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AN OVERVIEW OF THE CURRENT RESEARCH CARRIED OUT IN THE FRENCH WESTERN ALPS KARSTS

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Abstract UDC: 551.44(234.31)

Philippe Audra: An overview of the current research carried out in the French Western Alps karsts

Current research encloses karst systems geomorphologic approach, recent advances in study of karst structures which date back from the Upper Miocene. Karst genesis in Western Alps is brought up by systemic analysis, according to a geomorphologic approach. It uses the "karst immunity" that conserves old drainage structures and their associated sediments. Karst landscapes can be sorted into horizontal and vertical forms. Speleothems are clearly connected to the presence of vegetation but they also record geomorphic crisis. Clastic sediments reveal mechanical erosion. This approach concludes with karst genesis and speleogenesis reconstruction, which blend together evolution stages, environment characterization and processes. Researchers reconsider the preponderant part previously attributed to glaciers. Karst appears immediately when a gradient exists and when the aquifer is stripped of its impervious cover. Such conditions occurred from the Upper Miocene and sometimes before. Karsts of the Pleistocene age are only met in the Inner Alps where cover stripping occurred later. Vertical systems composed of shaft series are old and become more complex. Field evidence refutes FORD's classification, which assigns a deep phreatic origin. A brief account of the present state of knowledge, according to region and researcher's scientific themes, allows establishing the last decade's advances. It also shows a disparity between the North and the South Western Alps, where Vercors appears to be one of the best studied massifs in the Alps.
Key words: geomorphology, karst, karst sediments, geodynamic, cave genesis, glacial processes, paleoenvironment, French Western Alps.

Izvleček UDC: 551.44(234.31)

Philippe Audra: Pregled novejših raziskav krasa v francoskih zahodnih Alpah

Tekoče raziskave na podlagi geomorfologije kažejo napredovanje pri preučevanju kraških struktur, katerih začetek sega v gornji Miocen. K poznavanju krasa Zahodnih Alp so pripomogle sistematične analize na podlagi geomorfologije. Pri tem veliko koristi »imunost krasa«, ki ohranja stare prevodne strukture in njihovo zvezo s sedimenti. Kapniki kažejo na očitno povezavo z vegetacijo, v njih pa se lahko odražajo tudi geomorfološke krize. Klastični sedimenti odkrivajo mehansko erozijo. Na podlagi geomorfološkega pristopa je mogoče ugotoviti nastanek krasa in jam, kar vključuje razvojne stadije ter značilnosti okolja in procesov. Raziskovalci ponovno tehtajo prevladujočo vlogo, ki so jo včasih pripisovali ledenikom. Kras se pojavi takoj, ko nastane gradient in ko je z vodonosnika odstranjen neprepustni pokrov. Take okoliščine so bile že v zgornjem Miocenu in včasih celo prej. Na kras pleistocenske starosti je mogoče najti le v notranjih Alpah, kjer je bil ta pokrov odstranjen kasneje. Navpični sistemi, sestavljeni iz vrste brezen, so stari in postajajo vedno bolj kompleksni. primeri s terena zavračajo Fordovo klasifikacijo, ki jim pripisuje nastanek v globoki freatični coni. Kratek pregled sedanjega stanja poznavanja tako ozemelj kot znanstvene snovi, ki jo raziskujejo, dovoljuje oceno napredka v zadnjem desetletju. Iz tega se tudi kaže neenakost med Severnimi in Južnimi Zahodnimi Alpami, kjer se Vercors izkaže za eno izmed najbolje preučenih planot v Alpah.
Ključne besede: geomorfologija, kras, kraški sedimenti, geodinamika, nastanek jam, glacialni procesi, paleookolje, francoske Zahodne Alpe.

It is a very hazardous challenge to establish a synthesis of French Alps karst, exceptional cases being so numerous. Restricting to some demonstrative types and establishing only the main evolution phases, one is often compelled to take the lowest common denominator. In that case, contents are often superficial and composed of simplistic concepts. In the following synthesis a compromise between huge encyclopedism and excessive abstraction will be attempt. The state of knowledge of French alpine geomorphologist studies, which promote a systemic approach for karst, across its structures, dynamics and evolutions, will be provided.

I – KARST SYSTEM GEOMORPHIC APPROACH

Karst is an underground drainage structure prone to change with time. Its main specificity lies in its possibility to conserve testimonies from old phases, saved as "paleo-structures".

These organized voids mark the paths of old flows. Channels also harbor sediments that were deposited during the active period. A combined morphologic and sedimentary study allows reconstructing karst dynamic and environmental conditions for each phase. This "karst memory" is the consequence of "karst immunity" that distinguishes karst from other external geomorphic features, which ancient traces tend to disappear with time. Moreover, the current karst dynamic reveals not only present environmental conditions and associated drainage structures, but it also blends together inheritances of past times.

So, karst study allows describing the morphologic events that induced successive karst and speleogenesis phase. It also establishes environmental setting for each phase and put in evidence the role of all processes (fig. 1).

A – MORPHOLOGY, SEDIMENTS AND HYDRODYNAMIC: THREE APPROACHES TO UNDERSTAND MORPHOGENETIC EVENTS

1 – Karst features

Morphology is a classic theme in our discipline. We focused on some significant features able to highlight the part of base level location and change. Located as much at depth as at surface, one opposite horizontal to vertical features. Horizontal features develop according to stable base level with low topographic gradient. Vertical features, on the contrary, develop after an abrupt base level change - lowering or rising - in a contrasted topographic setting.

• Horizontal surfaces

Within various scales and landforms, different processes elaborate horizontal surfaces according to low topographic gradient.

- **Erosional surfaces** are not exclusively karst features. Nevertheless, they are very well preserved in karst. An erosional surface results in almost no topographic gradient during very long periods (> Ma), giving rise to lateral planation. Erosion is limited to the surface, excluding other processes, especially vertical karst entrenchment. Therefore, erosional surface reveals extended periods of tectonic rest without any real karst process at depth [Quinif 1999].
- **Cone karst** display irregular mesoscale landforms. However, this landscape presents a horizontal trend at a global scale. It also develops in a low gradient setting during slow but continuous

uplift [Mangin & Bakalowicz 1990] under covers originating from the weathering of overlying strata or surface deposits [Maire & al. 1991].

- **Poljes** have more limited extensions. Instead of being one of the Karst symbols, they result in karst processes first having developed deep depression and then turning to surface planation. Such change results from a critical context: climatic, tectonic, human induced crisis [Delannoy 1997].

• Paleo- cave level

Large horizontal cave levels are presently drained and perched in the rock mass. They represent at depth an equivalent of flat surfaces. They embody flow path concentrations ("main drain") close to the water table. The location of paleo-cave level depends on base level position (for dammed karsts). It is possible to infer not only approximate old base level location but also old flow path directions, flow types and sometimes paleo-discharges. The duration required for the development of such structures is long, therefore base level should remain stable.

All the horizontal features, as much at surface as at depth, mainly record the position of stable old base levels. Vertical features, on the contrary, result in abrupt topographic changes.

• Linear entrenchment

Valley or canyon evolve when base level drops after a tectonic uplift or a sea level lowering. The length profile of a river becomes steeper and enhances the erosion capacity. An entrenchment then occurs that produces a proportional base level lowering for neighbouring karst massifs.

When entrenchment is abrupt, the valley cross-section is narrow. In such high gradient setting, climate influences morphogenic processes and entrenchment slows down or accelerates. Fluvial valley entrenchment during glaciation is a well-known example. On the contrary, flat and wide valleys covered with alluvium develop when solid load exceeds the transport capacity (known as a perched terrace when ancient). Therefore wide valleys can result either in base level stability or in base level rising. This decreases both the slope and the erosional transport capacity. On the other hand, a wide valley can result in load increasing induced by important erosion on the catchment area that the flow cannot evacuate. In that case, it results in base level rising or stability that leads to a lateral enlargement of the valley by slope retreat.

• Vertical cave systems

An abrupt base level lowering induces a subsequent deepening of the vadose zone inside karst. Shafts and canyons develop downwards and cut the old horizontal conduits that remain drained and perched [Audra & al. 1993].

Shaft systems strongly develop when the limestone mass is thick and jointed and the gradient is strong. On the contrary, gentle gradient and jointing allows developing gently sloped canyon.

When base level lowering is moderate, it will only produce a torrential linear entrenchment as a keyhole cross-section.

During base level rising, previous existing karst levels are found deeper than valley bottoms (or sea level). Deep karst is then flooded and water outpours as vauclusian springs. An important sea level rise (or tectonic subsidence) floods huge karst systems: Yucatan, French Calanques near Marseille… A gentle river aggradation at a metric-scale order produces a short phreatic zone in the downstream part of the system, e.g. in sedimentary basin plateau karsts: Côte des Bars [Jaillet & Gamez 1995], Entre-deux-Mers…

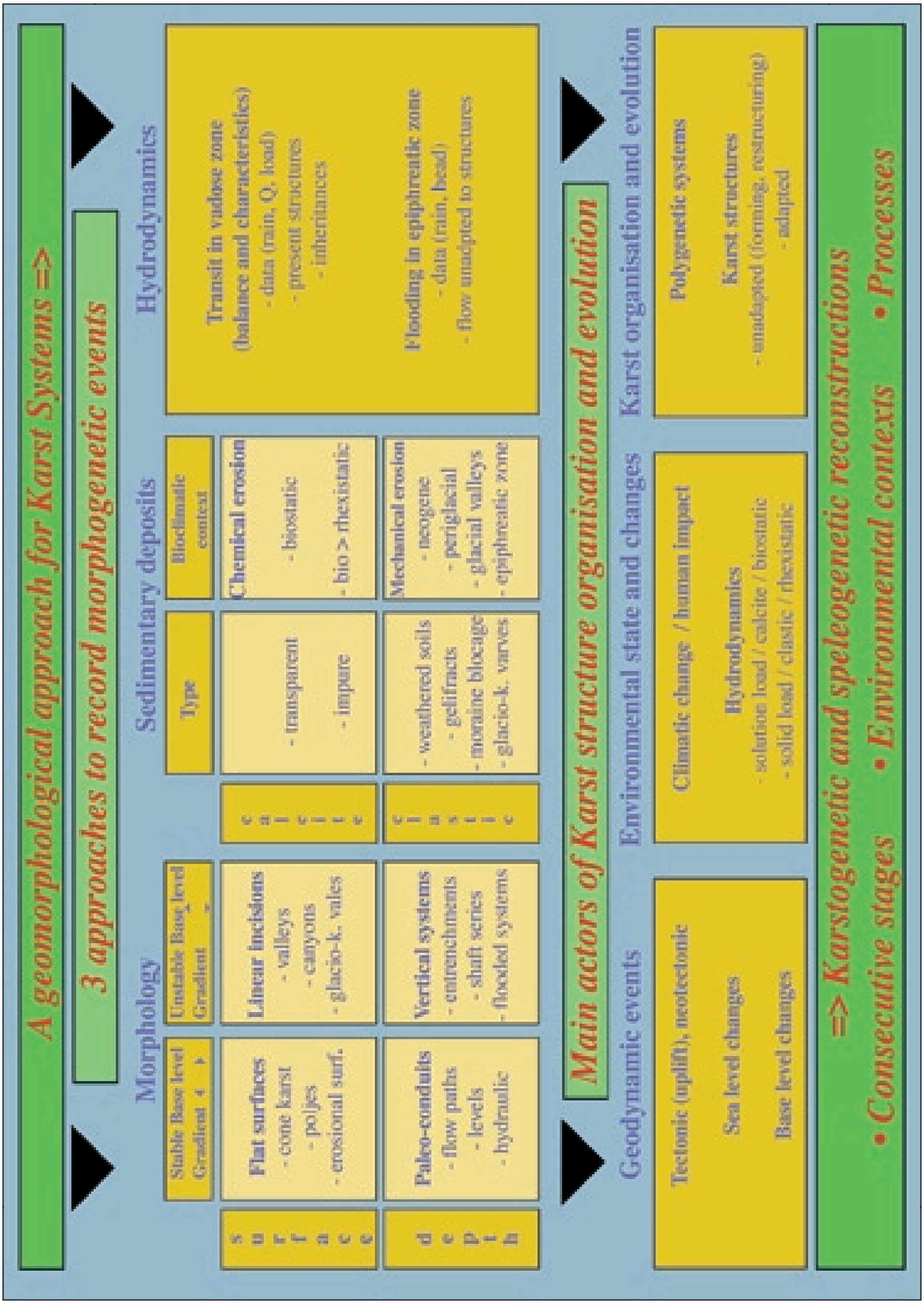

Figure 1: Organization chart about karst geomorphology study.

2 – KARST SEDIMENTS

Karst sediments benefit from karst immunity and are precious recorders, as much for karst hydrodynamic conditions as for environmental characteristics within the system boundaries [Quinif 1994]. As these facts are now well known, only the main aspects will be presented. There are two main types of karst sediments: speleothems and clastic sediments that originate from chemical and mechanical weathering.

• **Speleothem**s

Speleothems result from calcite deposition in underground voids; the solute load originates from limestone dissolution along joints by water previously saturated with dissolved CO2, acquired when crossing vegetation-covered soils. Crystalline structures of transparent calcite occur when these biopedologic covers act as filters hindering seepage of the solid load. They mark biostasy conditions. On the contrary, absence of transparent calcite shows the lack of at least one element of the system in a rhexistasy context: dry climate, soil erosion and the disappearance of vegetation, etc. Solid particles colouring calcite (clay, charcoal, and organic matter) show conditions turning from biostasy to rhexistasy [Maire 1990; Pomel & Maire 1995].

Moreover, the scanning of speleothems growing lamina can give information about environmental conditions, such as rainfall, type of soil cover and vegetation, on a yearly or even seasonal time scale [Perrette & al. 1999].

• **Clastic sediments**

Clastic sediments correspond to the transport of solid particles eroded away from rocky surfaces or soils by erosional processes, mainly in rhexistasy conditions and transported by runoff and glaciers. In mountain karst areas like the Alps, four main types occur [Audra 1995]:

- **Weathered rocks** are composed of residual elements (quartz, heavy minerals) or secondary minerals (clays and particularly kaolinite). They result from the weathering of diverse rocks or sediments during the Tertiary period in warm and humid conditions and constituted loose soil covers. During the Tertiary these soils were removed according to climate changes, e.g. drying or mainly Upper Pliocene cooling. Then they were trapped into karst [Maire 1990]. These sediments always constitute the first and the oldest sediments known in the large alpine systems.
- **Gelifracts** are characteristic of periglacial environments. They can form talus fans at the bottom of shafts or outwash deposits in galleries [Delannoy 1998].
- **Morainic plugs** are located especially in the bottom of valleys and at the foot of slopes. They display only at the entrance of cave systems that are more or less plugged. However, they can be reworked by torrential flows in the vadose zone and brought to considerable distance inside caves.
- **Glacio-karst varves** are silty laminated sediments comprised largely of calcite flakes. This material results partly from glacial abrasion on rocky surfaces and mainly from mechanical erosion by torrential flow in the vadose zone [Zupan-Hajna 2003]. During summer melting, large amounts of water arrive abruptly into the karst system and cannot be discharged, the outlets being blocked by moraines or glaciers [Maire 1990]. Flooding then occurs, sometimes over depths of several hundreds of meters. The important suspended load deposits by decantation in the lacustrine environment. Flow stops in winter and systems drain slowly until the next seasonal cycle that

produces a new lamina deposition. These sediments illustrate the ampleness of the epiphreatic zone in such conditions [Audra 1994].

3 – HYDRODYNAMICS

Studying water flow allows us to understand present characteristics of flow structures. It enables the indirect study of unattainable zones like the epikarst, the fissured zone or the unknown conduits [Mangin 1975, Bakalowicz 1979]. Several describers are used to characterize transformation functions operating during inertial filter crossing that is represented by karst flow structures: discharge changes, suspended or solute load, physical water parameters like temperature, etc.

Some approaches are crossed with morphological information, each enriching the other.

Vadose zone studies use the hydrologic balance of karst system with the recording of the main input and output parameters. Influence of paleo-structure and kinds of flow over present flow have been put in evidence [Delannoy & al. 1999].

Flooding in the epiphreatic zone is also a phenomenon that reveals relationships between flow type and karst structure morphology. The rising of the water table, reaching at times a sizeable depth, is the result of the difference between runoff and flow structure size. These differences are linked as much to environmental conditions in the system boundaries as to inheritances recorded in the shapes of these old flow structures [Audra 1998].

B – MAIN ACTORS OF KARST STRUCTURE ORGANIZATION AND EVOLUTION

Each of the three properties presented above highlights the main factors of karst structure organization and evolution: the main geodynamic events and changing environmental conditions together, allow us to better understand karst drainage structure organization and evolution.

• Main geodynamic events

One of the karst initial conditions is topographic gradient. Study of horizontal forms (planar surfaces, paleo-conduits) and vertical forms (valleys, vertical shafts and flooded systems) leads to the determination of successive general or local base level positions, stability periods or, on the contrary, sharp changes. These base level changes are induced by geodynamic history.

One can therefore identify uplifting phases, such as the Rhodanian orogeny at the end of the Miocene and other neotectonic uplifts that followed. Topographic gradient can change according to sea level changes. Quaternary glacio-eustatic changes have only affected Alpine belt parts directly in contact with Mediterranean basin. But Western Alps have been concerned especially by the Messinian-Pliocene eustatic cycle: 1/ the important Messinian regression, with nearly half a million year duration deep sea level; 2/ the following Zanclean transgression with a high stand (+ 80m) during about 1.5 Ma. Peripheral alpine areas directly linked to the Rhône or its main tributaries were particularly affected [Clauzon 1982].

• Environment states and changes

Among the conditions for karst development, the presence of water and CO2 can change with time. The first depends on climate and eventually on topography [binary karsts; Mangin 1975], the second on soils and vegetation. Sediment type (chemical / clastic) gives some information on both (supra). Stratigraphy gives information on each phase, which are shared by unconformity revealing environmental changes. One can detect climate changes (glaciation…), decrease in vegetation cover, soil erosion or human impact. These changes at the system boundaries affect hydrodynamics (water discharge, flow regime, load flux), in addition to changing the characteristics of sediments trapped or crossing karst systems.

• Karst organization and evolution

While taking in consideration all the approaches described above (morphology, sediments and hydrodynamics) and the light they shed on karst processes (geodynamic events, environmental conditions), it is possible to understand the present karst organization. Taking into account their long age, karsts are polygenetic and integrate a lot of inheritances. It is therefore possible to recognize in which manner karst dynamics are adapted to present conditions or influenced by inheritances.

Finally, using a systemic approach (state, dynamic, actors), one can achieve karsto- and speleogenesis reconstruction, integrating the successive stages of history, the characterization of environment and finally the nature and quantification of present or past processes.

Using this conceptual approach, several facts have been specified or put in evidence, showing advances of the discipline over ten years.

II – RECENT ADVANCES

A – Karst structures date back mainly from the Upper Miocene

Important advances have been made over the last decade. Ten years ago we knew almost nothing about the age of karst systems. They were simply estimated to be older than the range of U / Th dating method (350 000 years only!). At the other end of the scale, sediments or fossils dated some ante-Miocene paleokarsts. Between these two milestones we had to admit that we knew very little. Of course, we still do not know everything, but we now have some important milestones.

• Oldest systems are older than the last orogenic Rhodanian phase

In the northwestern French Prealps, the Miocene sea level is located at the present 1000-1200 m altitude. Relief was moderate and often corresponded to anticline ridges, syncline valleys being at the base level.

Some tunnel-caves, similar to present tropical ones, linked syncline poljes [Delannoy 1997]. Now these caves are completely disconnected, truncated or even unroofed by surface lowering. Nevertheless, in Vercors, some of these old systems are larger than one kilometer (antre de Vénus, Coufin-Chevaline upper level). Among these old levels, the older ones predate the beginning of orogeny (12 Ma) and were formed according to the Miocene sea, like the Chassillan shaft in Vercors [Barbier 1972].

• Highest level of large systems appears after alpine orogeny (the Upper Miocene)

The highest level of large systems generally corresponds to the most developed level and has the largest galleries (Dent de Crolles and Granier systems in Chartreuse, Gournier and Favot caves in Vercors). They are adapted to the new geological structure, so they are not older than the Upper Miocene.

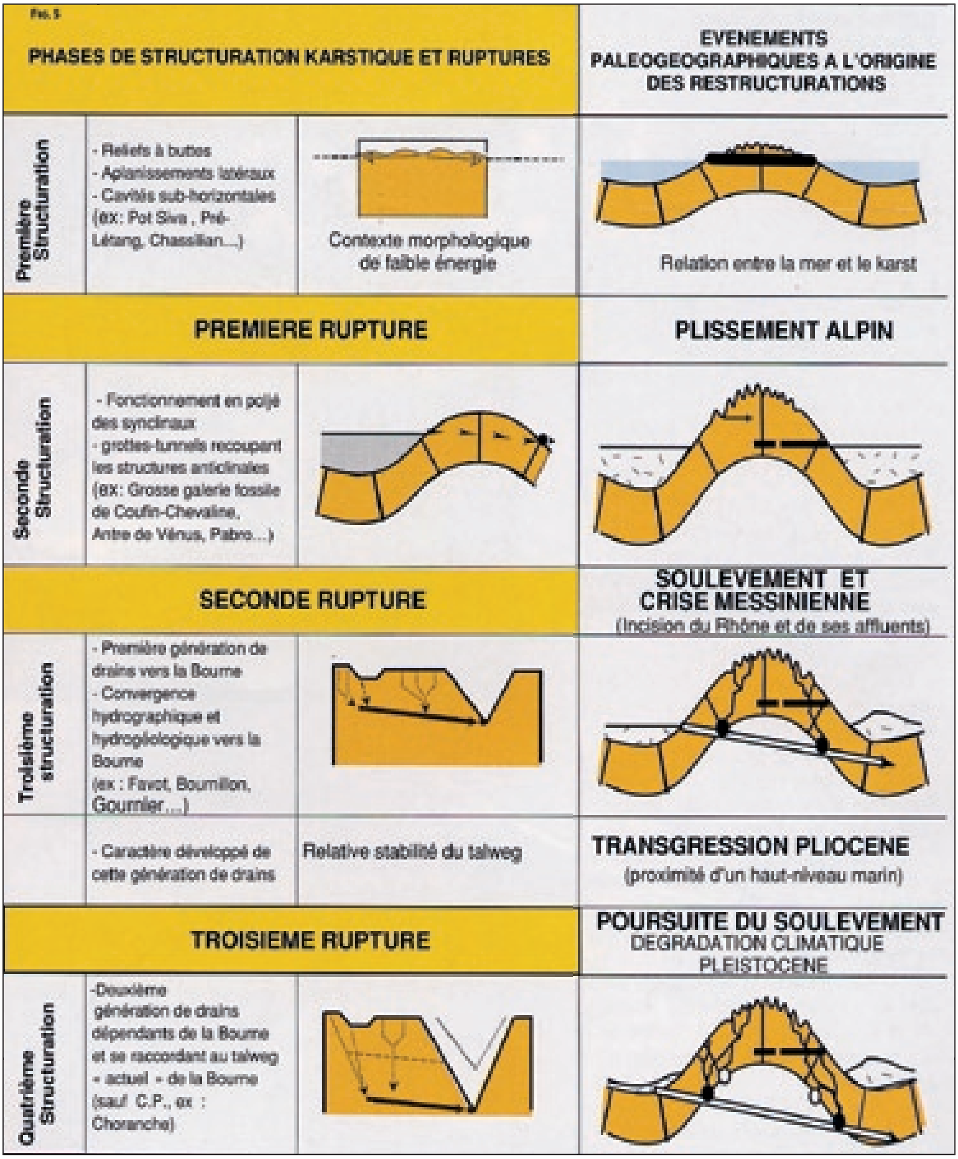

Figure 2: Karst development phases and ruptures in Vercors massif [Delannoy 1997].

The Messinian abrupt base level drop is inserted during uplifting. It activates valley entrenchment along the border of the range and subsequently the development of vertical cave systems. The Zanclean transgression causes a high sea level for a long time (1.5 Ma). It stops the generalized deepening of karst and valleys. During this long stability period, large galleries could have appeared and developed [Audra 1994, Delannoy 1997, Hobléa 1999].

• Lower levels develop according to the Plio-quaternary continuous base level deepening

Pliocene transgression brought a "morphogenetic break". But the uplift follow-up finally stopped it. Moreover, from the Upper Pliocene, cold climatic change announcing the Pleistocene activated the morphogenetic system. During each glaciation, a morphogenic crisis occurred. Consequently, base level lowers step by step, but karst evolution depends on its position with respect to glacier and base level. In the massifs perched above large alpine glaciers, such as Granier (Chartreuse), or located near the glacier front (Western Vercors) successive levels can develop. On the contrary, the evolution of karst massifs located close to large alpine glaciers is nearly blocked (infra).

We now benefit from milestones spread out quite regularly along the alpine karst evolution history. It is important to notice that they have been obtained mainly with geomorphologic studies. If the beginning of large systems evolution is quite well characterized, our knowledge about lower levels chronology is very restricted, except for the period covered by the U / Th dating method.

B – A LIMITED PART FOR GLACIAL PROCESSES

Up to now, theories of karst evolution strongly favoured glacial processes. This opinion was wrongly advanced by the U / Th dating results showing undoubtedly that interglacial calcite deposition alternated with glacial entrenchment. However, most ages of speleothems did not reflect the age of galleries and only the most recent systems can really be dated. For this period, important progress has been made with increasing dating data, first with U / Th radiometric method then with paleomagnetism and finally with geomorphologic interpretations. The results force us to reconsider the exaggerated role of glacial processes.

• Plugging of karst deep parts

Glaciation is often quoted as an origin of karst development at depth. However, nearly all the conditions are against this explanation.

Valleys filling with ice cause the karst lower parts to be blocked by the glacier itself and also by moraine injection into caves. This causes base levels to rise, which is not favourable for deep karst processes. The abrupt base level drop that follows glacial retreat has also been cited. But it appears that the volume liberated by melting ice is immediately substituted either by lakes or by sediment infilling [Audra 2000]. Effective low base level duration is too short to induce lowermost levels development [Delannoy 1997].

Inside karst, during the flow season, the cave system is flooded by the influx of melting waters bearing an important carbonated flour load. Lacustrine-type conditions occur, without any current. Mechanical erosion is non-existent and chemical aggressivity is switched by carbonate load. Conservation of fine speleothems after these floodings is the best proof. During winter draining, suspended load decantation plugs the voids, except along the main flow paths. Knowing that flooding can reach several hundreds of meters deep a great part of the karst evolves to infilling without entrenchment [Audra 1994].

• Vadose zone becomes more complex

In the vadose zone, flows are torrential. Discharges are sometimes huge. Shaft development possibilities exist here. However, field examples show that, in spite of the initiation of completely new systems, water flow tends to create parallel conduits by headward erosion using already opened joints (Dent de Crolles). The result is more a complication of existing systems than a real initiation of new ones, glacial water having no aggressivity to open new fissures.

• However, there exist some favourable settings for indirect "glacial" speleogenesis

The indirect role of glacier is evidence for massifs located near the glacier front, like in Western Vercors. In this case, powerful proglacial flows coming from eastern glaciated high plateaus activate valley entrenching and base level lowering. Consequently, when returning to interglacial conditions providing aggressive water, karst systems close to the valley evolved quickly [Delannoy 1997, Häuselmann 2002].

These facts have to be taken into account because the role of glaciers is probably subtler than the one first imagined [Bini & al. 1998].

C – KARST SYSTEM DEVELOPMENT AND EVOLUTION CONDITIONS

• Propitious conditions for speleogenesis

Karst rock should outcrop in both input and output areas so that meteoric water can flow through limestone. Excepting early deep phases [Klimchouk & al. 2000], karst flow from meteoric origin can appear when impervious covers are stripped enough [Maire 1990]. In addition, speleogenesis can begin when an adequate gradient exists. But after an abrupt base level drop, the entire karst restructures itself. If climatic conditions favour this process, their direct influence is not essential regarding base level changes. Conditions for karst development occurred at the end of the Miocene and even before. Anyway, karst did not "wait" the Pleistocene (and man!) to begin its evolution. Results presented above confirm this evidence.

• Where are Pleistocene karsts?

To "find" recent karsts, one has to look for settings where at least one of the development conditions was not effective in the earlier periods. In some inner Alps areas karst outcrops were recently cleared of their impervious covers [Maire 1990]. Moreover, these outcrops are often relatively thin and sandwiched between complex metamorphic structures. Topographic gradient was already important, water abundant and flow was torrential. So, when karst flowing conditions occurred after impervious covers were stripped, karst probably evolved very quickly during interglacials. Such a karst system dated from the Middle Pleistocene using U / Th is found near the Alpe d'Huez ski resort [Audra & Quinif 1997].

• Evolution possibilities

Karst aquifer extension can vary with base level change. Aquifer division can occur when a strong gradient appears in a neighbouring valley creating piracies, like in Bellefond / Dent de Crolles system [Lismonde & coll. 1997]. On the contrary, base level lowering can allow flowing across previously confined aquifers, enlarging catchment areas, like Siebenhengste [Bitterli & Jeannin 1997].

As regards the development of horizontal levels, they organize according to the lowering of base level. In a probably continuous uplifting context from the Upper Miocene, what are karst levels recording? A tectonic rhythm with breaks alternating with rapid uplifting? Climatic changes, such as glaciations, which can accelerate base level lowering? Or is it a karst intrinsic step-dynamic? The question of karst level significance is still wide open…

D – LONG SECTION PATTERN CHARACTERISTICS

Mountain system long section patterns show specific features. Except for the well-known vadose zone, many questions arise concerning deep zone genesis.

• Shafts zone

The location of large systems shows that an important topographic gradient already existed in the Upper Miocene, following last alpine orogeny. Large vertical shaft systems were obviously put in place from this period and also before. These systems further evolved by headward erosion making them more complex and by a downward extension of the vadose zone. Invasion vadose shafts cut paleo-drains previously perched [Ford 1977]. Really recent vertical systems are probably uncommon, except in some specific contexts (supra).

• Looping and flooding in the epiphreatic zone

Whether they are active or ancient, cave system organization processes are in the heart of these deep zones. A lot of cave systems harbor subhorizontal conduits, independent of geological structure, undoubtedly organized according to the water table and so-called “water table caves”. Others show successive loops, so-called “looping caves” [Ford 1977]. Some loops can reach several hundreds of meters of magnitude. According to the “Four-state model” [Ford 1977], which is presently the most widely accepted, horizontal drains were put in place along the water table and loops in deep phreatic zone. According to the author, the origin of these different settings would be the jointing intensity that diminishes the resistivity of the rock mass. Strong jointing would allow the establishment of water table flow paths which otherwise would have to “search” at depth for more open joints.

Evidence from at least two unquestioned and generalized field examples contradicts this model:

- loops with the greatest magnitude are precisely located in massifs intensively jointed by overthrusting (Siebenhengste, Tennengebirge…),
- strongly sloped tubes with several hundred meters of height difference and obvious connection with base level located lower than their position could not have evolved in the phreatic zone (Clot d’Aspres in Vercors…).

This led us to foresee another origin for looping caves [Audra 1994, Choppy 1994]. They put in place in the epiphreatic zone during flooding. This means above the water table. They only form during high water when aggressive flow is able to make them evolve. During low water, flow follows shorter paths near the water table’s lowest level. It has been demonstrated that high pressure caused by water table rising is able to generate three-dimensional labyrinths located above low water paths [Palmer 1975].

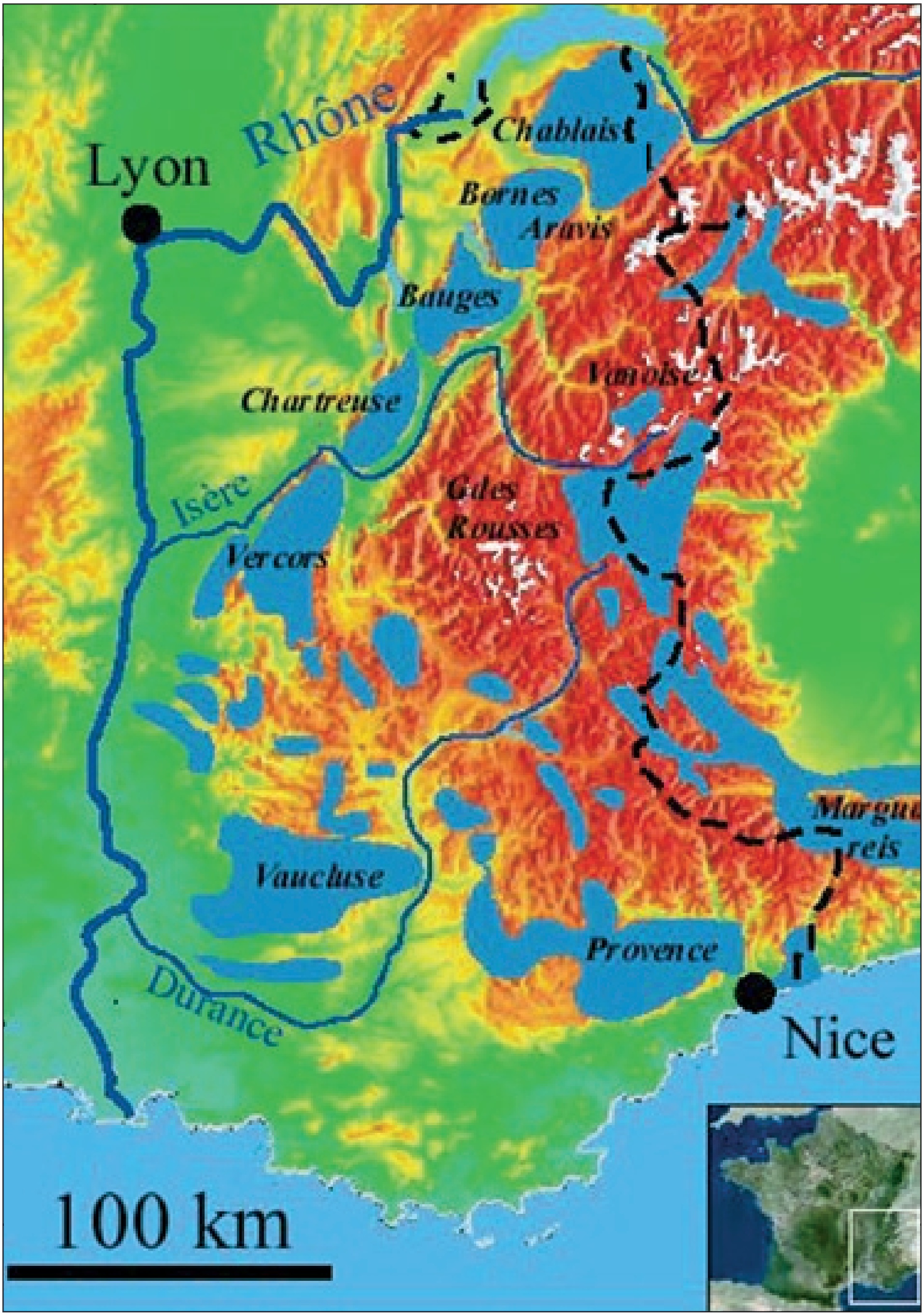

Figure 3: Western Alps. Karst massifs are in grey.

Otherwise, this requires a highly contrasting kind of flow (glacial environment, tropical…). Looping caves would be an indicator of such contrasted flows. More details about looping cave genesis are presented in Häuselmann & al. (2003) and Häuselmann (2002).

• Deep phreatic system are flooded

If cave systems do not initiate in the phreatic zone, there do exist, however, deep phreatic systems, such as the vauclusian springs, more than 100 m deep. Their location in the Western Alps is meaningful [Audra 1997]: none are located in the inner part of the range despite propitious structural conditions. This requires that plunging strata below base level is not a sufficient condition for deep phreatic genesis. All deep phreatic systems are located on the border with a direct connection to the Mediterranean basin, the Rhône River or one of its main tributaries. One cannot consider that karsts located on the border of the range are significantly less jointed. All the more these areas correspond to fault lines or main overthrustings. Very deep base level, located several hundreds of meters lower than the present one, occurred on the alpine range border during Messinian, according to the Mediterranean desiccated deep basin. Vertical vadose systems developed during this period and then flooded after the Pliocene transgression. These conduits had continued across time because they offered flow paths with lower head losses. Evidences observed at such depth, like vadose features or speleothems, are rarely, if ever, present [Audra & al. 2004].

On the contrary, base level oscillations during glacial-interglacial cycles that affected the large alpine valleys were probably too short to cause similar evolution models (supra).

However, some deep phreatic karst system, presently fossil or still active, can develop with hypogenic flow. They were only recently evidenced in the French Alps [Hoblea 1999] and in Provence [Audra & al. 2002]. They display original features and calcite deposits, which allow differentiating them from gravific karst systems.

This conception of karst structures, where base level and its changes play the main role in spite of other factors is innovating. New field research is necessary, particularly in deep phreatic systems, difficult to access. In addition, it would be interesting to test this hypothesis with the present studied karst development numerical models [Dreybrodt in Klimchouk & al. 2000].

III – FIELDS AND RESEARCHERS

A brief account about the present state of knowledge in different areas and fields of study allows us to see results in different domains and regional disparities.

• An important difference in knowledge between the north and the south of the Western Alps

Northern Alps benefited recently from a large number of studies concerning speleogenesis and karst genesis:

- Maire 1990 : Chablais, Haut-Giffre
- Audra 1994 : Vercors, Chartreuse
- Delannoy 1997 : Vercors
- Hobléa 1999 : Chartreuse, Bauges, Savoyian Inner Alps

The Vercors massif is probably the best known, as much by the quantity of large cave systems available for research as by the number of dedicated studies. Other massifs are also well studied, except Bornes that however harbors very interesting large cave systems (Diau, Bunant and Tournette…). Inner Alps study began only recently [Hobléa 1999].

In the Southern Alps, on the contrary, everything remains to be done. In the Dévoluy massif, only hydrology has been studied, with some palaeomagnetism [Audra 1996]. If the Fontaine de Vaucluse catchment area has aroused many hydrogeological studies, no monograph has been dedicated to its cave systems. The Provence, studied by Nicod more than 30 years ago, raises the crucial Messinian problem. In spite of its numerous massifs it benefited from only one study [Martin 1991]. Hypogenic origin for some Provence karst system is under study [Audra & al. 2002]. As regards

Marguareis, it remains virgin, knowing however that the most interesting systems are located on the Italian side.

• Diverse and innovative fields

In addition to the general study of alpine karsts, several people have specialized in more personal field themes, expanding in other areas:

- Ph. Audra : palaeomagnetism, epiphreatic zone, deep phreatic system connected to Messinian event, hypogenic caves
- J.-J. Delannoy : paleostructures, recent dynamic
- É. Gilli : neotectonic, off-shore springs, large underground voids
- F. Hobléa : speleography
- V. Lignet : glacial sedimentology
- B. Lismonde : flow generated features modelling (cave meanders, ceiling pockets)
- Y. Perrette : paleoenvironment reconstruction using speleothem laminas
- R. Maire : non-cohesive cover, high-alpine systems and associated sediments.

Others from outside the region have also done some local studies. Moreover, we did not list the hydrogeologist’s works here, since it does not deal directly with karst genesis.

CONCLUSION

Thanks to the fundamental advances we can re-evaluate some notions of karst- and speleogenesis and elaborate hypotheses for further studies. The important results of geomorphologic studies only add to their success, but other tools will have to be developed to answer new questions. The applying of new dating methods, such as cosmogenic isotopes, is a fundamental way to link together the studied phenomena with environmental setting at each period in karst history. The quantifying of processes in different settings opens new possibilities for the understanding of old processes by using the principle of uniformetarianism. This quantification promises important developments thanks to the monitoring possibilities linked to the development of data loggers and the important information analyses and treatment capabilities of computers.

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PANORAMA DES RECHERCHES ACTUELLES DANS LES KARSTS DES ALPES OCCIDENTALES FRANÇAISES

Résumé

I – L'approche géomorphologique des systèmes karstiques

La karstogenèse dans les Alpes occidentales est abordée par l'analyse systémique selon une approche géomorphologique. Elle s'appuie sur l'immunité karstique qui préserve les anciennes structures de drainage et leurs sédiments associés, enregistreurs des grands événements géodynamiques et des conditions environnementales à l'origine de leur formation et de leur évolution. Les morphologies karstiques, tant superficielles que profondes, se classent en formes à développement horizontal (surfaces planes, karst à buttes, poljés, paléodrains) et verticales (vallées encaissées, systèmes de puits, réseaux ennoyés). Les formes à développement horizontal résultent d'un gradient topographique faible à modéré et durablement stable, qui a favorisé en surface la planation latérale ou l'élaboration de reliefs peu marqués (karsts à buttes) et l'établissement en profondeur de drains horizontaux de grande taille. Les formes à développement vertical sont mises en place lors de brutales modifications du niveau de base. L'abaissement entraîne le creusement des vallées, des systèmes à polypuits. La remontée du niveau de base provoque l'ennoyage des parties profondes avec restitution des eaux sous forme d'émergence vauclusienne. Les formations sédimentaires enregistrent les conditions environnementales contemporaines. Les concrétions sont directement liées à la présence de couverture végétale (biostasie), mais elles peuvent enregistrer des crises avec passage à des conditions rhexistasiques. Les sédiments détritiques correspondent à des contextes d'érosion mécanique prononcée. Il s'agit, selon les cas, d'altérites issues du décapage de paléosols tertiaires, de formations

périglaciaires ou glaciaires. Les varves glacio-karstiques sont déposées lors de mises en charge considérables provoquées par les fusions glaciaires saisonnières. L'étude de l'hydrodynamique permet de caractériser le fonctionnement des zones inaccessibles (système fissural), mais également d'établir le rapport entre ce fonctionnement actuel et les structures de drainage connues, et le cas échéant de faire la part des héritages morphologiques acquis au cours de l'évolution des karsts. Cette approche identifie les principaux acteurs de l'organisation et de l'évolution des structures karstiques, c'est-à-dire les grands événements géodynamiques formateurs (périodes de calme et de surrection tectoniques, oscillations eustatiques) et les conditions environnementales évolutives, l'ensemble permettant de décrypter l'organisation et l'évolution des structures de drainage du karst. L'orogenèse alpine, la régression messinienne et la longue transgression qui suivit, les glaciations plio-quaternaires, rythment l'évolution karstique. L'ensemble débouche sur des reconstitutions karsto- et spéléogénétiques, intégrant les étapes évolutives, la caractérisation des environnements et des processus.

II – Les récents acquis de la recherche

- **La plupart des structures karstiques remontent au moins Miocène supérieur**
  Sur les bases des analyses géomorphologiques, on identifie de vieux systèmes segmentés et décapités anté-miocènes, organisés selon des gradients topographiques modérés. Les réseaux verticaux se développent dès l'orogenèse rhodanienne (5 Ma), dont l'effet sur l'abaissement du niveau de base fut dynamisé par la régression messinienne. La transgression pliocène stoppe cette verticalisation dont le haut niveau de base, stable durant 1,5 Ma, permet le développement des niveaux supérieurs des grands réseaux (Gournier). A partir du Pliocène supérieur, la poursuite de la surrection génère les étages inférieurs.
- **Le rôle limité des processus glaciaires**
  Le rôle prépondérant attribué aux glaciers est réinterprété. L'obturation des vallées et les mises en charge considérables tendent à colmater les parties profondes des karsts par des varves plutôt qu'à générer de nouveaux conduits. La courte durée des bas niveaux de base succédant au recul glaciaire ne permet pas non plus de structuration nouvelle. Dans la zone vadose, l'érosion est effective, mais elle se limite à complexifier par érosion régressive les réseaux existant auparavant.
- **Conditions de structuration et d'évolution des systèmes karstiques**
  Le karst apparaît dès qu'un gradient est présent et que l'aquifère est dégagé de ses enveloppes imperméables. De telles conditions existaient dès la fin du Miocène, ainsi qu'auparavant. Les seuls karsts pléistocènes reconnus se rencontrent dans les Alpes internes, oủ le dégagement des couvertures fut plus tardif. Avec l'abaissement du niveau de base, les aquifères peuvent se fragmenter ou au contraire s'étendre, selon les dispositions topographiques et structurales propres à chacun.
- **Aspect des profils verticaux des réseaux**
  Les réseaux verticaux composés de puits sont anciens et se sont complexifiés au cours du temps. Dans la zone épinoyée, les tubes ondulés (looping caves) ne sont pas interprétées selon la classification de Ford, qui leur attribue une origine noyée profonde, contredite par des faits observés. Ils se sont structurées dans la zone épinoyée, lors des mises en charge, dans un contexte de régime d'écoulement contrasté. Les réseaux noyés profonds, localisés sur la bordure rhodanienne et méditerranéenne, seraient d'anciens réseaux vadoses messiniens ennoyés.

III – Aires et thèmes d’études des chercheurs actuels

Une brève présentation de l’état des connaissances selon les régions et des thèmes d’étude des chercheurs permet de faire le point sur les domaines en cours d’évolution et sur la disparité des études entre le nord et le sud des Alpes occidentales, oů le Vercors apparaît comme l’un des massifs les mieux connus dans l’ensemble de la chaîne