A BRIEF PRESENTATION ON KARST HYDROLOGY AND GEOMORPHOLOGY

Dr. Tran Tan Van
Karst Research Center
Research Institute of Geology and Mineral Resources (RIGMR)
Tel: 84-4-854-3107, Fax: 84-4-854-2125
Email: trantv@hn.vnn.vn

Thai girls dance to celebrate the launching of a water supply system in Son La.

A good look on karst from his mother’s back (Ha Nhi people in Lai Chau).

Dao children in Lai Chau: Heavy load on a simple truck, but ….. No fighting.

Hard work but happy life for these Dao women in Lai Chau, NW Vietnam.

Look again! It seems that only women (the Hoa) work. Where are men?

Does not seem very happy with that. The only man who works for a minute.

While the rest are enjoying their traditional whisky. You can also try later.

CONTENT

INTRODUCTION

- *Karst* is originally the German name of a limestone area in western Slovenia, former Yugoslavia, north-east of the Adriatic Sea;
- It is derived from the Serbo-Croatian word *Kras*.
- Typical “*karst rocks*”:
  - Limestones and dolostones (Ca, Mg)CO_3;
  - Other soluble rocks, e.g. gypsum, anhydrite ($CaSO_4$) and salt (halite, NaCl);
- “*Karst rocks*” result specifically in unique “*karst hydrology*” (karst water) and “*karst geomorphology*”.

INTRODUCTION

This brief presentation aims at:

- Identifying karst features, karst formations and forms in the field, on maps, airphotos, satellite images etc.;
- Understanding karst processes and their factors (especially geological and structural factors, karst hydrology or the interactions between water and its reservoir rock);
- Introducing some environmental impacts specific to karst ecosystem due to its geomorphology and hydrology;
- Introducing speleological studies;
- Arriving at some general recommendations for a wise management of karst water and karst terrains.

INTRODUCTION

The idea behind this presentation is the underground itinerary of water in karst rocks:

- Water has strong ability in forming conduits in karst rocks;
- But conduit morphology (shape, dimensions and orientation) in turn, has very important influence on the water dynamics;

From chemical viewpoint the interaction is also highly reciprocal:

- Water dissolves rocks;
- But the quality of water at each point depends upon the bedrock that was dissolved upstream.

The originality of the karst process is thus in its chemical aspect.

1. NATURE AND CHARACTERISTICS OF KARST AND KARST WATER

- The original point of a *karst circulation* is the chemical process, which enables water to remove rock even without any kinetic energy or mechanical disintegration.
- The general result is that water (even a whole river) tends to disappear, to sink in caves, chasms or canyons, abandoning meanwhile the surface landscape.

1. NATURE AND CHARACTERISTICS OF KARST AND KARST WATER

Karst terrains:

- Very different from non-karst terrains;
- Easily recognizable from airphotos, satellite images, topographic maps and in the field (example).

1.1. Typical karst forms

- Some distinctive forms of karst are pits, caves, closed depressions, solution sculpture etc.;
- None is always present;
- All are specific of the karst circulation/evolution;
- All are related, at some moment of their evolution, with the dissolution action of water.

1. NATURE AND CHARACTERISTICS OF KARST AND KARST WATER

1.1. Typical karst forms (cont')

- *Karren* (in French: *lapies*): Minor dissolution forms of rock sculpture, carved by rainwater or by percolating water;
- *Closed depressions*:
  - *Dolines (sinkholes)* - Small elementary depressions, usually circular;
  - *Uvalas* - Coalesced dolines;
  - *Poljes* - Large, often tectonically-controlled depressions, drained by an effluent river or more often by *ponors* (*swallowholes, "potholes"*).

These enable rainwater or streams to enter karst massives (Plate 2).

1. NATURE AND CHARACTERISTICS OF KARST AND KARST WATER

1.1. Typical karst forms (continued)

- *Blind valley*: A valley that is blocked by some uplifting massive and all flows in it end with a *swallowhole(s)*;
- *Dry valley*: Further downstream, the valley becomes without water, which can cease being dry at a *resurgence* of the swallowed water.

1. NATURE AND CHARACTERISTICS OF KARST AND KARST WATER

1.2. Underground karst water conduits

- *Fissures*: Most elementary, structurally controlled form of a karst net, can be enlarged by water corrosion;
- *Pits*: Generally formed by fast descending water, thus usually the base is wider than the top (due to increase of kinetic energy);
- *Tubes*: Formed by pressure flow, exhibiting thus a nearly circular cross-section.
- *Underground rivers*: Often carry allochtonous sediments:
  - Differ from above by a free upper surface, thus an important interface with cave air;
  - Differ from surface rivers by absence of valley-sides (thus slopedebris) and possible existence of siphons;
- *Phreatic caves*: Formed by rather standing water, incl. *boxwork* and *spongework*, i.e. microforms resulted from fine differential solution, with protrusion of calcite veins (in *boxwork*) or the less soluble parts of bedrock (in *spongework*).

In most caves, *breakdowns* can be very important.

1. NATURE AND CHARACTERISTICS OF KARST AND KARST WATER

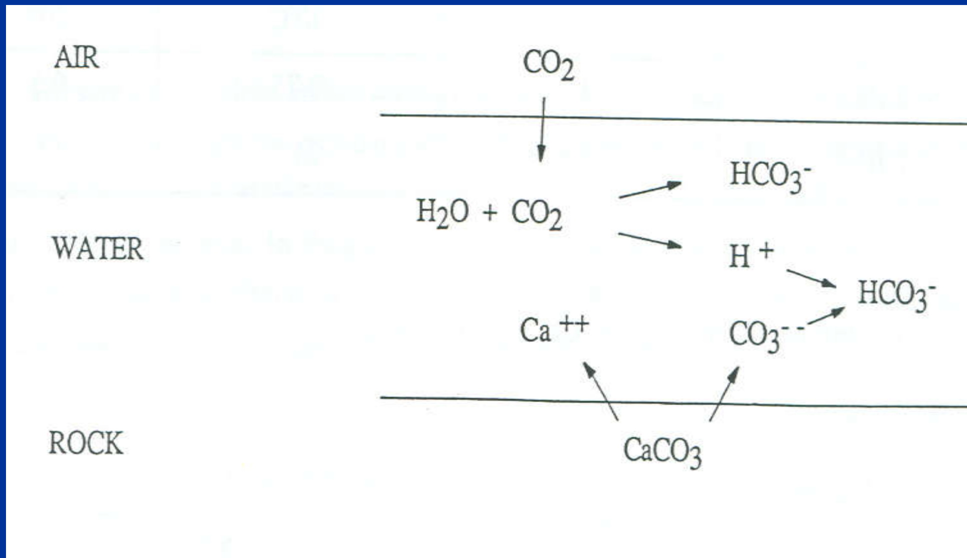
1.3. Water table in karst – some initial discussion

- WALTHAM et al. (1985): Difficult to identify a meaningful water table in karst area because *fissure flow* and *conduit flow* may be independent;
- Existence of underground rivers, with waterfalls and sumps (siphons), indicates traditional "*water table*" doesn't exist in karst (Plate 5);
- Plate 13, Fig.3 - boreholes made, wrong assumption about domed water table beneath crest-line.
- Cavers explored 250 sinkholes. All cave entrances dry in dry season, thus without exploration impossible to assess the presence of water.
- All caves deeper than 150 m displayed some dry-season flow, indicating role of fissure storage, but also role of cave exploration.

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.1. Distinctive characteristics of karst process

2.1.1. Dissolution process and equilibrium



Global reaction: $CaCO_3 + H_2O + CO_2 = Ca\,(HCO_3)_2$

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.1. Distinctive characteristics of karst process

2.1.1. Dissolution process and equilibrium (cont')

Soluble products and equilibrium constants:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \qquad \frac{(H_2CO_3)}{(CO_2)} = 10^{-3}$$

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \qquad \frac{(H^+)\,(HCO_3^-)}{(H_2CO_3)} = 10\ \text{-}7$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{--} \qquad \frac{(H^+)\,(CO_3^{--})}{(HCO_3^-)} = 10^{-11}$$

$$CaCO_3 \rightleftharpoons Ca^{++} + CO_3^{--} \qquad (Ca^{++})\,(CO_3^{--}) = 10^{-9}$$

$$H_2O \rightleftharpoons H^+ + OH^- \qquad (H^+)\,(OH^-) = 10^{-14}$$

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.1. Distinctive characteristics of karst process (cont')

2.1.2. Dissolution of $CaCO_3$ in water containing CO_2

Henry's Law: p CO_2 (air) = D. (CO_2) (water)

Fig.1 - Examples. D varies according to temperature.

p CO_2 (atm)	Solved CO_2 (mg/l)		
	0^0C	10^0C	20^0C
3.10^{-4}	1	0.75	0.5
1.10^{-2}	33	24	17

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.1. Distinctive characteristics of karst process (cont')

2.1.3. Influence of CO_2 on $CaCO_3$ solubility

At equilibrium:

p CO_2 (atm)	Solved $CaCO_3$ in water (mg/l)	
	10^0C	20^0C
3.10^{-4}	±60	±45
1.10^{-2}	±200	±150

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.1. Distinctive characteristics of karst process (cont')

2.1.4. Other acids

Dissolution of limestone can be due to other compounds:

- Inorganic: nitric acid from oxidation of ammonia in soils; sulfuric acid from pyrite or other sulfides in the bedrock etc.;
- Organic: humic and other acids produced by plants or their decay.

2.1.5. Solution kinetics

- Fig. 5 - According to Nernst's Law, a soft water corrodes limestone faster at the beginning than later on.
- Fig. 6 - When two, even saturated waters of different origins, hence different characteristics, mix, a new attack on the rock starts.
- Fig. 7 - Reaction rates increase when temperature rises.

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.1. Distinctive characteristics of karst process (cont')

2.1.6. Dissolution of non-carbonate rocks

- *Halite*: very soluble, more than 300 g/l at normal temperature.
  - Thus halite outcrops are rare, except in arid areas (Jelfa, Algeria).
  - But underground caves in it are not rare (Cardona near Barcelona, Spain);
- *Gypsum and anhydrite*: less soluble than halite but much more than calcium carbonate, approximately:
  - 2.65 g/l for gypsum; and
  - 2 g/l for anhydrite.
  - In Contrexeville (France), thermal springs produce 130 tons of $CaSO_4$ a year from underground;
  - In Belgium, an underground karst in anhydrite was recently discovered at a depth of 2000 m by boring.

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.2. Climatic factors of dissolution and their effects on karst conduits

2.2.1. Flow rate

- Flow rate is the main factor of the enlargement of karst conduits, by both dissolution and mechanical erosion;
- Fig. 8 and 9 show how much more carbonate can be dissolved in a rainy period, compared to a dryer period.

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.2. Climatic factors of dissolution and their effects on karst conduits

2.2.2. Aggressiveness

- The more acid the water, the more aggressive it is towards limestone;
- CO_2 is the main source of acidity (Fig. 2) but not the only one. Thus the use of pH in characterizing aggressiveness (Fig. 3).
- In most underground streams atmospheric CO_2 (3.10^{-4} atm) is only part of the total CO_2. Another part is CO_2 of organic origin.
- Fig. 2 and 3 distinguish "aggressive" from "super-saturated" waters. They show aggressiveness is also related to the content of previously dissolved carbonate. Some waters get saturated in carbonate before they reach limestone hence cannot corrode the latter any more.

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.2. Climatic factors of dissolution and their effects on karst conduits

2.2.3. Temperature

- Temperature inversely affects the D coefficient (Fig. 1):
  - At the same atmospheric CO_2 pressure, the 0°C water dissolves twice as much CO_2 as the 18°C water;
  - But CO_2 is usually much more (1-10 times) abundant in warm regions than in cold ones.
- Temperature enhances the chemical reaction rate:
  - Most reactions are twice as fast at 20°C as at l0°C. Hence, solution in warmer conduits is more favorable (Fig. 7).
- 0°C is an important limit in dissolution:
  - Below it, water freezes and practically does not dissolve any more limestone.

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.3. Action of water on its underground conduits: corrosion versus mechanical erosion

2.3.1. Usual cave evolution sequence

- Dissolution (corrosion) stage;
- Mechanical erosion-transportation stage;
- Breakdown stage.

From a speleogenetic point of view, corrosion is the original, the earliest, and the determining factor of cave evolution.

But, in large conduits, the main morphological features are often not the consequence of corrosion, but the result of physical actions.

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.3. Action of water on its underground conduits: corrosion versus mechanical erosion

2.3.2. Dissolution (corrosion) stage

- Initially there must be some discontinuity surfaces (fissures, cracks, bedding planes, cleavage etc.) in karst rocks, which are generally still rather tight;
- Each contains very little water, whose velocity is thus very low and can not carry away solid particles;
- Thus, dissolution is usually the only process initially.

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.3. Action of water on its underground conduits: corrosion versus mechanical erosion

2.3.3. Mechanical erosion-transportation stage

- In enlarged conduits, water velocities increase and solid transport can occur. The volume of solid material carried away increases with time. Subterranean streams sometimes carry very far into the caves allogenic clastics, silt, sand, pebbles, even garbage;
- In major underground rivers, dissolution can be reduced - even to zero - due to the saturation of water or the poor contact between water and rock. Instead, mechanical transport can become the main - not to say the only - erosion process;

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.3. Action of water on its underground conduits: corrosion versus mechanical erosion

2.3.4. Breakdown stage

- Finally, when water disappears lower or abandon the conduit, breakdown can occur;
- This can become an important, prominent process of cave evolution;
- But it tends to block the cave if alone, i.e. it can last only if the debris are gradually carried away, e.g. by an underground flow, or sometimes by man action.

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.4. Deposits in karst conduits

Deposits can be authigenic, as speleothems and eboulis (fallen blocks), or allogenic, as fluvial sands and pebbles etc.

2.4.1. Authigenic deposits

- Speleothems - most characteristic fills of caves;
- Isotopic studies - information on their age, climatic and botanic conditions during their growth;
- Other analyses (pollens, heavy minerals) - various events that occurred outside during their growth (vegetal evolution, volcanic activities etc.);
- Rockfalls can be studied in terms of their age (through related speleothems), causes (through shapes and dimensions of blocks) and their evolution (through their morphology).

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.4. Deposits in karst conduits

Deposits can be authigenic, as speleothems and eboulis (fallen blocks), or allogenic, as fluvial sands and pebbles etc.

2.4.2. Allogenic fills

- Petrographic analyses of allogenic fills can provide information on the catchment area of cave/conduits;
- Grain-size analyses can report about ancient velocities of the stream. They can also enrich the knowledge of the ancient floods.

2. KARST AND KARST WATER PROCESSES AND FACTORS

2.5. Hard water (HW) versus soft water (SW)

- Karst water is generally hard, containing 300-600 ppm $CaCO_3$;
- When heated above 60°C, carbonate precipitation may occur. This can be prevented by using polyphosphates;
- HW requires higher amount of soap (10 gr/ppm $CaCO_3.m^3$). Synthetic detergents, containing Ca^{++} sequestrate, can solve this;
- Heart diseases and cancer more popular in SW regions (Statistics);
- Thus HW is good for health. In EU, drink water must have no aggressivity and at least 150 ppm of $CaCO_3$.
- If necessary, softening can be applied, but kept to minimum, as:
  - Acidification of water makes it aggressive;
  - Replacement of Ca^{++} by Na^{+}, in some cases, is harmful for health; and
  - Lead-poisoning can be deadly.

3. PHYSICAL BEHAVIOUR OF KARST WATER

3.1. Porosity, permeability, karst-hydrological activity

- Pores can be open or closed. For open pores, one can distinguish:
  - *Total porosity*; and
  - *Absorption capacity* (volume of water that the initially dry rock can absorb);
  - *Specific yield* (volume of water that can effectively flow out of the rock by gravity);
  - *Primary porosity* from *secondary porosity* (e.g. in calcareous sandstones).
- *Fissure porosity* (joints, bedding planes etc., a few mm wide) leads to *hydrological permeability*, with flow velocity not exceeding a few mm/h;
- Widened further by corrosion, fissures can become *karsthydrologically active*. The karst-hydrological activity doesn't necessarily refer to the fast response of a spring to precipitation but to the potentially high velocity of the subterranean flow (often quite rapid, 10-100, even 500 m/h. In Switzerland, a river flows at 500 m/h for about 20 km at average slope of 4 %).

3. PHYSICAL BEHAVIOUR OF KARST WATER

3.2. Origin of water, catchment area

- Karst aquifers originate from several sources:
  - *Rainfall infiltration* through rock/soils;
  - *Subaerial streams* and *condensation water* (Plate 2, Fig. 4).
- *Karst catchment area* can be very different from the topographical connection of surface water divides. Depending on extent of soluble rocks, their dip, and structural factors, it can be larger or smaller.
- Some rivers in karst areas are *suspended* above the so-called water table (the aquifer) and not at all fed by it (e.g. some karst areas of Belgium where caves run a few meters below the surface stream, without being flooded).

3. PHYSICAL BEHAVIOUR OF KARST WATER

3.3. Piezometric surface. Laws of continuity and outflow.

Underground flows include:

- *Seepage water* (gravitational flow with a free surface);
- *Pressure flow* (filling the whole conduit, typically a tube); and
- The *karst water body*, including the whole phreatic zone (BOGLI, 1980).

Piezometric surface of water table is situated at the upper limit of the phreatic zone, where water could rise under its piezometric head.

3. PHYSICAL BEHAVIOUR OF KARST WATER

3.3. Piezometric surface. Laws of continuity and outflow.

Karst water should be considered in dynamics terms, with two main laws of continuity and outflow:

- *Law of continuity*: $Q = \Delta V/t$

where Q = flow rate, ΔV = volume, t = time, v = velocity;

- Consider a stream flowing through two different sections A_1 and A_2 of a conduit:
- $Q_1 = A_1.v_1$; $Q_2 = A_2.v_2$; $Q_1 = Q_2$;
- $A_1.v_1 = A_2.v_2$; and $v_1/v_2 = A_2/A_1$

3. PHYSICAL BEHAVIOUR OF KARST WATER

3.3. Piezometric surface. Laws of continuity and outflow.

- *Law of outflow*: $mv^2/2 = mgh$, or $v = \sqrt{2gh}$

where h = head difference between 2 points of interest.

- If velocity increases above 1 m/s, *friction* becomes significant, causing loss of pressure and warming of water, and v will be increasingly lower than calculated from this formula.

3. PHYSICAL BEHAVIOUR OF KARST WATER

3.4. Structural influences on karst conduits and karst evolution

- Structure (joint sets, bedding planes etc.) has a striking influence on the location and direction of karst conduits (example);
- Joint sets sometimes provide more favorable routes for water than bedding planes, because:
  - They often have steeper slope, thus favour higher velocity of water;
  - They are often more opened than bedding planes;
  - Their surfaces are often cleaner (example).
- Impressive galleries can develop along faults, but the latter can also limit karst circulations.

4. STRUCTURE AND WORKING OF KARST AQUIFERS, SPRINGS AND RESURGENCES

4.1. Structure of karst aquifer

The underground karst network comprises 3 zones (Plate 8) i.e. zones of absorption, vertical transfer and horizontal flow.

- *Absorption zone* contains 5-50% voids, where the classical formula applies:

$$P = E + R + I \qquad (1)$$

- On bare limestone, rock permeability at/near ground surface can be so high that *surface run-off* and *evaporation* become insignificant. Formula (1) reduces to:

$$P = I \qquad (2)$$

- When there is a soil layer on top of limestone formula (1) may become:

$$P = E + R + I \pm \Delta r \qquad (3) \qquad \text{(SCHOELLER, 1967)}$$

Where Δr is the deficit (+)/excess (-) of water that is retained in vegetation, soil voids/fissures, and/or ponded at ground surface. In dry season, Δr takes increasing positive value.

In some cases, the permeable absorption zone transits abruptly into the underlying less permeable rock. The transition zone can get saturated, forming the sub-superficial, or epikarst aquifer (Plate 8, fig. 2).

4. STRUCTURE AND WORKING OF KARST AQUIFERS, SPRINGS AND RESURGENCES

4.1. Structure of aquifer (cont')

- *Zone of vertical transfer (vadose zone)*
  - Steep slopes;
  - Sometimes crossing ancient horizontal channels.
- *Zone of horizontal flow*. This zone is situated at (and just below) the limit of the saturated zone. It can include an underground river.
- In each zone the water exists both as flowing through conduits and filling the surrounding rock blocks.
  - K in conduits is much greater than in blocks. Conduit flows are sometimes very rapid, around 0.1 m/s, i.e. 360 m/h;
  - However, rock blocks contain much more water, i.e. water in blocks accounts for a much greater portion of the total reserve.

4. STRUCTURE AND WORKING OF KARST AQUIFERS, SPRINGS AND RESURGENCES

4.2. Working of karst aquifer

- Karst aquifer functions as a *piston flow.* During floods, the first water reaching springs is the old, previously stored water. Then comes the freshly infiltrated water (seepage on channel walls);
- During maximum floods, water from conduits, in turn, feeds the surrounding rock blocks;
- During low water, water will be drained from rock blocks back to cave conduits.
- The difference in void sizes leads to the so-called theory of "*double porosity*". It results in the difference in permeability:
  - About 10^{-2}-10^{-3} m/s in conduits; and
  - About 10^{-6}-10^{-7} m/s in blocks.
  - ATKINSON (1985) even proposes to classify karst aquifers into 3 types corresponding to 3 sets of permeability (Plate 10).

4. STRUCTURE AND WORKING OF KARST AQUIFERS, SPRINGS AND RESURGENCES

4.3. Hydrographs

- Main parts of a classical hydrograph (Plate 9, fig. 2).
- Many curve-fitting equations, one most classically accepted is: $Qt = Qo.\ e^{-\alpha t}$

  where: α - the semi-log discharge slope or drying-up coefficient.
- In karst, however, one must distinguish water from reserves and the one from rapid infiltration during floods.

$$Qt = Qo\ res.\ e^{-\alpha t} + Qo\ fl\ .\ f$$

Where: Qo res - Initial flow rate of water from reserves of rock blocks;

Qo fl - Initial flow rate of the rapidly infiltrating flood water;

f - Function of infiltration velocity and infiltration amount.

- Hydrographs sometimes show, e.g. that some slight rains has no response at all, while some heavy rains have direct and important response.
- Plate 11: (DODGE, 1985) shows the relationship between the hydrographs of 3 springs and structure and permeability of corresponding aquifers.

4. STRUCTURE AND WORKING OF KARST AQUIFERS, SPRINGS AND RESURGENCES

4.4. Springs

Springs can be classified according to various characteristics:

- *Outflow*: Perennial spring, periodic spring, rhythmic (intermittent) spring etc.;
- *Structural conditions*: Contact spring, bedding spring, fracture spring, overflow spring, vauclusian spring etc.;
- *Origin of water*: Resurgence (re-appearance on ground surface of a river after disappearing underground), exsurgence (spring form a local aquifer, autochthonous water), emergence (any of these cases).

Discharge of karst spring is often high, because of:

- concentration of water in main, structured channels underground;
- fast infiltration, reducing the losses by E and R in the formula:

$$P = E + R + I$$

- Some big karst resurgences: Tobio (Papua New Guinea) 100 m^3/s (FORD & WilLIAMS, 1989); Buna (Yugoslavia) 40 m^3/s; max. 400 m^3/s; Vaucluse (France) 30 m^3/s; max. 150 m^3/s.

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.1. Aims and purposes

- Disappearance of streams in karst areas always intrigues man since ancient time;
- Hay, sawdust etc. have been tried for studying this phenomenon;
- Nowadays, tracing technique is very popular in karst hydrology:
  1. To determine if there is a connection between two sites, most frequently between a sinkhole and a spring;
  2. To delineate a karst drainage area, by tracer injection at different points;
  3. To determine directions of groundwater flow;
  4. To study other flow characteristics, e.g. flow rate, flow velocity etc., by measuring time and establishing a quantitative dye recovery vs. time curve;
  5. To identify pollution source, rate of pollution transmission etc.

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.2. Tracers

FORD & WILIAMS (1989) provide the most complete classification of tracers:

- *Natural tracers*: Ions in solution, naturally occurring isotopes, micro-organisms;
- *Artificial tracers*: Dyes, salts, spores, radio-isotopes;
- *Pulses*: Natural and artificial pulses.

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.2.1. Natural tracers

- Some natural properties or components (e.g. salts, radioactive elements, stable isotopes, micro-organisms etc.) of water can be used to identify it;
- This method is very elegant and advantageous because it helps eliminate:
  - Cost of an artificial tracer; and
  - The possible pollution of water by this tracer.
- These tracers are found by chemical, isotopic or micro-biological analysis of water;
- Natural isotopes can be radioactive or non-radioactive, e.g. ^{3}H (Tritium, with 12 years half-life) and ^{14}C (with 5730 years half-life);
- Stable isotopes include D (^{2}H), ^{18}O and ^{16}O etc. The proportions of D/H and $^{18}O/^{16}O$ can be measured by mass spectrometry;
- Micro-organisms are frequently present in karst water and can be used to identify water sources.

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.2.2. Artificial tracers

5.2.2.1. Dyes

- *Fluorescent dyes*: Most used tracers. Many different types, some are easy to use and not too expensive;
- Consider only non-toxic tracers (very low, even inexistent content of toxicity, incl. carcinogenic and mutagenic hazards), i.e. *Fluorescein Sodium*, *Rhodamine WT* and *Tinopal CBS-X*, a fluorescent brightener (SMART, 1984).
  - *Fluorescein Sodium* ($C_{20}\ H_{10}\ Na_2\ O_5$): An orange powder giving, when strongly diluted, a fluorescent green color to water. The most used tracer, detectable with naked eyes by concentrations of 1 µg/l (1 mg/m^3);
  - *Rhodamine WT* ($C_{28}\ H_{31}\ N_2\ O_3\ Cl$): A red dye;
  - *Fluorescent brighteners*: Colorless under normal light (no water coloring occurs, thus advantageous), but can be detected similarly as fluorescein.
- All these tracers can be used together, using fluorometric separation. This allows to trace several possible flow paths at the same time.

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.2.2. Artificial tracers (cont')

5.2.2.1. Dyes (cont') - Evaluation of three usual fluorescent tracers

	Fluorescein Sodium	Rhodamine WT Colorless	Optical Brighteners
Color	Green	Red light	Colorless u. normal
Passive detector	Activated charcoal 6-14 mesh	Activated charcoal 6-14 mesh	Unbleached cotton
Test (elutriant)	Ethyl alcohol and 5 % KOH Visual test or fluorometer	Ethyl alcohol and 5 % KOH Fluorometer	Visual examination under U-V light.
Maximum excitation and emission nm	485 515	550 580	360 435
	above figures (particularly excitation) are not necessarily exact		
Advantages	Visual test possible. Inexpensive.	Photochemically stable.	No coloring of water. Inexpensive.
Disadvantages	Photochemically instable. Moderate adsorption on clay. May lose fluorescence below pH 5	Requires a fluorometer. Moderate adsorption on clay.	Background readings may be high. Adsorption on organics.

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.2.2. Artificial tracers (cont')

5.2.2.2. Salts

- *Sodium chloride (NaCl)*: A non-toxic, particularly cheap tracer;
- Detected by chemical analysis or by conductivity;
- Huge quantities are needed (hundreds of kg, even several tons), especially when background content or conductivity is high;
- It is, however, useful where dyes are excluded (e.g. because of fluorescence background conditions);
- Other salts are also used, such as lithium chloride (LiCl) and potassium chloride (KCl).

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.2.2. Artificial tracers (cont')

5.2.2.3. Spores and yeast

- *Spores (e.g. that of club moss, Lycopodium)*: Can be dyed in 6 different colors, thus allow 6 injection sites in one test;
- Small (app. 30 µm in dia.), can drift even in narrow karst conduits;
- Recovered by nylon plankton nets at recovery sites;
- Need adapted, elaborated equipment and time-consuming techniques, but allow complex and refined operations;
- Do not affect color of water, and vice versa, not affected by pollution.
- *Yeast*: Inexpensive and non-toxic, used recently. Its cells are app. 2-3 µm (same size as many bacterias), thus useful for testing bacterial pollution problems.

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.2.2. Artificial tracers (cont')

5.2.2.4. Radio-isotopes

- *Radio-isotopes tracers*: ^{82}Br, ^{35}S and others, but not ^{3}H (too long half-life decay cycle);
- *Of concern*: Possible toxicity. Post-sampling activation analysis is thus proposed to overcome;
- This requires, however, sophisticated equipment and procedure, incl. irradiation by neutrons in a nuclear lab.;
- *Main disadvantages*: High cost, hazard and sophisticated handling;
- Although being non-toxic, this method should generally be avoided for health and psychological reasons.

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.2.3. Pulses

- *Flow pulses (e.g. change in discharge)*: A storm, a sudden snow melt, the break-down or release of water from a reservoir;
- FORD & WILLIAMS (1989) classify natural and artificial pulses;
- Discharge pulses travel much faster than the water flow itself:
  - *Pressure pulse*: Through completely flooded conduits, the discharge wave is almost instantly transmitted;
  - *Kinematic wave*: Through vadose, thus aerated conduits, the flood wave will be quickly but not instantly transmitted;
- If more than one tributary (or sinkhole) provide a discharge pulse, the two (or more) input pulses will combine to give a complex output pulse (Plate 16, fig. 26).

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.2.3. Pulses (cont')

5.2.3.1. Natural pulses

- EK.C. (1969) described a natural pulse caused by an exceptionally heavy storm on July 23rd, 1963 at Remouchamps Cave (Belgium). The underground river overflowed all its gauges. No flow rate record could be established except temperature, alkalinity and hardness at every 2 hours intervals;
- Records show:
  - 3 hours after the storm started, a warm, much softer rainwater pulse invaded the cave;
  - 3 hours later, two successive pulses of hard water from the old stock followed (Plate 16, fig. 27);

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.2.3. Pulses

5.2.3.2. Artificial pulses

- *Artificial pulses*: Generated by building small temporary dams or dumping several cubic meters of water from tank trucks;
- *Much larger pulses*: Generated by water releases from big dams;
- WILLIAMS (1977) using this technique in the Zakaka Valley (New Zealand), showed by cross-correlation analysis that the induced flood waves traveled about 35 km in 15 hours;
- The Tritium (^3H) content of the spring suggests a minimum flow through time of 2-4 years.
- Pulse analysis can thus demonstrate connections over long distances through large flooded zones.

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.3. Test design and procedure (Jones, 1984)

- For the dyes considered above, the minimum detectable concentration is about *1.0-0.1 ppb*, depending on background, turbidity, equipment etc.;
- When *Fluorescein Sodium* is used, the amount to be injected can be calculated using the empirical formula of ALEY & FLETCHER:

$$W = 1.478\ (DQ/V)^{0.5}$$

Where:

- W - weight of the fluorescent dye (kg);
- D - straight line distance (km);
- Q - discharge (m^3/s); and
- V - estimated velocity (m/h).

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.3. Test design and procedure (cont')

- Gather all existing hydrogeological and hydrological information;
- Explore and map carefully all geological and hydrogeological features (faults, sinkholes, dolines etc.);

Cautions:

- Simplify whenever the problem is simple;
  - Don't use sophisticated techniques where sawdust is enough;
  - Don't inject two dyes where one is sufficient;
  - Don't use dyes where natural tracers can work;
- Try to avoid the appearance of dye in a water supply intake or in a surface stream; and
- Authorities should be aware of.

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.3. Test design and procedure (cont')

- Dilute the dye to a concentration of 1/10 before pouring;
- To prevent contamination, before testing place passive detectors of:
  - Activated charcoal in small plastic window screening bags (for fluorescein and rhodamine); or
  - Unbleached cotton sheets (for optical brighteners);

Caution: Change these detectors (if periodically needed) only by people who are not yet in contact with the dye.

- Analyze:
  - Charcoal detectors under sunlight and in a filter fluorometer, using the fluorescein filter combination; and
  - Cotton detectors under hand-held U-V lamp.

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.3. Test design and procedure (cont')

Caution:

- Negative tests do not necessarily signify there is no connection between injection and detection points;
- Negative tests can sometimes result from one of the following conditions:
  - Too slow motion of water, particularly during low water period;
  - Extreme dilution of dye, particularly during flood period;
  - Adsorption of dye by clay or other organic matters;
  - Hiding of dye by an excessive background; etc.

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.4. Interpretation of quantitative tracing tests

For quantitative interpretation, as frequently as possible during the whole period of dye recovery at every concerned site, one should:

- Use calibrated fluorometer to record the amount of tracer recovered;
- Measure discharges; and
- Establish dye recovery curve for each site (Plate 17, fig. 28).

The total amount of dye recovered at each site is given by:

$$W = Qo\ Cdt$$

Where:

- *W* is the weight of pure dye recovered;
- *Q* is the discharge; and
- *C* is the dye concentration at the sampling site at time *t* (JONES, 1984).

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.4. Interpretation of quantitative tracing tests (cont')

Notes:

- No tracer can be 100 % conserved between input and output. Part of the dye is always lost, increasingly with testing time, by adsorption on clay or organic matter, by photochemical decomposition or by precipitation;
- Underground dye recovery curves are frequently influenced by unknown factors: successive vadose and phreatic flows, unknown inputs or outflows, anastomoses, etc.;
- The curves reflect:
  - Conduit network pattern;
  - Flow type, conditions, and variations during the test; and
  - Adsorption and dispersion characteristics of the tracer (Fig. 29, 30).

5. WATER TRACING TECHNIQUE IN KARST HYDROLOGY

5.5. Concluding remarks on tracing tests

- Water tracing is a powerful tool in karst hydrology, but it requires careful collection of available data about structure, hydrology, geomorphology, climate, etc., of the concerned catchment area;
- Natural tracers/pulses should be used first and as much as possible;
- If artificial tracers/pulses are required, the qualitative aspect of connection should be solved first. Attention should be paid to possible environmental impacts. Dyes and salt are the easiest-to-use and safest products;
- If a quantitative tracer test is needed, it should be carefully planned in terms of personnel, knowledge, equipment, procedure etc.

6. SPELEOLOGICAL STUDIES

6.1. Single rope technique (examples)

6.2. Cave mapping technique (example)

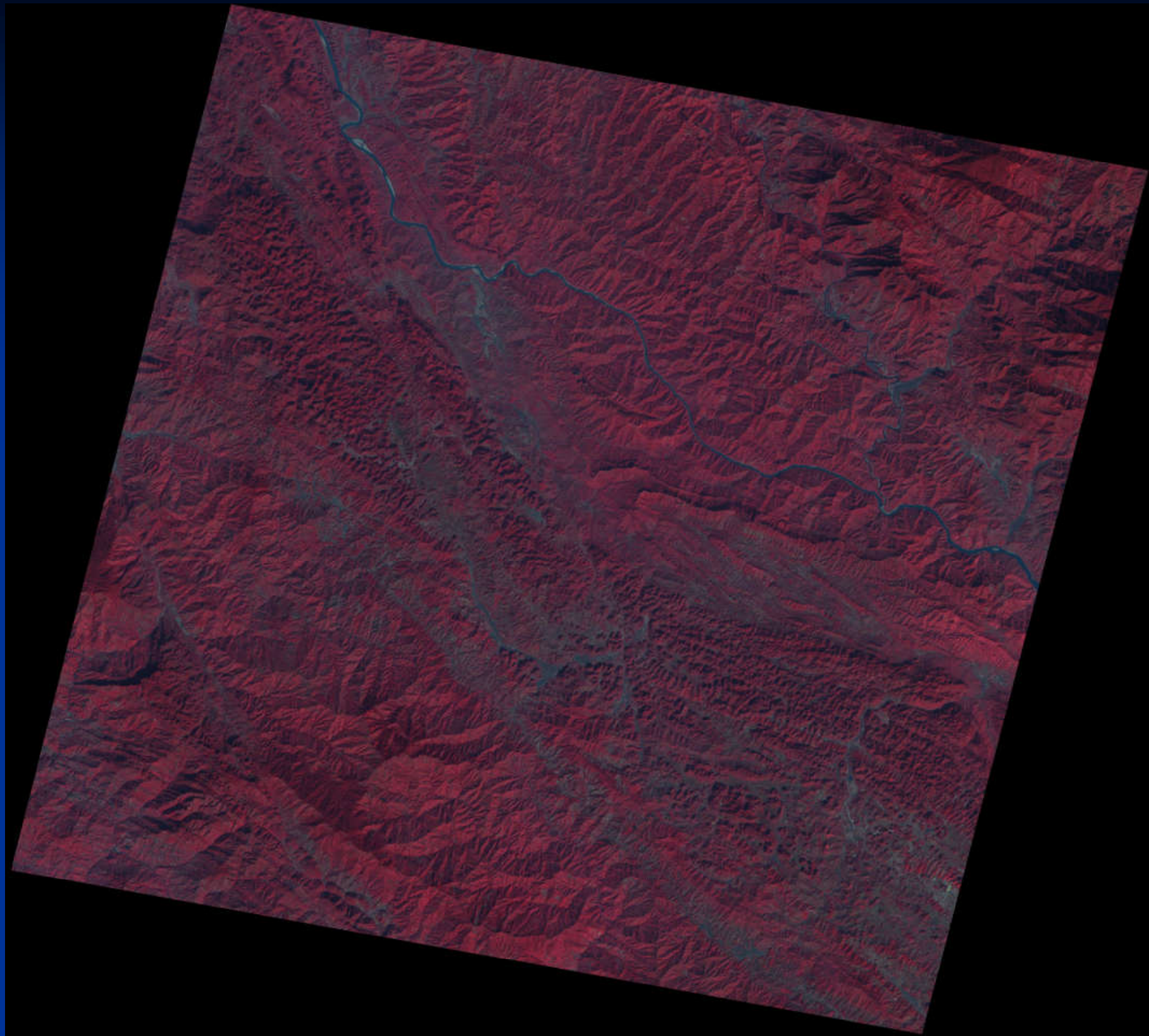
6.3. Speleological studies in Vietnam

7. SOME ENVIRONMENTAL IMPACTS SPECIFIC TO KARST ECOSYSTEM - A FEW CONCLUSIONS/RECOMMENDATIONS

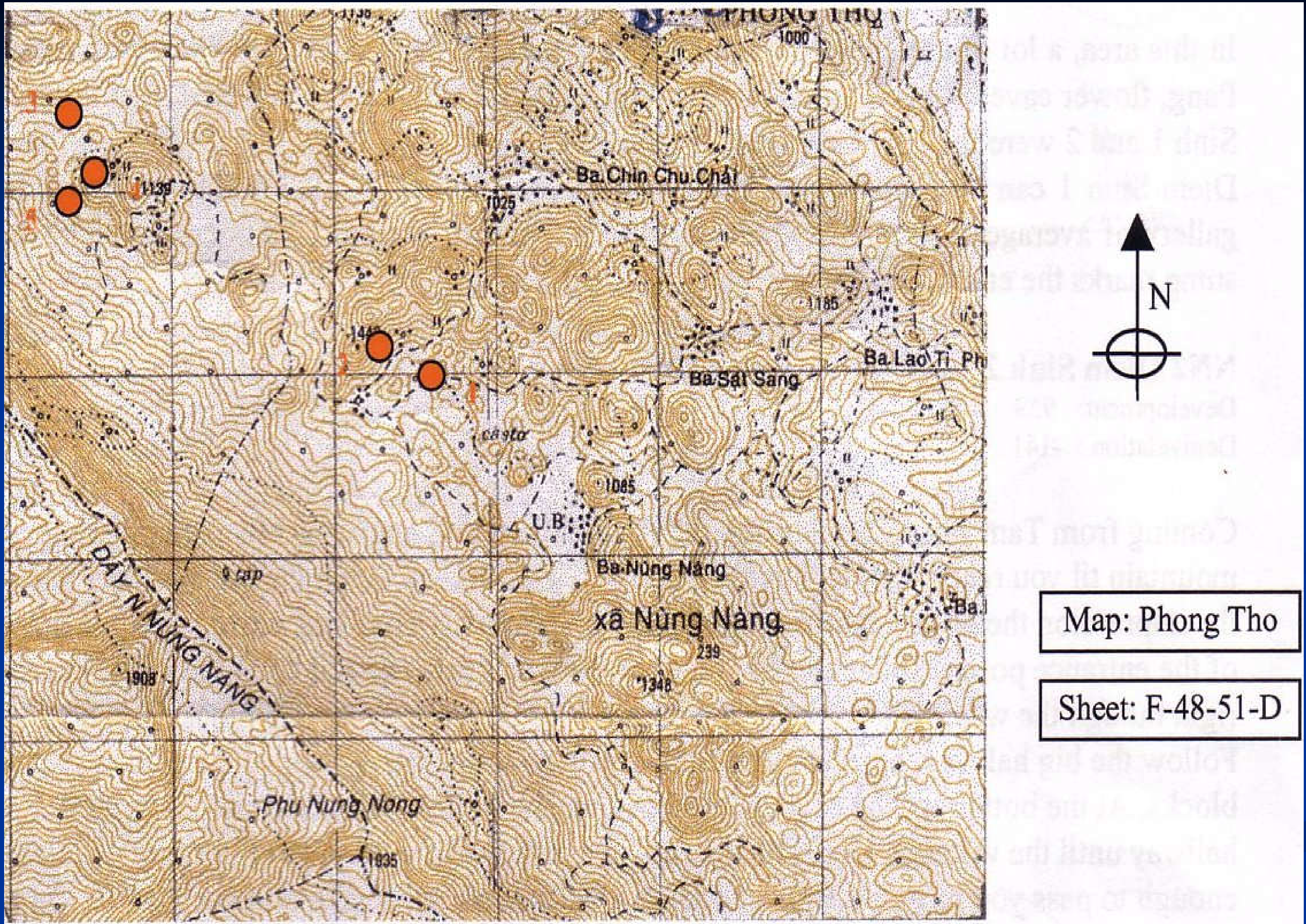
- The original nature of karst is the chemical action of water on soluble rocks;
- Karst hydrology and morphology (underground drainage and superficial features) are very interrelated and cannot be studied separately;
- Seemingly dry on the surface, karst areas can contain important and accessible water reserves underground;
- The so-called “double space” or “double porousity” of karst indicates high transmissivity of this medium, which is also source of pollution problem;

7. SOME ENVIRONMENTAL IMPACTS SPECIFIC TO KARST ECOSYSTEM - A FEW CONCLUSIONS/RECOMMENDATIONS (*cont'*)

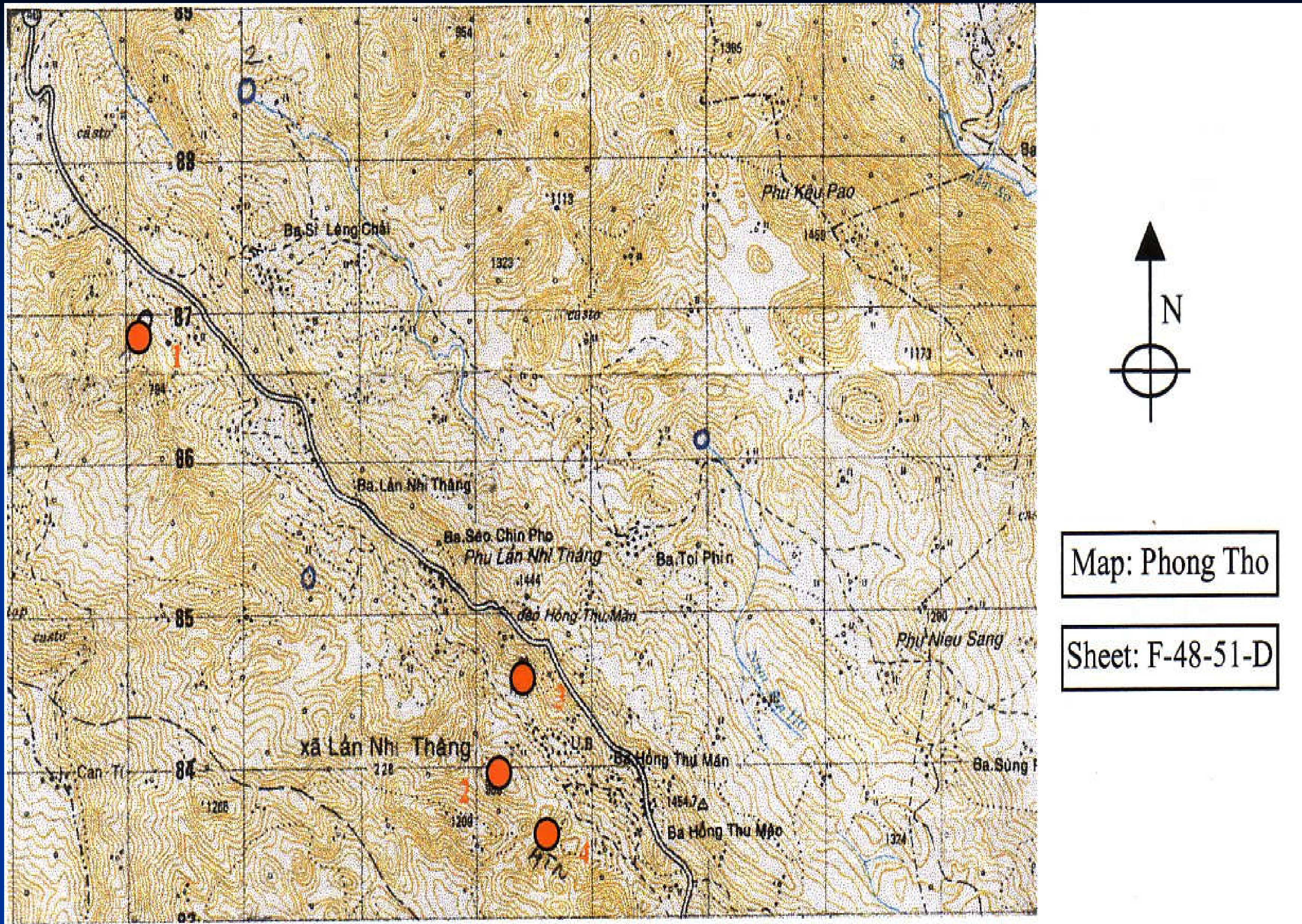
- Natural and human factors (variations of piezometric surface, instability of cave roofs, excessive pumping, civil works, soil fertilization, forest fire or intentional destruction etc.) are among causes of many hazards in karst areas (breakdown, subsidence, flood, aquifer pollution, drying-up of water resources etc.);
- Development and conservation activities in karst areas should, therefore, be carefully planned and preceded by detailed and systematic studies;
- Karst hydrology and geomorphology indicate that arable land in karst areas is very scarce. Self-reliant agriculture alone is not viable;
- But its unique features also suggest that alternative ways for development and conservation are available, e.g. geopark and geo-tourism.



A karst range in the middle of a SPOT image of Northwest Vietnam.



A karst and non-karst terrain on a topographic map of Northwest Vietnam.



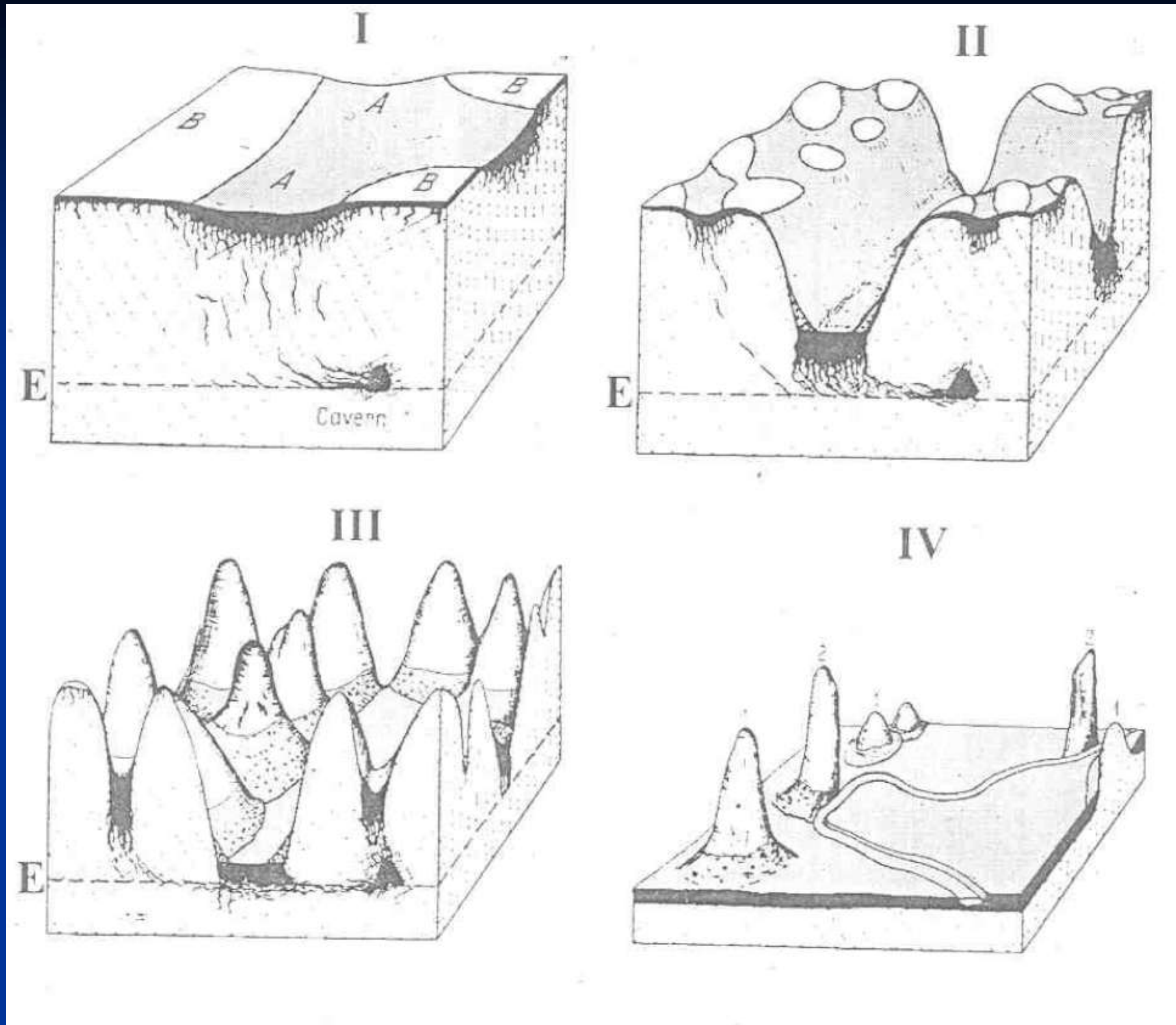
Another example of karst and non-karst terrain on a topographic map.

Karst range and non-karst landform in Bac Son Commune, Tan Lac District, Hoa Binh Province.

A typical karst field.

And how they look like in the field – peak cluster karst (pyramid karst form).

And how they look like in the field – peak cluster karst (pyramid karst form).



Evolutional stages of a karst terrain.

A typical II stage karst landform in Dong Van area, Ha Giang Province.

II-III stages of karst landform in Tam Duong area, Lai Chau Province.

IV stage – relict karst field in Quan Ba District, Ha Giang Province.

IV stage – relict karst field in Tan Lac District, Hoa Binh Province.

Typical karren in Triassic limestone.

Another look at karren.

A sinkhole in Triassic limestone range in Tam Duong area, Lai Chau Province.

Another sinkhole in the same area, Lai Chau Province.

A series of sinkholes (or uvala) in Ngo Luong area, Hoa Binh Province.

Another look at uvala in the same area.

And another look at uvala in the same area, Hoa Binh Province.

A polje in Carboniferous limestone in Tua Chua area, Lai Chau Province.

Another polje in Carboniferous limestone in Tua Chua District, Lai Chau Province.

A blind valley with swallowholes at its end in Triassic limestone range in Thuan Chau area, Son La Province.

A resurgence point in Triassic limestone in Tam Duong area, Lai Chau Province.

A very big resurgence point in Ban Mu Village, Tu Do Commune, Lac Son District, Hoa Binh Province.

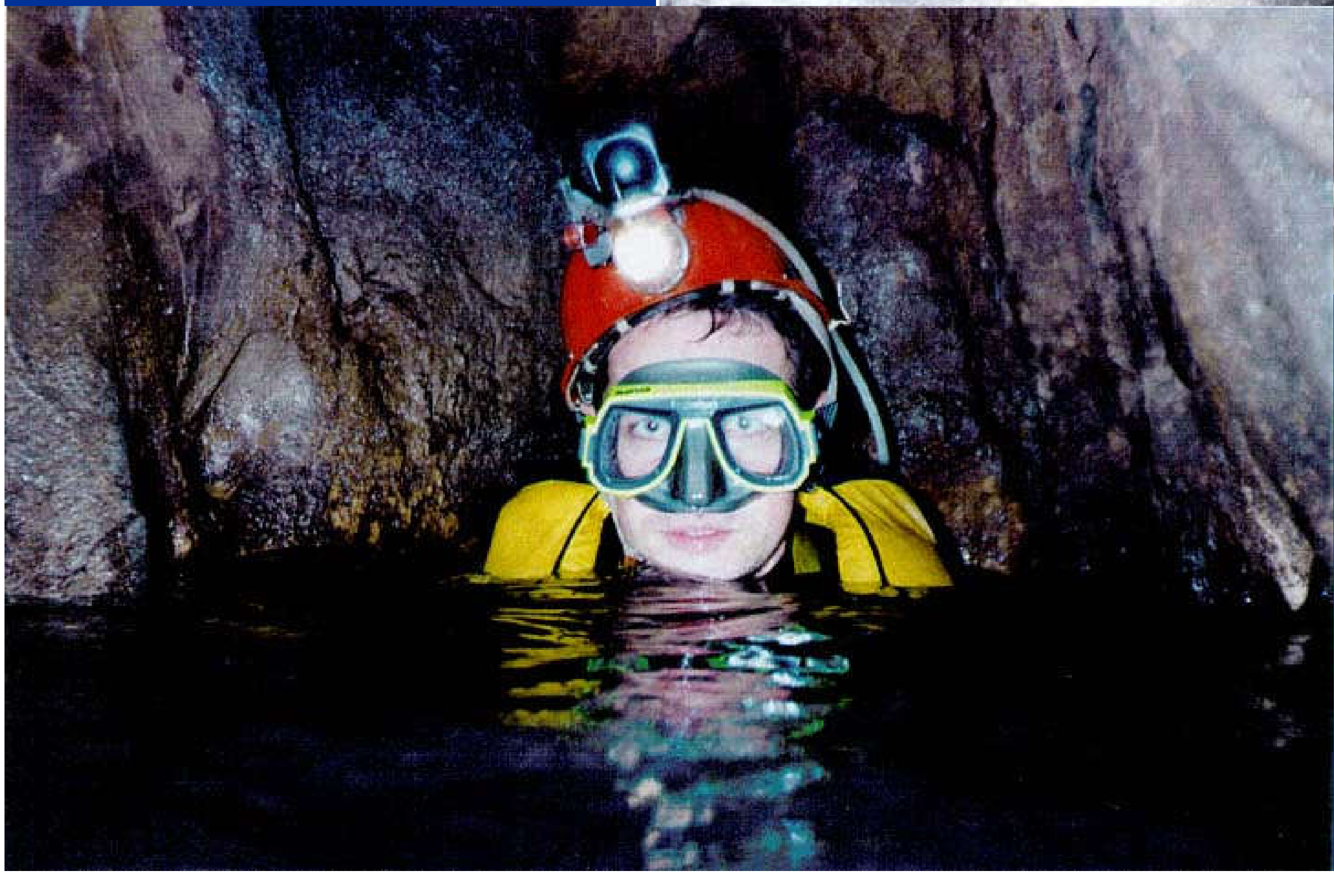
Another resurgence point at Lang Lua cave in Pu Luong Nature Reserve. Enough water to think of an irrigation system.

Measuring a joint set in Triassic limestone in Tam Duong area, Lai Chau Province.

9 Measuring another joint set in Triassic limestone in Bac Son Commune, Tan Lac District, Hoa Binh Province.

A very big vertical pit (110 m deep, 20 m in dia.) - Cang Ti 2 cave in Carboniferous limestone in Tua Chua District, Lai Chau Province.

A surface river disappearing into underground in Triassic limestone in Son La Province.



Another underground river.

A series of folds in Devonian limestone on the way to Meo Vac District, Ha Giang Province.

An overview of a very big anticline in the same limestone.

39

A closer look at the bedding planes in Devonian limestone on the way to Meo Vac District, Ha Giang Province.

A fold in Triassic limestone in Tam Duong area, Lai Chau Province.

A karst spring at the crest of an anticline in Triassic limestone in Tam Duong area, Lai Chau Province.

Solid transport in Cang Ti 2 cave in Carboniferous limestone in Tua Chua District, Lai Chau Province.

Breakdown in Sin Chai cave in Carboniferous limestone in Tua Chua District, Lai Chau Province.

SOLUTION OF CALCIUM CARBONATE

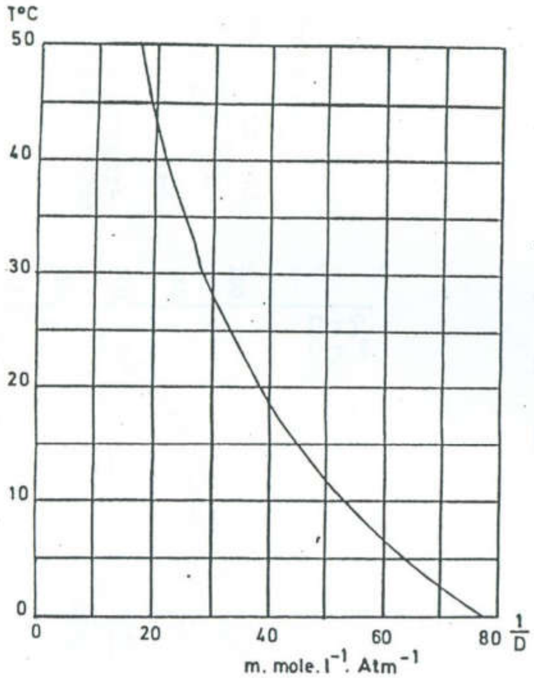


FIG. 1

Dissolution coefficient 1/D of CO_2 in water (according to H.ROQUES, 1962)

$$(CO_2)_w = \frac{pCO_2}{D}$$

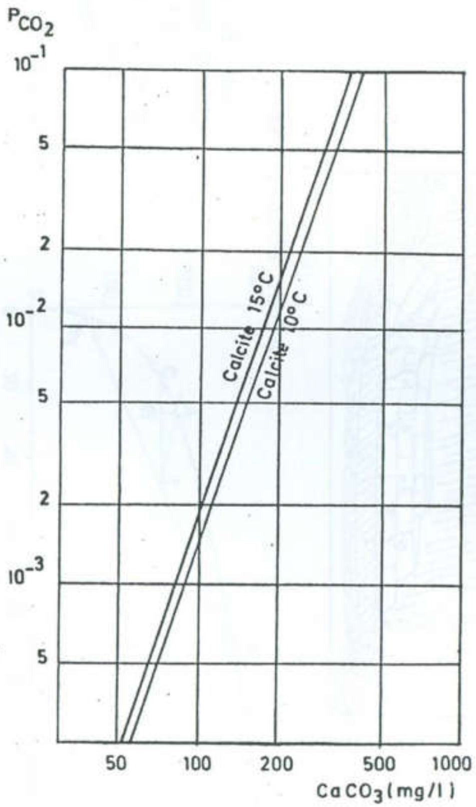


FIG. 2

Equilibrium pCO_2 versus amount of solved $CaCO_3$ (according to H.ROQUES, 1964)

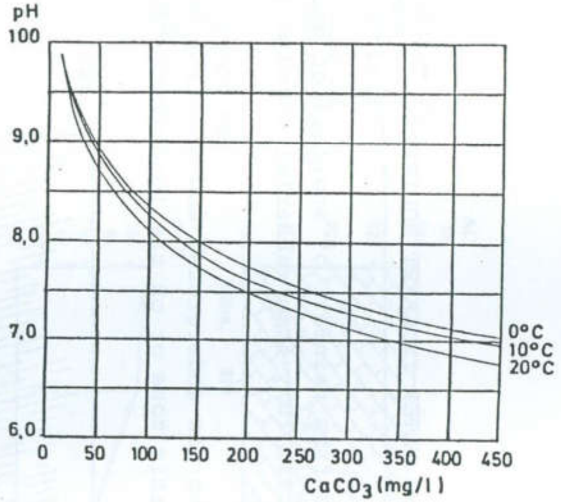


FIG.3

pH versus $CaCO_3$: equilibrium curves (TILLMANS, 1932, slightly modified).

PLATE 1

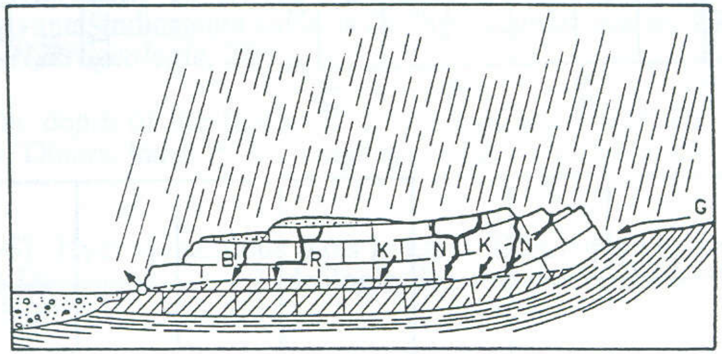
PLATE 2

FIG. 4

ORIGIN OF THE WATER IN KARST AQUIFERS

Karst water comes from rainfall or snowfall on bare limestone (N), or on soil (B), from subaerial streams (G) and condensation water (K).

All the components mix underground and are finally collected in the phreatic zone or on the impervious "floor".



after BÖGLI, 1980

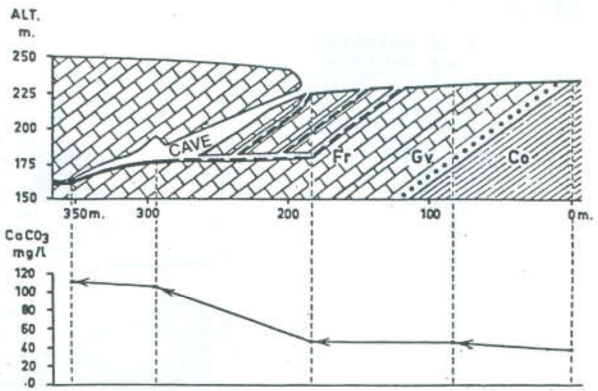
FIG. 5

The swallowhole of Rouge-Thiers at Louveigné (Belgium)

Above: profile of Rouge-Thiers Creek and geological section.

Below: evolution of the hardness of the water.

(EK, 1969)

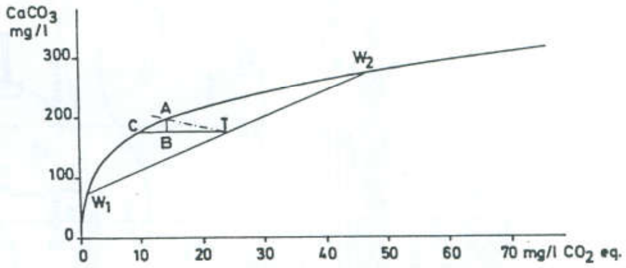


According to Nernst's Law, a soft water corrodes limestone faster at the beginning than later on.

FIG. 6

Mixture of two saturated waters, W_1 and W_2. The result is a water T, not saturated.

(after BÖGLI, 1964)

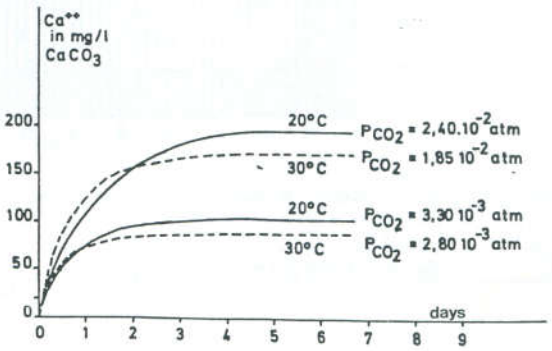


Mixture of two saturated waters results in an under-saturation and a new attack on karst rocks.

FIG. 7

Solution rate of calcite. Experiments at 20 and 30° C, and under CO_2 pressures of approx. 2.10^{-2} and 3.10^{-3} atm.

(after T.STCHOUTZKOY-MUXART, 1971)

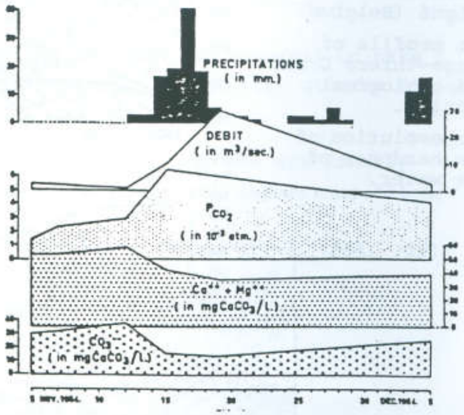


Reaction rates increase when temperature rises.

FIG. 8

Influence of rainfall
on the river Amblève
at Pont-de-Scay (Belgium)

(C. EK, 1969)



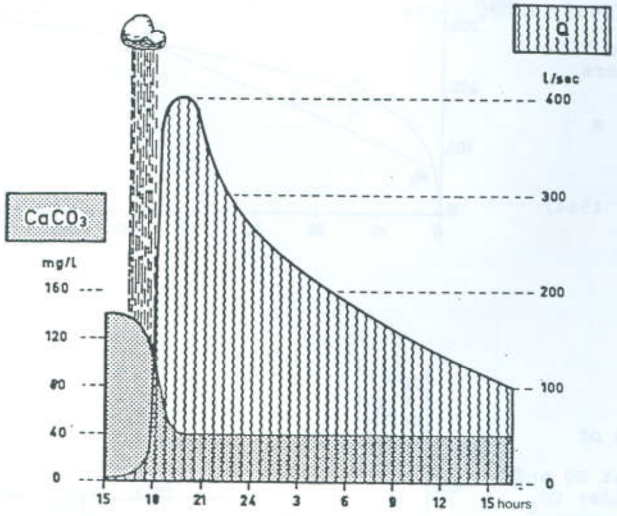
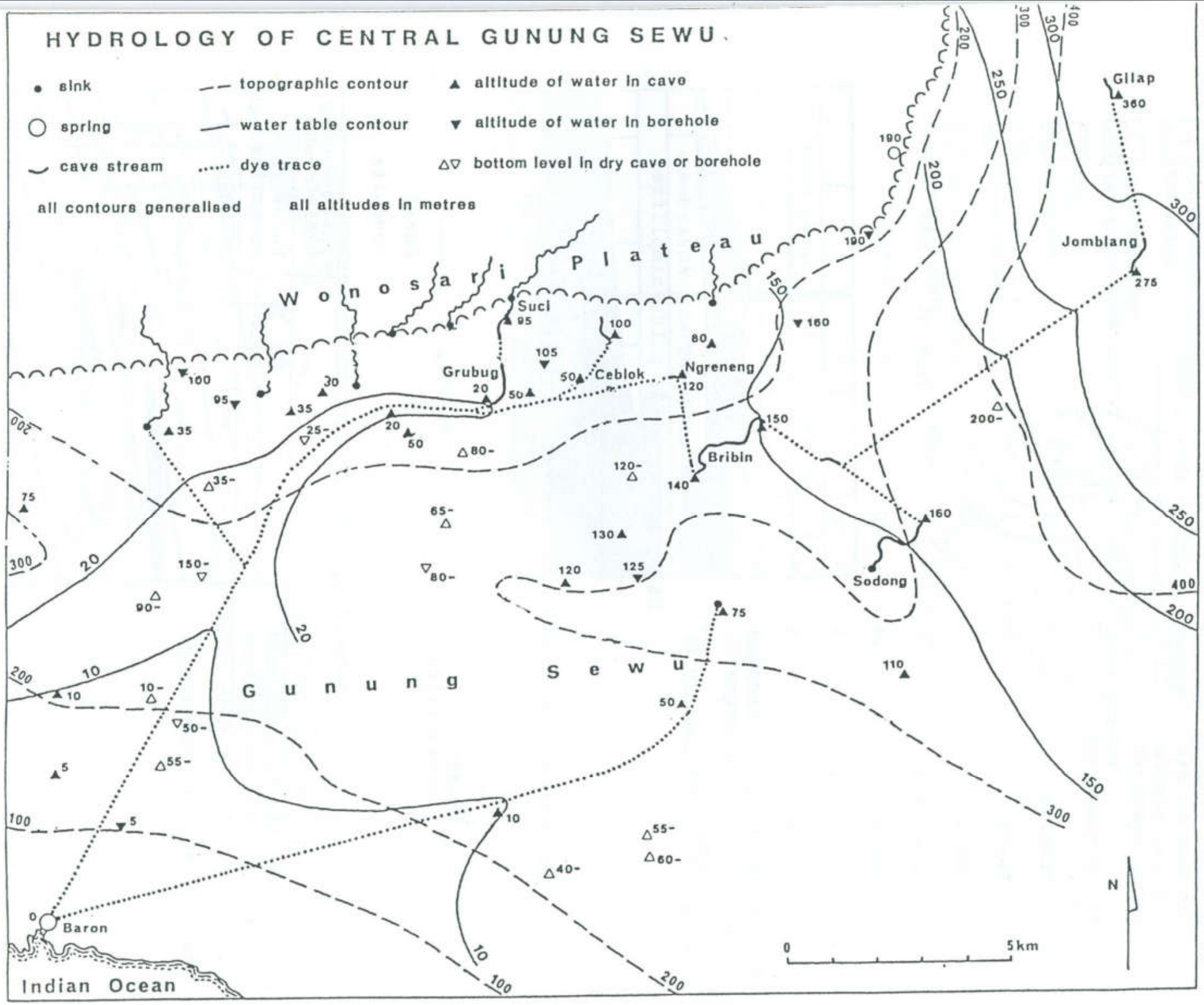


FIG. 9 : Grandchamps Creek at its swallowhole at Louveigné (Belgium). Influence of a rainstorm.

Flowrate Q in l/sec
Solved $CaCO_3$ in mg/l

(C. EK, 1969)

Much more carbonate can be dissolved in a rainy period, compared to a dryer period (C. Ek, 1969).



EXERCISE

TRENT POLYTECHNIC
NOTTINGHAM NG1 4BU
TEL: 0602 418248 EX. 2133

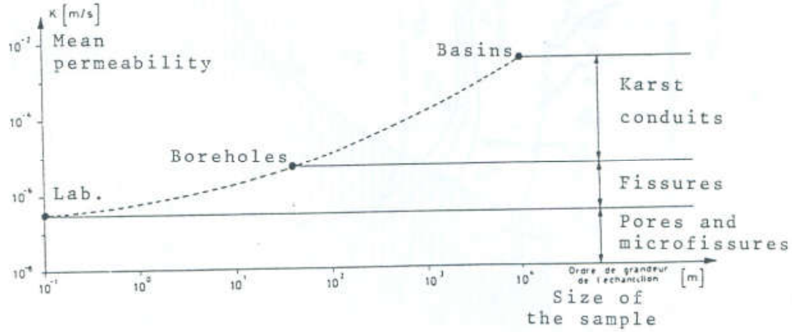
PERMEABILITY OF LIMESTONES

Volume of pores in various rocks, in %

Granite	0,1 – 1	
Slate	0,5 – 1	
Sandstone	3 – 40	
Limestones	0,7 – 3	free of joints
Chalks	14 – 40	" "
Dolomites	1 – 22	" "
Marble	0,1 – 0,5	" "
Sand	40 – 50	
Loam	50 – 54	

After BÖGLI, 1980, p.10, simplified

Variation of permeability in karst, according to the scale



(according to Kirali, 1978)

After DODGE, 1983

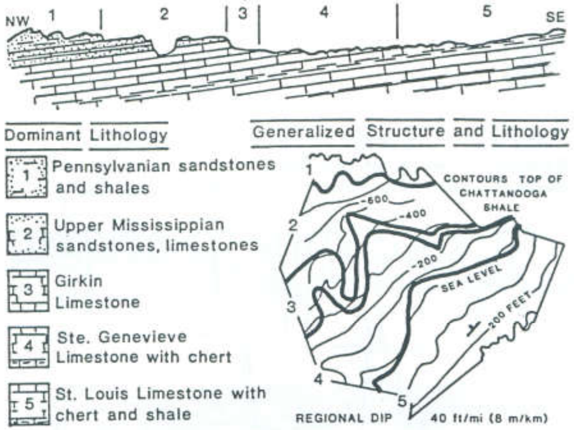
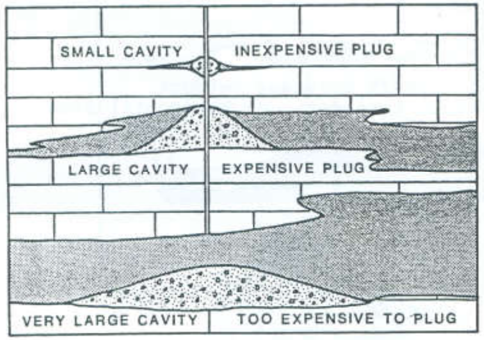


PLATE 7

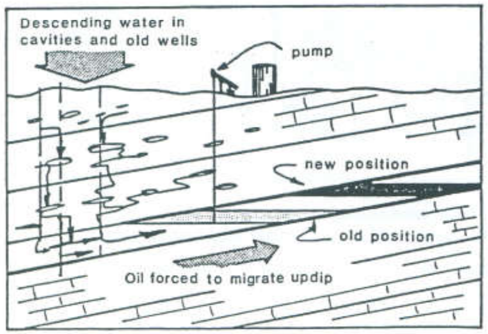
Lithology and structure of Warren County. Oil zones are in several strata beneath St.Louis Limestone.

(DILAMARTER, 1985, p.23).



Schematic representation of attempts to plug cavities.

(R.DILAMARTER, 1985, p.24)



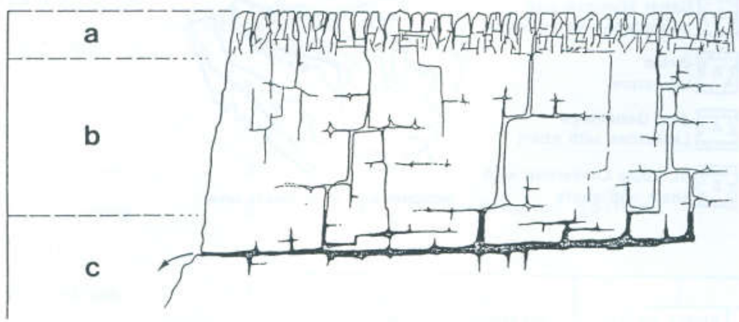
Migration of oil pool leaves well dry or pumping water, not oil.

(R.DILAMARTER, 1985, p.24)

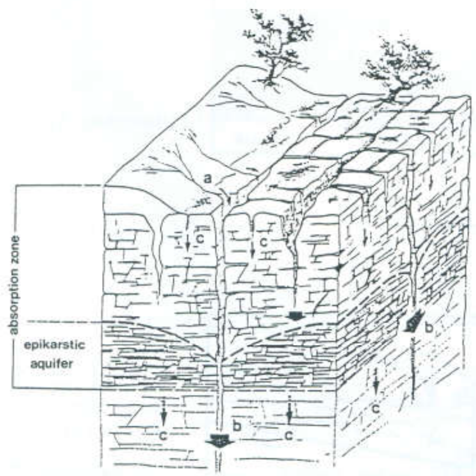
C. EK

PLATE 8

STRUCTURE OF KARSTIC AQUIFERS



1. The three zones of the karstic drainage network.
a: absorption; b: vertical transfer; c: horizontal flow.



2. Infiltration mode in the absorption zone.
a. fast local flow; b: fast flow in the main cracks;
c: slow seepage.

After D. DODGE, 1983

Typical karst drainage network:

a) Absorption zone

b) Vertical transfer zone

c) Horizontal flow zone

Infiltration in the absorption zone:

a) Fast local flow

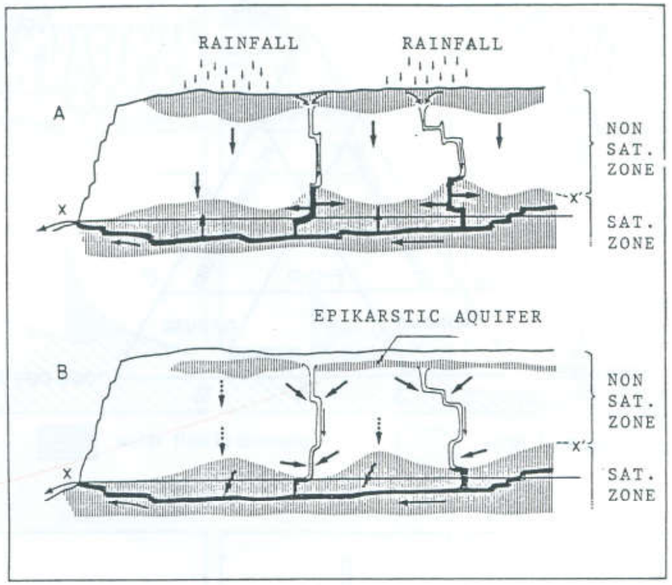
b) Fast flow in main cracks

c) Slow seepage

C. EK

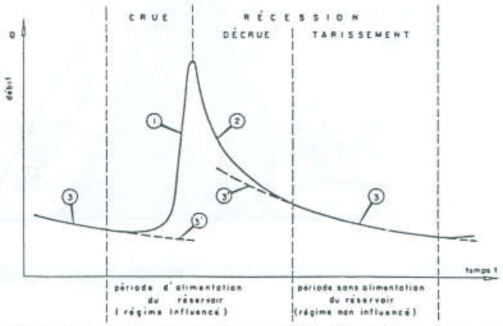
PLATE 9

WORKING OF KARSTIC AQUIFERS



1. Conduits and blocks work differently in the hydrodynamics of karstic aquifers (according to THEROND, 1972, modified).

A. In flood
B. At low water



2. The main parts of a hydrogram after Castany and Margat, 1977. 1: flood; 2: fall; 3: drying up; 3': drying up, extrapolated.

In: DODGE, 1983

Main parts of a hydrograph:

1) Flood
2) Fall
3) Drying up
4) Drying up, extrapolation

Atkinson's conceptual classification of karst aquifer.

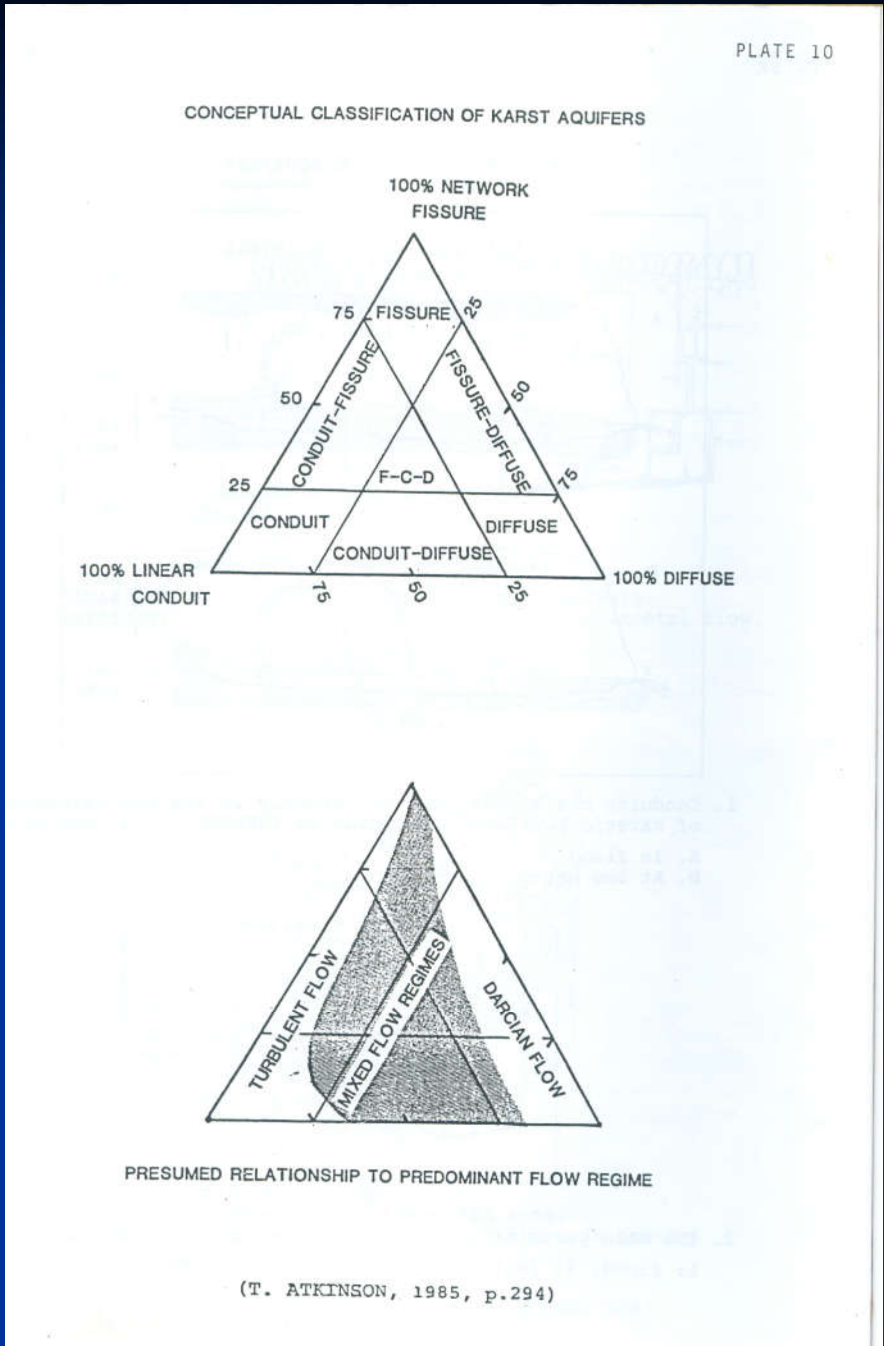
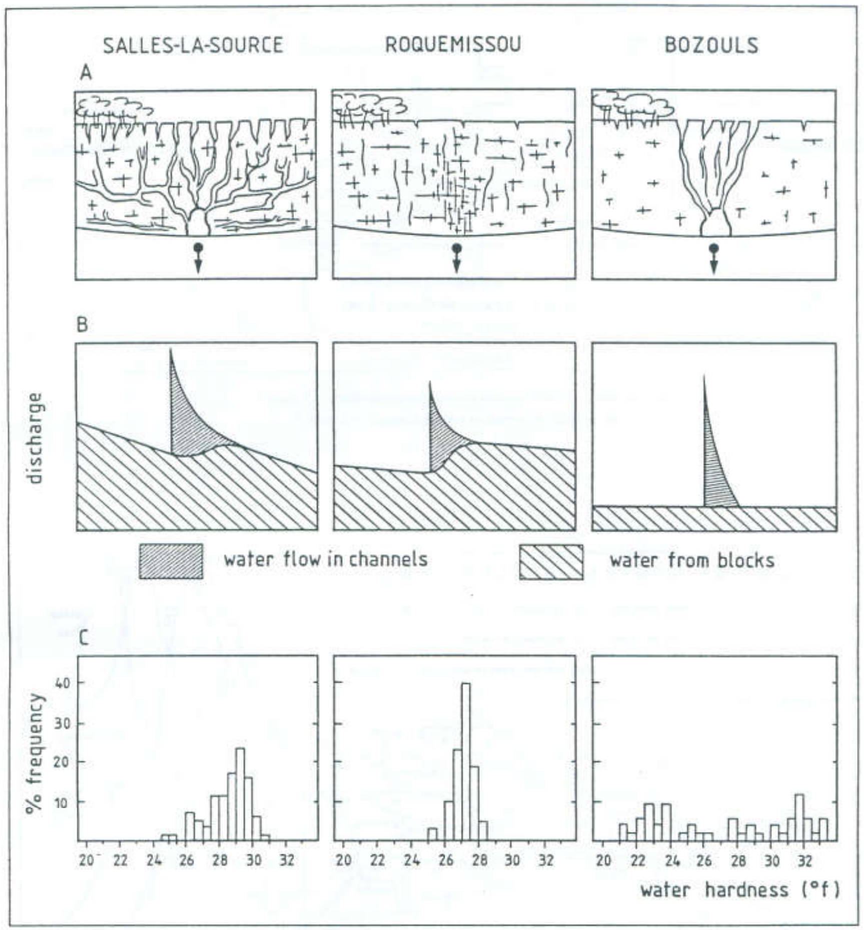


PLATE 11



Comparison of hydrogeological characteristics in the three basins of the Causse Comtal: Salles-la-Source, Roquemissou and Bozouls.

A. Illustration of aquifer structure and permeability.

B. Schematic semi-log hydrograms showing influence of blocks and channels.

C. Water hardness frequency histograms (based on 91, 45 and 50 samples analysed in 1981).

(D. DODGE, 1985, p.46)

A. Illustration of aquifer structure and permeability

B. Schematic semi-log hydrographs showing influence of blocks and channels

C. Water hardness frequency histograms

PLATE 12

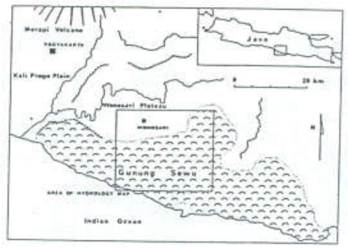


Figure 1. – The Gunung Sewu karst.
Figure 1.– Le karst de Gunung Sewu.

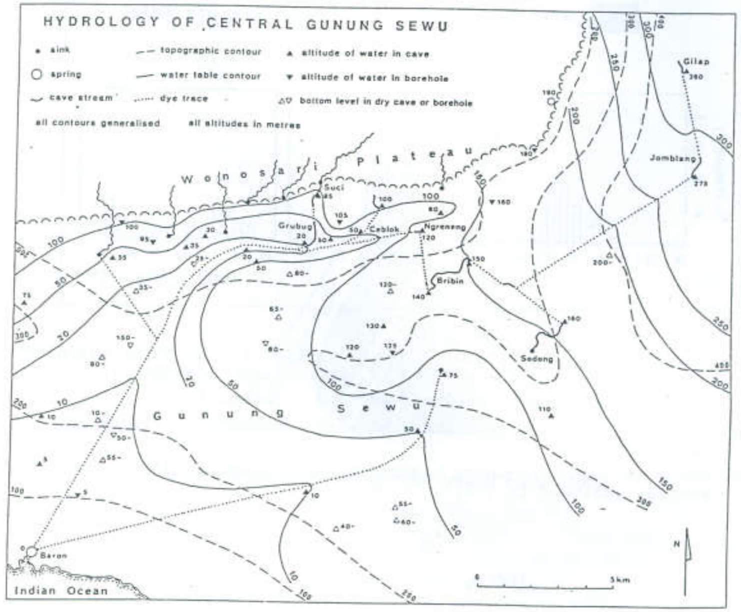


Figure 2.– Water table map of central Gunung Sewu.
Figure 2.– Carte du niveau hydrostatique du centre de Gunung Sewu.

Antony C. WALTHAM, Peter L. SMART, Hans FRIEDERICH & Timothy C. ATKINSON

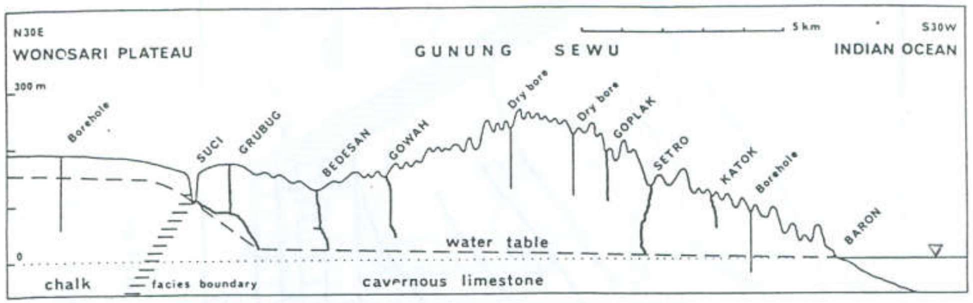


Figure 3.– Projected cross section through central Gunung Sewu.

Figure 3.– Coupe à travers le centre de Gunung Sewu.

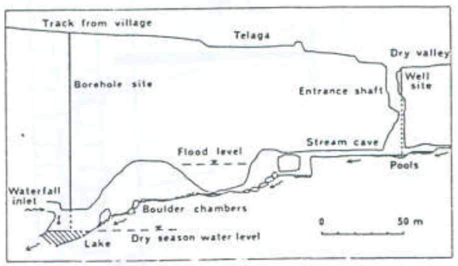
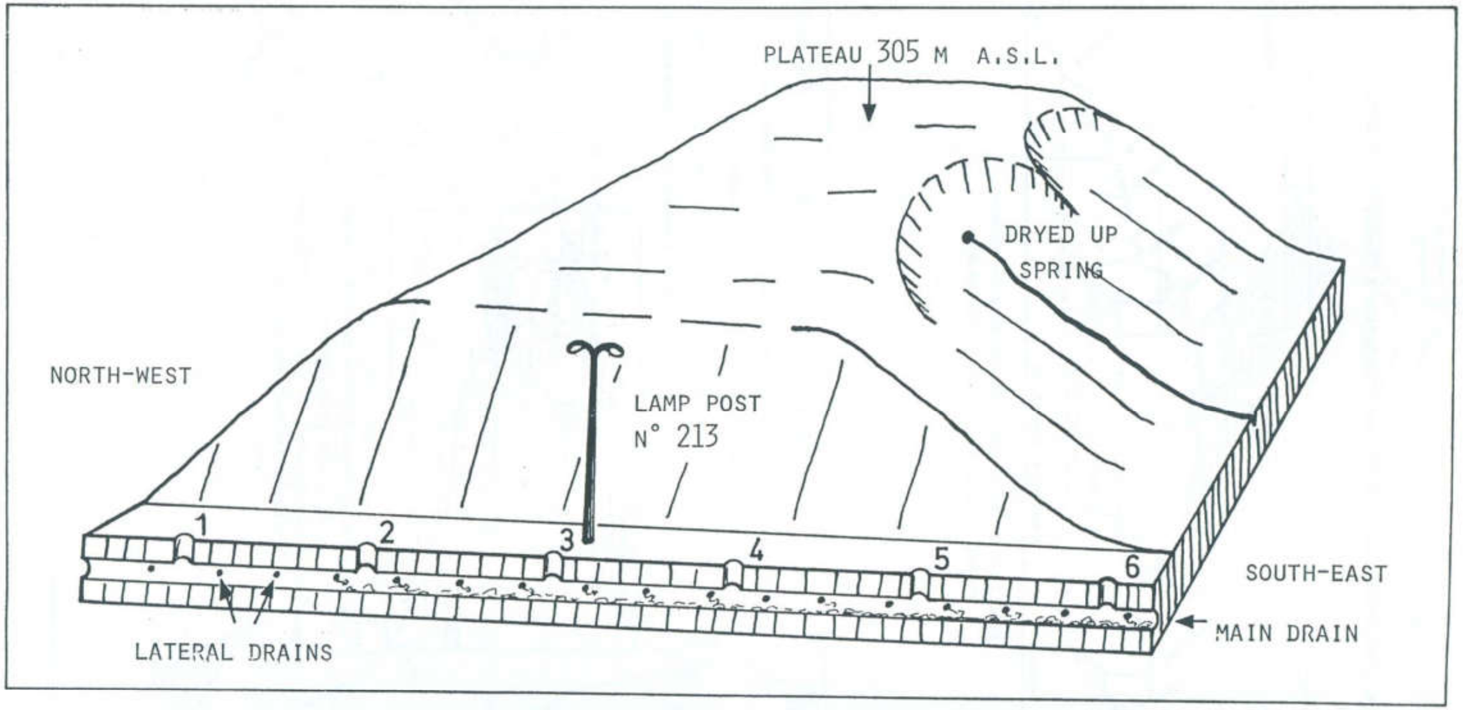


Figure 4.– Simplified cross section of the Ceblok sinkhole, with potential abstraction sites.

Figure 4.– Coupe simplifiée dans le ponor de Ceblok, avec sites potentiels de prélèvement d'eau.

Projected cross-section through Central Gunung Sewu (WALTHAM C. et al., 1984).



Drying up of a spring after digging an entrenchment for a highway.

(M. GEWELT, 1979)

PLATE 14

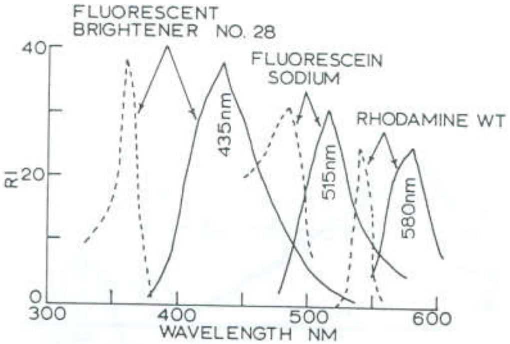


Fig.24. Excitation (dashed lines) and emission (solid lines) spectra of fluorescent brightener no. 28, fluorescein sodium, and Rhodamine WT. Samples scanned using an American instrument company SPF-125 Spectrofluorometer and 2 mm slit widths for excitation and emission.

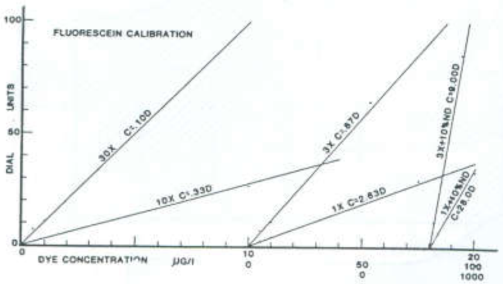


Fig.25. Typical set of calibration curves for fluorescein sodium. Each batch of dye, and each instrument requires a unique standardization to convert the dial readings (or relative fluorescent intensity) to concentration.

PLATE 16

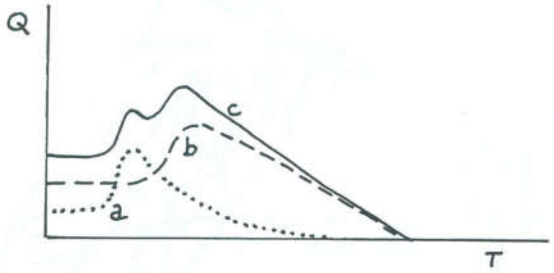


FIG. 26. Two input pulses (a,b); complex output pulse.

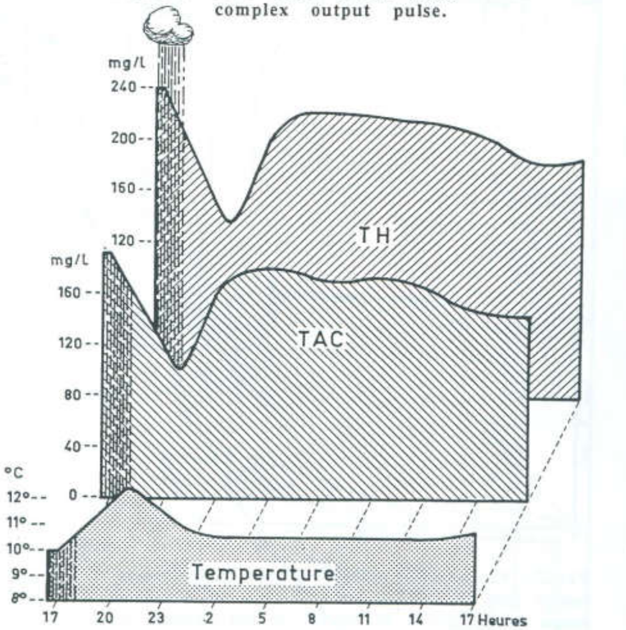


FIG. 27. Effects of a rainstorm on an underground river at Remouchamps (Belgium). After EK, 1969.
TH: Hardness.
TAC: Alcalinity.
(heures: o'clock).

Fig. 26 shows:

Two input pulses (a, b) mix to result in a complex output pulse.

Fig. 27 shows:

- The first pulse of warm, thus light, water had passed above the cold old water, but they began to mix thereafter;
- The continuous supply of rainwater increased the pressure, hence increasing the hardness and lowering the temperature;
- As these parameters approached their original values the old stock mixed

PLATE 17

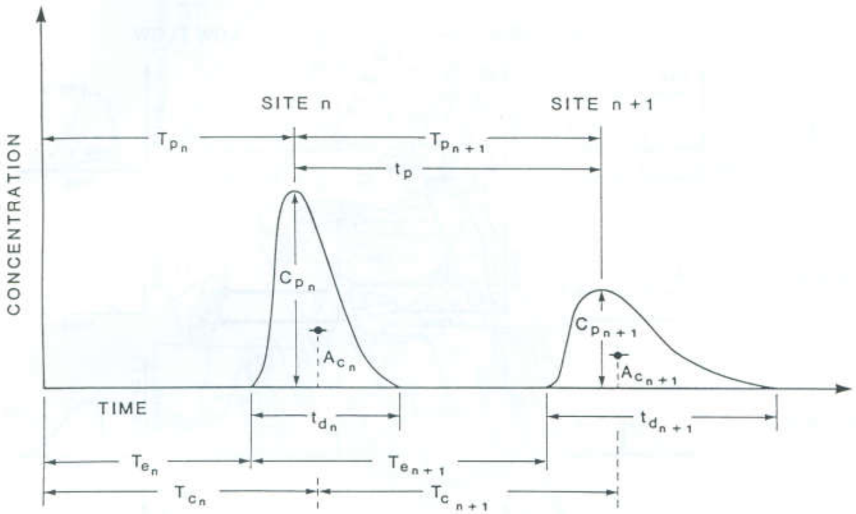


Fig.28. Definition sketch of dye recovery curves resulting from instantaneous dye injection. Two sampling stations (site n and site n + 1) on an unbranched channel with no lateral inflows or outflows are shown. The principal components of the curves are: Time of first arrival (T_e), Time to peak concentration (T_p), Time to centroid (T_c), Total Time of dye passage (T_d), Peak (maximum) dye concentration (C_p), and point representing mean dye concentration (A_c). For a conservative tracer, the area under the curve at site n equals the area under the curve at site n + 1.

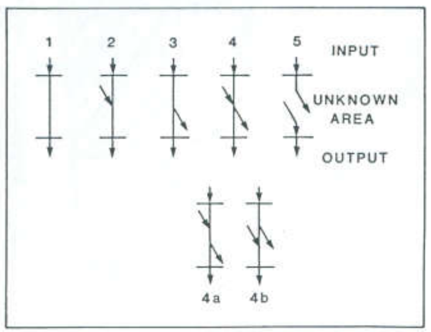


Fig.29. Five types of Karst flow systems (Black box model) (After Brown and Wigley, 1969).
Type 1—Single input to single output.
Type 2—Unknown lateral input.
Type 3—Unknown additional outputs.
Type 4—Additional unknown inputs and outputs.
Type 5—Input unknown, output unknown.

Fig.28: Definition sketch of dye recovery curves.

Two sampling stations (n) and (n+1) on an unbranched channel with no lateral inflows or outflows.

Principal curve components:

Time of first arrival (Te); Time to peak concentration (Tp); Time to centroid (Tc), total time of dye passage (Td); Peak dye concentration (Cp) and point representing mean dye concentration (Ac).

For conservation, the area under curves at site n and n+1 are equal.

PLATE 18

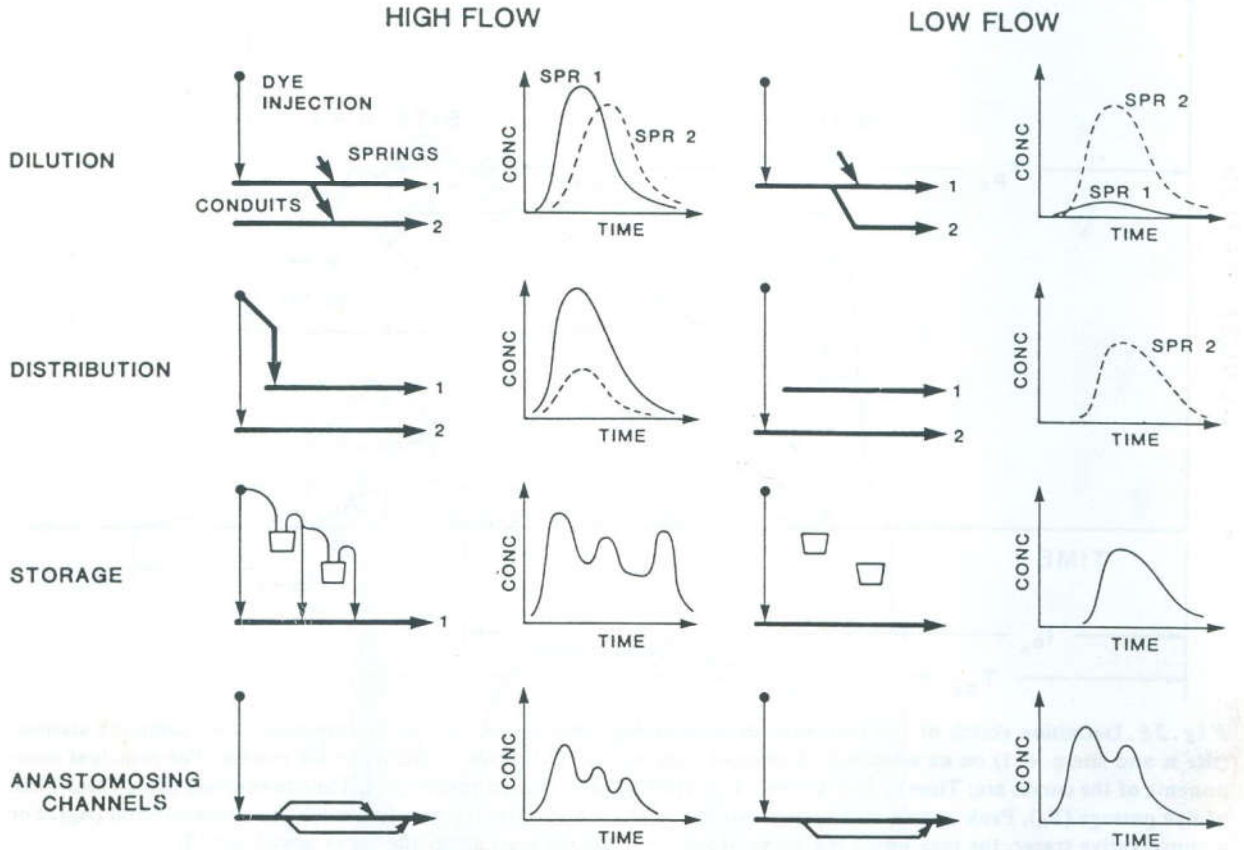


Fig.30. Simple shaft-conduit interpretations of dye recovery patterns (After Smart and Ford, 1982). The expected dye recovery curves influenced by changing hydrologic conditions (high to low flows) and geometry of the conduit system is illustrated. Note that multiple peak recovery curves may be due to flushing of dye from dead zone storage or anastomosing conduit routes.

LA POLLUTION DES EAUX D'UN MASSIF CALCAIRE

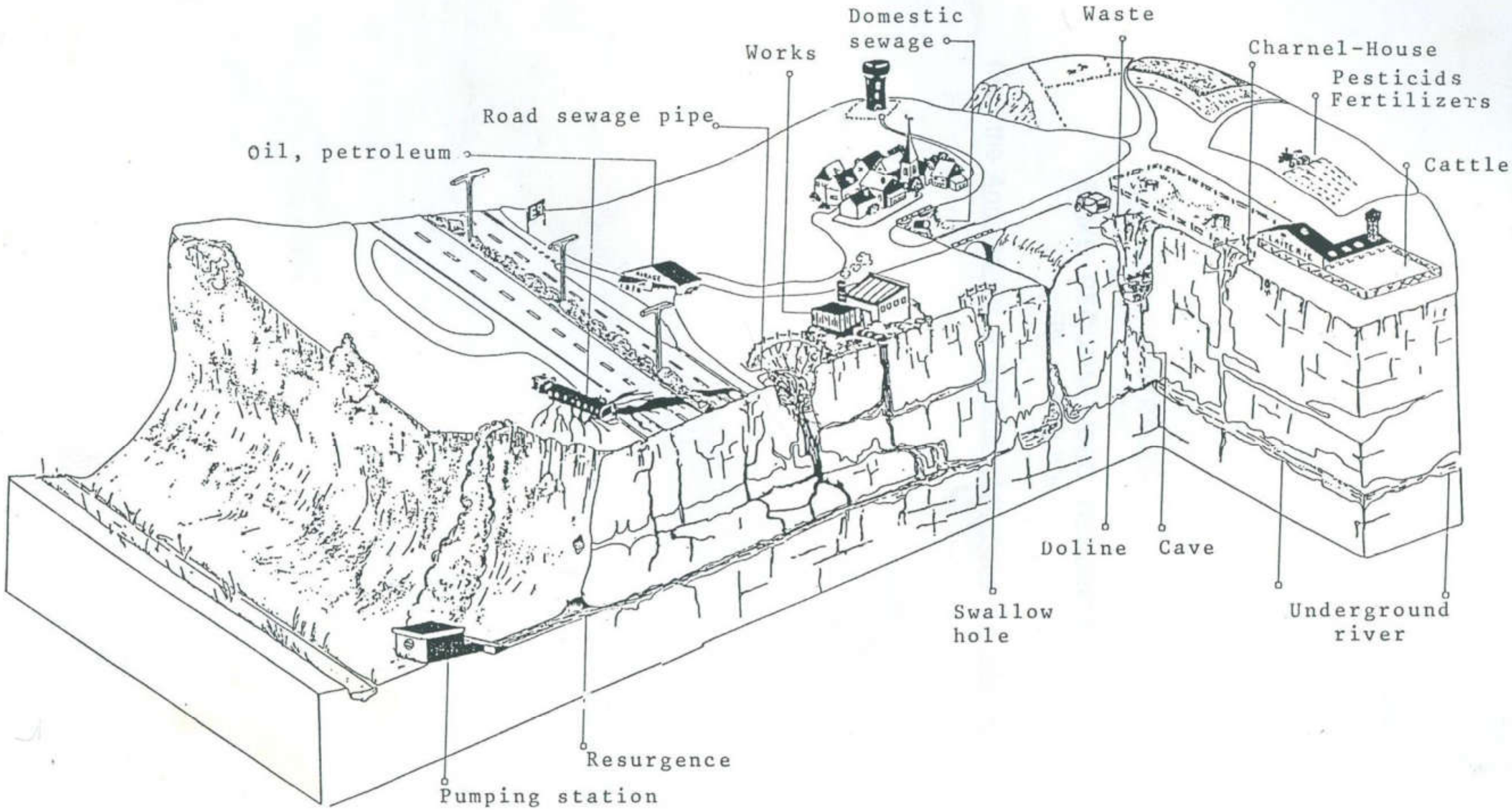
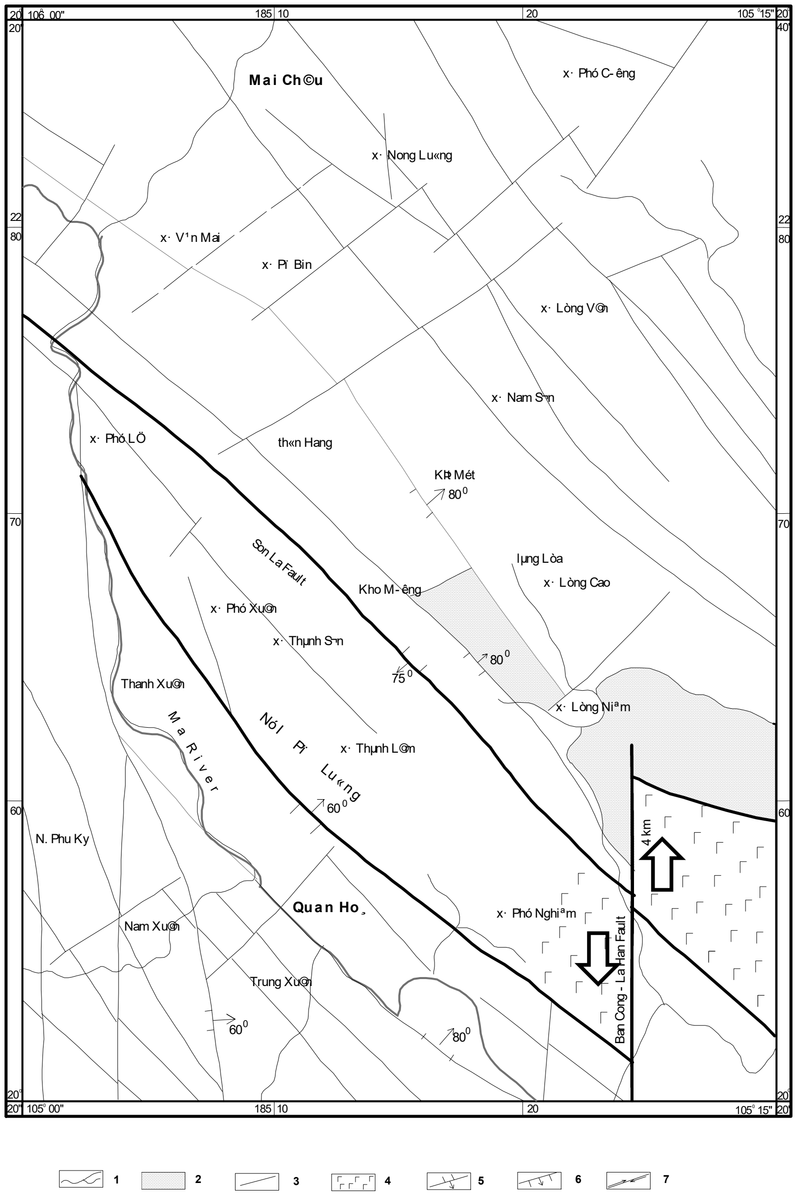


PLATE 19

from : Commission nationale de Protection des Sites spéléologiques, Brussels, Belgium

Sketch of faulting systems and their movement in the Pu Luong Nature Reserve area, Thanh Hoa Province



Legend: 1. River, stream; 2. Limestone; 3. Dominant fault; 4. Effusive rock;
5. Reverse fault and dip-slip; 6. Horizontal fault and dip-direction; 7. Dip-slip fault and strike.

Properly equipped before entering a cave.

Properly equipped before entering a cave.

Making anchor points.

Descending a cave.

Descending a cave.

Taking a short rest.

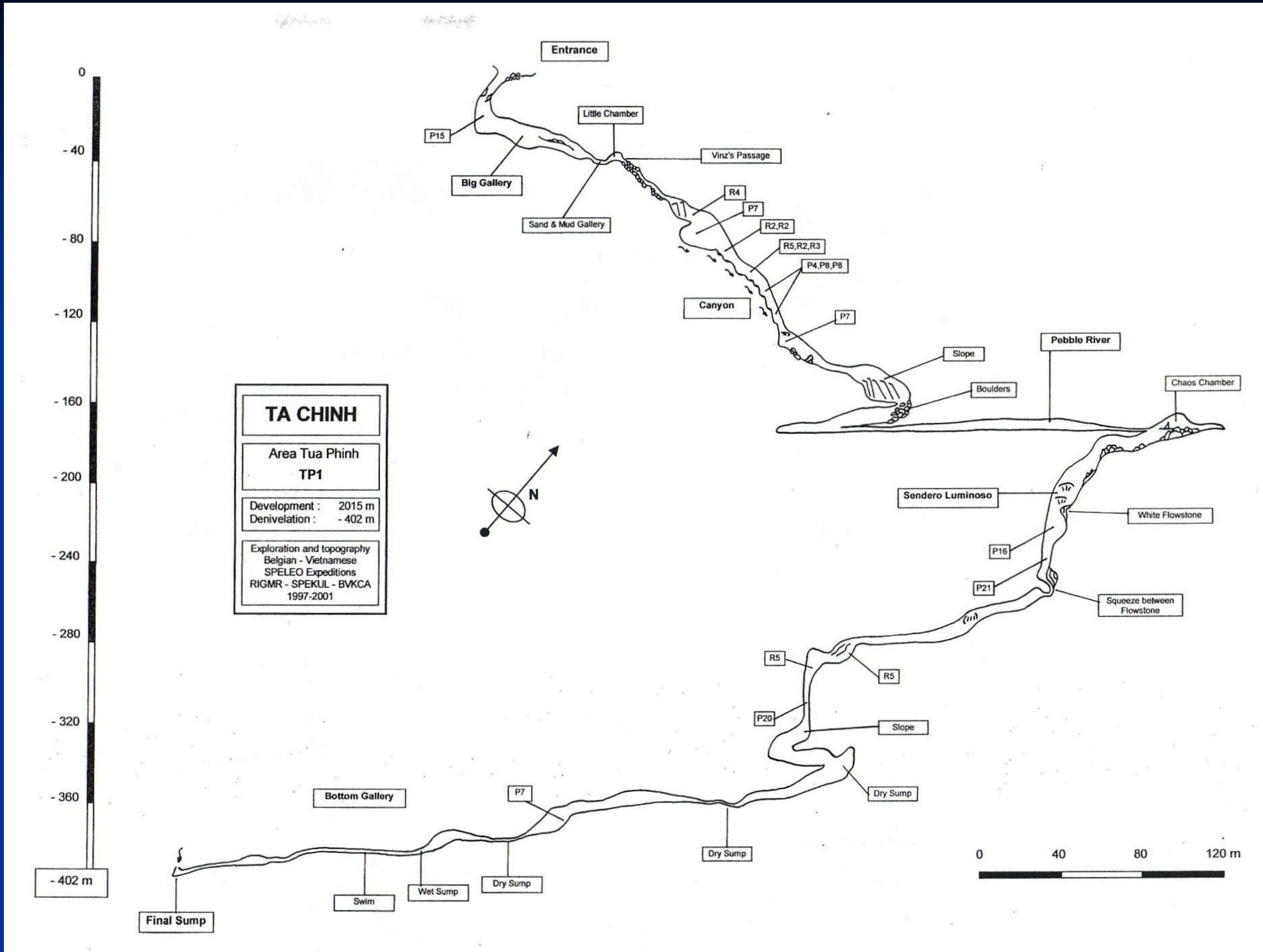
At the cave end, deeply in mud, but……


………happy. And preparing to go up.

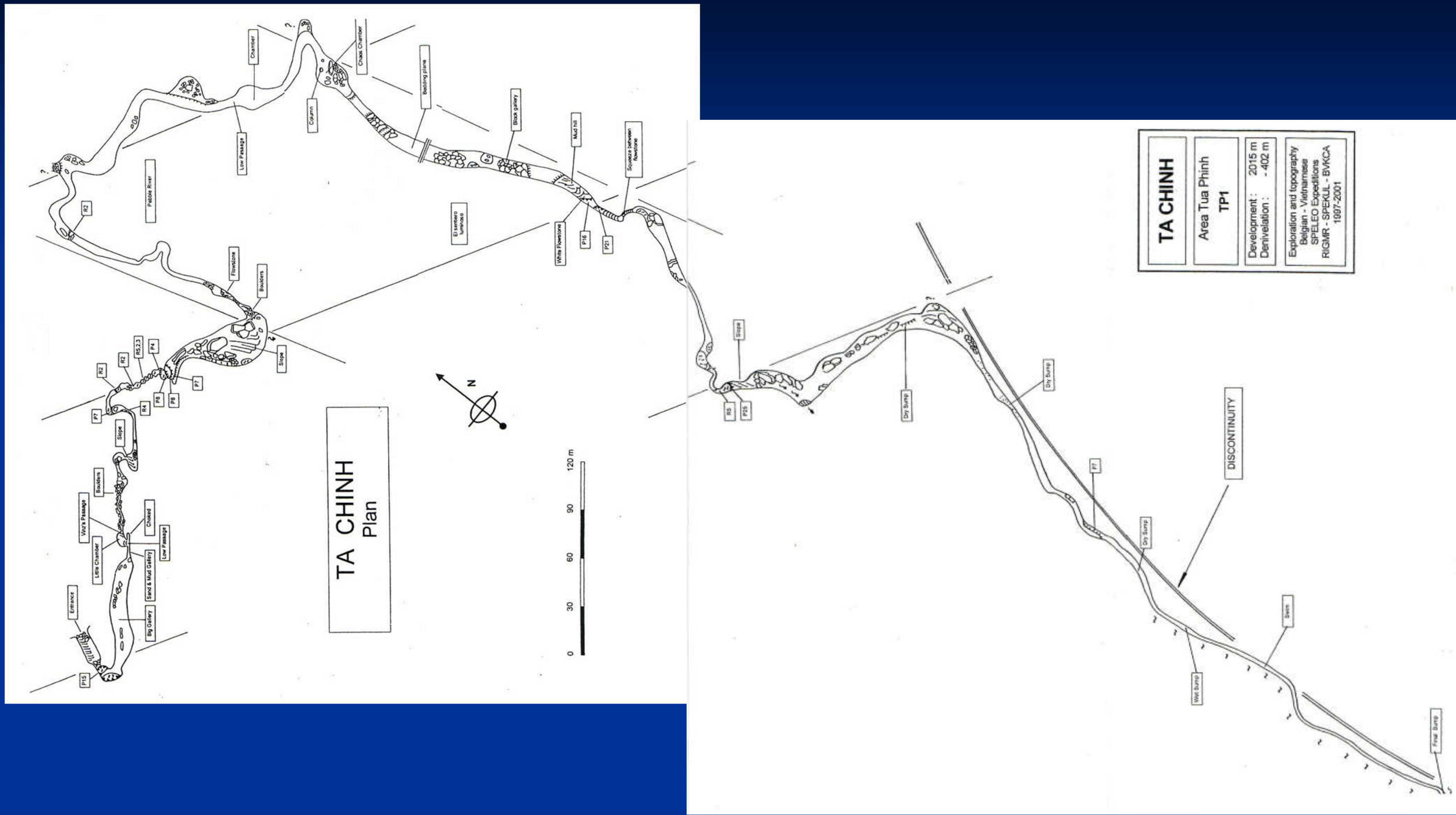
In a wet cave.

Mapping a cave with tape.

Mapping another cave.



Ta Chinh cave in Tua Chua – the second deepest cave found so far in NW Vietnam.



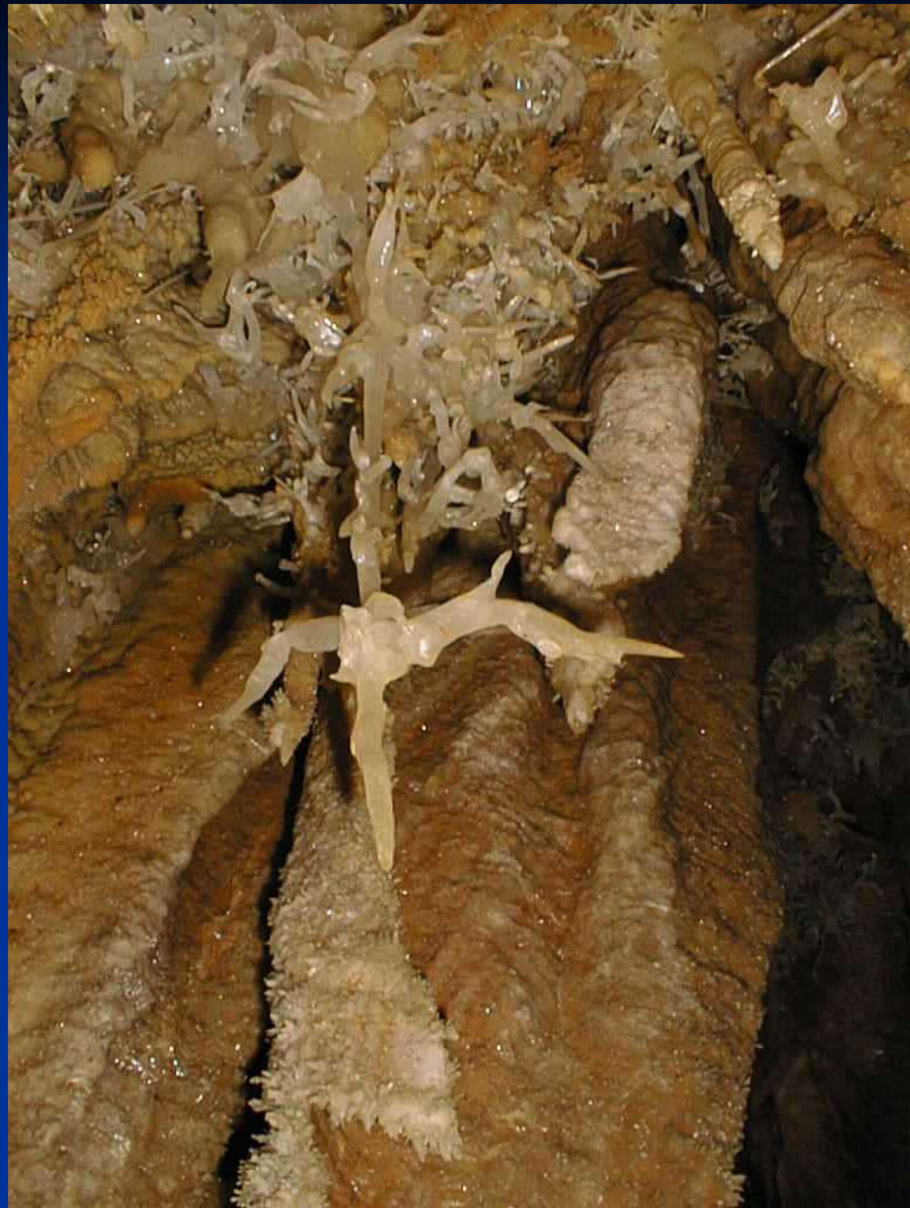
Ta Chinh cave in Tua Chua – the second deepest cave found so far in NW Vietnam.

Some nice moments in caves.

Some nice moments in caves.

Wonderful nature’s creatures in caves:

- Above: Dragon’s egg;
- Right: Calcite flower.

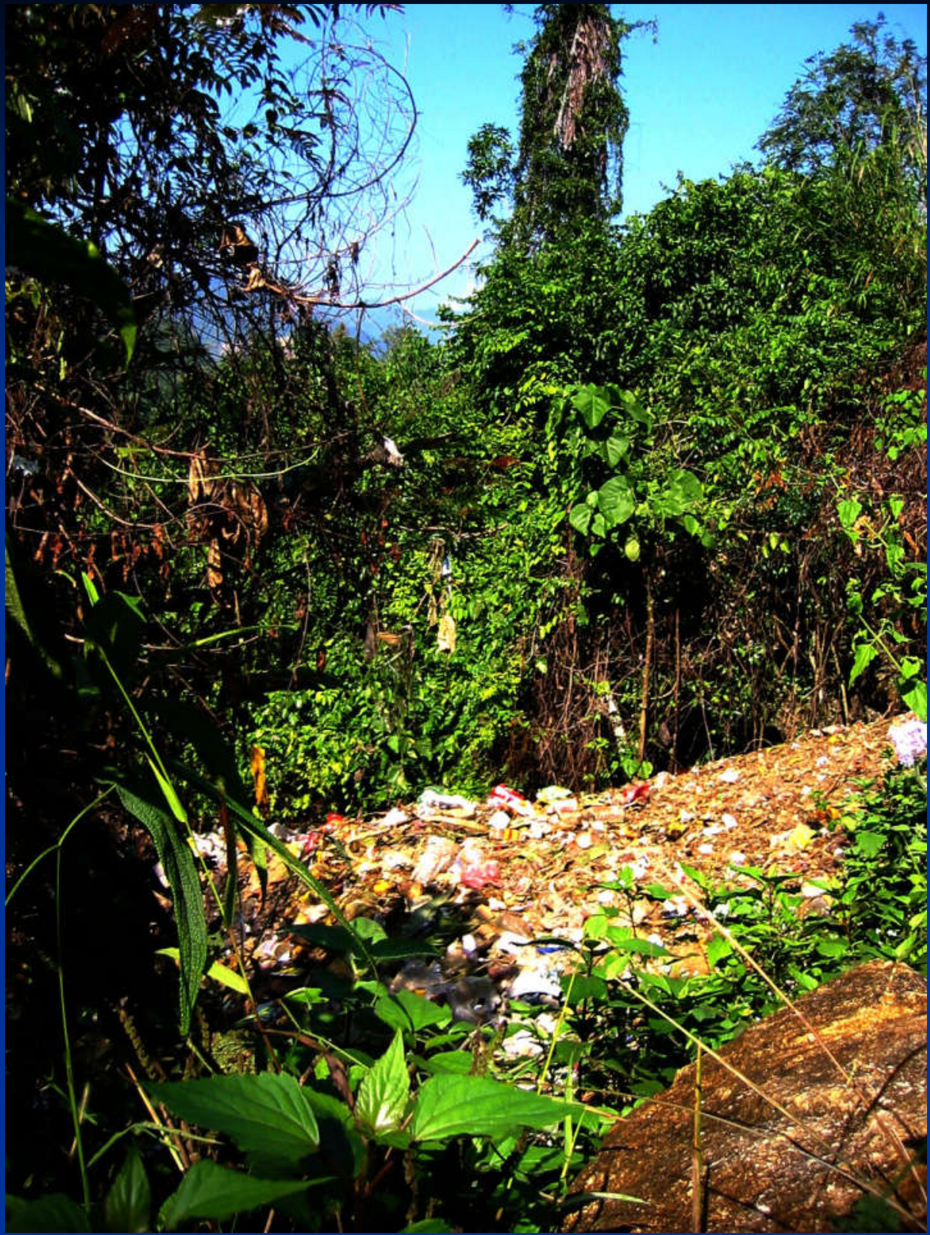


Nature’s creatures: Snake (Left) and Devil (Right).

Nature’s creatures: Excentric.

Going to the forest…..

…..And going back.



Dumping garbage in a karst sinkhole in Tam Duong District, Lai Chau Province.

Another dump site in Tam Duong District, Lai Chau Province.

Washing and cleaning directly in one of the main resurgences in Tam Duong.

A collapse in a karst area of …. South Africa.

Well preserved forest in Cuc Phuong National Park. Enough water even for a swimming pool.

Fortunately untouched forest in Tam Duong area, Lai Chau province.

Another piece of tropical rain forest in karst area.

The Da River Canyon in NW Vietnam - the major collector of local karst water.

The Nho Que River in Ha Giang Province - the major collector of local karst water.

Ha Giang Province - a breath taking view.

Ha Giang Province - “Stone forest” on top and a cave entrance in Devonian limestone.

Some karst inhabitants.

Some cave inhabitants.

Some more calcite flowers in cave.

Some more calcite flowers in cave.

But more importantly, the warm and peaceful people - future of Vietnam.

But more importantly, the warm and peaceful people - future of Vietnam.

But more importantly, the warm and peaceful people - future of Vietnam.

But more importantly, the warm and peaceful people - future of Vietnam.

But more importantly, the warm and peaceful people - future of Vietnam.

Thank you!