper Triassic limestones and Oligocene andesite tuffs, volcanics and limestone breccias (fragments of limestone, dolomite, andesite and quartz keratophyre, and tuffitic matrix), with stratal dip to the south (Buser 1978).

Tajna jama is a ponor cave 1,300 m long and 30 m deep. Entrance section is of up to 3 m wide and up to 15 m high meandering passages. The main passage has a keyhole-shaped profile. A meandering vadose canyon mostly less than 1 m wide and up to 8 m deep was entrenched in the upper wide part of the passage, with traces of paragenesis. In places, the meander is cut by older, now dry, passages filled with clastic sediments (gravel, sand, silt, clay) and speleothems (calcite, aragonite, gypsum).

PROFILE

A profile about 2 m high of fine laminated sediments is preserved in the upper part of the meandering canyon (Fig. 261). We sampled it twice, in 2005 (44 samples; Fig. 262) and for better statistic results also in 2006 (70 samples).

LITHOLOGY

Most of the exposed infill consisted of coarse-grained gravel with some sandy or finer-grained intercalations (Fig. 263). Pebbles were well rounded and highly weathered. Where the upper part of the passage was about 5 m wide, finer-grained sediments were deposited, also. Later, erosion and some subsidence into the entrenched meander left a profile about 2 m high of fine-laminated sediments. The upper part of the profile is horizontal; the lower parts have slightly inclined layers.

The top of the profile consisted of an alternation of yellow and clays with interbeds of sand and gravel. The clays were underlain by greyish yellow sand and gravel with pebbles up to 2 cm in diameter. The pebbles were highly weathered; they decomposed readily in the hand). Below were an orange, highly plastic

Figure 259 *Site location; Tajna jama (N – central part of Slovenia).*

Figure 260 *Entrance to the cave, Tajna jama.*

clay with some 1 mm thick black bands underlain by yellowish brown clay with thin dark black bands and small lenses of gravel. The lower part was of grey clay with scarce, badly weathered pebbles and yellowish grey clay without any coarse-clastic admixture.

MINERALOGY

Two samples (sand and silty clay) were analysed. Quartz and gypsum prevails in the sand, with small amounts of mica, kaolinite, K-feldspar and chlorite in the traces. Quartz prevails also in the silty clay, with small amounts of gypsum, kaolinite, mica, smectite and chlorite in the traces.

PALAEOMAGNETIC RESULTS

All 114 samples from the Tajna jama profile were studied for their palaeomagnetic properties and subjected to detailed AF demagnetization in 14 steps. The sediments are characterized by low to intermediate NRM intensities between 0.1 and 17 mA.m^{-1} and MS values from 58 to 365 x10^{-6} SI units. Mean values of J_n and k_n moduli are documented in Table 74 and show trend from low of both magnetic values in base to high in top of profile. From both sets of values, the profile may be divided into four parts and categories. Samples are characterized by intermediate up to high J_n and k_n magnetic values.

Multi-component analysis was applied to separate the respective RM components for each sample.

Figure 261 *Profile position on the cave map, Tajna jama (after Cave Register of IZRK ZRC SAZU and JZS).*

Figure 262 *About 2 m high profile of fluvial sediments in Tajna jama; sampling in 2005.*

Figure 263 *Profile Tajna jama with the samples from 2006.*

Table 74: Mean palaeomagnetic values and standard deviations, Tajna jama

Tajna jama	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	5.111	181.5	0–0.36
Standard deviation	3.561	80.6	
Number of samples	21	21	
Mean value	1.212	97.5	0.37–0.95
Standard deviation	0.722	15.9	
Number of samples	39	39	
Mean value	0.360	77.1	0.975–1.545
Standard deviation	0.169	9.6	
Number of samples	39	39	
Mean value	1.133	98.0	1.56–1.80
Standard deviation	0.290	6.6	
Number of samples	15	15	

* from top to base

Three components were isolated after the AF demagnetization. The *A-component* is undoubtedly of viscous origin and can be demagnetized in the AF (0–5 up to 10 mT). The characteristic *C-HFC* is stable. It can be demagnetized or isolated in the AF (ca 10–80 up to 100 mT).

The stereographic projections of the C-component with N and R polarity are shown on Figures 264 and 265. Table 75 summarizes results of the mean direction of samples from this profile. The mean palaeomagnetic directions of C-components for the N

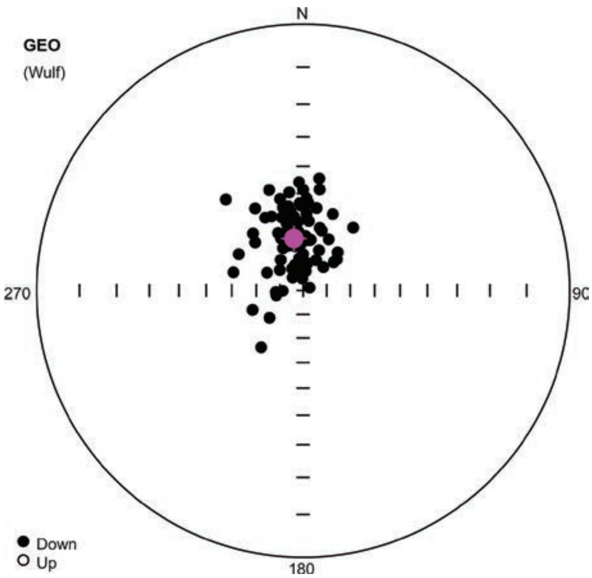

Figure 264 *Directions of C-components of remanence of samples with N polarity, Tajna jama. For detail description see Figure 34.*

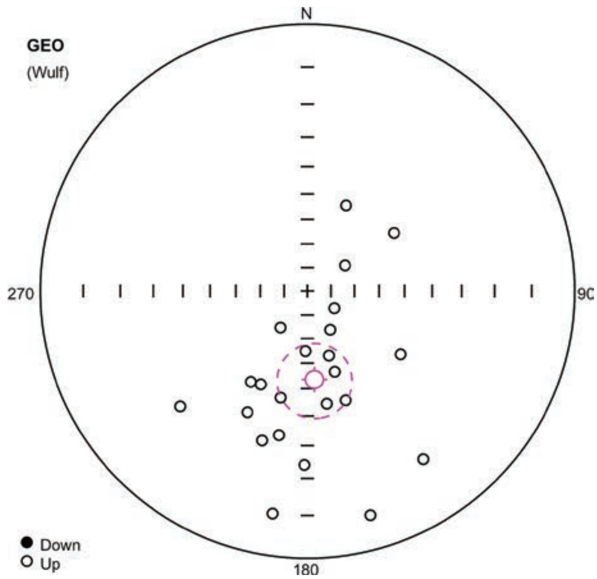

Figure 265 *Directions of C-components of remanence of samples with R polarity, Tajna jama. For detail description see Figure 34.*

Table 75: Mean palaeomagnetic directions, Tajna jama

Tajna jama	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	349.73	67.53	3.05	25.16	84
	R	175.44	-53.42	12.57	5.4	23

polarity are D = 350°, I = 64° and for R polarity part are D = 191°, I = -45°. Systematic acquisition of palaeomagnetic data within the section studied allowed the construction of a detailed magnetostratigraphic profile (Fig. 266).

DISCUSSION OF RESULTS

There was a stage in the development of the cave passage when it was filled with fluvial sediments deposited from a sinking stream. These sediments were later partly eroded, leaving profiles only in the inner part of the cave. The slightly inclined lower part of the profile could be a consequence of plastic deformations during the erosion of sediment from the passage.

The ~2 m high profile of fine laminated sediments consists of two parts: (1) a horizontally bedded upper part, and (2)a slightly inclined lower part. An alternation of N and R magnetized zones was discovered, which permits the following possible interpretations: (a) the sediments date back to about 3.0 to 3.4 Ma, i.e. to the Gauss chron. The erosion surface within the lower R magnetized zone is related also with the change of inclination. The boundary, if representing a prominent hiatus, could shift the age of the lower R/N boundary down to 4.18 Ma (top of the Cochiti subchron). This interpretation can be supported by some palaeomagnetic parameters (especially average D values) and layer inclination. (b) the other possibility is younger: the upper N/R boundary is at the Brunhes/Matuyama (0.78 Ma), the lower N zone is then the Jaramillo subchron (0.99–1.070 Ma) and bottom R/N boundary is the top of the Olduvai subchron (1.77 Ma).

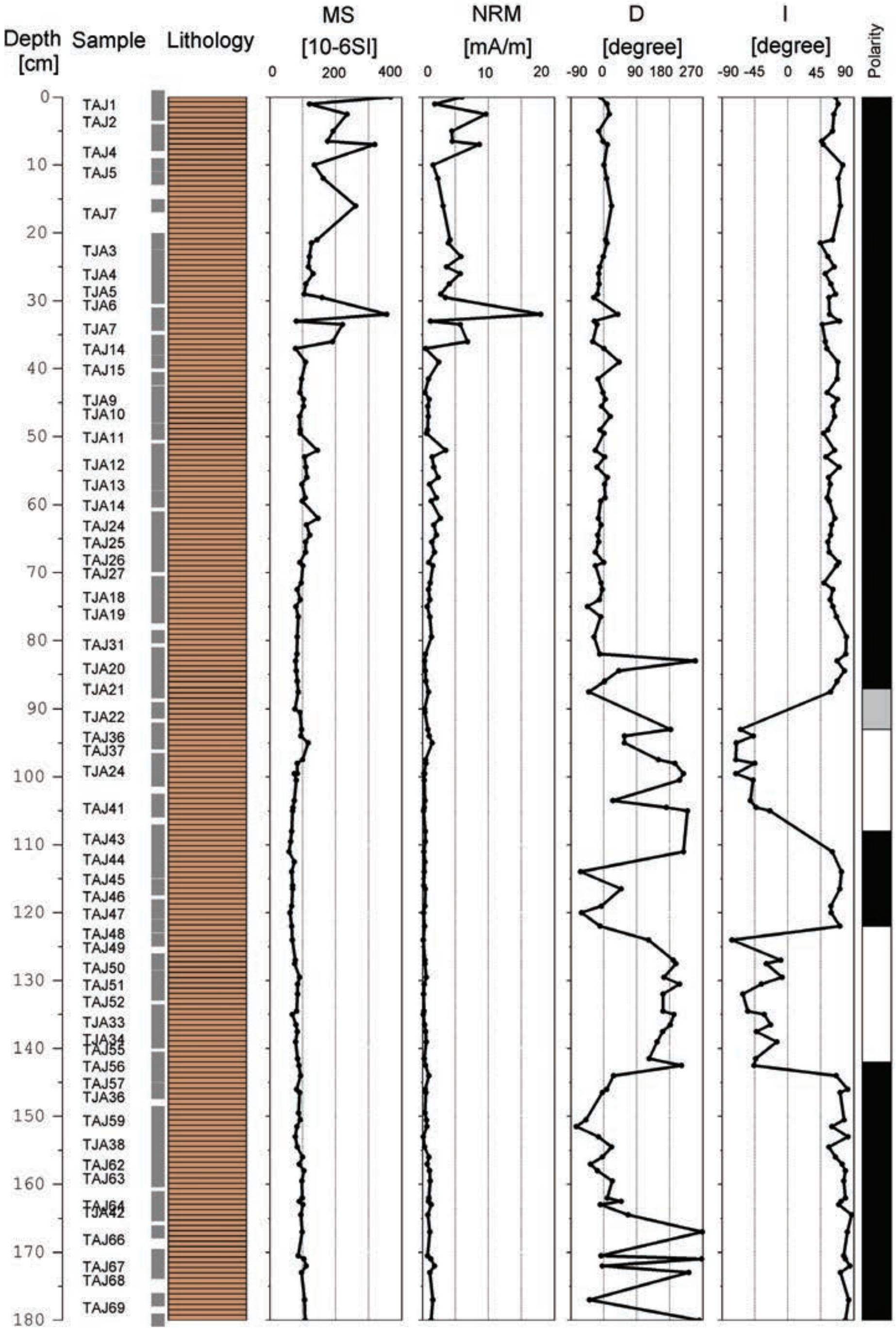

Figure 266 *Basic magnetic and palaeomagnetic properties, Tajna jama. Legend: see Figure 37.*

VELENJE

SITE LOCATION AND CHARACTERISTICS

The profile was located on the northern side of the Velenje Lake on the ridge between the Velunja river and a lake (46°22´53.57˝N; 15°04´23.51˝E, at 390 m a.s.l.; Figs. 26 and 267). The lake was formed in a collapse depression above a lignite mine.

The Velenje basin is a Plio/Pleistocene pull–apart basin (half-graben) related to transtensional dextral strike-slip movements on the Šoštanj fault (Vrabec et al. 1999). The basin basement consists of Oligocene andesite tuff and marls on the south and of Lower Triassic dolomites on the north (Mioč & Žnidarčič 1977). The basin was filled by more than 1,000 m of Plio/Quaternary terrestrial to lacustrine sequence and contains a 160-m-thick lignite seam (Vrabec 1999) within Pliocene mudstones and sands. The basin was filled by fluvial sediments from the north during the

Figure 267 *Site location; Velenje (N – central part of Slovenia).*

Figure 268 *Excavation of the site, Velenje.*

Quaternary. The Quaternary deposits, characterised by abrupt alternations of sands, gravels (with well-rounded quartz pebbles) and clays, are exposed in road cuts and sand pits in the northern part of the lake.

PROFILE

The profile was dug by excavator in several steps to a composite thickness of about 6 m (Fig. 268).

LITHOLOGY

The top of the Velenje profile consisted of brown-orange sand. Grey clays composed the rest of the profile. Sandy conglomerates of grey and brown colour were inter-bedded in the middle part of the profile and formed its base (Fig. 269).

PALAEOMAGNETIC RESULTS

Palaeomagnetic and magnetostratigraphic investigations were carried out on 31 samples to determine the principal magnetic properties and identification of palaeomagnetic directions. Values of the NRM (J_n) and MS (k_n) moduli in their natural state show small scatter. The sediments are characterized by low up to very low NRM intensities (0.1-6 mA.m^{-1}) and MS values from 61 to 250 x 10^{-6} SI units. The mean values of J_n and k_n moduli are documented in Table 76. From both sets of values, the profile may be divided into three parts and categories.

All samples were subjected to detailed AF demagnetization. The RM directions inferred by the above

Table 76 Mean palaeomagnetic values and standard deviations, Velenje

Velenje	J_n [mA.m^{-1}]	k_n x 10^{-6} [SI]	Interval [m]*
Mean value	0.724	101.5	0–4.928
Standard deviation	0.445	28.0	
Number of samples	25	25	
Mean value	4.029	128.9	5.144–5.501
Standard deviation	1.392	85.9	
Number of samples	3	3	
Mean value	0.651	87.5	5.685–6.062
Standard deviation	0.365	6.9	
Number of samples	3	3	

* from top to base

Figure 269 *Upper part of the Velenje profile.*

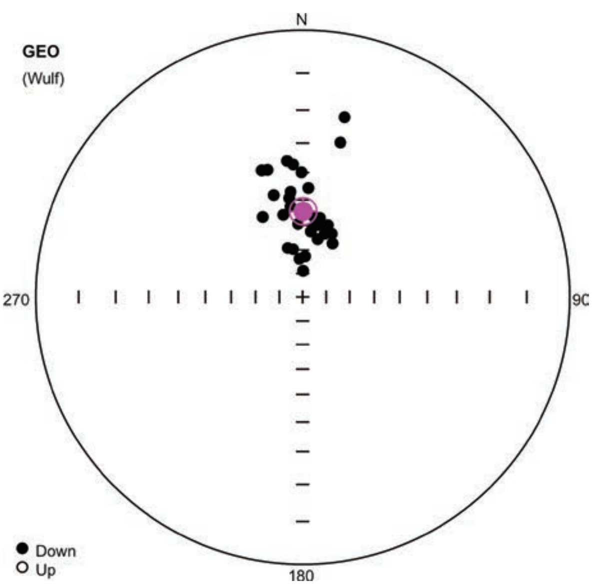

Figure 270 *Directions of C-components of remanence of samples with N polarity, Velenje. For detail description see Figure 34.*

Table 77 Mean palaeomagnetic directions, Velenje

Velenje	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n
		D [°]	I [°]			
	N	0.3	54.46	5.05	25.64	30

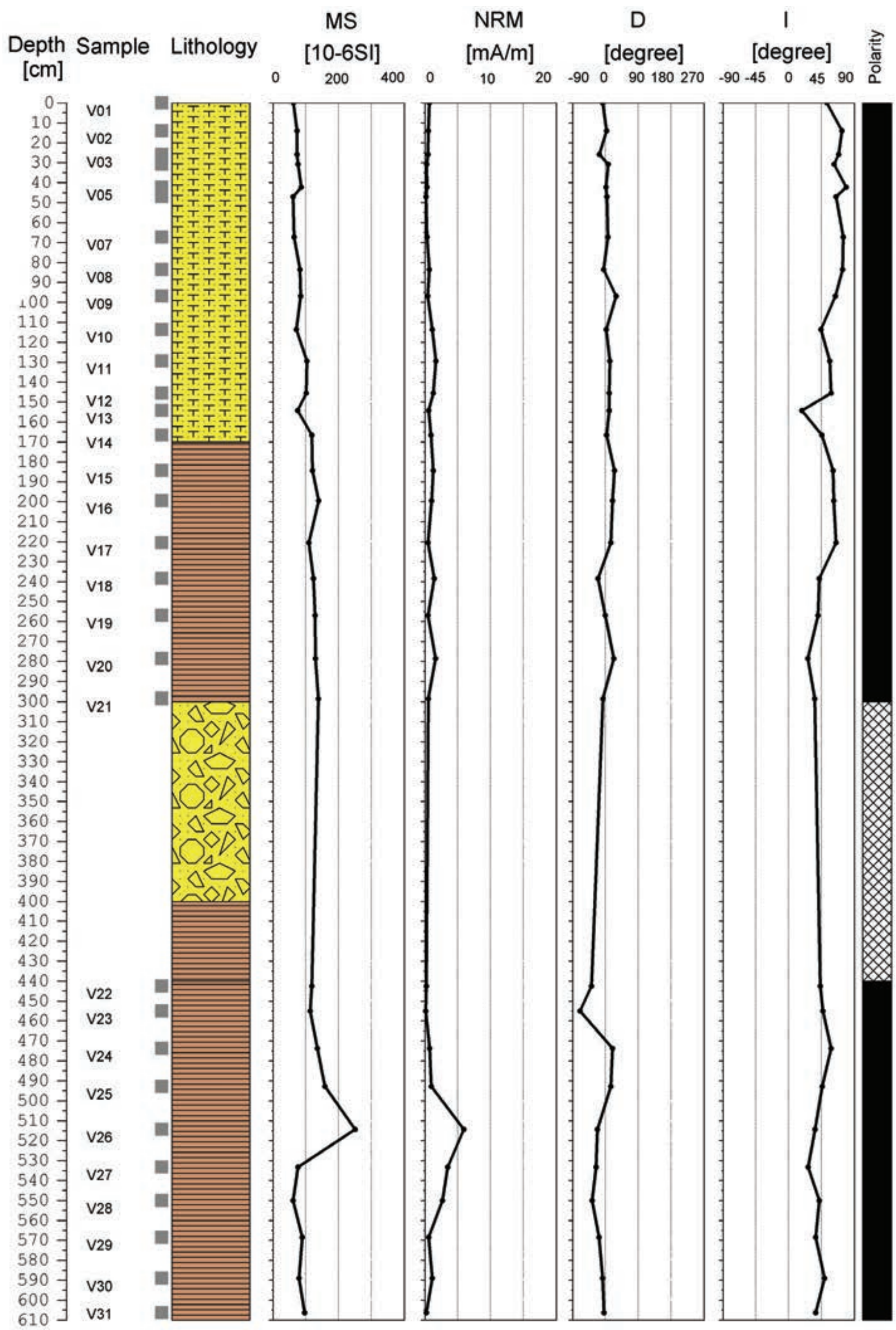

Figure 271 *Basic magnetic and palaeomagnetic properties, Velenje. Legend: see Figure 37.*

given procedures were tested using multi-component analysis. *A-components* of remanence are mostly of viscous origin and can be demagnetized in the AF (0–5 mT). The characteristic *C-HFC* is stable and can be demagnetized or isolated in the AF (ca 10–65 up to 80 mT).

The stereographic projection of the C-component with N polarity is shown in Figure 270. Table 77 summarizes results of the mean direction of samples from this profile. The mean palaeomagnetic directions of C-components for the N polarity are D = 1°, I = 54°. Systematic acquisition of palaeomagnetic data within the studied section allowed the construction of a detailed magnetostratigraphic profile (Fig. 271).

DISCUSSION OF RESULTS

The whole Velenje profile is N polarized and we assume the deposition most probably within the Brunhes chron (<780 ka), which is accordance with general geological data.

DISCUSSION

Dating cave sediments by the application of the palaeomagnetic method – magnetostratigraphy – is a difficult and sometimes risky task, as the method is comparative in its principles and does not provide absolute ages. For dating clastic cave sediments and speleothems it is limited by the complex conditions occurring underground so that it is often necessary to combine it with other methods that offer supplementary absolute-, relative- or correlate-ages.

Nevertheless, the application of the method on a large scale, as was done by our team during the past ten years in Slovenia has produced much new data (Fig. 272) and opened new horizons for the interpretation of karst and cave evolution, both in individual geomorphologic units and over such extensive areas as the Dinaric and Alpine karsts. The findings have taught us that there are a number of common features and evolutionary trends in all of the studied sites, depending largely on the post-Oligocene tectonic and palaeogeographic evolution of Dinarides and their foreland. On the other hand, there are distinct differences in the evolution of smaller geomorphic units within the more extensive ones, which resulted mostly from differentiated tectonic movements connected with the post-6 Ma counter-clockwise rotation of the Adria Microplate. Palaeotectonic evaluation of the data in this respect is still progress and is not considered in this summary.

Figure 272 *Arranging of the collected samples in the underground office; Spodnji Tartarus.*

METHODS

Repeated sampling in some profiles from Slovenia (especially Divaška jama, Trhlovca, Umetni tunel I in Postojnska jama) has shown that only dense sampling, i.e. a high-resolution approach, can ensure reliable results. Sample spacing of 2–4 cm in clastic sediments (Fig. 273) and continuous log/core in speleothems excludes the necessity of returning to caves or other sites several times. The differences in magnetostratigraphic results during the sequence of sampling campaigns are exemplified in the Divaška jama sampling comparisons of 1997, 1998 and 2004 (Fig. 274). The high-resolution programme began in Snežna jama in 2001 (Bosák et al. 2002b) and has been applied to all other cave sediments in Slovenia and elsewhere since.

The application of complete palaeomagnetic analysis, both by thermal demagnetization and alternating field demagnetization, only to pilot samples (i.e. the approach in Slovenia applied by Šebela & Sasowsky 1999, 2000; Sasowsky, Šebela & Harbert 2003) and the shortened selected field/step approach to other samples (as with Panuschka, Mylroie & Carew 1997) does not offer sufficient data set for interpretation. It is necessary to apply complete demagnetization to obtain reliable data.

Measured data should be subjected to multi-component analysis of the remanence (Kirschvink 1980). The individual components must be precisely established to determine the ChRM directions. Mean ChRM directions must be analyzed using the statistics for spheres (Fisher 1953) but small number of samples could not be used for a reliable interpretation.

Figure 273 *Dense sampling of the Tajna jama profile; sampled in 2006.*

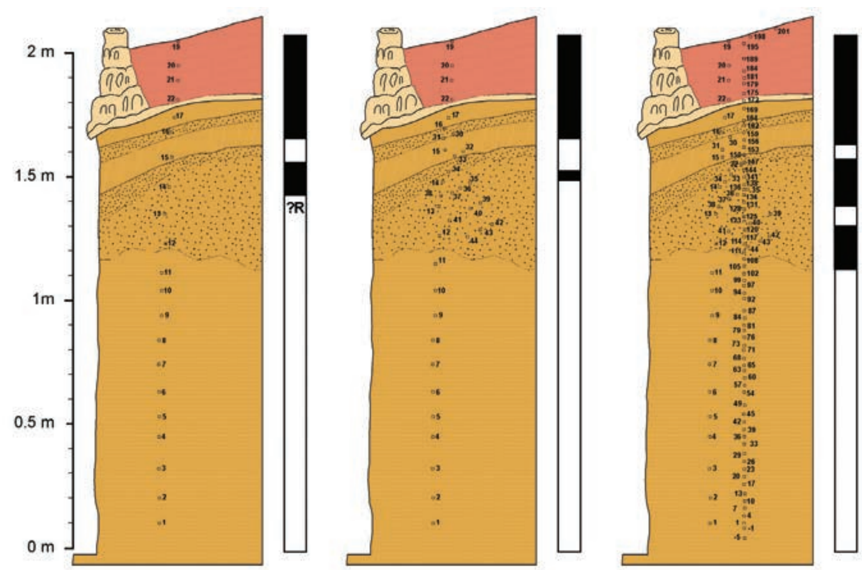

Figure 274 *Comparison of magnetostratigraphic interpretation results of the profile in Divaška jama with different density of sampling: left column – 1997; middle column – 1998; right column – 2004. Legend: yellow – laminated clays and silts; red – red clay; beige – speleothem, flowstone.*

INTERPRETATION OF THE MAGNETOSTRATIGRAPHIC RESULTS

The application of magnetostratigraphy to both clastic and chemogenic cave sediments originally seemed to be an ideal tool for dating. Nevertheless, our practical experience both with the cave interior deposits and with the palaeomagnetic methodology (sampling, construction and interpretation of magnetostratigraphic profiles) has shown that there are substantial real problems. Some of them have been already considered in some of the previous studies cited, but only in a more limited form and case by case depending on local situations and interpretation problems. There are also other problems with the stratigraphy of cave fills, erosion features, available palaeontology, etc. mentioned (*cf.* in lit. especially publications of M. Noel and L. Thistlewood and their co-authors, see reference list).

Correlation of the magnetostratigraphic results we obtained, and the interpretations tentatively placed upon them has shown that in the majority of cases, application of an additional dating method is needed to either reinforce the palaeomagnetic data or to help to match them with the GPTS (Bosák, Pruner & Kadlec 2003). The most helpful data are from absolute dating and palaeontological (biostratigraphic) correlative age estimates. Nevertheless, these also have limits to their utility.

It is generally known that fossils will be preserved mostly in the upper parts of a sedimentary fill and/or in entrance cave facies, and the time ranges of most absolute dating methods applicable to karst deposits is relatively short (*cf.* Ford and Williams 1989, 2007).

Some fossils in such cave facies can have been redeposited by the erosion of older sediments and/or derived from collapsed near-surface (epikarst) fills of greater age (*cf.* e.g., Horáček and Kordos 1989) or represent only fragmental and poorly preserved material (Horáček et al. 2007). Paleontological remains which were deposited in entrance parts or in shallow caves are destroyed by the denudation in relatively short time together with the caves they were deposited in. Because of that reason the faunal remains of the cave entrance facies can not be very old.

Palaeontological finds are rare in interior cave sediments, where phreatic conditions prevail (in main channels the remains are destroyed by gravel and in side passages with slow currents only fine sediments can be deposited). There are examples of the phosphorite caves in Quercy (Pelissie et al. 1991) or the unroofed caves at Riversleight (Archer el al. 1994) where fossil material that was carried deep into caves has remained well preserved until denudation exposed the sediments to the open surface. Sometimes the nature of cave sediments, does not favour the preservation of fossil remains that could contribute to the dating of cave sediments or to the correlation of magnetozones with the GPTS.

Up to the present time we have studied a total of 85 caves and 143 sedimentary profiles in Slovenia, Slovakia, Czech Republic, Hungary, Italy and Korea. Faunal remains were found only in eight profiles, pollen also in eight profiles and archaeological finds at two sites. Most of the fauna and pollen could not be identified (e.g., the Divača profile, Bosák, Pruner & Zupan Hajna 1998; the Kozina profile, Bosák et al. 2000a; Črnotiče I, Bosák et al. 1999; Trhlovca). Majority of sediments which we analysed, in sedimentological point of view, belong to interior cave facies and was mostly not rich on fauna. Sediment sequences in some of the caves contained remains of Pleistocene large mammals, but only in their uppermost layer (e.g. Holštejnská Cave, Czech Republic, Horáček and Ložek 1988; Na Pomezí Cave, Czech Republic, or Račiška pečina (Mihevc 2003) and Križna jama (Ford & Gospodarič 1989; Fig. 275) in Slovenia. Remains of cave bears were found also in the upper part of the Medvedia chodba (Bear Passage) in Demänovská jaskyňa Slobody (Freedom Cave), but not in any direct relationship to the sediments studied by palaeomagnetism (Pruner et al. 2000). In contrast, cave bear remains in Stara jama (Postojnska jama, Slovenia), U Hájovny Cave (Kadlec et al. 2005) and in Šošůvská Cave (Kadlec et al. 2002) occurred as regular deposits within the analyzed sediments: palaeomagnetism helped to provide a more precise bone dating (a.o. Kadlec et al. 2002). Small mammals that are index fossils of the younger Cenozoic were found only in Žabia Cave (Poland, Bosák et al. 1982), Črnotiče II and Račiška pečina (Slovenia; Horáček et al. 2007). Especially important was the discovery of troglodytic *Marifugia cavatica* worm tubes attached to cave walls under the sediment fill in the Črnotiče II profile. This find also yielded valuable information on the nature of the depositional environment (Mihevc 1999).

Like finds of large mammal bones, archaeological evidences, were limited to the upper parts of just three profiles (i.e. Kůlna Cave, Czech Republic, Šroubek et al. 1996; Biśnik Cave (Poland; Cyrek 2002) and Račiška pečina (Jamnik 2001).

The application of absolute dating methods to our sites also has some substantial limitations. Some methods cannot be used for dating cave materials

Figure 275 *The lower jaw of Ursus spelaeus; remains of the cave bears lie between two flowstone layers on the top of the fluvial sediments in Medvedji rov; Križna jama.*

at all (for example K–Ar dating; because there is no K available in primary minerals precipitated in the karst), others are limited by low contents of necessary elements, or the time-span of the method is too short for the magnetostratigraphy of a given site (*cf.* Bosák 2002). Our interpretations of the magnetostratigraphic results at the majority of the studied sites is that their ages are greater than the age limit of the classical and current Th/U dating methods (both α-spectrometry and thermally induced mass-spectrometry, i.e. 350 and about 550 ka); however, uranium isotopic equilibria can indicate whether an age below or over 1.2 Ma is some instances.

There is also another method available to date speleothems without a limit in time – Pb/U dating method; the decay of parent uranium to stable lead in principle permits it (Ford & Williams 2007). But the method requires high quality TIMS (expensive method) and to estimate the initial $^{234}U/^{238}U$ ratios, which remains a considerable problem where ages are less than a few million years. With this method Derek Ford has tried to date tubes of *Marifugia cavatica* from Črnotiče site for us (see Črnotiče II profile description – palaeontology), but no result was obtained due to low initial U content and pollution with detritic Th.

Cosmogenic isotope dating (Granger & Muzikar 2001) can be used on the quartz grains washed in caves by sinking rivers. The recent use of cosmogenic nuclides on quartz containing sediment permits dating back to 5 Ma. First attempts to date the sediments in some Alpine caves in Slovenia were made by Philipp Häuselmann, but we have no results yet.

Interpretation of magnetostratigraphic results faces other serious problems that may endanger palaeomagnetic studies in given caves if they are not detected. The sedimentary fills of a number of our profiles were separated into individual sequences and cycles, mostly of fluvial or ponding nature, because they were divided by breaks in deposition (unconformities). Unconformities and/or intercalated precipitates indicate the highly complicated deposition dynamics that can be found in many sedimentary sequences; entire caves and cave systems can be completely filled and emptied several times (*cf.* Panoš, 1963, 1964, 1965; Ford & Williams 2007). Erosion removes parts of the originally deposited logs. Therefore, unconformities within sedimentary profiles can hide substantial amounts of geological time (Bosák, Kadlec & Pruner 2003). The fill of Divaška jama provides one of the clearest examples of temporary interruption of speleogenetic processes. After an infilling phase dated before 1.2 and/or 1.77 Ma, the cave was inactive for a long time because deposition was renewed only around 540 ka after a break lasting 0.7 to 1 Ma. This time-span is documented by erosion of the old cave fill and deposition of speleothems with complex morphology. The geometry of the magnetostratigraphic log in Račiška pečina was disturbed by numerous breaks in deposition especially within the lower part of the profile. The derived subchron arrangement helps us to estimate that the duration of individual breaks was about 150–250 ka, but in some sequences probably substantially more. The long-lasting breaks can also explain some differences in declination values between upper and lower parts of a section that indicate rotations of the particular tectonic block containing the cave. The geometry of individual magnetozones and their arrangement in Snežna jama, for example, indicates that substantial time is hidden in the unconformities.

Some of the unconformities were expressed by post-depositional changes, erosion and/or precipitation features. The breaks were often associated with mass movement and sediment re-deposition within caves. Sedimentary sections can be undercut by erosion, resulting in slumping and/or inclination of the fill. This can be exemplified on the Trhlovca, where the central part of the section subsided, probably as consequence of erosion below it. Both sides of the profile were affected by sliding, and the depression created in the centre was filled at the end of the movements. In Tajna jama the fill was partly eroded, leaving profile only in the end part of the cave. Slightly inclined lower parts of a profile can result from plastic deformation due to erosion of the cave fill. The Divača profile was disturbed by fissures that originated during slumping caused by a collapse that was probably due to rejuvenated karstification.

Other slope movements could occur within caves due to cold during Pleistocene glacial periods. Numerous examples of solifluction movements are known (e.g., Snežna jama in undated allogenic fluvial deposits) as well as frost loosening of cave sediments (e.g., Križna jama, profile II). The frost activity can be followed by substantial downslope movement of near-surface layers of sediments.

Compaction, especially of fine-grained deposits can lead to sandwiching. For example, in the Markov spodmol (Fig. 276) sediments compaction continued after deposition of the top flowstone. Immediately beneath it there is yellow plastic clay (about 5 cm) resulting from deposition from younger floods (sandwiching). The remains of cemented pebbles at the base of the flowstone cap indicate that (a) profile was much thicker, containing another gravel deposition (new cycle), and/or (b) sandwiching could occur in other phases as well as that which deposited the yellow clays. In Spodmol nad Planino Jezero, the top clay filled narrow openings between the cave wall and sediments already at least partially compacted. The roof channel, which formed when cave was completely filled, was later filled by the top clay as well.

Repeated erosion phases were described from Trhlovca. Before the deposition of the first generation of flowstone crust, earlier sediments were partly eroded and gravels deposited. The thick flowstone crust developed in two principal periods interrupted by deposition of red clays. The ensuing phase of erosion was very intensive. It partly destroyed the thick crust, and was partly active below it. The following generation of flowstone crust developed on a deeply eroded surface and was itself nearly destroyed during the next erosion phase (flowstone remnants only on cave walls). These erosional and depositional events resulted from oscillations of the karst water level.

Figure 276 *The profile of fine-grained sediments below flowstone in Markov spodmol. The yellow clay on the top of the profile, directly below flowstone, is younger than flowstone (sandwiching).*

Ceiling breakdowns are often associated with unconformities, e.g., in Trhlovca, Račiška pečina (here dated to about 1.9 Ma), Spodnji Tartarus (here dated to 127–91 ka), Črnotiče II.

Unconformity surfaces are often emphasized by precipitation of iron-rich substances. Limonite crusts, sometimes enriched in Mn-bearing compounds, were formed in the Divača and Črnotiče II profiles and in Umetni tunel I during longer breaks in deposition, some of them accompanied by weathering. Percolation of iron-rich solutions through porous sediment resulted in the formation of so-called Liesegang features (e.g. Markov spodmol, Divača profile, Trhlovca, Zguba jama, profile II), which can present dangerous problems for magnetostratigraphic research.

Corrosion of speleothems (weathering) connected with hiatuses can be mentioned from Račiška pečina or Trhlovca sites. Weathering of exposed cave fill *in situ* within the caves has been also noted. Ferricrete-enhanced erosion surfaces were accompanied by repeated fossil weathering in the Divača profile (Fig. 277). A multi-coloured zone about 2 cm thick represents the *in situ* weathered surface below the prominent break in the deposition in Markov spodmol. The distinctly more lithified upper part of the profile in Male Jame contains clear traces of *in situ* weathering such as decomposed sandstone pebbles derived from flysch or cementation by Fe/Mn-enriched compounds and coatings on pebbles. Traces of *in situ* weathering indicate quite prolonged hiatuses in deposition during warm/humid external climate conditions. Therefore such kinds of weathering support the concept of greater ages in studied sequences.

The dynamic character of cave fill deposition is reflected in the start or termination of individual magnetozones at unconformities in a number of profiles, which is comparable with situation reported on a number of Quaternary carbonate platforms (McNeil et al., 1988, 1998). The general character of cave depositional environments with their numbers of post-depositional changes, hiatuses, reworking and re-deposition does not allow precise calculation of the temporal duration of individual interpreted magnetozones. All these factors contribute to the fact that exact calibration of the geometric characteristics of the magnetostratigraphic logs with the GPTS cannot be attained at all or only with problems, if it is not adjusted using results of other dating and geomorphic methods.

Figure 277 *Ferricrete-enhanced erosion surface from lower part of the Divača profile.*

INTERPRETATION OF THE MINERALOGICAL RESULTS

The mineral assemblages in almost all samples from south-western Slovenia reflect their sources in the Eocene flysch, weathered to different degrees. The colour of weathered flysch is yellow to yellowish brown at the surface. Yellow to red colour is typical for sediments deposited in fissures, depressions and other negative karst forms where they were exposed to the more prolonged influence of atmospheric agents. The change of colour reflects the phase transitions in the mineralogy of iron-bearing compounds, typically the change of iron hydroxides (limonite) into oxides (hematite, for example). This transformation does not necessarily require some extreme hot and wet climate such as the tropical; in general the influence of the Mediterranean-type of climate is enough intensive.

In general also, the mineral composition in the studied samples was rather uniform or highly similar. Difference could be found only in the amounts of individual minerals, which varied from sample to sample. Clastic material in the karst and cave sediments was substantially homogenized before it was deposited. The principal reason for homogenization is the geological and tectonic structure of the catchment areas. The relief cuts across the imbricated alternations of flysch and limestones. The different stratigraphic (lithostratigraphic) units of Eocene flysch are all exposed in a given catchment area at the same time. Therefore it is not possible to detect the different mineralogical composition of individual flysch lithosomes (especially the heavy minerals) and it is not possible to use any changes of mineral assemblages to estimate relative age from the succession of eroded lithosomes in individual catchments. Even where some variations in mineralogical compositions, e.g. increased chromite content, are known in individual geotectonic units, (e.g. Brkini hills, Matarsko podolje), they are not detectable in adjacent regions. In spite of the fact that individual catchment areas are quite extensive, they are very poorly interconnected both at the surface and subsurface due to the imbricated structure where flysch thrust slices function as aquicludes and aquitards.

Another reason of the homogenization of weathering products is reworking and re-deposition within the catchment areas and, subsequently, in the subsurface. Poljes represent the most important component in this system. Sediments are transported through caves, and then deposited in the poljes where they are subjected to subaerial influences, mixed with allogenic fluvial material and colluvial deposits, and then later eroded and deposited again in cave environments. Sediments derived from flysch rocks show that source rocks weathered intensively in repeated periods related to alternation of palaeoclimate types. Their weathering products were transported over karst surfaces and into pre-existing caves and depressions. The weathering phases did not necessarily coincide with erosion phases and events in the time, as indicated by periodical transport of products of red earth-type weathering into caves. The erosion of flysch rocks and their weathering products was probably accelerated during phases with increased rainfall (mostly in colder climatic phases), or due to tectonic uplift of the landscape. This process is continuing today, but with much lower intensity.

Alternation of climates in post-Oligocene times produced very similar weathering products and profiles in several phases. The intensity of weathering is reflected in the composition of clay minerals of cave sediments. Nevertheless, the changes in clay mineral assemblages are too small to be able to utilize them for the compilation of relative stratigraphy, as was done by Vít (1996) in the Moravian Karst (Czech Republic) where increased kaolinite content indicated increased age of cave fill. The reasons for this are both the homogenization of source clastic materials and the repeated episodes of similar weathering production, contrary to the successively eroded source weathering profile of Cretaceous–Paleogene age in the Moravian Karst.

The transport of weathering products over extensive karst regions is well-documented. Freshly deposited yellow-coloured flysch-derived sediments remained on the surface, where they weathered. They could be mixed with brown- and red-coloured products of pedogenesis (terra rossa) and with eolian sediments (loess and silt of different composition including volcaniclastics). Brown- or red-coloured weathering products represented another source material for cave sediments; they may be derived from profiles on limestones as well as on other rocks. Fluvial sediments from allogenic streams and blind valleys in the contact karst underwent similar weathering. Horizons with *in situ* weathered flysch-derived sandstone pebbles appearing now as decomposed rocks are known to authors from a number of different places in regions studied.

Subsurface *in situ* weathering has been also detected, for example in Male jame in the Postojnska system. It resulted in the decomposition of sandstone pebbles to soft material, deposition (sometimes extending to cementation) of Fe- and Mn-enriched compounds, calcite cementation, sometimes colour changes, etc. *In situ* subsurface weathering needs both favourable climatic conditions outside the cave and quite prolonged time spans.

Unroofing of caves represents the third reason for the homogenization of source material of cave fill. Cave sediments derived from already weathered and homogenized sources re-appear at the surface due to the denudation. Such cave fill represents important source for pedogenic processes on the surface of the karst. The resulting soils can be washed back down into the subsurface system and become newly deposited cave fills.

Mineralogical and geochemical data from red clays and their constituents can help to explain the origin of some of surface weathering products. Data from Črnotiče, Križna jama or Trhlovca indicate that red clays are closely related to terra rossa type of soils known from karsts in the Mediterranean area. Most probably, the red clays are not red soils directly washed but are reworked paludal sediments from eroded weathering profiles both on limestones and flysch in the water-saturated environment of lakes and marshes. The paludal sediments sometimes underwent an initial phase of bauxitization (suggested by increased chromium content, indications of aluminium replacement of some Mn-rich pellets, and abundant gibbsite). They represent *in situ* weathering profiles and are not reworked and re-deposited Mesozoic bauxites (*cf.* also Gospodarič 1974).

A cut through the large cave passage filled with allogenic sediments at Divača. Yellow, bottom part of the sediment was deposited in the cave by a sinking river. The red sediment above was later washed in the cave by percolating water. Both sediments have origin in the weathered flysch rocks.

SEDIMENTOLOGICAL INTERPRETATIONS

Studied sedimentary profiles indicate some standard features in the sediments, although their ages may substantially differ. The common textures resulted from similar types of depositional environments.

The most common clastic sediments from studied sites are fine-grained laminated sediments (laminites), which often constitute quite thick sequences within profiles (Fig. 278). Laminated fine-grained sediments were deposited from suspension; their laminas are parallel to the depositional surface. There may be fining upwards within lamina, which creates a colour change. Lamination and fining upwards are normal and represent deposition from waning floodwaters or other pulsed flow or result of ponding as consequences of the blockage of outflow routes (collapses, tectonic movements, etc.; Ford & Williams 2007). The depositional environment was mostly calm but not completely stagnant. Such a sedimentary environment is described in Table 78 as cave lacustrine or deposition from pulsed flow. Laminated silts and clays prevail in the phreatic environment.

In vadose or shallow phreatic caves and close to the sinks of the rivers coarser sediments are more common. It is also characterised by series of cut-and-fill sedimental structures with marked lateral fining (Ford & Williams 2007). Those kinds of sediments were the other type of clastic sediments in our studied sites, where gravels and laminated sands are interbedded with silts and clays.

The distribution of the NRM (J_n) and total MS (k_n) in palaeomagnetic profiles in some sites indicates changes in deposition, especially changed mineralogical/petrological composition of allogenic terrigeneous influx or changes in deposition of speleothems. Such records can be illustrated with the example of Snežna jama. Here, the composition of the sequence of two distinctly different units is indicated by both palaeomagnetic parameters. The lower part of the profile has substantially higher NRM values. The unit is composed of banded brown speleothem with high content of terrigeneous-derived material resembling reworked and re-deposited terra rossa-like soil. The

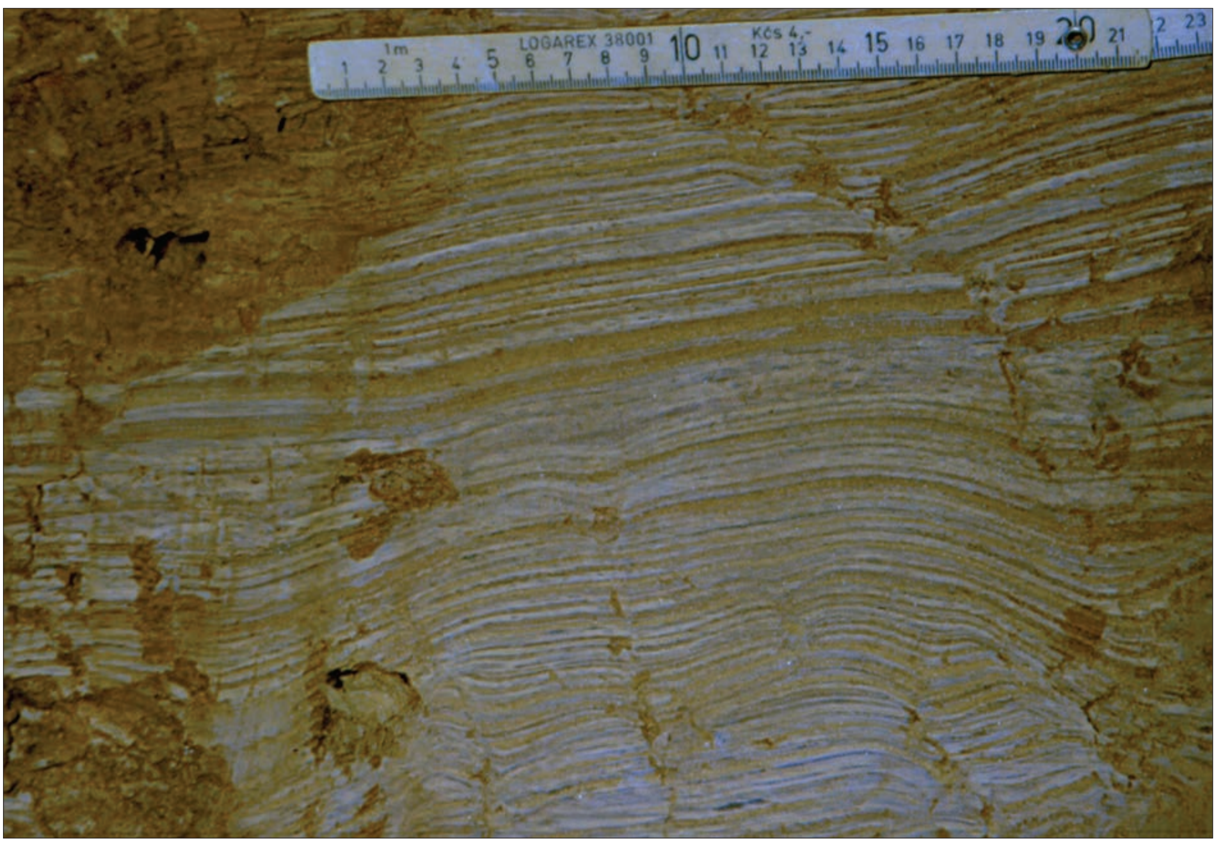

Figure 278 *Laminated sediments from the bottom of the Divaška jama profile.*

upper part, composed of a typical light-coloured banded flowstone sequence, has a negligible NRM value. The total MS curve indicates similar trends. The change can indicate completion of deposition of load from allogenic streams due to the beginning of uplift and detachment from original catchment area as well as the change of external climatic conditions (*cf*. e.g., Sroubek et al. 2001),. So we can expect the different palaeo-environmental conditions during evolution of both parts of the profile.

The character of the J_n and k_n moduli in Jama pod Kalom (borehole S1) and Briščiki (S3) shows similar trends in both palaeomagnetic profiles and reflects the major lithological boundaries detected in both boreholes. The lower parts of both logs represent re-deposited weathering residua of Eocene flysch, while the upper parts contain gradually increasing proportions of re-deposited *terrae calcis* products (soils from limestone areas). The reason for such change can be found in some re-arrangement of source (catchment) areas of streams feeding the karst and/or in climatic change. The differences in rock magnetic properties can be traced also in the geochemical log of sediments, assemblages of heavy minerals, and in composition of clay mineral fractions (*cf.* Tremul 2001).

The general character of cave deposition described above does not allow calculation of the rate of deposition in most profiles. Summarized palaeomagnetic parameters (especially those of the NRM – J_n and mass-specific MS – k_n,) presented in tables for each profile can help in the estimation of the depositional rates, rapid or not. Both parameters depend on climatic change (in the cave as reflected by changes in the mineral composition of the sediments) or changes in depositional velocities related to the evolution of the particular cave gallery and system. The greater the number of distinct segments and categories interpreted within the profile, the more complicated was the depositional history (rapid changes of depositional velocity, breaks in deposition, changes in mineralogical composition of deposited load, etc.). The magnetic polarity detected in such segments is mostly uniform, however, with rare instances of some brief polarity changes recorded only in one or in a few samples. Some segments with uniform palaeomagnetic parameters can be quite thick (up to several metres), as in Planinska jama (Fig. 279), Spodnji Tartarus North, the lower half of Spodnji Tartarus South, Črnotiče II (right profile), Kozina, Briščiki, Jama pod Kalom. Such situations suggest relatively rapid general deposition rates in most of the profiles. Individual magnetozones in the Pliocene and Quaternary, (i.e. in the period of interest), have durations ranging from 1–9 ka (excursions) to about 12–980 ka (subchrons). The longer ones can be sub-divided by short-lived excursions. The duration of individual subchrons gives us a rough time span for the duration of individual segments, i.e. mostly from several thousands up to a few hundred thousand years. It is not impossible that some segments can represent just single flood or repeated floods occurring shortly after one another, or the consequence of a single ponding in a cave passage. This explanation can be an acceptable alternative particularly for the laminated fine-grained deposits interpreted as sediments of the calm (lacustrine) cave depositional environment.

Fossil cave stromatolites were described from the Črnotiče I site for the first time in caves by Bosák et al. (1999). They originated from organic-rich films (algal or diatom mats) on which fine carbonate and quartz grains were trapped of crystallized. Recent examples have been found in some other caves e.g., from Škocjanske jame (A. Mihevc, unpubl.).

Figure 279 *Thick profile of laminated sediments from Rudolfov rov in Planinska jama has shown uniform palaeomagnetic parameters (archives of IZRK ZRC SAZU).*

DATING CAVE FILL

The evolution of the cave from its very beginning (proto-channel) up to the time when it is destroyed by denudation and erosion or completely fossilized (e.g., buried, metamorphosed) is guided by number of factors (*cf.* e.g., Ford & Williams 2007). The most important one, especially in the Slovenian case studies, is the evolution of the regional and local karst water level (karst aquifer) as the consequence of the evolution of morphostructure units in the Dinaric and Alpine orogenic belts.

The research extended across an extensive region with different geological structure and geomorphologic situations, containing a number of cave and fragments of cave systems. Good profiles of cave sediments were not abundant, so we focused on the most available and accessible ones. Different genetic types of caves were studied – from hypogenic (e.g., Jama pod Babjim zobom) and phreatic ones (e.g., Grofova jama, Zguba jama) to ideal water-table cave systems (e.g., Postojnska jama, Markov spodmol). Results from individual sites and their discussion clearly indicated some similarities in evolution both of caves and their fills. They are also provided information on the evolution of the surface, weathering conditions, pedogenesis, etc.

The analysis of data obtained from ten years of magnetostratigraphic studies in Slovenia that are summarized in this volume, show some quite interesting results. The most important one is the discovery that cave fills have substantially older ages than was generally supposed earlier (summarized by Gospodarič 1988), shifting the possible start not only of the speleogenesis but also of cave filling processes in Slovenia far below the Tertiary/Quaternary boundary (*cf.* already Bosák, Pruner & Zupan Hajna 1998 or Bosák et al. 2000b).

Nevertheless, the concept of much cave origin being in the Upper Tertiary was not completely new. Habič (1992) in his article, despite poor field and analytical evidences, indicated that there were numerous Upper Tertiary "fossil caverns" now occurring at 100 up to 2900 m a.s.l. in the broad area from Southern Alps to Adriatic Sea and Pannonian Basin. He placed their origin in warm-humid (tropical) climatic conditions and their different altitudes were attributed to displacement by younger tectonic movements (Habič 1982, 1984, 1992 and pers. comm. 1998).

Here, we are using the term Pliocene in a traditional sense. The Plio-Pleistocene boundary is located at 1.8 Ma (Aguirre & Pasini 1985), close to the base of the Olduvai normal subchron (C2n) at 1.77 Ma (within the Matuyama Chron). The newly proposed Plio-Pleistocene boundary is located at about 2.6 Ma (close to Matuyama/Gauss boundary, base of Chron C2Ar at 2.581 Ma and at the base of the MIS 103 at 2.588 Ma; Ogg 2007).

Unroofed cave discovered during road construction was filled with allogenic sediments (Photo: T. Slabe)

PALAEOGEOGRAPHIC BACKGROUND

Dates obtained by magnetostratigraphy in combination with other dating methods and summarized in Tables 78 to 81 should be compared with the main thresholds in the history of geologic/geomorphic evolution of the region since regression of the Eocene sea. Only deposits in caves and on karst surfaces (e.g., soils, spring, lacustrine and river deposits) can help to decipher the younger geological and tectonic history of the studied regions. The problem is that only cave sediments are available for the reconstruction, because biostratigraphically well-dated correlative sediments younger than 6 Ma are missing and the fill of tectonic basins contains mostly sterile or poorly palaeontologically dated fill.

The post-Eocene history was not completely uniform or simple. Mesozoic/Palaeocene limestones started to be exposed on the surface after the regression of the Eocene sea some 40–30 Ma ago as a consequence of the northward movement of the Arabian (Nubian) Plate and its collision with Eurasian Plate (*cf.* a.o. Jolivet et al. 2006). Limestones were exposed in complicated overthrusted structures belonging to Dinarides, which principally formed during Oligocene to early Miocene (Vrabec & Fodor 2006).

After the last massive marine transgression during the Eocene, when a thick pile of flysch siliciclastics was deposited, there is no direct evidence of younger marine sediments covering the broader region. Nevertheless, detailed palaeogeographic and biostratigraphic analyses detected the so-called "Trans-Tethyan-Trench-Corridor" in Slovenia connecting Central Paratethys with the Mediterranean (Venetian Basin) during lower and middle Badenian (about 16.4 to 14.5 Ma; Middle Miocene; Rögl & Steininger 1983, 1984; Rögl 1998; see also Popov et al. 2004 and Kvaček et al. 2006). The position of the corridor was interpreted to be just north from the Istria peninsula, with the width of several tens of kilometres. Unfortunately no correlative sediments have been preserved on the surface; if they occurred, all were completely eroded away, presumably due to strong currents in the relatively narrow and shallow corridor. A lengthy stabilization of sea level for about two million years and presumably low relief marked an important threshold in karstification of the whole region.

Miocene correlated sediments preserved in isolated basins belonging to Paratethys (Pannonian Basin) are about 10–6 Ma old (e.g., Márton et al. 2002), which is the time when the deposition slowly ceased due to the change in geodynamic evolution (for details see Vrabec & Fodor 2006). Their evolution could influence karstification only in the eastern part of Slovenia.

Miocene evolution with favourable climatic conditions and prolonged stability in karst water levels would have contributed substantially to quite intensive speleogenesis. This period can be compared with the Northern Calcareous Alps (a.o. Frisch et al. 2002). We cannot exclude the possibility that some of the now unroofed caves can belong to this phase of evolution, lasting from about 16.5 to 6 Ma.

The geodynamic change at the beginning of the Pliocene created an important structural threshold – the Adriatic Microplate started its counter-clockwise rotation (at 6 to 4 Ma; Márton et al. 2003) causing predominantly transpressional deformation in the territory of Slovenia (Vrabec & Fodor 2006). The reactivation of Dinaric faults, rotation and over-thrusting of smaller tectonic blocks, and evolution of present-day landscape and surface forms resulted from the change.

The so-called Messinian salinity crisis was closely connected with this change. The crisis started (5.96 Ma) over the entire Mediterranean Basin. It was isolated from the Atlantic Ocean between 5.59 and 5.33 Ma, resulting in an extreme decrease in the sea level (up to -1,500 m, *cf.* Hsü 1973; Hsü, Cita & Ryan 1973; Hsü et al. 1977). The initial stages (5.59–5.50 Ma) were characterized by extremely rapid erosion, creating several canyon systems around the Mediterranean (e.g., valleys of Ebro, Durance, Var, Po or Orontes rivers, valley of Rhône River in southern France with extreme thicknesses of Plio/Quaternary fill – Clauzon 1973, 1980; Clauzon, Puig & Guendon 1997, valleys in Lombardy, Italy – Tognini 2001, Nile Valley in Egypt – Khumakov 1967, 1971, valleys in the carbonate plateau of Cyrenaika in Libya – e.g., Maštera 1985 or in carbonate-flysch region of Istria, Croatia). Deep karst with potential depths to 1 to 3 km developed in the entire Mediterranean region (Perna 1996; Audra et al. 2004; Mocochain et al. 2006, a.o.) as a result of underground karst drainage directed into the Mediterranean Basin from its foreland (Głazek 1993). Perna (1996, p. 12) described the resulting karst forms as the Messinian karst cycle. The now submerged parts of such systems are often expressed by large submarine springs (along the Adriatic coast, Cyrenaica, Apulia, southern France, etc.) and other features (Sardinia).

Rapid base level rise followed refilling of the Mediterranean Basin by Atlantic water after opening of the Gibraltar Strait around 5.332 Ma; (Hsü 1973; Cita & Corselli 1993). Climatic change to wetter conditions coincides with geodynamic change during the final phases of the Messinian salinity crisis and caused increased erosional flux from the Southern Alps (Willet, Schlunegger & Picotti 2006).

This geodynamic change could influence karstification to a great extent. Sudden changes of regional karst water level could both accelerate speleogenesis (lowstands) and halt it (highstands). At the beginning of the Messinian salinity crisis; speleogenesis was induced by the drop of sea level and changes in the organization of subsurface drainage with the changes in hydraulic head. At the end of the Messinian salinity crisis, the cave systems could be filled by sediments, as has been detected at numerous places in the circum-Mediterranean area (a.o. Tognini 2001; Mocochain et al. 2006) and by our data (Tabs. 79 and 80). This evolution could affect only the coastal tectonic blocks, however, because more distant hydrological structures

Figure 280 *Underground water connections according tracing tests in SW Slovenia (archives of IZRK ZRC SAZU).*

were protected by impermeable structures and lithologies following the Dinaric trend, i.e. roughly parallel with the past and recent Mediterranean shorelines. Dinaric-trending structures helped to create isolated perched hydrological systems, which then evolved in relation to the nearest tectonic inter-montane basins. This can be demonstrated by the example of the evolution of the Ljubljansko barje (Ljubljana basin) and the catchment of the Ljubljanica river (Pivka basin, Postojnska–Planinska cave systems, Cerkniško or Planinsko poljes) for the last 1.1 Ma and maybe 2.2 Ma (Pruner et al. 2004).

The succession of Pliocene (3.5–3.0 Ma) and Pleistocene marine transgressions and regressions in the Mediterranean region could also be responsible for the changes of regional base level that occurred, at least in tectonic blocks close to shorelines (as in the Messinian), but the influence of such changes on areas farther inland was presumably negligible. Nevertheless, no evidence of correlative sediments has been detected. The sea-level oscillations could contribute to evolution of karst subsurface drainage following the hydraulic head. Tracing tests (Gospodarič & Habič 1976; Krivic et al. 1987; Habič 1989; Krivic, Bricelj & Zupan 1989) indicated different drainage directions, which are parallel to sub-parallel to Dinaric trends, or oblique to them and crossing structural and lithological boundaries (following cross-Dinaric trends; Fig. 280). The latter could easily represent the rejuvenated drainage routes developed during the sea level lowstands (Messinian, Pliocene, Pleistocene), i.e. periods with steep hydraulic head. For illustration, during Pleistocene lowstands the coast of the Adriatic Sea was situated far to the south near the city of Zadar in Croatia.

Levelled surface of the Cerknica polje is at elevation about 550 m.

DISCUSSION OF THE AGE INTERPRETATIONS

The principal results and interpretations of individual caves and profiles studied between 1997 to 2006 in Slovenia are summarized in Tables 78 to 81.

Table 78 summarizes principal lithological features, sedimentological interpretation of the depositional environments and fossil finds discussed in the individual sub-chapters. The interpretation of age of cave fills in Tables 78 to 81 is based on all available numerical- and correlated-ages obtained from all sources (literature, new analyses), but the primary source of age estimation is the results of the magnetostratigraphy of the cave sediments. Maximum ages, except sites where proven by other method, therefore represent rough estimates only and could be far from the reality. Further, at most sites the sedimentary profile was not excavated completely up to the cave rock floor, and so the beginning of deposition can be substantially older (e.g., ages designed as over 0.78 Ma). Nevertheless, Tables 79 to 81 show some identical features in the ages of the cave fills deposited principally under vadose conditions. Three principal periods of deposition of the cave fills can be distinguished as follows:

Sediments older than 1.2 Ma (numerical age)/1.77 Ma (palaeomagnetic age); up to or greater than 5.0 Ma. The interpretation of the upper age limit, if based on the palaeomagnetic data, represents the rough estimate of the alternation of R and N polarized magnetozones typical for the period of Matuyama and older chrons. Ages in this category are adjusted to the age interpreted at the Črnotiče I site and the common characteristics of the respective cave fills in Briščiki, Jama pod Kalom, Divača and Kozina profiles or Divaška jama. Jama pod Babjim zobom most probably belongs to this period also, but the data are too scarce. Filling can be dated to uppermost Miocene and Pliocene. The cave with the presumably oldest sediment in our study is Grofova jama. The montmorillonite fill, if derived from intensive weathering of volcanoclastic products, should originate from products of Oligocene to early Miocene volcanic activity in Italy or north-eastern Slovenia. The age of the fill can be up to 34–35 Ma, but probably is between 33 and 11 Ma old; it can represent a much older period of cave evolution in the Kras region.

Sediments dated from about 0.78 Ma (palaeomagnetic age) up to more than 4.0 Ma (palaeomagnetic age). This group contains a succession of detected ages. The base of most profiles can be interpreted as probably not much older than 3.58 Ma, i.e. the datum adjusted by palaeontological finds in the Črnotiče II and Račiška pečina sites. It seems that some phases could be distinguished: (a) more than 0.78 up to about 4.2 Ma (palaeomagnetic ages; e.g., Račiška pečina, Črnotiče II, Tajna jama, Markov spodmol), and (b) less than 0.78 to about 2 Ma (palaeomagnetic ages), i.e. something between Brunhes/Matuyama boundary (and somewhat younger) and base of Jaramillo and/or Olduvai subchrons (and somewhat older). Dates from Postojnska jama (Male jame, Spodnji Tartarus – white sandstone) and Zguba jama do not allow more detailed age determinations. It cannot be ruled out that the Spodmol nad Planino Jezero could belong to this stage also.

Data summarized in Tables 78 to 80 and the brief review given above clearly indicate that the substantial part of cave fills were deposited in period probably not older than 6 Ma, i.e. associated with the change of geodynamic regime (*cf.* Fodor et al. 1998; Márton et al. 2003; Vrabec & Fodor 2006). The counter-clockwise rotation connected with the reactivation of the Dinaric faults led to rotation and over-thrusting of smaller tectonic blocks, especially in the Dinarides but also in the Southern Alps (Ilić & Neubauer 2005; Neubauer 2007). The movements caused changes of altitudinal position of the caves or parts of cave systems and changes of hydrological conditions. Those changes led to complete or partial filling of their respective cave passages. This can be exemplified in the region of Kras with the Kozina and Divača profiles, Trhlovca, Črnotiče, etc. Although fossilization of the caves was originally associated with the Messinian and post-Messinian changes in regional base levels (Bosák, Zupan Hajna & Pruner 1998; Bosák et al. 1999, 2000a, b), the tectonic movements after 6 Ma were probably decisive in this process. This is indicated also by the inclined strata dip in some of the profiles and the rotations detected within sedimentary profiles (e.g., Črnotiče I; Črnotiče II).

Table 78 Summary of results from all Slovenian sites and profiles

Region	Type of site	Name of site	Name of profile		Lithology	Depositional environment	Fossils	Profile segment	Age	
									Min.	Max.
Dinaric Karst	Unroofed Caves	*Črnotiče*	I		Flowstone, cave stromatolite, clay interbeds	Cave vadose, calm fluvial, periodic floods (pulsed flow)	Fish teeth?		>1.77 (4.2)	5.4
			II	Main	Cyclic set of layers lower part: clays, silts, sands upper part: micro-conglomerates and conglomerates, sands, clays to silts	Cave vadose Upper: dynamic fluvial, periodic floods (pulsed flow) Lower: calm fluvial	Marifugia cavatica, rhodents, crabs, fishes, lizard, insectivores, tree leafs		*>1.8*	*3.58*
				Right	Silts, clays and sand	Cave vadose: calm fluvial to lacustrine, pulsed flow	None		>1.77?	*<3.58*
		Briščiki			Clays and silts, scree, flowstone, carbonate concretions	Cave vadose: calm fluvial (pulsed flow) to lacustrine, roof collapses	None		>1.77	>5.0
		Kozina			Clays to silts, local sandy interbeds, breccia interbed	Upper: cave fluvial Lower: calm, pulsed flow	Pollen		>1.77	>5.0
		Divača			Upper sequence: fluvial cycles Lower sequences: clays to silts	Upper: cave fluvial, dynamic Lower: calm, pulsed flow	None		>1.77	>5.23
	Caves	*Jama pod Kalom*			Upper part: clays, scree Lower part: clays to silts, sandy laminas, scree, flowstone	Cave vadose: fluvial to calm lacustrine, pulsed flow	None	Upper Lower	*<0.05*	>**0.374** <0.78 >5.0
		Grofova jama			Montmorillonitic clays	Cave phreatic: calm fluvial	None			Up to 35
		Divaška jama			Clays to silts with sandy interbeds, flowstone interbed	Cave vadose: lacustrine to calm fluvial, pulsed flow	None	Upper Lower	**0.092** >**1.2**	**0.576** >5.0

Dinaric Karst	Caves	*Trhlovca*			Sediment: alternation of clays, silts and sands	Cave vadose: calm lacustrine to fluvial, pulsed flow	None		>1.77	>5.0
					Brown flowstone	Cave vadose	Pollen		>1.77	>5.0
		Račiška pečina	Profile		Flowstone, clays, sands	Cave epiphreatic: slow flow, redeposition, intermittent dry periods	Cave bear Rhodents, crabs, pollen	Top Middle Lower Base	≈<u>0.09</u> *1.77* *1.95*	*<1.77* *1.95* *3.58* >5.0
			Fold test		Stalagmite	Cave vadose	None			≥3.4
		Pečina v Borštu			Stalagmite	Cave vadose	None		**0.194**	<0.78
		Križna jama	I		Clays to silts, flowstone	Cave vadose: slow flow to lacustrine, pulsed flow	Cave bear	Upper Lower	≥*0.03*	>**0.244** <0.78
			II		Clays to silts, flowstone	Cave vadose: slow flow to lacustrine, pulsed flow	Cave bear		≥*0.03*	<0.78
		Planinska jama	Rudolfov rov		Clays to silts,	Cave vadose: pulsed flow to lacustrine	None			<0.78
		Postojnska jama	Spodnji Tartarus	North Red	Clays to silts	Cave vadose: pulsed flow to lacustrine	None			<0.78
				North Yellow	Clays to silts	Cave vadose: pulsed flow to lacustrine	None			<0.78
				South	Clays to silts	Cave vadose: pulsed flow to lacustrine	None			<0.78
				White sandstones	Cemented white sandstone	Cave vadose: ?fluvial	None		>0.78	
			Umetni tunel 1		Sands, top clays	Cave vadose: fluvial	None		<0.99	>2.15
			Umetni tunel 2		Clays and sands	Cave vadose: fluvial, pulsed flow	None		No data	No data
			Biospeleološka postaja		Scree covered by clays, flowstone at top	Cave vadose: slow flow, slope deposits	None			<0.78

Dinaric Kars	Caves	*Postojnska jama*	Male jame	Upper: gravel and sand Lower: clays to silts	Cave vadose Upper: fluvial Lower: pulsed flow to lacustrine	None			>0.78
			Stara jama	Top: clays with sands Middle: clays to silts Bottom: gravel	Cave vadose: fluvial and pulsed flow	Cave bear			<0.78
			Pisani rov	Clays to silts, top flowstone	Cave vadose: pulsed flow to lacustrine	None		>**0.35**	<0.78
		Markov spodmol	I (upper part)	Laminated and multi-coloured clays	Cave vadose: calm fluvial to pulsed flow	None		<0.78	3.58
			II (trench)	Clays with sands, laminated clays	Cave vadose: calm fluvial and pulsed flow, lacustrine	None		>0.78	3.58
	Surface karst sediments	*Hrastje*		Clays and silts	Surface: lacustrine (pond) or paludal	None		<0.78	>0.78
Alpine Karst	Caves	*Jama pod Babjim zobom*		Calcite crystals Flowstone	Cave phreatic (hydrothermal) and vadose	None		>0.78	>1.77
		Spodmol nad Planino Jezero		Top: clays and silts Middle: sands and clays Bottom: quartz sandstone	Cave vadose: change from fluvial to pulsed flow	None		>0.78	
		Snežna jama		Flowstone	Cave vadose	None		>**1.2**	>5.0
		Tajna jama		Clays with pebbles	Cave vadose: fluvial, floods, pulsed flow	None		±0.78	4.18
	Surface fluvial sediments	*Velenje*		Clays, quartz sands and conglomerates	Surface: fluvial to delta sediments	None			<0.78

Explanations: bold = Th/U data; italics = paleontological data; underlined = archaeology

Table 79 Ages of cave sediments interpreted on studied sites from Dinarski kras

Name of site	Name of profile	**Age** (Ma)		Age of cave fill
		Min.	**Max.**	
Grofova jama		?	Up to 35	**Miocene/Pliocene**
Črnotiče	I	4.2	5.4	
Briščiki		>1.77	>5.0	
Jama pod Kalom	Lower part	>1.77	>5.0	
Divača profile		>1.77	>5.23	
Kozina profile		>1.77	>5.0	
Trhlovca		>1.77	>5.0	
Divaška jama	Lower part	>**1.2**	>5.0	
Črnotiče	II Right	1.77?	*<3.58*	**Pliocene to Pleistocene (Günz/Mindel)**
Črnotiče	II Main	1.8	3.58	
Račiška pečina		1.77	>3.4	
Markov spodmol	I	<0.78	3.58	
Markov spodmol	II	>0.78	3.58	
Postojnska jama	Umetni tunel I	<0.99	>2.15	
Postojnska jama	Male jame	?	>0.78	
Postojnska jama	White sandstone	?	>0.78	
Zguba jama	I+II	<0.78	>0.78	
Divaška jama	Upper part	0.092	0.576	**Pleistocene (Mindel/ Holocene)**
Jama pod Kalom	Upper part	*<0.05*	<0.78	
Postojnska jama	Tartarus North	?	<0.78	
Postojnska jama	Tartarus South	>**0.122**	<0.78	
Postojnska jama	Pisani rov	>**0.35**	<0.78	
Postojnska jama	Stara jama	?	<0.78	
Planinska jama	Rudolfov rov	?	<0.78	
Račiška pečina	Top	<0.09	<0.78	
Križna jama	I+II	*≥0.03*	<0.78	
Pečina v Borštu		**>0.194**	<0.78	

Explanations: bold numbers = Th/U data; italics = palaeontological data; underlined = archaeological data

For the first time, the combination of vertebrate fossil records and magnetostratigraphy, have proven the expected antiquity of the cave infilling and related surface landforming processes. According to data from Črnotiče II site and Račiška pečina, one of the important older phases of speleogenesis in the region finished during MN15–MN17, i.e. in the period between 1.8 and 3.581 Ma. Palaeontological finds helped to set those processes well into the stratigraphic position and proved the expected ages of cave filling processes deciphered from magnetostratigraphic and geomorphic interpretations. Data from Črnotiče indicate also the age of the levelled surface of the Podgorski kras, which is younger than the age of the fill because the surface cuts the cave and caused the roof collapse.

Paragenetic features developed in a number of the caves (e.g., Postojnska jama – Spodnji Tartarus or Stara jama, Črnotiče II, Trhlovca, Račiška pečina, Snežna jama) prove that they were completely filled by sediments. Sediments preserved in Postojnska jama system indicate multiple fillings and exhumation of the fill, which may be case in other caves, as well (Fig. 281). It is clear that the evolution of caves and their fill can be much longer than indicated by the data obtained from dating particular cave infilling phases.

The substantial age of cave fills can be also judged from the fact that some studied sites in the Alpine karst of Slovenia occur at high altitudes and the cave entrances are on the upper slopes of deeply entrenched valleys. This is the case of Jama pod Babjim zobom, Spodmol nad Planino Jezero and Snežna jama. The fill of caves are clearly older than 1.77 Ma. Speleothems in Snežna jama can be 5.0 Ma or even older. The evolution of those karst plateaus and massifs is comparable with another part of the Alpine chain – the Northern Calcareous Alps – where caves occur also from 1300

Figure 281 *Remains of old sediments at different elevations in Postojnska jama indicate multiple fillings and exhumation of the fill.*

to 1700 m a.s.l. and up (Zötl 1989; Frisch et al. 2000, 2001, 2002), i.e. up to 900 m above recent river-beds (*cf.* Schauberger 1956; Bauer & Zötl 1972; Zötl 1989). It seems that the timing of changes of the original hydrological systems can be correlated with some other caves in Slovenia, especially from the Kras.

Concerning Pliocene/Pleistocene fill from the systems of Postojnska jama and Planinska jama, we can emphasize some new ideas. Our research indicated that the general stabilization of the hydrological system of Pivka basin – Planinsko polje for more than two million years (Pruner et al. 2004) led to the development of long and complicated cave systems. The evolution cannot be based on a young evolution during the last 30 to 100 ka as proposed by Šušteršič, Šušteršič & Stepišnik (2003). Their model was based on re-interpretation of the original stratigraphy of Gospodarič and his evolution phases (1988). The succession of events that is proposed may be correct, but proposed time for such dynamics of infilling and erosion phases is unrealistic, being much too short. Our interpretation is based on (1) all numerical- and correlative-ages (including archaeology; *cf.* Brodar 1969) referred to or described in this book; (2) the morphology of Planinsko and Cerkniško poljes. The present geographical limits of the flat bottom surface are far from the faults limiting the Idrija fault zone. If poljes along Idrija fault zone really represent a pull-apart basin (Vrabec 1994), their lateral enlargement by lateral corrosion to the present extent needed a much longer time than 100 ka, during which the karst water table needed to be stabilized, and (3) the knowledge on dynamics of filling and erosion phases in the system of the Postojnska jama (e.g., Pruner et al. 2004). The data obtained indicate that several depositional and erosion phases alternated in Postojnska jama. It cannot be excluded that individual cave segments or passages were fully filled and exhumed several times during the cave evolution, as indicated, for example, by remains of cemented sediments on walls and ceilings in the main passage of Stara jama or in other places. The alternation of depositional and erosion phases may be connected with changing conditions within the cave system, functions of the resurgence area, collapses, climatic changes, tectonic movements and the intrinsic mechanisms of the contact karst. It can be expected that the deposition was not uniform throughout the entire cave at the same time, most likely there was erosion in one part of the cave and deposition in another. Repeated reworking and re-deposition of the same sedimentary material can be also expected within the long, voluminous and complicated cave system. All those data indicate quite prolonged development of the drainage system as a whole.

Table 80 Ages of karst sediments interpreted on studied sites in the Alpine and Isolated karsts

Name of site	**Age** (Ma)		Age of cave
	Min.	**Max.**	
Snežna jama	>**1.2**	>5.0	**Miocene/ Pleistocene**
Tajna jama	±0.78	4.18	
Jama pod Babjim zobom	>0.78	>1.77	
Spodmol nad Planino Jezero	>0.78	?	

Explanations: bold = Th/U data

Sediments younger than 0.78 Ma. This category includes also young depositional phase(s) in caves with older fills (e.g., Jama pod Kalom, Računa pečina, Divaška jama). Caves containing sedimentary fill younger than the Brunhes/Matuyama boundary have one common and typical feature – a part of the cave is still hydrologically active, with one or more streams flowing in the lower levels (e.g., Postojnska jama, Križna jama, Planinska jama).

Cave sediments in unroofed caves are not always very old. The palaeomagnetic and Th/U dating of borehole S1 (Jama pod Kalom) indicates the young geomorphic evolution of the cave. Speleothem layers buried in the fill dated back to ca 194 and 332 ka establish the existence of the cave ceiling at that time. The ceiling had to be enough thick to prevent the collapse (i.e. the recent entrance to the Jama pod Kalom at least 3 to 4 m thick). The roof collapse is younger than 194 ka and it causes quite dramatic changes in the sedimentary profiles (e.g., the erosion of the older fill after the Blake event – ca 111–117 ka – and before the deposition of bone-bearing beds dated back to ca 50 ka).

Palaeomagnetic, Th/U and biostratigraphic dating enabled us to detect and roughly date short excursions of the palaeomagnetic field within the Brunhes chron. Dates from the Križna jama I and II indicate that such short-lived R magnetozones are older than about 146–160 ka. Interpretations from Jama pod Kalom (borehole S1) showed that the longer R magnetozone could represent the Blake event dated to 117.1 ±1.2 to 111.8 ±1.0 ka BP from Chinese loses (Zhu et al. 1994).

The evolution of vadose zones and related forms associated with uplifts of individual tectonic units and blocks were dated as well. Some kind of cave re-shaping and evolution of vadose invasion and drawdown shafts was clearly documented in mountainous cave settings (Snežna jama, Jama pod Babjim zobom, etc.) with rapid uplifts and valley entrenchments. Similar evolution was documented also at lower altitudes, e.g. in Podgorski kras. Vertical shafts here were developed after the uplift and filled during Middle to Late Pleistocene interglacials. This is proved by finds of mammals and Th/U data of carbonate cement of gravel (211 ± 43 and 143 ± 13 ka; Mihevc 2001).

Table 81 Ages of karst sediments at studied sites on the surface

Name of site	**Age of sediments** (Ma)	
Hrastje	<0.78	>0.78
Velenje		<0.78

The relatively great ages of cave sediments detected by magnetostratigraphy and the other dating methods is supported by the calculated/expected chemical denudation rates of 30–50 m per 1 Ma (Gams 1981, 2003; Cucchi, Forti & Ulcigrai 1994), i.e. denudation (dissolution) of 150–250 m of rocky overburden. The present depth of the vadose zone is up to 220–346 m (e.g., in the system of Škocjanske jame and underground Reka river; a.o. Gams 2003). However, it appears that the true chemical denudation rate must closer to the lower expected limit or even less than it, because the origin of the conduit itself is much older and thus (at the higher rates) the denuded overburden would be unrealistically thick.

The differences in cave infill processes can indicate some important pulses in the evolution of the karst water level, reflecting the uplift/subsidence of individual tectonic blocks, especially within the Dinarski kras and its individual geomorphic units as already predicted by Habič (1984, 1992). The recent tectonic activity along the transect from the northern coast of Istria peninsula up to South-Alpine thrust front shows movements within the range of -1 to 6 mm per year, with typically increased velocities at thrust fronts and the north-western margins of individual tectonic blocks, while forelands of principal thrust slices can subside slightly (Rižnar, Koler & Bavec 2007). Some block rotations and movements after a cave was filled are indicated by differences in strata dips in different units of the cave fill, e.g., in Tajna jama, Kozina profile and Črnotiče II site and result from such neotectonic activity. Slickensides in sediments from the Umetni tunel I site (Postojnska jama) represent results of such movements, which were younger than 2.15 and/or 1.1 Ma.

The karst phenomena of Slovenia analyzed in this study are the result of relatively young evolution that results from this particular geotectonic location. It extends from the Oligocene to the present and thus is placed within the "Neokarstic Period". The term 'neokarst' (neocarsismo) was introduced by D´Argenio (1978) to define the karstification that occurred during so-called Neotectonic Period i.e. when the principal modern geological structures were built. The period before this is defined as 'palaeokarstic'.

Figure 282 *Cave sediments represents tool for reconstructing landscape evolution and tectonic regimes in their respective areas; sediments in Postojnska jama.*

CONCLUSIONS

Intensive palaeomagnetic research in Slovenia has contributed substantially to the understanding of cave sediments in different tectonic and geomorphic settings in the territory. The most important result is the discovery that cave fills have substantially older ages than generally expected earlier (max. about 350 ka see summary in Gospodarič 1988). Palaeomagnetic data in combination with other dating methods, especially biostratigraphy, have shifted the possible beginning not only of the speleogenesis but also of the cave filling processes in Slovenia far below the Tertiary/Quaternary boundary (here assigned its traditional age at 1.8 Ma). The data support and better define the estimated ages of the surface and cave sediments that were based on geomorphic evidences, especially from unroofed caves.

Repeated sampling in some profiles from Slovenia have shown that only dense sampling, i.e. high-resolution approach with sampling distance of 2–4 cm, can ensure reliable results. The application of complete palaeomagnetic analysis, both thermal and alternating field demagnetization only to pilot samples and an abbreviated selected field/step approach to other samples did not offer sufficient data for confident interpretation. It is necessary to apply a complete demagnetization process to obtain reliable data.

The evolution of the caves (from the start up to their total destruction by denudation) took part within one karstification period, which began with the regression of Eocene sea and exposing of limestones at the surface within complicated overthrusted structure, which formed principally during Oligocene to early Miocene. The interpretation of palaeomagnetic data, with some support from palaeontological finds, indicates that karst developed in pulses tightly linked with tectonic evolution and changes of the geodynamic regime. Individual pulses were not sharply limited, however, and therefore cannot be tied to precisely defined karst phases. Moreover, the complicated geological structure and tectonic/geomorphic evolution makes the picture less clear due to the differing tectonic evolution of individual morpho-structural units, which often have also quite different histories of evolution of the relief and karst.

The reconstruction of evolution of karst and caves is complicated by the lack of surface karst sediments. Correlative deposits in surrounding depositional basins are either too old (Pannonian Basin), or poorly dated (e.g., fills of Plio/Quaternary inter-montane basins). Sediments representing the last 6 Ma are preserved only in caves or unroofed caves. They contain records of past climatic, palaeogeographic and tectonic changes, although not continuous. Cave sediments therefore are good tools for reconstructing landscape evolution and tectonic regimes in their respective areas (Fig. 282).

Research in the Dinaric, Alpine and Isolated karsts opened new horizons for the interpretation of karst and cave evolution, both of individual geomorphologic units and of extensive areas. The data inform us that a number of common features and evolutionary trends exist in all the studied areas. On the other hand, there are distinct differences of evolution of smaller geomorphic units within the more extensive ones, which result mostly from differential tectonic movements connected with the post-6 Ma counterclockwise rotation of the Adria block. The analysed cave fills indicate that there were all deposited within one, still lasting period of (post Eocene) karstification. However results suggest that there were probably some distinct phases of massive deposition in caves. The oldest one took place from about 1.8 to more than 5.4 Ma (with two distinct phases at 1.8 – 3.6 and about 4.1 – 5.4 Ma). For the first time in Slovenia, biostratigraphic data helped to correlate magnetostratigraphy logs with the GPTS and to allocate the cave fill ages more precisely to pre-Quaternary times.

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