CAVE AND KARST EVOLUTION IN THE ALPS AND THEIR RELATION TO PALEOCLIMATE AND PALEOTOPOGRAPHY

RAZVOJ JAM IN KRASA V ALPAH V LUČI PALEOKLIME IN PALEOTOPOGRAFIJE

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Abstract   UDC 551.435.84(234.3)
Philippe Audra, Alfredo Bini, Franci Gabrovšek, Philipp Häuselmann, Fabien Hobléa, Pierre-Yves Jeannin, Jurij Kunaver, Michel Monbaron, France Šušteršič, Paola Tognini, Hubert Trimmel & Andres Wildberger: Cave and Karst evolution in the Alps and their relation to paleoclimate and paleotopography
Progress in the understanding of cave genesis processes, as well as the intensive research carried out in the Alps during the last decades, permit to summarize the latest knowledge about Alpine caves. The phreatic parts of cave systems develop close to the karst water table, which depends on the spring position, which in turn is generally related to the valley bottom. Thus, caves are directly linked with the geomorphic evolution of the surface and reflect valley deepening. The sediments deposited in the caves help to reconstruct the morphologic succession and the paleoclimatic evolution. Moreover, they are the only means to date the caves and thus the landscape evolution. Caves appear as soon as there is an emersion of limestone from the sea and a water table gradient. Mesozoic and early tertiary paleokarsts within the alpine range prove of these ancient emersions. Hydrothermal karst seems to be more widespread than previously

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V članku predstavimo nova spoznanja o razvoju alpskih jam. Ta temeljijo na sintezi novih dognanj o procesih speleogeneze in rezultatih intenzivnih terenskih raziskav v Alpah v zadnjih desetletjih. Razvoj freatičnih delov jamskih sistemov poteka v bližini freatične površine, ki je vezana na položaj izvirov, ti pa so vezani na dno alpskih dolin. Torej je razvoj jam neposredno vezan na geomorfološki razvoj terena in poglabljanje dolin. Jamski sedimenti nosijo informacijo o zaporedju morfoloških in klimatskih dogodkov. Še več, določanje starosti jam in poteka razvoja površja, je možno edino z datacijo jamskih sedimentov. Razvoj jam se začne ob emerziji apnenca in vzpostavitvi hidravličnega gradienta. Mezocojski in zgodnje terciarni paleokras v območju Alp so dokaz starih emerzij. Hidrotermalni kras je očitno bolj razširjen, kot so domnevali v preteklosti. Te jame so bile pozneje preoblikovane z meteorno vodo, ki je zabrisala sledi zgodnjega hipogenega zakrasevanja. Ledeniki zavi-

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presumed. This is mostly due to the fact that usually, hydrothermal caves are later reused (and reshaped) by meteoric waters. Rock-ghost weathering is described as a new cave genesis agent. On the contrary, glaciers hinder cave genesis processes and fill caves. They mainly influence cave genesis indirectly by valley deepening and abrasion of the caprock. All present datings suggest that many alpine caves (excluding paleokarst) are of Pliocene or even Miocene age. Progress in dating methods (mainly the recent evolution with cosmogenic nuclides) should permit, in the near future, to date not only Pleistocene, but also Pliocene cave sediments absolutely.

Key Words: Karst, Cave genesis, Alps, Glaciations, Messinian event, Paleoclimate, Paleotopography.

rajo procese speleogeneze in zapolnjujejo jame. Na razvoj jam vplivajo posredno, preko poglabljanja dolin in brušenja površja. Novejše datacije kažejo, da so številne jame v Alpah pliocenske ali celo miocenske starosti. Nove datacijske metode – predvsem metoda kozmogenih nuklidov – bodo omogočile absolutno datacijo sedimentov do pliocenske starosti.

Ključne besede: kras, geneza jam, Alpe, poledenitve, mesinska stopnja.

INTRODUCTION

Progress in cave exploration and cave genesis studies (Audra 1994, Jeannin 1996, Palmer 2000) permitted to recognize the potential of caves for the study of landscape evolution, valley deepening and thus erosion rates and climate changes (Häuselmann *et al.* 2002; Bini *et al.* 1997). Most of the information that is sheltered within the cave's morphology and sediments is no more available at the surface, mainly due to the intensive erosion, especially during the glaciations.

This article gives information about cave genesis and its potential for the reconstruction of the evolution

and timing of the landscape: Part I presents the latest results concerning cave genesis and their link with the landscape. Part II deals with new concepts about early cave genesis, including pre-existing karst systems (paleokarst), hydrothermal karst, and pseudokarst. Many caves are older than the glaciations and glaciers generally are rather hindering cave genesis processes. Part III consequently presents evidences supporting a high age of many cave systems. In Part IV, ages obtained by different dating methods prove that karst genesis in the Alps started far before the Quaternary, as far as the Cretaceous.

SETTING

The Alpine belt extends from Nice (France) to Vienna (Austria) into seven countries (France, Switzerland, Italy,

Liechtenstein, Austria, Germany and Slovenia). Karsts and caves are found in each country, the largest karst areas being located in periphery (Fig. 1). All massifs are dissected by deeply entrenched valleys which divide continuous structures into different physiographic units. Annual precipitation range from 1500 to more than 3000 mm.

The French Western Prealps consist of folded and thrusted massifs of mainly Cretaceous rocks. The elevation ranges generally between
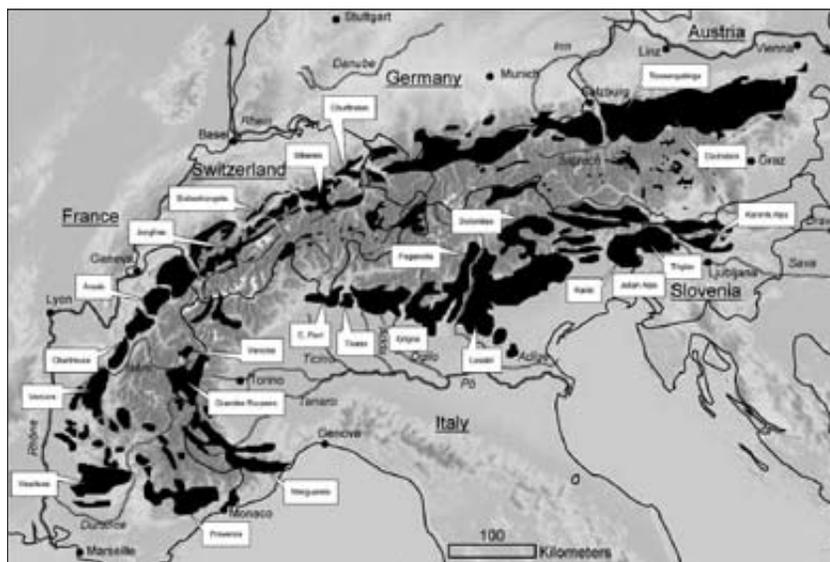
Fig. 1: Map of the alpine karsts (dark color) with location of the mentioned massifs (karst areas after: Buzio & Faverjon 1996; Mihevc 1998; Stummer & Pavuza 2001; Wildberger & Preiswerk 1997. Map: D. Cardis).

1000 and 2000 m. The Vercors displays a landscape of ridges and valleys, whereas the Chartreuse presents a steep, inverted relief.

The Central Swiss Alps harbors the highest alpine karst areas at Jungfrau (3470 m ASL). The Siebenhengste (2000 m ASL) and the Hölloch-Silberen (2450 m ASL) consist of nappes of Cretaceous and Eocene rocks.

The Italian Southern Alps are located to the south of the Insubric Line. The carbonate rocks range in age from Carboniferous to Cretaceous-Eocene. They are deformed and displaced by S-vergent thrusting and large scale folding. The elevation ranges from 200 m to 2400 m ASL.

The Northern Calcareous Alps in Austria are composed of a slightly folded succession of Trias limestones and dolomites with a thickness of more than 1000 m. Large plateaus extend from 1800 to 2200 m ASL.

In the Slovenian Alps, the Julian and the Kamnik Alps correspond to the roots of the Austrian nappes. Thus the landscape is often similar, with plateaus and narrow steep ridges dominated by high peaks reaching more than 2800 m ASL.

GENERAL CONCEPTS OF CAVE GENESIS

The basics of cave genesis are beyond the scope of this paper. The reader can refer to the most comprehensive and up-to-date work *Speleogenesis: Evolution of Karst Aquifers* (Klimchouk *et al.* 2000).

GENESIS OF CAVES AND MORPHOLOGY OF PASSAGES RELATED TO WATER TABLE POSITION

Water flowing into limestone corrodes and erodes the rock. Driven by gravity and geological structure, it flows down more or less vertically, until it reaches either the karst water table or impermeable strata. Then it continues flowing more or less horizontally towards the spring, collecting water from other lateral passages. Water flowing in the vadose (unsaturated) zone can only erode the floor of a gallery creating a meandering canyon. On the other hand, water flowing within the phreatic (saturated) zone corrodes over its whole cross-section, giving a rounded cross-section (Fig. 2). The morphologies that are preserved once the watercourses have been abandoned give information about the prevailing position of the phreatic zone during the genesis of the galleries.
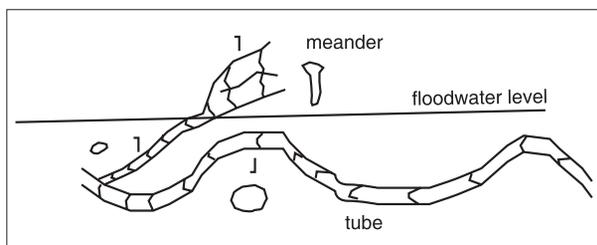
Fig. 2: An undulating phreatic tube is co-fed by a vadose meandering canyon, whose shape turns into a tube below the floodwater table. The arrow marks the transition from vadose to phreatic.

RECOGNITION OF CAVE GENESIS PHASES AND RELATION TO THE SPRING

Within the saturated zone, two geometric types of conduits prevail (Ford 1977, 2000): 1) the *water table caves,* represented by horizontal conduits located at the top of the saturated zone; 2) the *looping caves,* represented by vertically lowering and rising conduits, whose amplitude may reach as much as 300 m, or even more.

A "phase of cave genesis" corresponds to the network of active conduits related to a given (paleo)spring. As springs move together with valley bottoms, we usually find many different "phases of cave genesis" in a given karst region.

As described on figure 2 the transition between phreatic conduits (elliptical shape) and vadose ones occurs at the top of the epiphreatic zone, i.e. more or less at the top level reached by water during highwater stages. Due to headlosses, highwater level is inclined towards the outlet of the system, namely the karst spring (Jeannin 2001, Häuselmann 2003). Most of the time conduits are located within a given range of altitudes (sometimes more than 300 m) below the (inclined) water table limit. These conduits go up and down (hence their name: "loops") within this range and towards the spring. Sometimes main conduits of a given phase can be followed for kilometers and display a phreatic morphology all along. Sometimes the highest passages clearly show vadose entrenchment because they were located higher than the top of the epiphreatic zone, at least most of the time.

Reality is a little more complicated that exposed here (see Häuselmann *et al.* 2003 for instance), but the principle is the same. The main exceptions to this model, linking quite directly the phases of cave genesis to the (paleo)spring positions, i.e. valley bottom, occur when

impervious barriers dam water somewhere inside the aquifer.

SUCCESSION OF CAVE GENESIS PHASES, CAVE LEVELS RECORDING BASE LEVEL CHANGES

If the spring lowers gradually, the cave system behind also adapts gradually by entrenchment to the new situation: no distinct phases exist. If the spring lowers in a stepwise manner, followed by a time of relative stability, the flowpath readjustment in the cave also occurs rapidly and a new cave genesis phase develops. Calculations show that, once a proto-conduit has been formed, caves may evolve very rapidly, in the order of 10'000 years, to reach penetrable size (Palmer 2000). Therefore, after a new entrenchment of a valley, pre-existing or newly created *soutirages* (Häuselmann *et al.* 2003) allow for the water to reach the spring level quite quickly and a new water table, i.e. phase of cave genesis is created (Fig. 3). Former conduits, perched in the vadose zone after the deepening of the karst system, are abandoned and remain dry (fossil passages). Provided that the cave genesis phases reflect the deepening of the valleys through time, they give information for the reconstruction of paleorelief.
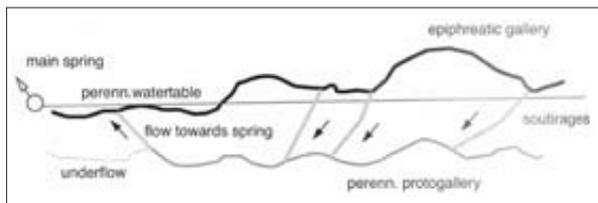
Fig. 3: Schematic flow system. Black = main (epiphreatic) gallery; light grey = soutirages (downward) and upflow (upward); dark grey = perennial phreatic conduit.

Equivalent information at the surface is usually no longer present, mostly due to river or glacier erosion.

In some cases, the base level may rise again after a period of deepening (e.g. post-messinian infilling of the overdeepened canyons in the southern part of the Alps; Felber & Bini 1997). This caused a flooding of pre-existing karst systems and a reactivation of previously vadose or abandoned passages (Tognini 2001).

THE RELATION BETWEEN MORPHOLOGY, CLIMATE, AND SEDIMENTS

Cave morphology depends on the position of the epiphreatic water table. The size of the passage, however, depends (among others, mostly geological factors) on time and flow rate. Worthington (1991) puts forward that there is an "equilibrium size" of a phreatic passage for a given flow rate. After this size is reached, the passage hardly grows anymore, and a growth above this size is mainly dependent on an increase in flow rate, either by capturing another catchment, or related to an increase in precipitation. For example, in the Siebenhengste system, the size of the main conduits doubles between two phases (700 m and 660 m). This very probably corresponds to the capture of the Schrattenfluh catchment, which significantly increased the size of the catchment area (Fig. 4). Conversely, a reduction in the catchment area due to valley entrenchment produces rearrangement of the cave system. Newly formed passages will be smaller than in the previous phase.

Beside the size of the conduits, sediments also provide direct information about the flow velocities, i.e. discharge rates in the conduits. Grainsize distribution of cave sediments and conduit size make it possible to assess paleodischarge rates quite precisely.
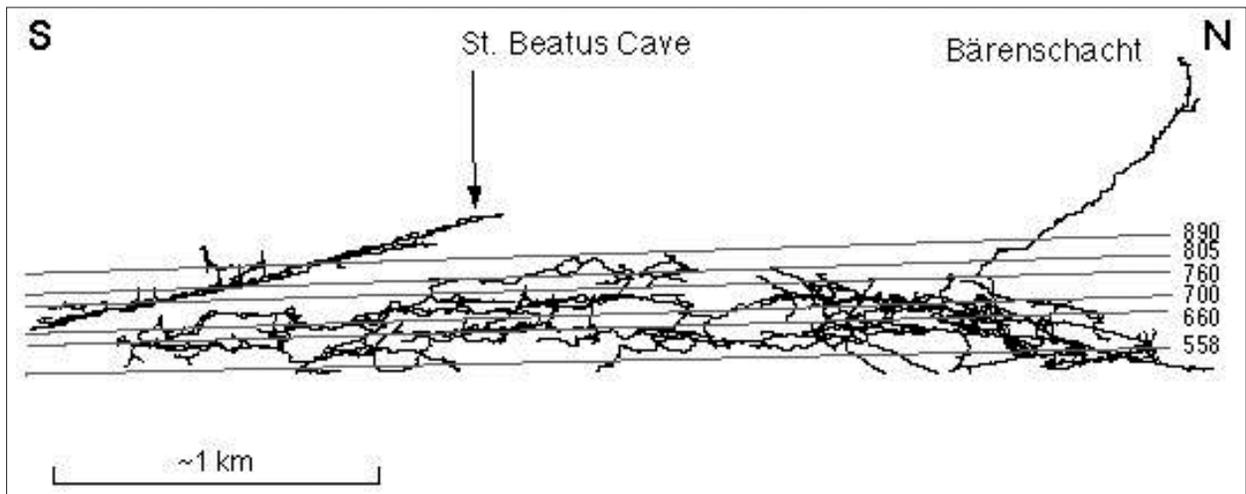
Fig. 4: N-S-projection of Bärenschacht and St. Beatus Cave with the recognized phases. The numbers are the elevations (in m ASL) of the corresponding spring. Phase 558 is the present one.

NEW CONCEPTS ABOUT CAVE GENESIS

THE INFLUENCE OF EARLY PHASES: PRE-EXISTING KARST SYSTEMS (PALEOKARST), HYPOGENIC KARST AND PSEUDOKARST

Syn- and post-sedimentary paleokarsts

"Paleokarst" are features that are not related to any present water circulation and completely obstructed. Since most of the caves (including fossil tubes) are related to present rivers and valleys, they are not considered as paleokarst.

Some paleokarsts have been formed during or immediately after the sedimentation of carbonate platforms (Upper Triassic, for example Calcare di Esino/Grigna; Dachsteinkalk/Northern Limestone Alps). Dolines, pockets and red paleosoils interfere within the cyclic sedimentation of the so-called loferitic succession. Under a premature diagenesis, dissolution and concretion produced evinosponges (Bini & Pellegrini 1998) and dolomite-filled fractures that contain iron oxides from paleosoils. In the Julian Alps, paleokarstic conduits have been filled with carbonate mud and later lithified, so that – presently – a paleoconduit is just a portion of somehow differently colored solid rock. Other paleokarst had been set up after the emersion of the limestone strata. They are fossilized by Jurassic sediments (Swiss Prealps, Julian Alps), Upper Cretaceous sandstone (Siebenhengste), Eocene sands (Vercors), or Miocene conglomerates (Chartreuse).

Those paleokarsts features may form highly porous discontinuities that may have guided the placement of later cave systems.

- Hydrothermal caves related to tectonic build-up

Some caves have a hydrothermal origin, which can be recognized after their typical corrosional cupolas originating from convection cells and their sediments like large calcite spar (Audra *et al.* 2002a; Audra & Hofmann 2004; Bini & Pellegrini 1998; Sustersic 2001; Wildberger & Preiswerk 1997). Those hydrothermal upflows are usually located near huge thrust and strike-slip faults. Such karstifications created well connected cave systems which later had generally been re-used by "normal" meteoric water flow after uplift above the base level. Since this change has mostly deleted the marks of their origin, they are only conserved when rapidly fossilized.

- Pseudokarst creating rock-ghosts (cave phantoms)

Models of apparent karst features created by processes other than pure dissolution are called pseudokarst. The phantomisation (rock-ghost weathering) was recently described as a major agent of karstification in impure limestones (Vergari & Quinif 1997). In such limestones flow remained guided by fractures but partially occurred in the matrix around the fracture. In a favorable context, warm and humid climate and long-term stability of the base level, this type of flow could dissolve the limestone cement, but impurities remained in place, in place, preserving the parent material tex-
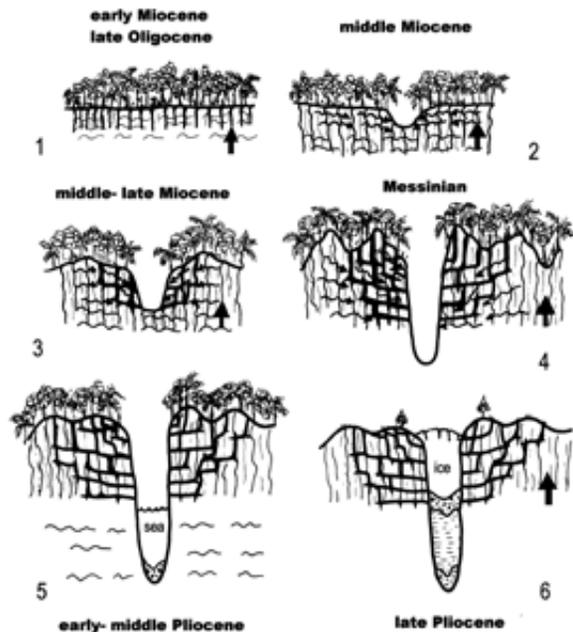
Fig. 5: Pseudoendokarst cave system in the marly-silicated Moltrasio Limestone of Mt. Bisbino, Lake of Como (Tognini 1999, 2001).

1 – Late Oligocene-Early Miocene: The tectonic structure was achieved during the neo-alpine phase. Uplift raised the area above sea level, producing a gentle relief dissected by valleys.

2-3 – Middle-Late Miocene: According to very long base level stability under warm and humid climate, deep soils develop. With very low gradient and water movements, weathering progressively penetrates deeply into the water-filled zone. Uplift gradually deepens the valleys.

4 – Messinian: Valleys dramatically entrench, water table lowers, inducing an active flow. The weathered rock-ghosts are eroded away by piping, causing the formation of cave systems, which extend progressively in size and complexity. Steep hydraulic gradients prevent a further weathering at depth. The present remnants of rock-ghosts mark the maximal depth (700 m) reached by weathering that corresponds to the present 500-600 m altitude. With a continuous entrenchment, pseudoendokarsts become perched and only "classical" cave system develop below.

5 – Early-Middle Pliocene: Pseudoendokarstic caves systems stopped developing.

6 – Late Pliocene-Quaternary: Sequences of erosion and deposition are developing (e.g. lacustrine caves sediments recording the presence of the Adda glacier close to the caves entrances; speleothem deposition is enhanced during interglacials).

tures and structures. Rock porosity increased up to 35%, causing a dramatic increase in hydraulic conductivity. This weathered material is called rock-ghosts, or phantoms. The downstream part of such systems, close to the surface, can be eroded by piping because of the absence of cement. This may produce caves (Tognini 2001). Some peculiar features may point out their different origin (weathered walls, regularly spaced 3D network, brisk change in passage morphology, dead-end at gallery terminations with conservation of the ghost of the weathered host-rock). After the piping event, the rock-ghosts remained perched on an unweathered rock, in which only "classical" karst processes adapted to the new base level began to be active.

COMPLEX RELATIONSHIPS TO GLACIERS

Some older theories supported a direct relationship between glaciations and genesis of cave systems through glacial meltwater. However, recent datings (U/Th, paleomagnetism) and fieldwork has clearly proven that many caves are older than the glaciations. The role of the glaciers seems to be mostly limited to valley deepening, base level rising during glacial periods and related sedimentation in the conduits (Audra 1994, 2004; Bini 1994; Häuselmann 2002). The genesis of new caves only takes place in certain contexts, where the glacial influence often is only indirect.

Glacial processes mainly fill caves
In the Alps, glaciers were temperate with flowing water. As valley bottoms were filled by ice, base levels raised all along the valleys. Furthermore, tills obstructed the pre-existing springs. Therefore, a large glacier body may have raised karstwater level by several hundreds of meters, for instance 500 to 600 m in the Bergerhöhle/Tennengebirge (fig. 6). Such a rising karstwater level reactivated many older conduits, increasing drastically flow cross-sections and leaving only restricted flow velocities in each conduit. Fine-grained carbonate-rich sediments found in very many caves are good indicators of these stages. Since this carbonate flour could obviously not be dissolved by the natural aggressivity of the water, it implies that a chemical erosion of cave walls was very probably negligible. This is confirmed by old speleothems, preceding such phases, that are hardly dissolved (Bini *et al.* 1998). Mechanical abrasion in the flooded zone is also improbable because of the small flow velocity. Therefore, it must be postulated that the genesis of deep-seated cave conduits is not favored by glaciations (Audra 1994, 2001a; Bini *et al.* 1998; Maire 1990).

In contrast, interglacials induce the presence of vegetation and soil at the surface. Both elements greatly enhance the CO_2 content of the water (Bögli 1978), and reduce the amount of debris washed into the cave. So, water has a much higher initial acidity and can therefore enlarge caves (Audra 2004). During the same time, water from the fine fissures and matrix, which entered the system below the soil and epikarst, where pCO2 is high, is oversaturated with respect to calcite when it reached a (ventilated) cave passage. Therefore many speleothems formed. In some low valleys with flat bottoms, lakes filled the previously overdeepened valley and kept the water table high. Therefore, in spite of the sometimes considerable valley deepening by glaciers, the karst water table could never reach the total depth of the valley, blocking thus the genesis of deeper cave levels (Kanin). Nevertheless, in the South Alpine domain, the fluvial valley deepening may have allowed deep (and today submerged) karstification.
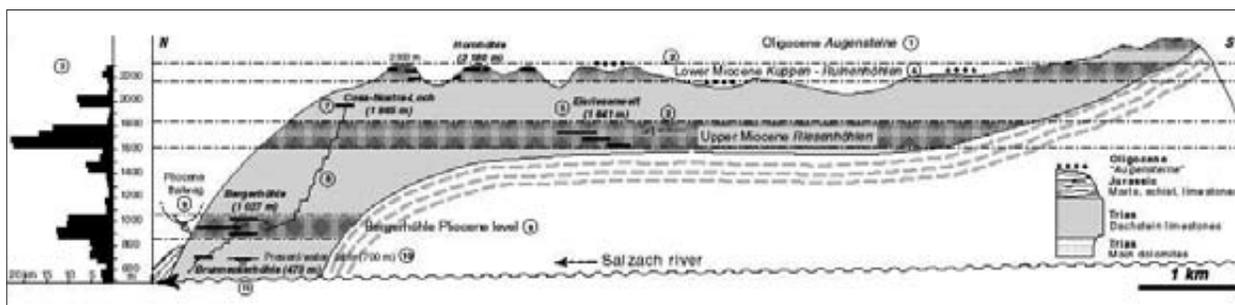
Fig. 6: The Cosa Nostra-Bergerhöhle system/Tennengebirge, Salzburg Alps (Audra et al. 2002b). To the left (3), relationship between cave passage altitude and old karst levels. Karst development began during the Oligocene beneath the Augensteine (1). During the Miocene, horizontal systems developed with alpine water inputs (2), showing different levels (3) related to successive phases of stability: Ruinenhöhlen (4) and Riesenhöhlen (e.g. Eisriesenwelt – 5). Following Pliocene uplift, alpine systems developed (e.g. Cosa Nostra-Bergerhöhle – 6). Horizontal tubes at the entrance correspond to a Miocene level (7). A shaft series (6) connect to horizontal tubes from Bergerhöhle-Bierloch (8), corresponding to a Pliocene base level (9). The present water table at 700 m (10) pours into Brunnecker Cave, which connects to the Salzach base level (11).

	Cave system	Massif	Difference in heigh, horizontal cave levels / present base level (m ASL)	Dating	Allogenic fluvial pebbles	Old sediments - weathered soils - presently removed covers	Partly eroded catchment, large dimensions not related to present topography, truncated by erosion	Presumed age of the system	References
France	Ch. du Goutourier	Dévoluy	2300 / 875 m	> 780 ka (paleomag.)		Tertiary weathered soils		Upper Miocene?	Audra 1996
	Gr. Vallier	Vercors	1500 / 200 m	Tertiary, Lower Pleistocene glacial varves (paleomag.)		Tertiary weathered soils	yes	Upper Miocene	Audra & Rochette 1993
	Réseau de la Dent de Crolles	Chartreuse	1700 / 250 m	> 400 ka (U/Th)		Cretac. sandstones	yes	Upper Miocene?	Audra 1994
	Gr. Théophile	Gdes Rousses	1900 / 1850 m	95 ka (U/Th)				Middle Pleistocene	Audra & Quinif 1997
	Gr. de l'Adaouste	Provence		Stratigraphic correlation		Miocene pebbles	Artesian	Tortonian	Audra & al. 2002
	Système du Granier	Chartreuse	1500 / 1000 m	> 1-1,5 Ma (^{234}U / ^{238}U equilibr., paleomag.) 1,8-5,3 Ma (cosmonucleides)	Upper cretac. and oligo. limest.	- Cretac. sandstones - weathered soils	yes	Upper Miocene?	Hobléa 1999; Hobléa & Häuselmann 2007
Switzerland	Beatushöhle – Bärenschacht	Siebenhengste	890 / 558 m	> 350 ka (U/Th)				Pleistocene	Häuselmann 2002
	Siebenhengste	Siebenhengste	1900 / 558 m	4.4 Ma (cosmonucleides)				Pliocene	Häuselmann & Granger 2005
	Jochloch	Jungfrau	3470 m	Lower Pleistocene? (palynology)			practically no catchment today	Lower Pleistocene	Wildberger & Preiswerk 1997
	Ofenloch	Churfisten	655 / 419 m	> 780 ka (paleomag.)				Pliocene	Müller 1995
	Hölloch– Silberensystem	Silberen	1650 / 640 m	>350 ka (U/Th), <780 (paleomag)				Lower Pleistocene?	
Italy	Battisti	Paganella	1600 m	> 1-1,5 Ma (^{234}U / ^{238}U equilibr.)		Cherts from Eocene limestones	yes	Oligo-Miocene	
	Conturines	Dolomite	2775 m	> 1-1,5 Ma (^{234}U / ^{238}U equilibr.)			yes	Oligo-Miocene	Frisia & al. 1994
	Capana Stoppani, Tacchi-Zelbio	Pian del Tivano	900 / 200 m	> 350 ka (U/Th)	Boulders from glacial sinkholes		yes	Oligo-Miocene	Tognini 1999, 2001
	Gr. dell'Alpe Madrona	Mte Bisbino	1000 / 200 m	> 350 ka (U/Th)				Miocene	Tognini 1999, 2001
	Covoli di Velo Ponte di Veia	Mte Lessini		33-38 Ma (K/Ar)		yes		Eocene and Oligocene	Rossi & Zorzin 1993
	Gr. Masera	Lario	200 / 361 m	≈ 2.6 to 7.2 Ma (cosmonucleides)	Fluvial pebbles			Pliocene or older	Häuselmann unpub. Bini & Zuccoli 2004
	Gr. On the Road	Campo dei Fiori	805 / 300 m	> 1-1,5 Ma (234U / 238U equilibr)				Oligo-Miocene	Uggeri 1992
	Gr. Via col Vento	Campo dei Fiori	1015 / 300 m	> 350 ka (U/Th) Upper Plio. glacial sediments				Oligo-Miocene	Uggeri 1992
	Gta. sopra Fontana Marella	Campo dei Fiori	1040 / 300 m	Middle Pleistocene (micro-fauna)	Conglomerate with crystalline pebbles	Ferralitic soils	yes	Oligo-Miocene	Zanalda 1994
	Ciota Ciara – Cuitarun caves	Mte Fenara			Large miocene fluvial pebbles		yes	Oligo-Miocene	Fantoni & Fantoni 1991
Austria	Cosa Nostra-Bergerhöhle	Tennengebirge	1600-1000 / 500 m	> 780 ka (paleomag)	yes	Augensteine	yes	Miocene – Upper Pliocene	Audra & al. 2002
	Mammuthöhle	Dachstein	1500-1300 / 500 m		yes	Augensteine	yes	Miocene	Trimmel 1961, 1992; Frisch & al. 2002
	Eisriesenwelt	Tennengebirge	1500 / 600 m		yes		yes	Lower Pliocene?	Audra 1994
	Feichtnerschacht	Kitzsteinhorn	2000 / 1000 m	118 ka (U/Th)				Pliocene?	Audra 2001, Ciszewski & Recielski 2001
Slovenia	Poloska jama	Mt Osojnica	750 / 500 m				yes		
	Crnelsko brezno	Kanin	1400 / 400 m	> 780 ka (paleomag) Glacial varves					Audra 2000
	Snezna jama	Kamnik Alps	1600 / 600 m	1.8 to 3.6 or 5 Ma (paleomag)	yes	yes	yes	Miocene?	Bosak & al. 2002

Tab. 1: Synthesis of information about the quoted caves systems

As a conclusion, a warm climate induces passage growth and speleothem deposition, whereas a cold climate generally tends to obstruct the lower passages by sediments.

Glacial sediments covering older speleothems: cave systems may predate glaciations

Some cave sediments correspond to very old glaciations, according to paleomagnetic measurements that show inverse polarity: Ofenloch/Churfirsten (Müller 1995), grotte Vallier/Vercors (Audra & Rochette 1993), Crnelsko brezno/Kanin (Audra 2000). These sediments often overlie successions of alterites or massive flowstone deposits, which in turn prove the existence of a warm and humid climate, thus showing that the cave systems predate those glaciations. Some of the old speleothems are more or less intensely corroded by flowing water postdating their deposition.

Cave development and glacial activity

- Glacial abrasion at the surface and erosion in the vadose zone. At the surface, the glacial activity is without doubt responsible for the abrasion of a variable amount of bedrock (50-250 m), which has surfaced old conduits that previously were deeply buried. This is manifested by wide open shafts, cut galleries and arches. During glacial melt, meltwater disappeared into distinct sectors. As soon as fractures were connected to preexisting conduits, they enlarged quickly and thus formed the "invasion vadose shafts" (Ford 1977), which can reach several hundred meters of depth: Granier, Silberen, Kanin (Kunaver 1983, 1996). The effectiveness of such meltwater is mainly due to its velocity in the vertical cascades as well as their abrasive mineral load originating from bedrock and till material.

- Some new cave systems appeared in the intra-Alpine karst area due to glacial erosion. Thin limestone belts or marbles intercalated with metamorphic series were freed from their impervious cover by glacial erosion. Some caves are still in direct relationship with the periglacial flow, and act as swallowholes. Their morphology reflects the cascading waterflow and has a juvenile form: Perte du Grand Marchet/Vanoise, Sur Crap/Graubünden (Wildberger *et al.* 2001). At the Grotte Théophile/Grandes Rousses, U/Th datings evidenced that the cave was active at least along the two glacial-interglacial cycles that are marked by the sequence of passage-forming/filling with gravel/sinter deposition (Audra & Quinif 1997). Since cave development mainly occurred during interglacial, the effect of the glacier is only indirect, by eroding the impervious covers (Audra 2004).

- The lower phases of huge cave systems are indirectly generated by glacial valley-deepening. While the uppermost cave systems are often older than the glaciations *(infra),* the lower passages are often of Quaternary age, since they are related to valleys evidently deepened by glaciers. In this respect, glaciers are indirectly responsible for the creation of new cave passages (Siebenhengste, Chartreuse, Vercors). This strongly contrasts with the South Alpine domain, where valleys were deepened during the Messinian event. Here, glaciations contributed merely to the infilling of the preexisting valleys. Thus, most of the South Alpine cave systems are thought to be older than the glaciations.

MORPHOLOGIC AND TOPOGRAPHIC EVIDENCES FOR A HIGH AGE OF CAVE SYSTEMS

Some existing caves and karst features clearly correspond to a strongly different topography than today. They are therefore supposed to be older. In the following paragraphs, the position and morphology of caves are compared to today's landscape. Then cave sediment characteristics are presented and discussed. In a third part, links between caves and well-recognized paleotopographies are explained. All those indications are clear evidences for a high age of cave systems.

CAVE SYSTEMS VS. PRESENT TOPOGRAPHY

Perched phreatic tubes

Conduits with an elliptical morphology are sometimes perched considerably above the present base level (Tab. 1, 3rd column). They developed close to a paleo base level, long before today's valley deepening. At the Siebenhengste, the highest phases even show a flow direction opposite to the present one.

Caves intersected by current topography

Old perched caves are often segmented by a subsequent lowering of the surface. Two situations are usually found in the field:

- Old phreatic caves at the surface of karst plateaus, which have been eroded by glacial abrasion (Grigna, Dolomites, Triglav, Kanin, Tennengebirge…)

- Old phreatic caves along valley flanks, obviously cut by the lowering of the topography (Adda, Adige, Salzach, Isère): Pian del Tivano, Mt. Bisbino, Mt. Tremez-

zo, Campo dei Fiori (Southern Alps), Paganella (Dolomites).

Dimensions too large with respect to the present catchment and climate

The dimensions of some conduits are far too large compared to the present catchment area, thus proving that the older catchment areas had been much larger, but are now truncated by erosion (Eisriesenwelt/Tennengebirge (fig. 6); Antre de Vénus/Vercors; Snezna jama na Raduhi/Kamnik Alps, caves at Pokljuka and Jelovica plateaus at Julian Alps, Siebenhengste, Pian del Tivano, Campo dei Fiori/Southern Alps).

Spring location vs. present base level

If the position of a spring is not due to a geologic perching above an impervious layer, it has to be close to base level (see part I). However, in some cases springs did not lowered down to today's base level. In other cases springs are obviously located far below the base level. This can be explained by the following hypotheses:

- Some springs are perched, because the valley incision is very recent and rapid (Pis del Pesio/Marguareis).

- Others are presently submerged below the base level and hidden by alluvial fill or till (Emergence du Tour/Aravis; Campo dei Fiori). They were set into their place before the base level raised and they continue to function due to the high transmissivity of the sediment fill.

A specialty is given when old vertical vadose caves are suddenly stopped by the present water table, proving that the horizontal drains are at much greater depth and completely drowned. Typical vadose morphologies (speleothems, karren) are known in some drowned conduits (Grotta Masera, Grotta di Fiumelatte/Lake of Como; Fontaine de Vaucluse/Provence). Here, the spring location is adapted to the present base level, but the caves are proof that the base level may, in some cases, also rise. This is especially true for areas affected by the Messinian crisis (Bini 1994; Audra & al. 2004).

CAVE SEDIMENTS SHOWING EVIDENCE OF A REMOTE ORIGIN, DIFFERENT CLIMATE AND OLD AGE (tab. 1)

Old fluvial material

The presence of some caves sediments is inexplicable with the present waterpaths. Big rounded pebbles found in caves perched high up on top of cliffs mean that a valley bottom had to exist at this level. Afterwards, the valleys deepened so much that they are far below such perched massifs (Salzach/Salzburg Alps; Granier/Chartreuse). Often, gravels found in these caves have a petrog-

raphy and mineralogy that is not found in the present rocks. They are issued either from caprock that has disappeared a long time ago (Fontana Marella, Campo dei Fiori) or from distant catchments, as proven by fluvial pebbles (Augensteine/Northern Limestone Alps in Austria), quartz sandstones (Slovenian Alps), fluvioglacial sediments (Lake of Como). Dating of fluvial pebbles by cosmogenic nuclides from the Grotta Masera (Como), yielded a probable age comprised between 2.6 to 7.2 Ma, showing a pliocene age, or maybe older (Häuselmann unpub.; Bini & Zuccoli 2004). In the Granier system, this method yields ages comprised between 1.8 to 5.3 Ma (Hobléa & Häuselmann 2007).

Record of climatic changes in subterranean sediments

Often, the analysis of the sediments evidences climate changes, with a change from biostatic conditions, marked by the rarity of allogenic sediments, towards rhexistatic conditions, with lots of allogenic sediments. These sediments come from the erosion of soils in a context of climate degradation and general cooling. They usually are interpreted to reflect the climatic change in the Pliocene, before the onset of the glaciations. Such sediments are present in most of the old cave phases, which therefore should be older than the end of the Pliocene: Grotte Vallier/Vercors; Tennengebirge (Audra 1994, 1995), Campo dei Fiori (Bini *et al.* 1997), Monte Bisbino (Tognini 1999, 2001). In the Dachstein-Mammuthöhle, which dates back to the Tertiary and shows a phreatic tube perched 1000 m above the Traun valley, flowstones grown during the interglacials interfinger with a series of debris-flow conglomerates of glacial origin (Trimmel 1992). In the Grotta di Conturines/Dolomites (2775 m ASL), the mean annual temperatures deduced from the ^{18}O of speleothems were between 15 and 25°, which implies that speleothemes deposited in a warmer climate within the Tertiary, probably also at a lower altitude than it is found today (Frisia *et al.* 1994). Furthermore, in many caves, either conduits or flowstones have been deformed by late Alpine tectonic movements: Grotta Marelli, Grotta Frassino/Campo dei Fiori (Uggeri 1992; Bini *et al.* 1992, 1993).

Dating results prove the antiquity of cave systems

The calculated age of old speleothems are regularly above the U/Th limits (700 ka, even 1.5 Ma according to the $^{234}U/^{238}U$ equilibrium (Bini e*t al.* 1997); Tab. 1). The paleomagnetic measurements often show inverse magnetism, sometimes with multiple inversion sequences, proving of a very old age of the cave sediments (Audra 1996, 2000; Audra & Rochette 1993; Audra *et al.* 2002b). The use of the new cosmonucleide method to date old quartz sediments also confirms this trend and yield ages reaching

back to about 5 Ma (see the details for Siebenhengste example in this volume).

RELATIONS TO AN OLD TOPOGRAPHY

The geomorphologic approach, which uses external markers of old base levels (paleovalleys, paleoshelves with associated sediments) that are well dated, offers precious possibilities for the dating of karst systems. Sadly, correlations are almost impossible up-to-date due to the scarcity of such information. In the northern flank of the Alps, the glaciations often caused the remnants of an old topography to disappear. The southern Alps, less glaciated and better studied in this context, offer more possibilities, also thanks to the presence of guiding events like the Messinian incision and the following Pliocene marine highstand.

Old erosion surfaces
The identification of old erosion surfaces is a precious tool in geomorphology. Large surfaces often top the relief and cut across very old caves that are difficult to link to an old drainage system because of their fragmented character. The cave systems developing below those high surfaces are more recent, such as the stacked surfaces in the Vercors, of Eocene, infra-Miocene and Pliocene age (Delannoy 1997). Shelves along slopes, created by lateral corrosion of the rim of ancient depressions, have the same significance as perched valley bottoms. In Vercors, Pliocene caves could be associated on them, such as the Antre de Vénus and the Grotte Vallier (Delannoy 1997). In the area of Varese (Lombardy), the Oligo-Miocene surface that cuts across limestone, porphyritic rocks and granites, is dissected by the late Miocene valleys that had

been deepened during the Messinian (Bini *et al.* 1978, 1994; Cita & Corselli 1990; Finckh 1978; Finckh *et al.* 1984).

Morphological and sedimentological evidences of pre-pliocene paleovalleys
A fluvial drainage pattern of Oligo-Miocene age, incised in the relief, predated the Alpine tectonic events of the late Miocene. The drainage originated in the internal massifs, cut through the calcareous border chains, and ended in alluvial fans in the molasse basins. In the border chains, perched paleovalleys are found more than 1500 m above the present ones (Salzburg Alps), as well as fluvial deposits coming from siliceous rocks (Augensteine/Northern Calcareous Alps; siliceous sands/Julian Alps (Habic 1992)), sometimes buried in caves near the valley slopes (Grotta di Monte Fenera/Piemont, Grotta Fontana Marella/Campo dei Fiori).

In the northern flank of the Alps, these valleys have been destroyed by the deepening of the hydrographic network, aided by the action of the glaciers. In the South, the old valleys have been deepened by the Messinian incision and filled by Pliocene sediments (Lake of Como/Adda, Varese, Tessin, Adige, Durance). As a consequence, the horizontal karstic drains that were linked to the old valleys had been truncated by slope recession, and are presently perched (Grotta Battisti/Paganella; Grotte Vallier/Vercors; Pian del Tivano, Monte Bisbino (Tognini 2001); Campo dei Fiori (Uggeri 1992)). The almost generally observed input of allogenic waters coming from impermeable rocks upstream, combined with a tropical humid climate with considerable floods, explains the giant dimensions of those caves.

AGE OF ALPINE KARSTIFICATION: FROM PALEOKARSTS TO RECENT MOUNTAIN DYNAMICS

PALEOKARST, A MILESTONE FOR OLD KARSTS

The study of paleokarsts is a separate domain. No cave system has survived in its integrality from the periods predating the Miocene. In the Northern Limestone Alps of Austria, the possibility that caves of the highest level (Ruinenhöhlen) may be relicts of an oligocene karstification has been discussed (Frisch *et al.* 2002). However, Paleogene paleokarsts are frequent, as evidenced by natural or artificial removal of their filling:

- In Siebenhengste, upper Cretaceous paleotubes and fractures are found in Lower Cretaceous limestone,

filled with Upper Cretaceous Sandstone (Häuselmann *et al.* 1999).

- In many places, (Switzerland, Vercors, Chartreuse) vast pockets covering a karst relief and filling up some conduits can be observed.

- In Southern Alps, upper Eocene and lower Oligocene sediments have been found into large cavities infilled by basaltic intrusions (Covoli di Velo, Ponte di Veia/Monte Lessini) Their age could be determined by K/Ar datings (Rossi & Zorzin 1993).

In several regions (Vercors and Chartreuse, Monte Lessini), karstification is more or less continuous from the Eocene onwards. However, the tectonic and paleo-

geographic changes have only left dispersed paleokarsts. Since the Miocene on, several massifs emerged from the molasse basins, thus allowing a karstification that continues today.

ESTIMATION OF THE FIRST EXPOSURE ACCORDING TO MOLASSE PETROGRAPHY

The main phase of karstification begins when suitable rocks are exposed at land surface. Since the oldest remnants of karst are often eroded, it is possible to calibrate the beginning of the karstification by the foreland sediments (mainly the Molasse), which contain limestone pebbles eroded away at the surface. However, absence of evidence is not evidence of absence: sedimentary gaps are frequent, and a karst in biostatic conditions does not spread detritic elements towards the foreland. As a general rule, the Miocene molasse registered the beginning of the last big karstification phase, earlier in Italy, later in Switzerland:

- Upper Oligocene-Lower Miocene (30 to 20 Ma) in the Southern Molasse, based on dated fluvial sediments located in paleovalleys (Gelati *et al.* 1988).

- Lower Miocene (20 Ma) in the molasse south of Grenoble, corresponding to the erosion of the emerged anticlines of the Vercors and Chartreuse (Delannoy 1997).

- Lower Miocene (20 Ma) in the Austrian Nord-Alpine molasse, corresponding to the erosion of the Augensteine cover, which is of Upper and Middle Oligocene age (Lemke 1984; Frisch *et al.* 2000).

- Upper Freshwater Molasse in the Eastern Swiss basin (Hörnli fan, Middle Miocene 17-11 Ma) which contains pebbles of the first erosion of Helvetic nappes (Siebenhengste, Silberen, Speck 1953; Bürgisser 1980).

DATING THE YOUNGEST PHASES AND EXTRAPOLATION

The most generally applied dating method for cave sediments is U/Th. It makes it possible to date speleothems. In best cases, it allows for going back to as far as 700 ka – dating only the sediment contained within the cave and not the cave itself. The use of paleomagnetic dating makes it possible, in some scarce cases, to push back the datable range to 2.5 Ma. The use of cosmogenic isotopes (Granger *et al.* 2001) is the only recent method that opens new possibilities, having a dating range between 300 ka and 5 Ma. Another solution consists in dating lower cave phases that are supposed to be younger, and in progressively going up the phases towards the oldest cave systems, until reaching the limits of the used methods. From the calculated rate of valley deepening, one can then extrapolate the age of the uppermost phases. Of course, such an approach can only give a general idea about the age.

The lowermost phases of the Siebenhengste cave system, St. Beatus Cave and Bärenschacht, have been dated by U/Th. The following ages have been obtained: Phase 558 (youngest) began at 39 ka (max. 114 ka) and is still active today; Phase 660 was active between 135 and 114 ka; Phase 700 was active between 180 and 135 ka; and Phase 760 started before 350 ka and ended at 235 ka (Fig. 4). These age values indicate a general valley incision rate of 0.5 to 0.8 mm/a, with a tendency to slow down as the age gets higher. Extrapolation indicated an age of about 2.6 Ma for the oldest cave systems, at 1850 m ASL. Absolute cosmogenic dating yielded an age of 4.4 Ma for the oldest sediment, contained in the second-highest cave phase at 1800 m, showing a slower entrenchment in the older phases (Häuselmann & Granger 2005; see also this volume). Dating of the cave systems at Hölloch/Silberen gave maximal rates of valley incision in the range of about 1.5 to 3.5 mm/a.

RELATIVE UPLIFT RATES AND EROSION VOLUMES IN FORELAND SEDIMENTS

Uplift rates are generally calculated for long periods of time, taking the average of variable rhythms and integrating vast parts of the area, without taking into account block tectonics which can differ considerably from one massif to the other. In the same range, the estimated volume of the foreland basins only gives a global approach. Such results only may give a general frame for a validation. Modeling the fission-track measurements of the Swiss Central Alps (Reuss valley) give an average uplift of 0.55 mm/a (Kohl, oral comm. 2000) comparable to calculations of recent uplift (0.5 mm/a; Labhart 1992) and consistent with the rates inferred from dating in caves. Uplift is maximal in the central parts of the mountain chains, therefore the rocks are more deeply eroded in this area. As a consequence, the oldest caves had to have disappeared from the central zones, compared to the border chains where they are better preserved due to the slower erosion.

CONCLUSION

The examples mentioned above are distributed throughout the Alpine belt. Therefore, the conclusions drawn here are valid for Alpine Caves at least, but they may be applied to other cave systems also. The main following conclusions can be drawn from the above synthesis:

- In contrast to some earlier views, caves are not directly linked to glaciations. On the contrary, there is evidence that during glaciations caves are mainly filled with sediments, while they are enlarged during the interglacials. The main influence of glaciers upon cave genesis is the deepening of the base level valley, thus inducing a new cave genesis phase to be formed.

- U/Th datings, coupled with paleomagnetism, inferred a Lower Pleistocene to Pliocene age for several cave sediments. Fossil or radiometric datings of solidified cave fills (sandstone, volcanic rocks) gave ages reaching back to the Upper Cretaceous. It follows that caves are not inherent to the Quaternary period, but are created whenever karstifiable rocks are exposed to weathering. Due to later infill, however, most explorable caves range from Miocene to present age.

- We have shown that caves are related to their spring, which is controlled by a base level that usually consists of a valley bottom. So, the study of caves gives very valuable information about valley deepening processes and therefore about landscape evolution.

- Caves constitute real archives, where sediments are preserved despite the openness of the system. The study of cave sediments gives information about paleoclimates. Moreover, the combination of cave morphology and datable sediments allow to reconstruct the timing of both paleoclimatic changes as well as landscape evolution between the Tertiary and today. Differential erosion rates and valley deepenings can be retraced. Information of this density and completeness has disappeared at the surface due to the erosion of the last glacial cycles and the present vegetation.

- Correlations between well-dated cave systems can significantly contribute to the geodynamic understanding of the Alpine belt as a whole. The location of most cave systems at the Alpine border chains is very lucky: since they are dependent on base level (in the foreland), recharge and topography (towards the central Alps). They inevitably registered changes in both domains. Caves are therefore not only a tool of local importance, but may have a wide regional/interregional significance.

- The dating method by cosmogenic nuclides was recently applied in some French, Italian and Swiss alpine cave systems which partially contain pre-glacial fluvial deposits. The dated sediments yielded ages ranging between 0.18 and 5 Ma, which are consistent with other approaches. Advances in modern dating techniques (cosmogenic isotopes, U/Pb in speleothems) therefore open a huge field of investigations that will very significantly contribute to the reconstruction of paleoclimates and topography evolution along the last 5, possibly 15 to 20 Ma.

- The messinian event influenced cave genesis over the whole southern and western sides of the Alps by overdeepening valleys. However, the subsequent base level rising flooded those deep systems creating huge deep phreatic aquifers and vauclusian springs (Audra *et al.* 2004).

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