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INTERPRETATION OF A CAVE SYSTEM BASED ON TRACER EXPERIMENT, GEOSTRUCTURE AND CAVE DEVELOPMENT ANALYSIS

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Abstract. This paper presents an interpretation of a cave system, the Khau Muong - Lan Trong conduit, in the National Natural Reservation Zone of Phu Luong in NW Vietnam. Geological and cave surveys are carried out which predict the existence of possible underground connections between the Khau Muong sinkhole and the Lan Trong resurgence. Tracer experiments, using common salt (NaCl) as a tracer, are implemented to verify these connections, which result in a two-peak break-through curve. The two peaks are interpreted as the result of the tracer transport through a cavern conduit system having a sump that act as a hydraulic barrier to postpone the tracer transport process. This interpretation is strongly supported by the analysis on geostructure and cave development, which shows that the conduit system is composed of two passages developed along two respective faults, and the sump is found at the intersection of the two faults.

Keywords: Vietnam, carbonate rocks, tracer experiment.

1 Introduction

Tracer experiments have been applied in karst hydrological study and proved as one of the most effective tool to investigate underground conduits in karst environment. Many essential hydrogeological and hydrodynamic properties of the conduit system under investigation can be obtained by interpretations of break-through curve resulted from tracer experiments. Ideally and theoretically, a tracer experiment shows a single-peaked break-through curve of a skewed "bell" shape which corresponds to the analytical solution of the Fick's equation. However, many tracer experiments also exhibit multi-peaked break-through curve, i.e. a curve composed of a largest peak and a series of precedent and subsequent smaller peaks. The multi-peaked feature can be interpreted as (i) the conduit system is composed of several parallel branches, and the movement through these branches leads to the different arrival times of the tracer creating respective peaks of the break-through curve (ii) the system is of a single conduit composed of several hydraulic resistances (e.g. sumps) which delay the movement of a part of the tracer and thus also creating respective peaks. This study presents a two-peak break-through curve of the tracer curve conducted in an underground cavern conduit system in NW Vietnam. Analysis on the regional geological structure and the conduit development is also carried out, which shows that the conduit system is composed of a sump and conduit passages. This sump, acting as a high hydraulic resistance, traps a part of the injected tracer volume. That results in the two distinct transports of the tracer: the first is a quick movement of the groundwater flow through the conduit, and the second is the subsequent release of the trapped volume of the injected tracer. Thus, two peaks are created in the break-through curve, and the result strongly supports the above-said second interpretation.

2 Geological setting and cave development

The conduit system of Khau Muong - Lan Trong is one of the largest underground cavernous systems recently investigated in the National Park Zone of Cuc Phuong - Phu Luong in NW Vietnam (Ke et. al., 2003). In the study area, the carbonate rocks, aged Middle Triassic (Anizian stage), are of the Dong Giao formation T_{2a} dg (Fig. 1). The

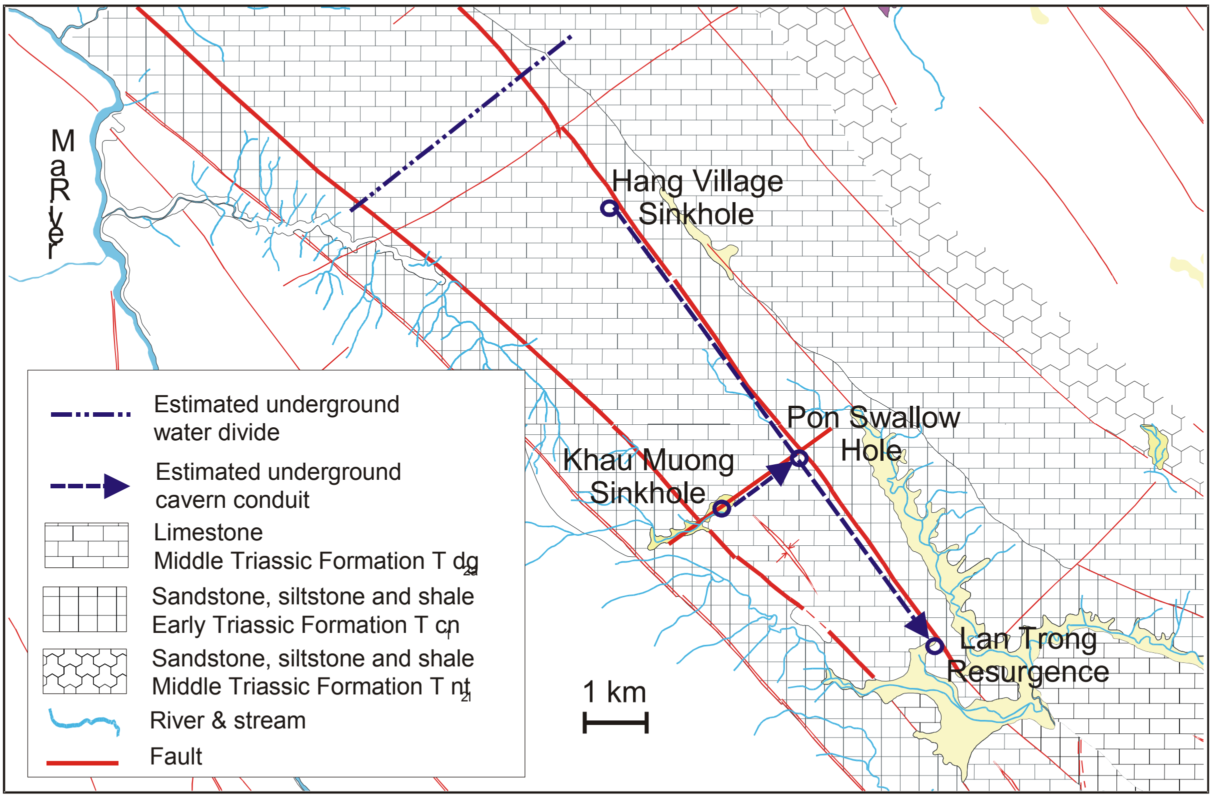


Fig. 1. Geological sketch of the Khau Muong – Lan Trong conduit system.

rocks are moderately-thickly bedded, and are regionally dipping to SE and NW, forming a series of NW-SE striking anticlines and synclines. Furthermore, these formations are intercalated by poorly permeable terrigenous rocks, namely sandstone, siltstone and shale, aged Early and Middle Triassic (Ladinian stage), of the Co Noi formation T_1 cn and the Nam Tham subformation T_{21} nt. Principal faults, which are often deeply seated and act as stratigraphical boundaries, mainly develop in NW-SE and NE-SW directions. Other faults, which are either sub-longitudinally or sub-latitudinally striking, are often younger and formed after the orogeny.

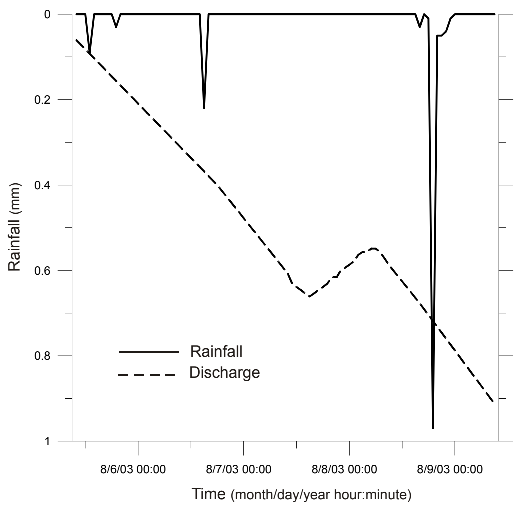
The conduit system develops within the Dong Giao formation. Due to tectonic - neotectonic activities and favourable exogenous factors, the limestones are fractured and especially strongly karstified. Most of the cavern passages develop in the NE-SW direction, along faults and crashed zones, or follows the stratigraphical boundaries stratified the limestones and the impermeable terrigenous formations. The conduit system is composed of several entrances, one of which is the Khau Muong sinkhole, and an exit, the Lan Trong resurgence. The underground basin, which drains to the conduit system, is confined by the impervious terrigenous formation of Co Noi in the NE and SW. In the NW, as the groundwater discharge take place in several springs located along the Ma Tributary, it is assumed that there is an underground water divide existing somewhere between the river and the Hang Village. Assuming the Lan Trong Resurgence as the outlet, the underground basin area of conduit system is therefore estimated at about 50 km^2.

Only a few passages of the conduit system between the Khau Muong Sinkhole, the Pon Swallow Hole and the Lan Trong Resurgence were surveyed with the total surveying length of 1270 m. The cave surveying data shows that the main conduit branch follows the crashed zones of the NW-SE trending fault, starting from the Hang Village and ending at the Lan Trong resurgence. Many cave expeditions were carried out in NW Vietnam (Dusar, 1994; Lagrou, 2001), which show that the caves often exhibit multilevel or multi-step pattern, e.g. they are composed of horizontal passages, each develops at a respective elevation and connects to each other by vertical shafts. Each level corresponds to a change in groundwater discharge point in the geological development history of the region. The lowest level is relatively equal to the local erosional base. Furthermore, it is shown that the vertical cavern shafts often coincide with the intersection location of two faults or fractured zones (see the Queen Cave in Lagrou *et al*., 2001). The elevation of the Hang Village, Pon Swallow Hole, Khau Muong Sinkhole, and Lan Trong Resurgence is 240 m, 160 m, 480 m, and 145 m a.s.l., respectively. The elevation of the Ma Tributary is the same as the Lan Trong Resurgence and is considered as the local erosional base. Comparing the elevation of Ma Tributary with the Pon swallow hole and the Lan Trong Resurgence, it is assumed that the Pon – Lan Trong cavern passage is relatively horizontal and is located at the local erosional base. As the elevation of the Hang Village elevation is much higher than the Pon – Lan Trong passage, it is estimated that there is at least a jump-down in elevation from the Hang Village level to the local erosional base of the Pon – Lan Trong passage. The jump-down can take place in one or several vertical cavern shafts, which might exist somewhere along the NW-SE trending fault segment between the Hang Village and the Pon Swallow Hole. The passage between the Khau Muong Sinkhole and the Pon Swallow Hole is considered as one of the branches of the system. This passage starts at the Khau Muong Sinkhole and develops along the crashed zone of the NE-SW trending fault towards the Pon Swallow Hole (Fig. 1). This swallow hole is located in a doline, where is also the intersection of the NW-SE trending fault and the SW-NE trending fault. Based on the common cave development pattern discovered in NW Vietnam, it is estimated that somewhere nearby there is a vertical shaft connecting the Khau Muong cave development level to the main conduit level.

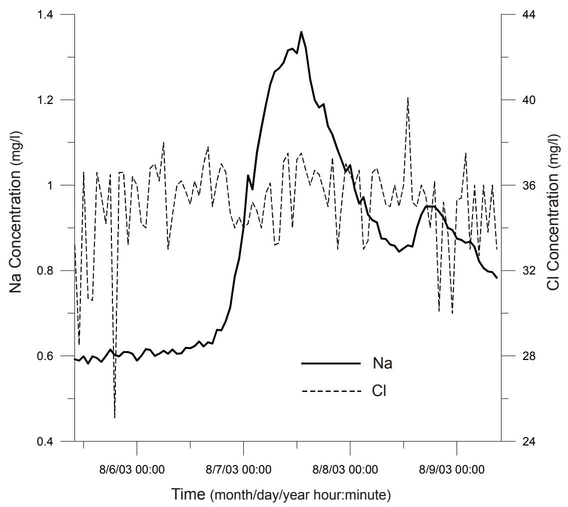
A relatively large sump is found a few meters beyond the swallow hole. The groundwater flowing from the Hang Village and the Khau Muong Sinkhole is temporarily ponded in the sump and subsequently drains towards the Lan Trong Resurgence. During extensive rainy periods, the doline is often flooded. A possible explanation for this is the inflow volume of water from the Hang Village and Khau Muong Sinkhole is larger than the conveying capacity of the main conduit segment between the Pon Swallow Hole and the Lan Trong Resurgence. Therefore, it is concluded that the sump acts as a high hydraulic resistance, which delays the water movement from the Hang Village and Khau Muong Sinkhole to the Lan Trong Resurgence.

3 Tracer experiment and break-through curve analysis

During the rainy season of the year 2003, 600 kg of common salt (NaCl) was used as the tracer and injected to the Khau Muong Sinkhole (Tuy *et al*., 2003). In the Lan Trong Resurgence the tracer sampling was undertaken at the same time as the tracer was



(a)



(b)

Fig. 2: (a) Rainfall and discharge measured during the tracer test (b) Break-through curve of Sodium and Chloride

injected. Time interval between every sampling is one hour and the sampling lasted for four days. One day before the experiment there was a light rain which caused the resurgence discharge slightly increased. During the sampling campaign, the rainfall and the discharge was monitored by automatic reading devices installed in the Lan Trong Resurgence (Fig. 2a). The samples were analyzed for Sodium and Chloride content by the Atomic Absorption Spectrophotometer (AAS GBC 905 AA) and the standard titration method, respectively. The sensitivity of the AAS is 0.004 mg/l, and the resulting break-through curve of the Sodium is presented in Fig. 2b. Because of poor analytic result of the titration method and maybe also other unknown factors, the break-through curve of the Chloride exhibits too much chaotic variations and no apparent peak (Fig. 2b).

The tracer mass recovery rate, R_m, is estimated as

$$R_m = \frac{M_{out}}{M_{in}} x100\% = \frac{\int_{t_o}^{t_n} C(t)Q(t)dt}{M_{in}} x100\% \qquad (1)$$

where M_{in} is the tracer mass injected in the sinkhole, M_{out} is the tracer mass recovered at the resurgence, t_0 is the fist sampling time, t_n is the last sampling time, and $C(t)$ and $Q(t)$ are the concentration of the tracer and the resurgence discharge at time t. As the background concentration of the Chloride could not be estimated, the estimation of the respective tracer mass recovery is also unable. With regards to the Sodium the background concentration is estimated at 0.589 mg/l and the respective tracer mass recovery rate is 72%. Apparently, the sampling duration is not sufficient to recover the entire mass of injected tracer (Fig. 2b). The cut-off of 28% of the injected tracer mass is assumed to be recoverable if the sampling was continued for a few days more. Therefore, the experiment is considered relatively perfect and the coefficient of tracer sorption to the conduit is almost zero.

The mean tracer residence time $\bar{t}$, defined as

$$\bar{t} = \frac{\int_{t_0}^{t_n} tC(t)Q(t)dt}{\int_{t_0}^{t_n} C(t)Q(t)dt} \qquad (2)$$

gives relevant information on the time required for the centroid of a nonreative pollutant mass spilled in the vicinity of the injected tracer to be discharged. For the Khau Muong – Lan Trong conduit system, the mean tracer residence time is estimated at $\bar{t}$ = 47.37 hrs, and the karst conduit volume, defined as

$$V = \int_{t_0}^{\bar{t}} Q(t)dt \qquad (3)$$

is 124770 m^3.

The Péclet number, a measure of the relative contribution of mechanical dispersion and diffusion to solute transport, is estimated at 0.66 for the conduit system under investigation. This value indicates that diffusion/dispersion and advection are in transition and thus approximately equal to each other. This conclusion is also strengthened by relatively low value of mean tracer velocity, $\bar{v}$ ≈ 0.06 m/s, which is estimated by

$$\bar{v} = \frac{\int_{t_0}^{t_n} \frac{1.5x_s}{t} C(t)Q(t)dt}{\int_{t_0}^{t_n} C(t)Q(t)dt} \qquad (4)$$

where x_s is straight-line distance between the Khau Muong Sinkhole, the Pon Swallow Hole and the Lan Trong Resurgence. The coefficient of 1.5 is taken into account as the average sinuosity estimate of the travel distance of the tracer from the sinkhole to the resurgence.

Ideally and theoretically, the tracer break-through curve should have a positive skewed bell shape corresponding to the Fickian one-dimensional transport equation described bellow

$$\frac{\partial C}{\partial t} + v(t)\frac{\partial C}{\partial x} - D_L \frac{\partial^2 C}{\partial x^2} = 0 \qquad (5)$$

where $D_L = \alpha_L \text{ x } v(t)$ is the longitudinal dispersion, α_L is the longitudinal dispersivity, and x is the distance variable. Equation 5. describes the variation of pollutant concentration in time and space, provided the injection is done immediately (Dirac injection). However, the tracer break-through curve of the Khau Muong – Lan Trong conduit system shows two peaks as though two sources of tracer of were injected, the second injection

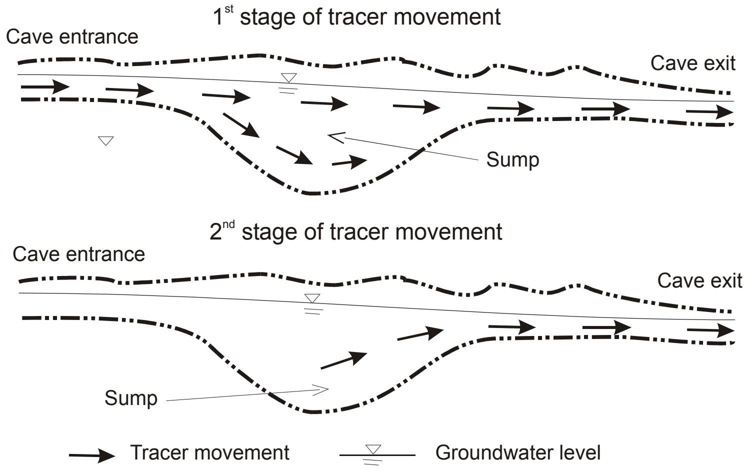


Fig. 3: Schematic illustration of the tracer movement in a conduit system having a sump

comes after the first injection about 35 hrs. As the common salt was certainly injected only in the Khau Muong Sinkhole, the "second injection source" is interpreted as the portion of the salt trapped in the sump. That is, upon the injection the salt starts movement through the conduit system; not entire volume of injected salt move straight and immediately to the resurgence but a certain portion is trapped in the sump when the solution fluid passes there (1st tracer movement stage in Fig. 3) and is subsequently released as the second injection source (2nd tracer movement stage in Fig. 3). The resulting break-through curve likely shows a superimposition of the curve yielded by the injected source and the curve yielded by the trapped source which starts at the above-estimated delay time. However, it is not expected this trapped portion of salt to exhibit a second skewed "bell" peak as described by Eq. 5 since this source is not a true Dirac injection. Instead, the peak shape caused by this source should be flatter than the theoretical shape because the trapped solution is gradually released.

Finally, the duration for the salt to transport from the Pon Swallow Hole to the Lan Trong Resurgence is estimated as the subtraction of the delay time from the mean tracer residence time, which is equal to 12.37 hrs.

4 Conclusions

The analyses on geostructure – cave development and tracer break-through curve show that there exists a sump in the Khau Muong – Lan Trong underground cavern conduit system. This sump is associated with a vertical shaft which appears in the intersection location of two fault system. Furthermore, this sump acts as a high hydraulic resistance to delay the groundwater movement from the Khau Muong Sinkhole to the Lan Trong Resurgence. A portion of the tracer injected in the sinkhole is trapped in the sump as it passes there. This quantity of tracer is subsequently released, forming the second peak of the break-through curve. This study result shows that a multi-peak tracer breakthrough curve is likely an indication of a multi-level cave system.

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