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Cave genesis in the Alps between the Miocene and today: a review

by

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with 6 figures and 1 table

Summary. Progress in the understanding of speleogenetic processes, as well as the intensive research carried out in the Alps during the last decades, permit to summarise the latest knowledge about Alpine caves. The phreatic parts of cave systems develop close to the karst watertable, 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 watertable gradient. Mesozoic and early Tertiary paleokarsts within the Alpine range prove of these ancient emersions. Hydrothermal karst seems to be more widespread than previously 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 speleogenetic agent. On the contrary, glaciers hinder speleogenetic processes and fill caves with sediment. They mainly influence speleogenesis indirectly by valley deepening and abrasion of the caprock. All present datings as well as morphological indications 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.

Zusammenfassung. *Höhlenentstehung in den Alpen vom Miozän bis heute: eine Rückschau.* – Das zunehmend besser werdende Verstehen von höhlenbildenden Prozessen sowie intensive Forschung in alpinen Höhlen während der letzten Dekaden erlauben eine Rückschau auf die Entstehung alpiner Karsthöhlen. Die phreatischen Höhlenteile entwickeln sich nahe des Karstwasserspiegels, der von der Höhenlage der Quelle abhängt. Diese wiederum steht zumeist in Zusammenhang mit dem Talboden. Deshalb sind Höhlen direkt mit der geomorphologischen Entwicklung der Oberfläche gekoppelt und geben die Taleintiefung wieder. Die in den Höhlen enthaltenen Sedimente helfen mit, die morphologische Abfolge und die paläoklimatische Entwicklung zu rekonstruieren. Mehr noch: sie sind die einzigen Mittel, um Höhlen und damit die Landschaftsentwicklung zu datieren. Höhlen entstehen, sobald Kalkstein über den Meeresspiegel gehoben wird und ein hydrographischer Gradient entsteht.

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Mesozoischer und frühtertiärer Paläokarst in den Alpen zeugt von diesen alten Verkarstungen. Hydrothermaler Karst scheint weiter verbreitet zu sein, als bisher angenommen wurde. Dies, weil hydrothermale Höhlen später zumeist von meteorischen Wässern benutzt und so überprägt werden. Phantom-Verwitterung von unreinen Kalksteinen ist eine neu beschriebene Art der Höhlenbildung. Dagegen verlangsamen oder stoppen Gletscher höhlenbildende Prozesse und füllen die Höhlen mit Sediment. Sie beeinflussen die Höhlenentstehung hauptsächlich, indem sie die Täler eintiefen und den Kalk überlagernde Schichten abtragen. Alle vorhandenen Datierungen sowie morphologische Indikationen deuten darauf hin, dass viele alpine Höhlen (ausser dem älteren Paläokarst) pliozänen oder miozänen Alters sind. Die Entwicklung absoluter Datierungsmethoden (vor allem die Entwicklung der kosmogenen Nuklide) dürfte in naher Zukunft ermöglichen, auch pliozäne Höhlensedimente zuverlässig zu datieren.

Résumé. *Nouvelles considérations sur la genèse des cavités dans les Alpes depuis le Miocène.* – Les progrès dans la compréhension des processus spéléogénétiques ainsi que les recherches intensives conduites dans les Alpes depuis quelques décennies donnent de nouvelles clefs à la compréhension des cavités alpines. Les parties noyées des réseaux karstiques se développent à proximité de la surface piézométrique, qui est déterminée par la position de l'émergence, elle-même généralement dépendante de la position du talweg. Par conséquent, les cavités sont directement en liaison avec l'évolution géomorphologique superficielle et enregistrent l'approfondissement des vallées. Les sédiments piégés dans les cavités permettent de reconstituer les phases morphogéniques et l'évolution paléoclimatique. De plus, ce sont les seules possibilités de dater les grottes et en conséquence l'évolution des paysages. Les grottes se forment dès lors que les calcaires émergent et qu'un gradient hydraulique est présent. Les paléokarsts du Mésozoïque et du Paléogène attestent de ces émersions précoces. Le karst hydrothermal semble beaucoup plus fréquent qu'envisagé auparavant, car les circulations postérieures ont souvent gommé les indices hydrothermaux originels. La fantômisation est décrite comme un nouvel agent spéléogénétique. En revanche, les glaciers ont plutôt ralenti les processus spéléogénétiques et colmaté les cavités. Leur influence n'est qu'indirecte, par l'approfondissement des vallées et le décapage des couvertures imperméables. L'ensemble des données chronologiques et morphologiques montrent que la plupart des cavités alpines (à l'exception des paléokarsts) sont d'âge pliocène ou même miocène. Les progrès des méthodes de datation (particulièrement l'essor récent des nucléides cosmogéniques) devrait permettre de dater les sédiments karstiques, non seulement pléistocènes mais également pliocènes.

1 *Introduction*

The progress in speleological exploration and theoretical bases of speleogenetic principles (AUDRA 1994, JEANNIN 1996, PALMER 2000) permitted to recognise the potential of caves for the study of landscape evolution, valley deepening and thus erosion rates and climate changes on a wider regional scale (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.

The aim of this article is to give information about the general facts of cave genesis, that is then usable to reconstruct the evolution of the landscape and its timing: Part 2 presents the latest results concerning cave genesis and their strong link with the landscape at the surface. Part 3 deals with new concepts about early speleogenesis, including paleokarst, hydrothermal karst, and pseudokarst. Many theories supported a strong link between caves and glaciers, thus suggesting that caves are mainly of Quaternary age. But today, it can be shown that many caves are older than the glaciations and that glaciers generally are rather hindering speleogenetic processes. Part 4 consequently presents evidence for a high age of cave systems, based on the relationship between surface, climate, and cave sediments. In Part 5, ages obtained by different dating methods prove that karst genesis in the Alps is not related to the Quaternary alone, but reaches back as far as the Cretaceous, even though most of the datings deal mainly with the Quaternary. This is due to the fact that dating methods are still evolving.

Setting

The Alpine belt extends from Nice (France) to Vienna (Austria). Its area is divided into seven countries (France, Switzerland, Italy, Liechtenstein, Austria, Germany and Slovenia). Karst landscapes are found in each of the countries, the largest karst areas are found around the main range. All massifs are dissected by deeply entrenched valleys which divide continuous structures into different physiographic units. Annual precipitation varies between 1,500 to more than 3,000 mm. The described caves are mentioned within the text with the massif where they are found (e. g. Eisriesenwelt/Tennengebirge). The massifs are located on fig. 1.

The French Western Prealps consist of folded and thrusted massifs of mainly Cretaceous rocks. The elevation is generally between 1,000 and 2,000 m. The Vercors displays a landscape of ridges and valleys, whereas the Chartreuse presents a steep, inverted relief.

Fig. 1. Map of the alpine karsts with localisation of the mentioned massifs (karst areas after: Buzio & Faverjon 1996, Mihevc 1998, Stummer & Pavuza 2001, Wildberger & Preiswerk 1997).

The Central Swiss Alps harbour the highest alpine karst areas at Jungfrau (3,470 m a. s. l.). The Siebenhengste (2,000 m a. s. l.) are located north of Lake Thun, and the Hölloch-Silberen area (2,450 m a. s. l.) in Central Switzerland. They consist of nappes of Cretaceous and Eocene rocks.

The Italian Southern Alps are located to the south of the Insubric Line. The series of 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 2,400 m a. s. l.

The Northern Calcareous Alps in Austria are composed of a slightly folded succession of Trias limestones and dolomites with a thickness of more than 1,000 m, in some parts covered by jurassic limestones. Large plateaus extend from 1,800 to 2,200 m a. s. l.

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 which are dominated by high peaks reaching more than 2,800 m a. s. l.

2 *General concepts of speleogenesis*

The topic of cave genesis, in relation to geology, climate, dissolution kinetics, and other related fields, has been a subject of interest for many decades. 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).

2.1 *Genesis of caves and morphology of passages related to watertable 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. Therefore, with time, a meandering canyon is created. On the other hand, water flowing within the phreatic (saturated) zone can corrode a passage over its whole cross-section, so that an ideally rounded passage forms (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.

2.2 *Recognition of speleogenetic phases and relation to the spring*

Within the saturated zone, two geometric types of conduits prevail (FORD 1977, 2000): 1) the *watertable 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.

With the help of the passage's morphology, speleogenetically distinct phases can often be recognised. In the first step, the ascending and descending phreatic tubes (loops) that have been created by the same waterflow are followed. The top of these tubes indicates the minimum elevation of the corresponding water level. Then, the

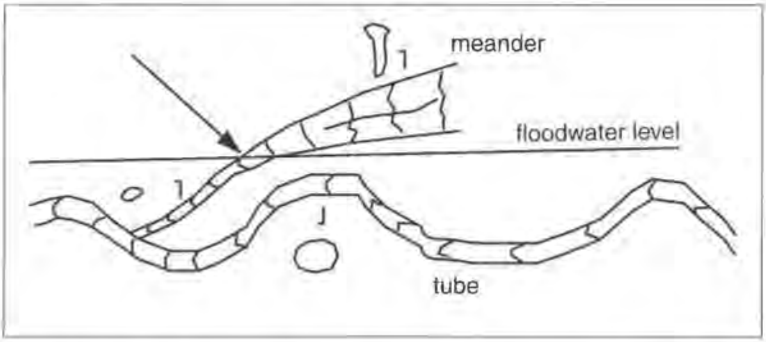

Fig. 2. An undulating phreatic tube is co-fed by a vadose meandering canyon, whose shape turns into a tube below the floodwater table. The arrow marks the transition from vadose to phreatic.

transition of vadose canyons into phreatic tubes gives an absolute indication of the karstwater level. This level is usually in perfect accordance with the top of the loops (fig. 2). One often observes an inclination of the water table of the order of 1 to 2 degrees. Because of this inclination, the definition of the water level is difficult. For obvious reasons it is done with reference to the presumed spring level. Observations show that when flooding, the water does not rise uniformly from the lower, permanently flooded galleries, but that the systems often function in the "filling-overflow" manner (HÄUSELMANN et al. 2003). This means that the water rises from upstream parts until it reaches a threshold leading into lower galleries, which in their turn are filled. The transition from meandering canyon to phreatic tube takes place at the top of the epiphreatic zone, thus creating the inclination toward the spring. Below the transition, the overall morphology of all galleries is phreatic, in spite of the vadose torrents sometimes prevailing. Therefore, we conclude that in the epiphreatic zone, phreatic corrosion is predominant and vadose entrenchment negligible. Because of this inclination, the definition of the water level is difficult between different, but separated parts of a cave system, unless there are horizontal water table caves. There has to be proof that the observed paleo-water tables are really controlled by spring position and not by geological structures (impervious barriers or levels such as folds or faults).

2.3 *Succession of speleogenetic phases, cave levels recording base level changes*

If the spring lowers slowly and gradually, the cave system behind also adapts gradually by entrenchment to the new situation: no distinct phases exist. If the lowering of the spring occurs rapidly, followed by a time of relative stability, the flowpath readjustment in the cave system also occurs rapidly and a next speleogenetic phase develops. Calculations have shown that, once a small paleo-conduit has been formed, caves may evolve very rapidly, i. e. within a few 10,000 years, to reach penetrable size (PALMER 2000). Through pre-existing or newly created *soutirages* (HÄUSELMANN et al. 2003), the water reaches the spring level and creates a new karstwater table, which then controls the evolution of the next phase (fig. 3). Former conduits, presently perched in the vadose zone, are abandoned as a dry level. Provided that the speleogenetic phases reflect the deepening of the valleys during time, then they give information for the reconstruction of paleorelief. Equivalent information at the surface is usually no longer present, mostly due to the erosion by the youngest glaciations or river incisions, by slope dynamics or by sediment deposition.

It has to be noted that in some cases, the base level may rise even within the Alpine domain (post-messinian infilling of the overdeepened canyons in the southern part of the Alps; FELBER & BINI 1997). This caused a drowning of pre-existing karst systems and a reactivation of previously vadose or abandoned passages (TOGNINI 2001).

2.4 *The relation between morphology, climate, and sediments*

It has been shown above that cave morphology depends on the position of the epiphreatic water table. The size of the passage, however, depends (among other, mostly geological factors) on time and flow rate. WORTHINGTON (1991) puts forward

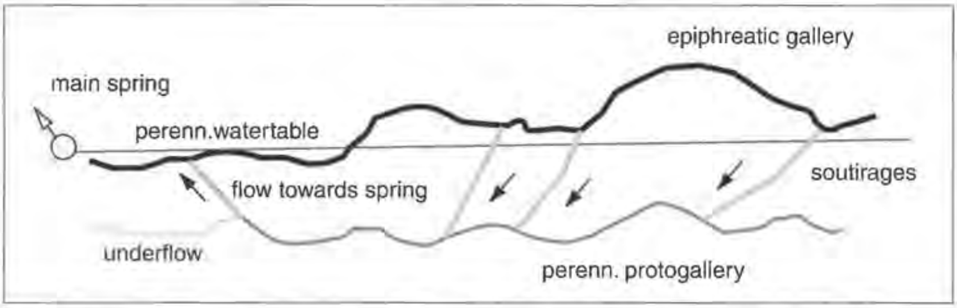

Fig. 3. Schematic flow system. Black = main (epiphreatic) gallery; light grey = soutirages (downward) and upflow (upward); dark grey = perennial phreatic conduit.

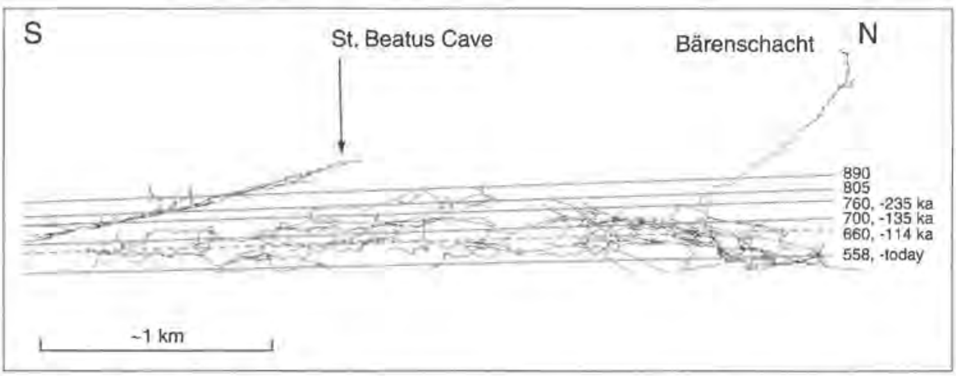

Fig. 4. N-S-projection of Bärenschacht and St. Beatus Cave with the recognised phases. The numbers are the elevations (in m a. s. l.) of the corresponding spring. Phase 558 is the present one.

that there is an "equilibrium size" of a phreatic passage for a given flow rate. After this size is attained, the passage hardly grows anymore, and a growth above this size is mainly dependent on an increase in flow rate. Such an increase is only possible either by capturing another catchment area, or by increased precipitation. Given a specific catchment, the passage size should therefore reflect, to a certain extent, the precipitation and thus the climate.

This theory was applied in the Siebenhengste area to assess the connection of the Schrattenfluh, which has a linear distance of about 20 km to the Siebenhengste springs. Volume comparisons of the passage sizes of speleogenetic phases of different age indicated an increase of at least double the original size between cave phase 700 m and 660 m (see fig. 4). The same principle can be used also to point out a reduction in the catchment area due to topographic variation, particularly to valley entrenchment, which often causes a dissection of the karst systems.

In contrast to the surface, flow within the cave is limited to the passage size. Therefore, an increase in water supply directly reflects an increase in head pressure and therefore in flow rate. So, the presence of gravel within a passage indicates a huge flow, whereas silt indicates almost stillstanding conditions of the water. Coupling the information from cave plan (directions and size of the galleries), morphology, and sediments, a picture of climate and climate changes can be made at the same time as information about the surface morphology is gained (Häuselmann 2002).

3 *New concepts about speleogenesis*

3.1 *The influence of early phases: paleokarst, hypogenic karst and pseudokarst*

3.1.1 *Syn- and post-sedimentary paleokarsts*

The term "paleokarst" summarises all karst features that are not related at all to present or near-present water circulations. Since most of the caves (including fossil tubes) that can be entered are related to present rivers and valleys, they are not considered as paleokarst, but, at the maximum, as fossil karst.

Some paleokarsts have been formed during or immediately after the sedimentation of carbonate platforms, mainly in Upper Trias age (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, dissolutional and concretional phenomena (as for example the evinosponges, Bini & Pellegrini 1998) form highly porous discontinuities, as do the dolomite-filled fractures that contain iron oxides from paleosoils. Other paleokarst had been set up after the emersion of the limestone strata. They now are fossilised by Jurassic cave sediments (Prealps of western Switzerland, Julian Alps), Upper Cretaceous sandstone (Siebenhengste), Eocene sands (Vercors), or Miocene conglomerates (Chartreuse). In the Julian Alps, many paleokarstic caves have been filled with carbonate mud and later were completely lithified, so that – presently – a paleocave is just a portion of somehow differently coloured solid rock. All of those paleokarsts are totally obstructed and not connected to the present water circulations, even if they might have guided the placement of later cave systems.

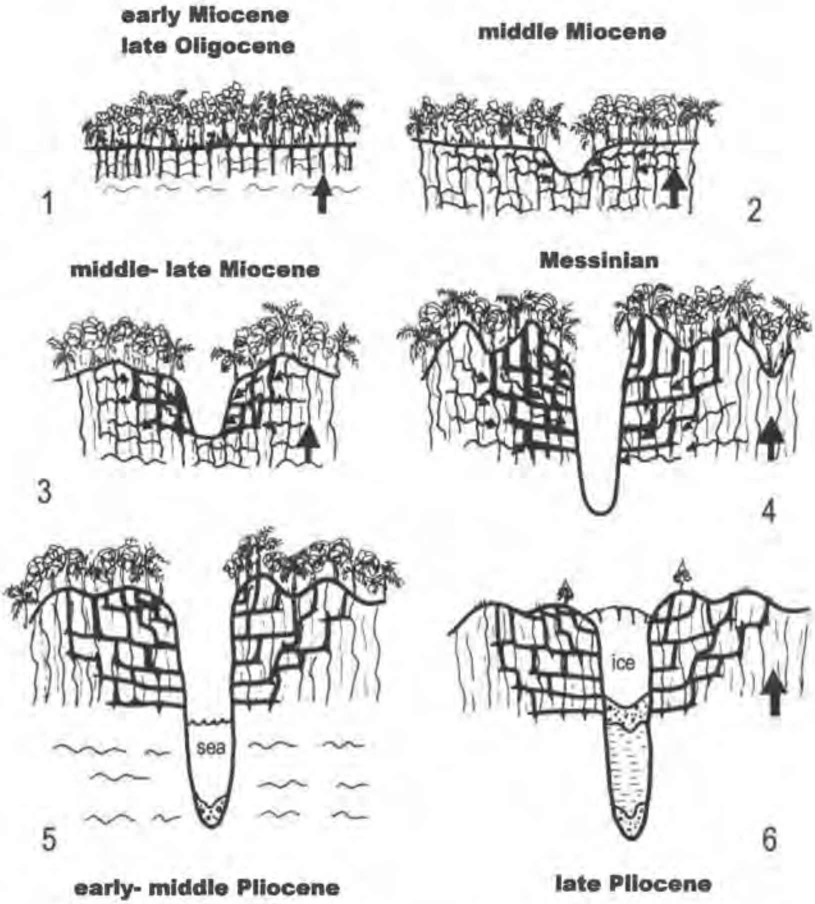

Fig. 5. Pseudoendokarst cave system in the marly-silicated Moltrasio Limestone of Mt. Bisbino, Lake of Como (TOGNINI 1999, 2001). **1 – Late Oligocene-Early Miocene:** The tectonic structure was achieved during the neo-alpine phase. From Late Oligocene onwards, uplift raised the area above sea level, 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, watertable 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 already got their present arrangement and stopped developing. However, pedogenetic processes occurred continuously since the beginning of continental evolution. **6 – Late Pliocene-Quaternary**: Sequences of sediment erosion and deposition are developing, e. g. lacustrine caves sediments recording the presence of the margin of the Adda glacier close to the caves entrances. Speleothem formation is enhanced during interglacials.

3.1.2 *Hydrothermal caves related to tectonic build-up*

Some caves are clearly hydrothermal in origin, proved by typical corrosional features originating from convection cells (p.ex ceiling cupolas) and sediments like large calcite spar. They are mentioned in the Glarus Alps in Jurassic limestone (WILDBERGER & PREISWERK 1997), at Grigna (BINI & PELLEGRINI 1998), within the *Dolomia principale* at Tremezzo/Lake of Como, which by the way is not very karstified, within marble lenses in the Inner Alps, Valtellina and Bernina, in the Provence (AUDRA et al. 2002), in the Julian and Kamnik Alps (SUSTERSIC 2001). Those hydrothermal upflows are usually located near huge thrust and strike-slip faults. Such karstifications created well organised cave networks which later had generally been re-used by "normal" gravitative flow after uplift above the base level. Since this change has mostly deleted the marks of their origin, they are only conserved when rapidly fossilised.

3.1.3 *Pseudokarst creating rock-ghosts (cave phantoms)*

Models of apparent karst features that were 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). Weathering of such limestones along fractures, mainly due to pedogenetic processes in a warm and humid climate and with a long-term stability of the base level, caused the limestone cement to dissolve. The impurities were kept in place, preserving the parent material textures and structures. Rock porosity increases up to 30–35 %, causing a dramatic increase in hydraulic conductivity. This weathered material is called rock-ghosts, or phantoms. After a base level lowering below the phantomised rock, the increase in hydraulic gradient generated fast flow across the highly permeable residual material and caused its erosion by piping. Thus cave systems similar to the "normal" ones were created. Their different origin may be traced by some peculiar features (weathered walls, regularly spaced 3D network, brisk change in passage morphology, dead-end gallery terminations with conservation of the ghost of the weathered host-rock at the end of the passage, TOGNINI 2001). 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. An example of cave phantom formation is shown in fig. 5.

3.2 *Complex relationships to glaciers*

Some older theories supported a direct relationship between glaciations and genesis of cave networks through glacial meltwater. However, more 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 and subsequent sedimentation of the conduits (AUDRA 1994, BINI 1994, HÄUSELMANN 2002). The genesis of new caves only takes place in certain contexts, where the glacial influence often is only indirect.

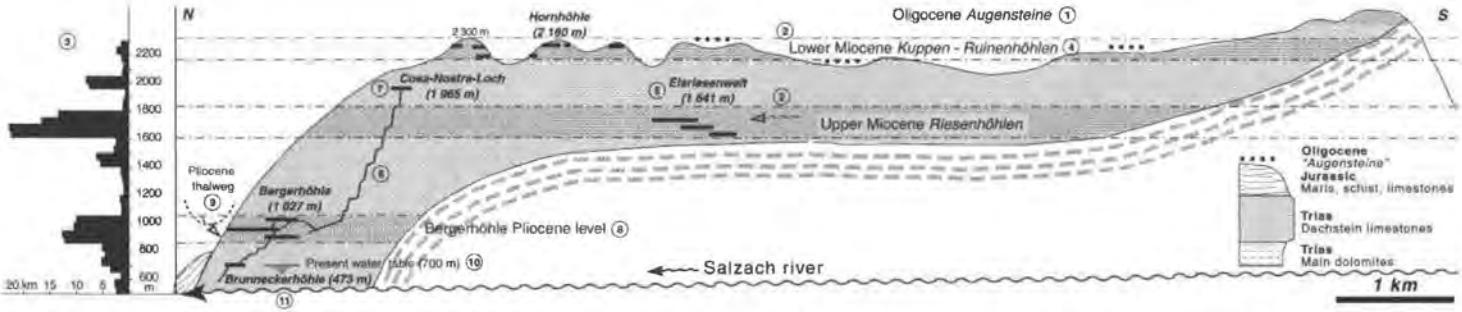

Fig. 6. The Cosa Nostra-Bergerhöhle system/Tennengebirge, Salzburg Alps (Audra et al. 2002). To the left (3), relationship between cave passage altitude and old karst levels. Karst development began during the Oligocene beneath the Augensteine (1). During the Miocene, horizontal systems developed with 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 watertable at 700 m (10) pours into Brunnecker Cave, which connects to the Salzach base level (11).

3.2.1 *Glacial processes mainly fill caves*

In the Alps, glaciers were temperate with flowing water. Since the ice itself and glacial sediments are prone to obstruct the preexisting springs, a large glacier body in a valley may rise the karstwater level 500–600 m higher than the original base level (Bergerhöhle/Tennengebirge, fig. 6). A rising karstwater level caused small flow velocities and therefore deposition of fine-grained carbonate-rich sediments. Since this carbonate flour could not be dissolved by the natural aggressivity of the water, it implies that a chemical erosion of the walls around the cave is also very improbable. Old concretions that show almost no erosional features are another proof. The only means to enlarge the cave would be mechanical abrasion which is also improbable because of the small discharge. We conclude that the genesis of deep-seated cave conduits is not favoured during glaciations (AUDRA 1994).

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), but reduce the amount of debris washed into the cave. So, the water has a much higher initial acidity and is therefore enlarging the caves. Water in the vadose zone reaching a passage is usually close to saturation, upon contact with the cave air, it degasses CO_2: speleothems form. In the low valleys with flat bottom, lakes filled the previously overdeepened valley and kept the watertable 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.

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

3.2.2 *Glacial sediments covering older speleothems: cave systems may predate glaciations*

Some 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 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.

3.2.3 *Conditions for cave development connected with 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 the glacial melt, the meltwater disappeared in 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 appear at the intra-Alpine karst due to glacial erosion. Thin limestone belts or marbles intercalated with metamorphic series were recently freed from their impervious cover. The caves still are more or less in direct relationship with the periglacial flow, and they act as swallowholes. Their morphology reflects the cascading waterflow and has a juvenile form: Perte du Grand Marchet/ Vanoise, Grisons (WILDBERGER et al. 2001). At the Grotte Théophile/Grandes Rousses, U/Th datings evidenced that the cave had been active for at least two glacial-interglacial cycles that are marked by the sequence of passage-forming/filling with gravel/sinter deposition (AUDRA & QUINIF 1997).

The lower phases of huge cave systems are indirectly generated by glacial valley-deepening. While it is hypothesized that the uppermost cave systems in many areas of the Alps are older than the glaciations (see Part 4 below), the lower passages often are of Quarternary age, since they are related to valleys of evidently glacial deepening. In this respect, glaciers are indirectly responsible for the creation of new cave passages, as is evidenced in many places (Siebenhengste, Chartreuse, and Vercors). This is starkly contrasting to the South Alpine domain, where the valleys were deepened during the Messinian event. Here, the 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.

4 *Morphologic and topographic evidences for a high age of cave systems*

Some existing caves and karst features correspond to a different topography than today and therefore have to be older than the present landform. In the first paragraph, the position and morphology of the caves are compared with today's landscape, whereas in the second, the sediments contained within the cave are analysed. In the third part, links between caves and well-recognised paleotopographies are explained. All those indications are clear evidence for a high age of cave systems.

4.1 *Cave systems unconsistent with the present topography*

4.1.1 *Perched phreatic tubes*

Conduits with a tubular morphology are present at various elevations, sometimes perched considerably above the present base level (table 1, 3rd column). They clearly correspond to different periods of time and elevations of the base level. At the Siebenhengste, the highest phases even show a flow direction opposite to the present one.

4.1.2 *Caves intersected by current topography*

Old perched caves are often segmented by the lowering of the surface. Several types of surface lowering that postdates the speleogenetic event can be distinguished:

- At the surface of karst plateaus by glacial abrasion (Grigna, Dolomites, Triglav, Kanin, Tennengebirge …).
- Along the valleys, by retreat of the valley flanks (Adda, Adige, Salzach, Isère): Pian del Tivano, Mt. Bisbino, Mt. Tremezzo, Campo dei Fiori (Southern Alps), Paganella (Dolomites). Such systems, formerly united and now fragmented, are difficult to be tied together.

4.1.3 *Dimensions too large with respect to the present catchment and climate*

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

4.1.4 *Spring location unadapted to the present base level position*

If the position of a spring is not due to a geologic perching above an impervious layer, it has to be at the base level. However, some rare cases attest that the springs didn't adapt to fluctuations of the base level:
- Some of them are perched, demonstrating a retarded adaptation of the karst to the valley incision caused by rapid uplift (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 rised and continue to function due to the high transmissivity of the sediment fill.

A speciality 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.

4.2 *Cave sediments showing evidence of a remote origin, different climate and old age*

4.2.1 *Old fluvial material*

The presence of some sediments found in the caves is inexplicable with the present waterpaths. Big rounded pebbles found in caves perched high up the cliffs mean that a valley had to exist at this level, whose water went partly or completely underground upon reaching the limestone. Since then, the valleys deepened so that they are no more in contact with the perched massifs (Salzach/Salzburg Alps; Granier/Chartreuse). Often, such gravel has a petrograpy and mineralogy that is not found in the present rocks. They are issued either from caprock that has disappeared long ago (Fontana Marella, Campo dei Fiori) or from distant catchments, as prove the fluvial pebbles (Augensteine/Northern Limestone Alps in Austria), quartz sandstones (Slovenian Alps), fluvioglacial sediments (Lake of Como).

4.2.2 *The record of climatic changes in the 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), Campo dei Fiori (BINI et al. 1997), Monte Bisbino (TOGNINI 2001). In the Dachstein-Mammuthöhle, which dates back to the Tertiary and shows a phreatic tube perched 1,000 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, the mean annual temperatures deduced from the ^{18}O of speleothems were between 15 and 25°, which implies that the cave was filled with the spelothemes in a warmer climate within the Tertiary, possibly also in a lower altitude than it is found today (FRISIA et al. 1994). Furthermore, in many caves, either the conduits or the flowstone have been deformed by late Alpine tectonic movements, for example: Grotta Marelli, Grotta Frassino/Campo dei Fiori (UGGERI 1992).

4.2.3 *Some 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 et 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.

4.3 *Links to an old topography*

The geomorphologic approach, which uses external markers of old base levels (paleovalleys, paleoborders 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 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.

4.3.1 *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

Table 1 Synthesis of informations about the quoted caves systems.

Cave system	Massif system	Difference in height, horizontal cave levels/ present base level (m a.s.l.)	Datings	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)		Cretaceous sandstones	yes	Upper Miocene?	Audra 1994
Grotte Théophile	Grandes Rousses	1900/1850 m	95 ka (U/Th)				Middle Pleistocene	Audra & Quinif 1997
Gr. de l'Adaouste	Provence		No dating		Miocene pebbles	Artesian	Tortonian	Audra & al. 2002
Système du Granier	Chartreuse	1500/1000 m	> 1–1.5 Ma ($^{234}U/^{238}U$ equilibr., paleomag.)	Upper Cretac. and Oligocene limestone	– Cretaceous sandstones, – weathered soils	yes	Upper Miocene?	Hobléa 1999
Switzerland								
Beatushöhle – Bärenschacht	Siebenhengste	890/558 m	> 350 ka (U/Th)				Pleistocene	Häuselmann 2002

Table 1 Continued.

Cave system	Massif system	Difference in height, horizontal cave levels/ present base level (m a.s.l.)	Datings	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
Switzerland (Continued)								
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
Grotta 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
Grotta On the Road	Campo dei Fiori	805 m	> 1–1.5 Ma ($^{234}U/^{238}U$ equilibr.)				Oligo-Miocene	

Grotta Via col Vento	Campo dei Fiori	1015 m	> 350 ka (U/Th) Upper Plio. glacial sediments				Oligo-Miocene	
Grotta sopra Fontana Marella	Campo dei Fiori	1040 m	Middle Pleistocene (microfauna)	Conglomerate w/crystalline pebbles	Ferralitic soils	yes	Oligo Miocene	Zanalda 1994
Ciota Ciara – Cuitarun caves	Monte Fenara		Large Miocene fluvial pebbles			yes	Oligo Miocene	Fantoni & Fantoni 1994
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

Vercors, of Eocene, infra-Miocene and Pliocene age (DELANNOY 1997). Flattened valley slopes, created by lateral corrosion of the rim of ancient depressions, have the same significance as perched valley bottoms. In the Vercors, Pliocene caves depend 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 (CITA & CORSELLI 1990, FINCKH et al. 1984).

4.3.2 *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 more than 1,500 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) are found.

In the northern flank of the Alps, these valleys had been destroyed by the deepening of the hydrographic network, aided by the action of the glaciers. In the South, the old valleys are 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 considerable dimensions of those caves.

5 *Age of Alpine karstification: from paleokarsts to recent mountain dynamics*

5.1 *Paleokarst, a milestone for old karsts*

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

- Upper Cretaceous (Siebenhengste): Paleotubes and fractures in Lower Cretaceous limestone, filled with Upper Cretaceous Sandstone.
- Eocene: Northern French Prealps (Vercors, Chartreuse): vast pockets covering the most external reliefs.
- Upper Eocene and Lower Oligocene (Covoli di Velo, Ponte di Veia/Monte Lessini), large cavities infilled by basaltic intrusions that had been dated by K/Ar (ROSSI & ZORZIN 1993).

In several regions (Vercors and Chartreuse, Monte Lessini), the karstification is more or less continuous from the Eocene onwards. However, the tectonic and paleogeographic changes have only left dispersed paleokarsts. From the Miocene onwards, several massifs emerge from the molasse basins, thus allowing a karstification that continues today.

5.2 *Estimation of the first exposure according to molasse petrography*

The main phase of karstification begins when suitable rocks are exposed to the surface. Since the oldest remnants of karst often are eroded, it is possible to calibrate the beginning of the karstification by the foreland sediments (mainly the Molasse), which contain limestone 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) registered in form of pebbles the first erosion of Helvetic nappes (Siebenhengste, Silberen, Speck 1953, Bürgisser 1980).

5.3 *Dating the youngest phases and extrapolation*

The most generally applied dating method is U/Th contained in the speleothems. In the best cases, it allows to go back as far as 700 ka – dating only the sediment contained within the cave and not the cave itself. The use of paleomagnetic dating permits, in some rare 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 datable range of 300 ka up to 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 began at 39 ka (max. 114 ka) and is still active today; Phase 660 was active between 135 and 114 (max. 39) 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 1,850 m a. s. l. Absolute cosmogenic dating yielded an age of 4.4 Ma for the oldest sediment, contained in the second-highest cave phase at 1,800 m, showing a slower entrenchment in the older phases.

Dating of the cave systems at Hoelloch/Silberen gave maximal rates of valley incision in the range of about 1.5 to 3.5 mm/a.

5.4 *Relative uplift rates and erosion volumes in sediment*

Uplift rates generally are 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 give a global approach. Such results only may give a general frame for 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).

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.

6 *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. We put forward evidence for the following:

- In contrast to some earlier views, caves are not directly linked to glaciations. On the contrary, there is evidence that during glaciations, caves mainly are filled with sediments, while they are enlarged during the interglacials. The main influence of glaciers upon speleogenesis is the deepening of the base level valley, thus inducing a new speleogenetic 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 information of valley deepening processes and therefore of landscape evolution.
- Caves constitute veritable archives, where sediments are preserved despite the openness of the system. The study of cave sediments gives information about the paleoclimate. Moreover, the linking 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 may further 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) and recharge and topography (towards the central Alps), they will inevitably register changes in both domains. Caves are therefore not only a tool of local importance, but may have a wide regional/interregional significance.
- The advances of modern dating techniques (cosmogenic isotopes, U/Pb in speleothems) will allow to gain more precise age information in the future, thus greatly enhancing the cave's potential for scientific research.
- The messinian event influenced cave genesis over the whole southern and western sides by overdeepening valleys. However, the subsequent base level rising flooded those deep systems creating huge deep phreatic aquifers and vauclusian springs.

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