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A COMPARATIVE STUDY BETWEEN THE KARST OF HOA QUANG, CAO BANG PROVINCE, VIETNAM AND TUSCUMBIA ALABAMA, U.S.A.

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Abstract
Some of the most beautiful karst features created by the dissolution of limestone are residual hills with steep or vertical sides rising from a flat plain, known as tower karst. Tower karst to be developed requires a “mean annual temperature of minimum 17°C to 18°C and 1,000 to 1, 200 mm/m^2 of annual rainfall (Jakucs, 1977). Two sites matching this criteria were selected: the karst of Hoa Quang District, Cao Bang Province, Vietnam, and Tuscumbia, Colbert County, Alabama, U.S.A. Preliminary observations regarding similarities and differences between these two sites are presented in this paper.

Introduction
The Hoa Quang karst area is located in the northern Vietnamese Province of Cao Bang. In 2014, a large number of karst springs, caves, sinking streams, and karst landforms were identified. Eighteen water samples were collected and analyzed for anions, cations, oxygen, and hydrogen stable isotope ratios.

The pH values are typical for karst waters and ranged from 7.23 to 7.97. Specific conductance values ranged from 153.2 to 421.6 µS/cm, the total alkalinity as $CaCO_3$ varies from 125 to 207 mg/L, and the carbon dioxide varies between 40.8 and 123.4 mg/L; whereas the values for the total hardness (as $CaCO_3$) are between 143 and 220 mg/L.

The local meteoric water line, based on our measurements is $\delta^2H = 7.93(\pm0.10)\ \delta^{18}O + 10.45\ (\pm0.86)$ with $r^2=0.998$, which is close to the global meteoric water line (GMWL) $\delta^2H = 8.17\ \delta^{18}O + 10.35$ defined by Craig (1961) and revised by Rozanski, et al. (1993). The intercept value differs very slightly from both local and global water lines. Due to the short sampling period, the information provided by the water stable isotopic composition is limited.

Carbonate rocks underlie many areas of north Alabama. Karst features can be found around Tuscumbia, in northwestern Alabama, which is part of the Tennessee-Alabama-Georgia karst area that is called TAG. TAG has the highest concentration of caves in United States, and home for a few large springs. Tuscumbia Spring is a municipal water supply with a base flow of 1,500 L/s. The field parameters, measured in January 2014, were: pH 6.81, specific conductance 292 uS/cm, and temperature 5.31° Celsius.

In 1989-1990, the Geological Survey of Alabama conducted an extensive investigation in the area, performing dye studies in storm water drainage wells (SDW-1 through SDW-20) to define the recharge area of Tuscumbia Spring. The storm water drainage wells can be a potential source of contamination for the springs. Two rock samples from Vietnam and one from Tuscumbia, Alabama (U.S.A.) were collected and examined using the X-ray diffraction (XRD) analysis, microscopic analysis in polarized light and Differential Scanning Calorimetry-Thermogravimetry (DSC–TG) analysis. The quality of limestones in Vietnam and Tuscumbia (38.7 percent and 39.6 percent versus 31.10 percent calcium concentration) and the amount of precipitation (1,500 to 2,000 mm/m^2 in Vietnam versus 947 mm/m^2 to 1,960 mm/m^2 per year in Tuscumbia) are comparable.

Thick limestone beds, massively jointed, combined with frequent tectonic uplifts and a complex geologic pattern result in the tower karst landscape in Vietnam versus a leveled landscape in Tuscumbia, Alabama. Tectonics is the primary driver for the formation of tower karst landscape in Cao Bang Province, Vietnam.

Karst of Hoa Quang District, Cao Bang Province, Vietnam

Geographic and Climatic Setting

Vietnam is in the eastern part of the Indochinese Peninsula (Figure 1, Insert). It covers a total area of 331,210 km^2 of which mountains, mostly covered by forest, represent 40 percent. Carbonate rocks are exposed over 60,000 km^2, which represents 18.12 percent of Vietnam (Clements et al., 2006).

Cao Bằng Province is located in northeastern Vietnam, 270 kilometers north of Hanoi, on the border with China. The province comprises 6,724.6 km^2 and has a population of 632,450. The topography of the region is characterized by mountain ranges with elevations over 900 m mean sea level (MSL), and karstic plateaus developed between 500 and 700 m MSL. The elevation of the town of Cao Bang is 300 meters MSL and it has a temperate climate throughout the year. Annual rainfall ranges between 1,500 and 2,000 mm/m^2 and temperature varies from 5° Celsius in December and January to 37° Celsius in July and August. The average temperature in the province is 22° Celsius. Winter temperatures in some areas occasionally fall below freezing with snow.

The study area is located in the Hoa Quang Districts. The topography consists of small alluvial plains along the Bac Vong River and its tributaries, with large poljes surrounded by limestone pinnacles and tower karst (Figure 1), sinkholes (dolinas), closed depressions, sinking streams, springs, and large underground streams or submerged passages (Ponta et al., 2013).

Regional Geology

Northeastern Vietnam is in a tectonic active region located at the boundary between the Indian Plate and Eurasian Plate, which created the Himalayas Mountain System and the Tibetan Plateau (Strong Wen et al., 2015). The area is underlain by numerous rock types and ages, which have undergone numerous phases of tectonic deformation from middle Paleozoic to present (Tran Thanh Hai, 2009). The site is located a few kilometers north of Ailao Shan-Red River Shear Zone and Song Ma Fault Zone, which divides North Vietnam into two main tectonic units: The Bac Bo Fold Belt (part of Eurasian Plate/ South China Terrane) and the Indochina Fold Belt (part of Indian Plate/ Indochina Terrane).

The Bac Bo Fold Belt is composed by three fold systems: Tay Bac, Viet Bac and Dong Bac. Cao Bang Province is located in the Dong Bac Fold System. Cao Bang Province is traversed by two deep fault systems, Lo - Gam and Cao Bang - Lang Son, which divide the region into three parts: the western uplift block (the "Viet BAC" with the Bong Son anticline), the central part (Song Hien), and the eastern Ha Lang zone (anticline). The province is underlain by a variety of rocks ranging in age from Cambrian to Quaternary (Long, 2001).

The Viet Bac uplift has Paleozoic rocks outcropping along the NW-SE axis. Between the two deep faults is a Mesozoic low with sedimentary and volcanic rocks of Triassic age (not shown on Figure 1), including iron and manganese deposits. Northeast of the Cao Bang - Lang Son fault, outcrops comprise Paleozoic sediments with complex folds and fault systems (Ha Lang zone, Figure 1).

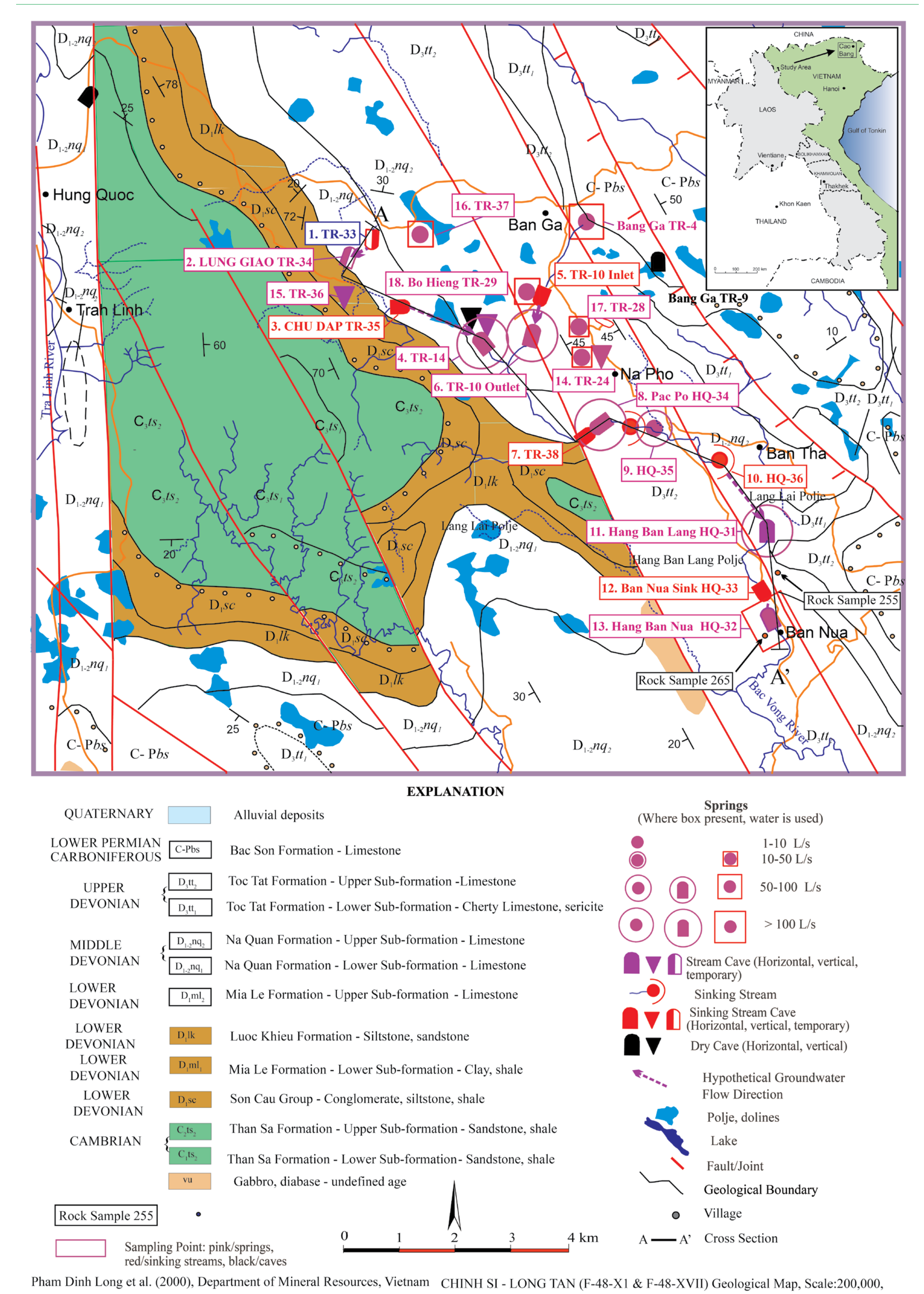

Figure 1. Geological map of Hoa Quang District, Cao Bang Province, Vietnam. Geology after Pham Dinh Long, 2000 (carbonate rocks are shown in white).

Geology of the Hoa Quang District

The Hoa Quang karst area is 15 km long and 14 km wide (210 km^2). The central part of the study area is mainly a NW-SE trending faulted anticlinorium plunging northwestward. The core of the anticline is formed by Cambrian and Devonian sandstones and siltstones belonging to the Than Sa ($C_{1-2}ts^2$) and Luoc Khieu (D_1lk) Formations, intercalated with conglomerates, shale, and clay layers of Lower Devonian age (Son Cau Group [D_1sc] and Mia Le Formation [D_1ml_1]). The western flank is crossed by two parallel faults one km apart, oriented north-south, and the eastern flank by several faults and thrust faults parallel with the anticline's axis, which separates the Na Quan ($D_{1-2}nq_{1-2}$) and Toc Tat (D_3tt_{1-2}) Formations of Devonian age. In the northeastern part of the study area the Bac Son Formation (C-P*bs*) outcrops with siliceous shale, shale-limestone, light gray limestone, and gray limestone (Long, 2001).

The limestone unit is up to 800 m thick, finely crystalline, and light gray to dark gray. Bedding is generally 30 to 50 cm thick, oriented NW-SE, dipping 19° to 25° SW, E, or NE.

Karst Landforms

The northeastern part of Vietnam provides a unique cave-forming environment with large rivers draining into the limestone valleys from the mountains. The Hoa Quang karst has developed into a tower karst landscape that overlooks valleys, poljes, and closed basins. The area underlain by limestones is extensive. Rainfall is abundant and the karst's vertical potential exceeds 200 m. Exokarst landforms are well represented by a variety of karrens, tsingi, small- to medium-sized sinkholes, and poljes. The limestone massifs (tower karst) are traversed by caves that carry rivers from one polje to the next that overlooks valleys, poljes, and closed basins.

East of the anticline, the tributaries of the Bac Vong River flow through a sequence of caves, springs, and poljes (Figure 2, Cross Section A-A'). The Ban Vong's tributaries collect waters a few hundred meters south of the border with China, and disappear underground through temporary or permanent swallets six times along a 13-km path, before resurging in the Hang Ban Nua stream cave (HQ-32) with a flow rate of 800 L/s.

The Hoa Quang area is an old karst where isolated hills (tower karst) remain upon residual plains developed on an 800-m thick limestone unit. As illustrated on cross section A-A' (Figure 2) tower karst emerges at the intersection of the land surface with faults/joints or bedding planes. These structural features appear on the 1:200,000-scale geologic map. More than likely, on a geologic map at a larger scale (1:10,000 to 1:100,000), more structural features will be documented.

The presence of caves, phreatic or vadose, at the contact between towers and alluvial plains (foot-hill caves) are common. In some areas, two levels of cave passages are developed, one as a stream passage at the present flood plain level, and a fossil cave at 50 m higher in elevation, marking a former flood plain level. The springs are "free draining," recharged by allogenic underground streams with a significant autogenic contribution in the rainy season. The flow pattern is dendritic (a branch-work cave pattern where underground passages are present). The type of tower karst landscape developed along the Bac Vong's tributaries and Tra Linh River is "residual hills on a planed limestone surface" (Ford and Williams, 2007).

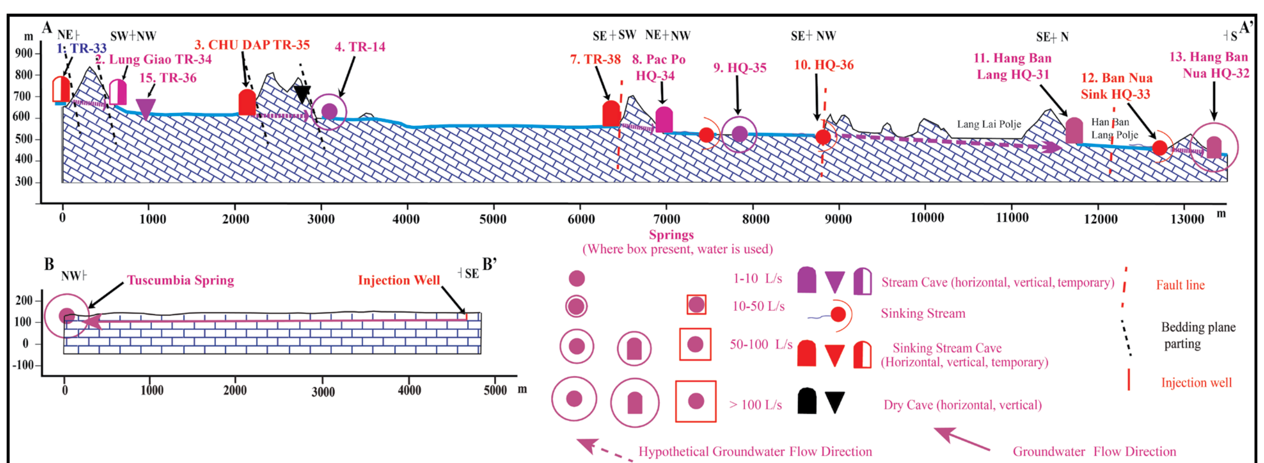

Figure 2. *Cross Section A-A' along Bac Vong River's tributaries, traversing tower karst landscape in Hoa Quang District, Cao Bang Province, Vietnam; B-B' Cross section in Tuscumbia, Alabama, U.S.A.*

Sampling Methods

Eighteen water samples from cave waters (rimstone pools), rainwater, sinking streams, and springs were collected and analyzed for anions, cations, and oxygen and hydrogen isotopes. Selected water-quality parameters (pH, temperature, specific conductance, and salinity) were monitored at each sampling point with an YSI 63 instrument. Additionally, a Digital Titrator (Hach Model 16900) was used in the field to determine total hardness as alkalinity, total hardness as calcium, and carbon dioxide (CO_2); whereas iron was measured with a Hach Ferrous Iron test kit Model IR-18C. UTM coordinates and elevation were recorded with a GPS (Garmin 62S) at each sampling point (Table 1).

Groundwater samples from each source were collected and pre-treated as shown below. Samples for cations were collected in 40 mL vials pre-treated with nitric acid. Samples for anions and stable isotopes were collected in 40 mL vials with no preservatives.

Anion analyses were performed at the University of Alabama using a Dionex DX 600 Ion Chromatograph. The trace metals were analyzed at the Department of Geology, University of South Florida, using a Perkin-Elmer Elan DRC II Quadrupole inductively coupled plasma mass spectrometer (ICP-MS) analytical instrument. Standards used were formulated stock standards with metals in concentrations from 1,000 mg/L to 10,000 mg/L.

The stable isotopes analyses were performed at Stable Isotope Laboratory of the Babeș-Bolyai University, Cluj-Napoca, Romania, using a Picarro L2130-i Cavity Ring Down Spectroscopy (CRDS) instrument.
To evaluate the limestones from the study area, three rock samples (two from Vietnam, and one from Tuscumbia, Alabama, U.S.A) were collected and examined at R&D National Institute for Nonferrous and Rare Metals Romania using the X-ray diffraction (XRD) analysis, microscopic analysis in polarized light, and Differential Scanning Calorimetry- Thermogravimetry (DSC–TG) analysis. The DSC-TG thermic analyses were conducted with Setsys Evolution instrument (Setaram). A Zeiss Axioimager A1m polarizing microscope was used for the thin section analyses, and the X-ray diffraction XRD) analysis was performed with Bruker D8 Advance diffractometer.

Assessment of Results

Water-Quality data

The field parameter data are presented in Table 1. Sampling locations are shown on Figure 1. The elevations of sampling points ranged between 443 m and 641 m MSL. The estimated flow rates of the sampled springs ranged from 0.5 L/s to 800 L/s. The observations were recorded

Sample Number	Sample Name	Type	Elevation	Discharge (Q)	Date	pH	Temperature (°T)	Specific Conductance	Salinity	Total Alkalinity as $CaCO_3$	Carbon Dioxide	Total Hardness as $CaCO_3$
	Units		m (MSL[1/])	l/s			°C	uS/cm	ppt	mg/l	mg/l	mg/l
1	TR-33 (Cave)	Rimstone Pool		0.0	2/5/2014					125.00	40.80	143.00
2	Lung Giao TR-34	Temporary Spring (Cave)		0.0	2/6/2014	7.88	13.50	338.10	0.20	156.00	40.90	169.00
3	Chu Dap TR-35	Sinking Stream	607	1.0	2/6/2014	7.89	17.80	332.50	0.20	170.00	56.60	183.00
4	TR-14	Spring	579	30.0	2/7/2014	7.89	22.50	279.50	0.10	143.00	73.20	154.00
5	TR-10 Inlet	Sinking Stream	599	30.0	2/6/2014	7.92	23.20	293.80	0.10	142.00	63.80	151.00
6	TR-10 Outlet	Captured Spring (Cave)	580	40.0	2/7/2014	7.53	19.60	299.50	0.10	146.00	58.80	158.00
7	TR-38	Sinking Stream (Cave)	569	250.0	2/7/2014	7.95	20.30	301.10	0.10	156.00	41.20	166.00
8	Pac Po HQ-34	Captured Spring (Cave)	535	300.0	2/8/2014	7.97	18.60	153.20	0.10	155.00	55.80	176.00
9	HQ-35	Spring		50.0	2/8/2014	7.40	18.60	314.80	0.20	156.00	88.20	179.00
10	HQ-36	Sinking Stream	518	40.0	2/8/2014	7.59	17.10	206.40	0.10	151.00	94.80	170.00
11	Hang Ban Lang HQ-31	Spring (Cave)	475	100.0	2/5/2014	7.40	22.70	351.10	0.20	162.50	58.40	179.50
12	Ban Nua Sink HQ-33	Sinking Stream		600.0	2/9/2014	7.74	19.90	324.20	0.20	172.00	89.80	194.00
13	Hang Ban Nua HQ-32	Captured Spring (Cave)	443	800.0	2/9/2014	7.75	20.90	314.50	0.20	170.00	76.80	175.00
14	TR-24	Spring (Pothole)		5.0	2/5/2014	7.40	21.60	319.70	0.20	164.00	87.40	172.00
15	TR-36	Pothole	627	0.0	2/6/2014	7.52	19.40	415.30	0.20	200.00	123.40	220.00
16	TR-37	Captured Spring	641	0.5	2/6/2014	7.62	17.50	421.60	0.20	207.00	94.40	209.00
17	TR-28	Spring	594	0.5	2/6/2014	7.53	18.30	395.50	0.20	190.00	56.20	199.00
18	Bo Hieng TR-29	Captured Spring	594	0.5	2/7/2014	7.23	20.70	350.10	0.20	174.00	87.80	182.00

[1/] MSL - Mean See Level
In Red: Water samples collected from sinking streams

Table 1. *Field parameters Hoa Quang District, Cao Bang Province, Vietnam*

in February 2014, at the end of the dry season, so these values are characteristic for base flow.

Temperatures ranged from 13.5° to 23.2° Celsius, which correspond to mean annual air temperature in the area. The pH values ranged from 7.23 to 7.97, typical for karst waters. The values measured for the specific conductance are typical for cave waters (between 153.2 and 421.6 uS/cm). Total alkalinity as $CaCO_3$ varies between 125 and 207 mg/L, the total hardness as $CaCO_3$ varies between 143 and 220 mg/L, and carbon dioxide (CO_2) ranged from 40.8 mg/L to 123.40 mg/L.

Laboratory results for anions and cations are provided in Table 2. Calcium concentration ranged from 51.75 to 81.23 mg/L. The water is classified as calcium-magnesium bicarbonate.

Stable Isotopes

Isotope fractionation accompanying evaporation from the ocean and condensation during atmospheric transport of water vapor causes spatial and temporal variations in the deuterium and ^{18}O composition of precipitation (Dansgaard, 1964). Regional-scale processes such as water vapor transport patterns across landmasses and the average rainout history of the air masses precipitating at a given place control the isotopic composition of local precipitation (Ponta et al., 2013).

Globally, the relation between the $\delta^{18}O$ and δ^2H is mainly explained by the general Rayleigh distillation principle. The relation between the $\delta^{18}O$ and δ^2H values was recognized by Craig (1961), and defined as "global meteoric water line" (GMWL). The complex processes that are involved in the isotope fractionation alter the general (oversimplified) principle and produce local relations (LMWL) between the water $\delta^{18}O$ and δ^2H values.

The relationship between ^{18}O and ^2H in world's fresh surface/cave waters is described by the global meteoric water line (GMWL) defined by Craig (1961) as:

$$\delta^2H = 8\ \delta^{18}O + 10‰.$$

The $\delta^{18}O$ values of the water samples collected ranged from -8.88 to -2.34‰ and the δD values from -58.89 to -7.87‰. The water sample with $\delta^{18}O$ value of -2.34‰ was collected from a rimstone pool in the cave TR33 (Table 1). This sample plots very close to the GMWL, which indicate a close link to a Rayleigh process. Higher values probably are linked to slower infiltration rate of precipitation water from warmer months.
The local meteoric water line (LMWL) in Vietnam is:

$$\delta^2H = 7.91(\pm 0.19)\ \delta^{18}O + 12.44\ (\pm 1.25)$$

with $r^2=0.990$ (Figure 3) on the basis of 38 measurements (between 2004 and 2007) from the IAEA rainfall monitoring station in Hanoi (N21°2'43'', E105°47'55'') (IAEA/WMO, 2015).

The local meteoric water line, based on our measurements (Table 3) is:

$$\delta^2H = 7.93(\pm 0.10)\ \delta^{18}O + 10.45\ (\pm 0.86)$$

with $r^2=0.998$ which is close to the global meteoric water line (GMWL) $\delta^2H = 8.17\ \delta^{18}O + 10.35$ defined by Craig (1961) and revised by Rozanski et al. (1993) The

		CATIONS					ANIONS				
Sample Number	Sample Name	Calcium	Magnesium	Manganese	Potassium	Sodium	Fluoride	Chloride	Nitrate	Phosphate	Sulfate
	Units	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
1	TR-33 (Cave)	57.66	2.32	0.003	0.407	0.76	0.004	2.24	8.72	0.052	8.76
2	Lung Giao TR-34	65.99	2.84	0.008	0.332	0.70	0.000	1.24	3.87	0.012	7.51
3	Chu Dap TR-35	51.75	10.84	0.018	0.607	0.78	0.006	1.60	2.01	0.000	4.60
4	TR-14	50.45	5.38	0.011	0.522	0.88	0.003	1.34	2.25	0.000	5.40
5	TR-10 Inlet	58.07	0.96	**0.125**	0.680	0.96	0.017	1.97	2.79	0.000	5.09
6	TR-10 Outlet	57.46	0.99	0.009	0.530	0.95	0.012	1.90	2.43	0.000	4.93
7	TR-38	56.33	4.66	0.010	0.609	1.07	0.004	1.50	2.30	0.000	5.18
8	Pac Po HQ-34	55.52	4.68	0.008	0.595	0.82	0.009	1.71	2.47	0.000	5.27
9	HQ-35	56.72	4.47	0.010	0.529	0.79	0.009	1.59	3.09	0.000	5.75
10	HQ-36	55.99	4.65	**0.083**	0.703	0.94	0.009	1.79	2.83	0.000	6.06
11	Hang Ban Lang HQ-31	66.52	2.13	**0.021**	0.590	0.77	0.011	1.78	4.13	0.124	4.72
12	Ban Nua Sink HQ-33	64.18	2.77	0.016	0.492	0.78	0.012	1.68	3.48	0.000	4.95
13	Hang Ban Nua HQ-32	65.66	2.94	0.010	0.510	0.95	0.008	1.56	3.38	0.044	4.95
14	TR-24	67.08	0.99	0.006	0.528	0.65	0.007	1.62	3.11	0.109	4.53
15	TR-36	64.58	9.18	**0.082**	0.227	0.87	0.007	1.83	3.26	0.000	5.89
16	TR-37	78.84	3.53	0.005	0.608	1.04	0.036	1.32	0.44	0.000	9.37
17	TR-28	81.23	1.38	0.042	0.116	0.81	0.000	1.21	5.77	0.000	4.63
18	Bo Hieng TR-29	68.64	1.18	0.002	0.353	0.69	0.008	1.00	2.35	0.114	4.32

In Red: Water samples collected from sinking streams

Table 2. *Summary of water-quality data Hoa Quang District, Cao Bang Province, Vietnam*

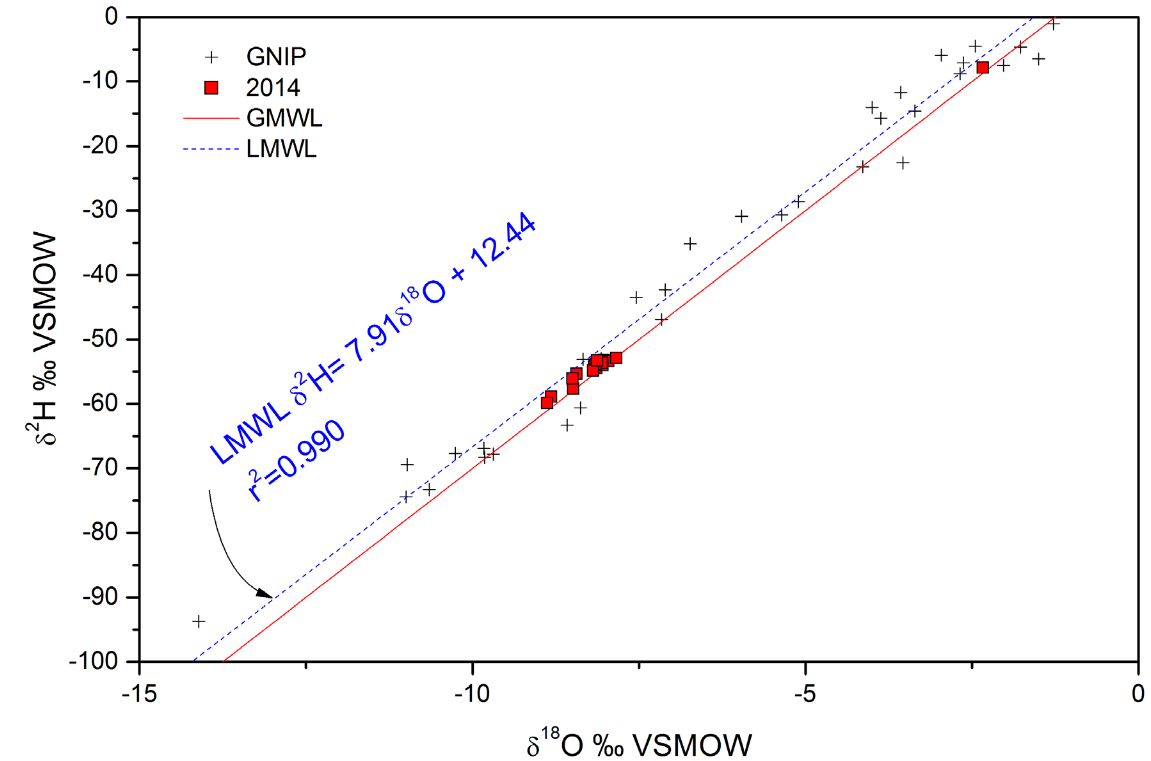

Figure 3. *The relationship between hydrogen and oxygen isotopes in karst waters collected from streams and caves from Vietnam. Additional data used: GNIP (IAEA/WMO, 2015) and GMWL (Craig, 1961)*

intercept value differs very slightly from both local and global water lines. Due to the short sampling period, the information provided by the water stable isotopic composition is limited.

Deuterium excess values, defined as $d = \delta D - 8\delta^{18}O$ (‰) (Dansgaard, 1964), calculated for the collected waters from karst areas (Table 3) are typical for continental meteoric waters (deuterium excess values of ~10 ‰) and have a median value of 11.51 ‰. There are some samples with lesser or higher deuterium excess values due to local variations in humidity, temperature, and wind speed

Karst of Tuscumbia, Alabama

Geographic and Climatic Setting

The Tuscumbia karst area is located in the northwestern part of Alabama (Colbert County), in the southeastern United States (Figure 4, Insert) along the Tennessee River, at latitude 34° N. The area has a mild humid climate. The annual precipitation ranges between 947 and 1960 mm/m² (1980 through 2014) and the average annual temperature is 18.70 Celsius. Occasional freezing temperatures last only a few days.

Regional Geology

The Tuscumbia karst area is located on the southern flank of the Nashville dome, in the Interior Low Plateaus physiographic province. The area is underlain by sedimentary formations of Mississippian age limestones, sandstones, and shales). Local geology is typical of the terrain associated with limestone bedrock, overlain by a mantle of clay-rich, unconsolidated material, 5 to 8 meters thick (Figure 4). The rocks dip generally toward the southwest at 5 m per kilometer (0.3° SW).

The Fort Payne Chert-Tuscumbia Limestone aquifer system with a thickness of 160 meters is the most important water-bearing unit in the Tuscumbia area. It is part of the Mississippian aquifer system that underlies three counties in northwestern Alabama (Colbert, Franklin, and Lawrence). The Chattanooga Shale (not shown on Figure 4), at the base of the aquifer system, restricts the downward movement of water to lower units, which are not known to be water-bearing (Chandler and Moore, 1991).

Sample Number	Sample Name	Date	δ18O	δ2H		
			d18O(VSMOW)‰	dD(VSMOW)‰	dD - GMWL	d-excess
1	TR-33 (Cave)	2/5/14	-2.34	-7.87	-8.72	10.85
2	Lung Giao TR-34	2/6/14	-8.49	-57.66	-57.92	10.26
3	Chu Dap TR-35	2/6/14	-8.44	-55.32	-57.52	12.20
4	TR-14	2/7/14	-8.16	-54.05	-55.28	11.23
5	TR-10 Inlet	2/6/14	-8.03	-53.19	-54.24	11.05
6	TR-10 Outlet	2/7/14	-7.96	-53.34	-53.68	10.34
7	TR-38	2/7/14	-8.17	-54.22	-55.36	11.14
8	Pac Po HQ-34	2/8/14	-8.14	-54.46	-55.12	10.66
9	HQ-35	2/8/14	-8.05	-53.97	-54.40	10.43
10	HQ-36	2/8/14	-7.84	-52.86	-52.72	9.86
11	Hang Ban Lang HQ-31	2/5/14	-8.06	-53.64	-54.48	10.84
12	Ban Nua Sink HQ-33	2/9/14	-8.15	-53.85	-55.20	11.35
13	Hang Ban Nua HQ-32	2/9/2014	-8.15	-53.90	-55.20	11.30
14	TR-24	2/5/2014	-8.19	-54.80	-55.52	10.72
15	TR-36	2/6/2014	-8.82	-58.89	-60.56	11.67
16	TR-37	2/6/2014	-8.13	-53.27	-55.04	11.77
17	TR-28	2/6/2014	-8.88	-59.88	-61.04	11.16
18	Bo Hieng TR-29	2/7/2014	-8.50	-56.06	-58.00	11.94
In Red: Water samples collected from sinking streams						

Table 3. *Summary of stable isotopes data Hoa Quang District, Cao Bang Province, Vietnam*

Geology of the Tuscumbia Area

The study area is 12 km long and 12 km wide (144 km^2). The Fort Payne Chert (not shown on Figure 4) of Lower Mississippian age consists predominantly of medium gray to light gray and white crystalline limestone containing abundant light gray to black bedded and nodular chert (Szabo, 1975).

Tuscumbia limestone (Mt) of Valmeyeran age is a medium-bedded light bluish-gray hard, dense, fine- to medium-grained bioclastic limestone containing abundant light-colored bedded and nodular chert (Szabo, 1975). The Tuscumbia limestone is overlain by the Pride Mountain Formation (Mpm) of Chesterian age and consists of shale, a basal limestone up to 3 m thick, and sandstone and siltstone (Szabo, 1975).

The Hartselle sandstone (Mh) is a light gray massive to thin-bedded quartzose sandstone, which unconformably overlies the Pride Mountain Formation (Szabo, 1975). The system of fractures (joints) at the site consists of a northwest-trending set, as evidenced by the alignment of closed depressions and sinkholes in the area (Figure 4), and a southwest-trending set identified through lineament interpretations by Chandler and Moore in 1991.

Karst Landforms

The karst plain developed at 152 m MSL in the study area looks like a river bedrock terrace. It is part of a mature karst with low topographic relief except for the southern edge of Pickwick Lake, where limestone bluffs occur (Chandler and Moore, 1991). Exokarst landforms are well represented by a variety of small to medium-sized sinkholes and closed depressions (Figure 2, Cross Section B-B').

The sinkholes were formed by the gradual removal, by solution, of the limestone at the base of the Pride Mountain Formation (Chandler and Moore, 1991). Sinkholes in this area are very effective in collecting surface runoff waters. The drainage is primarily subterranean (Johnston, 1933). Spring Creek, with its tributaries, is the only surface stream that crosses the sinkhole plain (Johnston, 1933).

Due to urban development, some of the karst features represented on Figure 4 (based on a 1975 7.5-minute

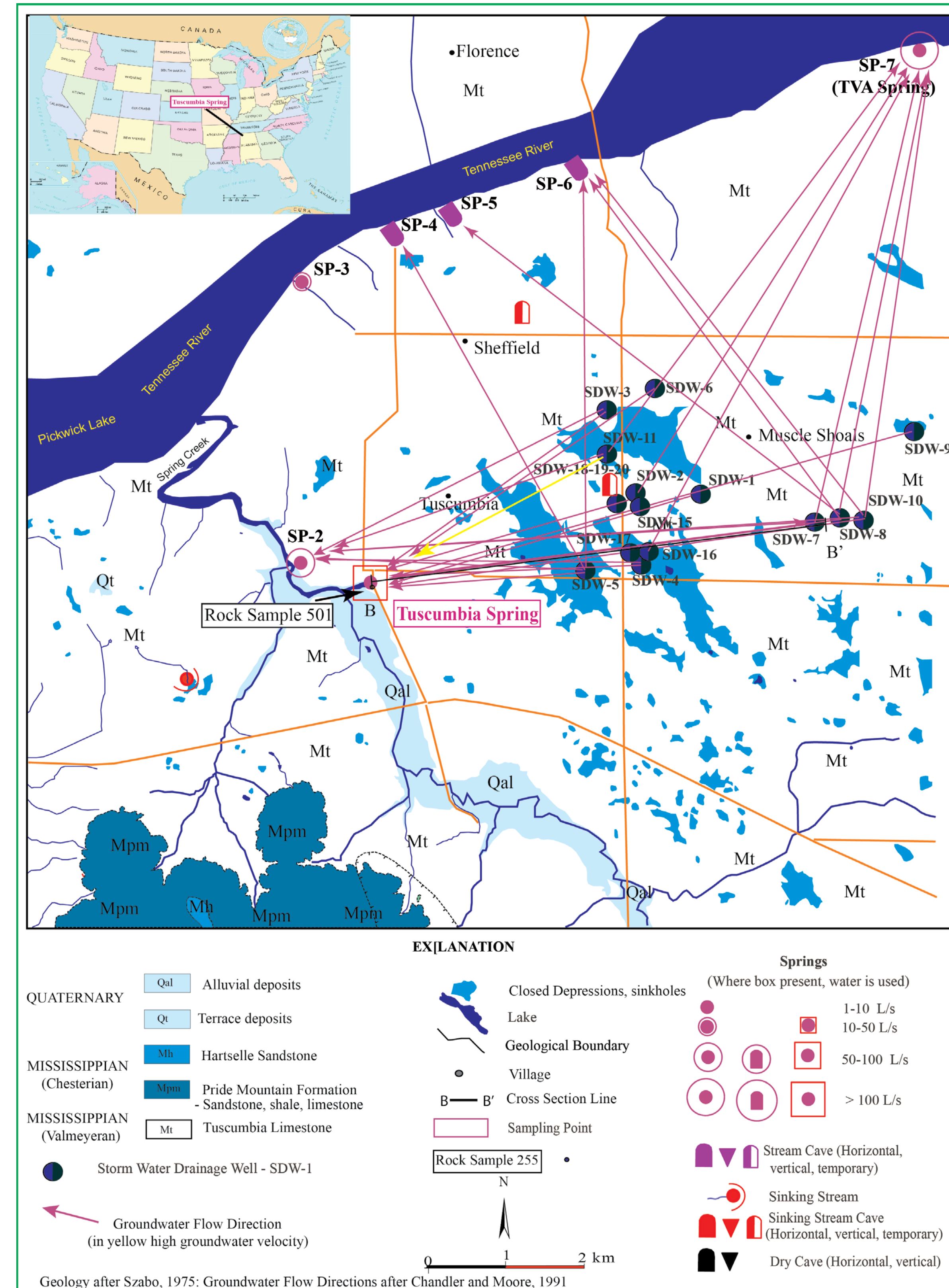

Figure 4. *Geological map of Tuscumbia, Alabama U.S.A. Geology after Szabo 1975. Groundwater Flow Directions after Chandler and Moore 1993 (carbonate rocks shown in white).*

topographic/geologic map) are difficult to identify today. The majority of the depressions were filled to accommodate the construction of dwellings or industrial facilities.

Tuscumbia Spring is a municipal water supply source with a base flow of 1,500 L/s. According to the Geological Survey of Alabama's Groundwater Assessment Program (Real Time Monitoring), between May 22, 2013, and February 9, 2015, the average flow was 2,133 L/s with a minimum of 1,423 L/s and a maximum of 6,211 L/s (Geological Survey of Alabama webpage). The field parameters, measured in January 2014, were: pH 6.81, specific conductance 292 uS/cm, and temperature 15.310^o Celsius. The recharge area of Tuscumbia Spring is 218 km^2.

Dye Studies

In 1989-1990, the Geological Survey of Alabama conducted an extensive investigation in the area, performing dye trace testing to define the recharge area of Tuscumbia Spring. Seventeen storm water drainage wells were selected for the dye study. The results of fluorescent dye-trace testing indicate that hydrologic interconnections exist between 17 wells and springs of the Tuscumbia area (Table 4).

Strong recoveries of tracers at Tuscumbia Spring were recorded from SDW-11 and SDW-16 (Figure 4, Table 4). The travel-time data (3 hours) and high groundwater velocities (463 m to 705 m/h) indicate channelized flow conditions between Tuscumbia Spring and storm water drainage well SDW-11. The water is of the calcium-sodium-bicarbonate-sulfate-chloride type, slightly alkaline and hard, but low in mineral and chemical constituents (Chandler and Moore, 1993).

Rock samples

Laboratory results are provided in Table 5. The two rock samples collected in Vietnam (latitude 22^o N., Figure 1) had calcium concentrations ranging from 38.7 percent and 39.6 percent, while the magnesium concentration fluctuated between 0.14 percent and 0.16 percent. The presence of silica was insignificant. The microscopic analysis in polarized light revealed that both samples collected in Vietnam are micritic limestones with veins filled with secondary calcite spar. The sample collected in Tuscumbia Alabama, U.S.A., (latitude 34^o N., Figure 4) had a calcium concentration of 31.1 percent, silica 8.9 percent, and 0.28 percent aluminum. The thin section reveals that the rock is a siliceous micritic limestone, coarsening to bioclastic wackestone and calcite spar. The assessment revealed chemical, mineralogical and petrographic differences between the samples, allowing classification into two categories of carbonate rocks: limestone (Hoa Quang) and siliceous limestone (Tuscumbia).

Summary

1. Hoa Quang, Vietnam is at latitude 22^o N., in the peri-tropical zone of excessive planation. Tuscumbia, Alabama, is located at latitude 34^o N., in a subtropical zone of mixed relief development (Budel, 1977).
2. In the area studied in Vietnam, bedding is generally 30 to 50 cm thick, oriented northwest-southeast, and dipping 19^o to 25^o southwest or northeast; the Tuscumbia limestone in Alabama (50 to 100 cm thick) dips gently southwestward at approximately 4.8 to 5.7 m per kilometer (0.3^o SW) (Szabo, 1975).
3. The two rock samples collected in Vietnam (Figure 1) have calcium concentrations ranging from 38.7 percent siliceous limestone to 39.6 percent, whereas the sample collected in Tuscumbia Alabama, U.S.A., (Figure 4) has a calcium concentration of 31.1 percent (with 8.9 percent silica, and 0.28 percent aluminum). In both cases, the carbonate rocks are middle to upper Paleozoic age.
4. In Vietnam, the central part of the study area is mainly a northwest-southeast trending faulted anticlinorium plunging toward the northwest. The western flank is traversed by two parallel faults one km apart, oriented north-south, and the eastern flank by several faults and thrust faults parallel with the anticline's axis.
5. In Tuscumbia, Alabama, on the 7.5-minute topographic/geological map (Szabo, 1975) no faults/joints are mapped. In Chandler and Moore's 1991 publication, relatively dense sets of lineaments oriented mainly northwest-southeast and northeast-southwest are interpreted from LANDSAT imagery, high altitude black and white, color photography, and 7.5-minute topographic maps.
6. The amount of precipitation in Tuscumbia, Alabama, ranged between 947 mm/m^2 to 1,960 mm/m^2 per year versus 1,500 to 2,000 mm/m^2 per year in Vietnam.
7. In the water samples collected in Vietnam, the amount of dissolved carbon dioxide (CO_2) ranged from 40.8 mg/L to 123.40 mg/L (Table 1) and calcium concentration ranged between 51.75 to 81.23 mg/L (Table 2).
8. In Vietnam, the flow network is dendritic with streams recharged by epigenetic springs and meteoric water. In Tuscumbia, Alabama, the surface flow pattern is poorly organized.
9. The maximum discharge of a spring in Vietnam is 800 L/s versus a base flow of 1500 L/s in Tuscumbia. The waters in Tuscumbia, Alabama, are collected from 280 km^2 versus 20 to 30 km^2 in Vietnam.

Tested Well/Injection Point		TUSCUMBIA SPRING (SP-1)	SP-2	SP-3	SP-4	SP-5	SP-6	SP-7
Flow (L/s)		200 - 905	0.0 6- 100	3.7 - 35	0.3 - 4	0.03 - 0.63	0.03 - 0.63	135 - 891
SDW-1	Distance (km)	4.51	5.31	5.63	5.15	4.99	4.67	6.44
	Travel Time (Days)	20						
SDW-2	Distance (km)	3.54	4.51	5.15	4.67	4.67	4.51	7.08
	Travel Time (Days)	20						
SDW-3	Distance (km)	4.02	4.67	4.34	3.70	3.38	3.38	6.11
	Travel Time (Days)	<1	5					
SDW-4	Distance (km)	3.54	4.51	5.63	5.31	5.15	5.31	5.63
	Travel Time (Days)	<1	<1					
SDW-5	Distance (km)	2.90	3.86	5.15	5.15	5.15	5.31	8.05
	Travel Time (Days)	<1	<1		10		5	
SDW-6	Distance (km)	4.51	5.15	4.67	3.86	3.54	3.22	5.63
	Travel Time (Days)	<1			<1			
SDW-7	Distance (km)	5.63	6.60	7.08	6.60	6.28	5.63	6.44
	Travel Time (Days)	5	5					<1
SDW-8	Distance (km)	5.95	6.92	7.24	6.76	6.28	5.79	6.28
	Travel Time (Days)	5				<1	<1	<1
SDW-9	Distance (km)	7.24	8.05	8.05	7.08	6.60	5.63	5.15
	Travel Time (Days)	5						
SDW-10	Distance (km)	6.28	7.24	7.56	6.92	6.60	5.95	6.28
	Travel Time (Days)	5	5				5.000	<1
	Velocity (m/h)	30.7 - 31.82						
SDW-11	Distance (km)	3.54	4.34	4.51	4.02	3.86	3.86	6.60
	Travel Time (Days)	<1	<1					<1
	Velocity (m/h)	462 - 705						
SDW-15	Distance (km)	3.54	4.51	5.15	4.67	4.67	4.51	7.08
	Travel Time (Days)	19	15		15			
SDW-16	Distance (km)	3.45	4.51	5.63	5.31	5.15	5.31	7.56
	Travel Time (Days)	<1	<1					29
	Velocity (m/h)	19.75 - 20.8						
SDW-17	Distance (km)	3.38	4.34	5.47	5.31	5.15	5.31	7.56
	Travel Time (Days)		<1				<1	<1
SDW-18	Distance (km)	3.54	4.34	4.99	4.67	4.51	4.51	6.92
	Travel Time (Days)		<1		5			<1
SDW-19	Distance (km)	3.54	4.34	4.99	4.67	4.51	4.51	6.92
	Travel Time (Days)		5					<1
SDW-20	Distance (km)	3.54	4.34	4.99	4.67	4.51	4.51	6.92
	Travel Time (Days)	<1	5.00	<1	10	19	<1	<1

Table 4. *Summary of dye study data Tuscumbia Alabama from Chandler and Moore 1991*

Sample Number	Sample Name	Northing (Y Coordinates)	Easting (X Coordinates)	Elevation	Date	Calcium (Ca)	Magnesium (Mg)	Silica (Si)	Aluminium (Al)	Iron (Fe)	Rock Type
	Units	UTM	UTM	m (MSL [1/])		%	%	%	%	%	
1	Rock sample # 264 (Hang Ban Lang HQ 32) Vietnam	48Q 2517455.96 m N	648889.47 m E	443	2/5/2014	**38.70**	0.14	0.005	0.002	0.011	Limestone-Micrite vein filled with a second generation of calcite spar
2	Rock Sample # 255 (Ban Nua Sink HQ 33), Vietnam	48Q 2517966.67 m N	648743.99 m E	512	2/6/2014	**39.60**	0.16	0.008	0.002	0.017	Limestone-Micrite vein filled with a second generation of calcite spar
3	Rock Sample # 501 (Tuscumbia), Alabama, U.S.A	16S 3843309.03 m N	435637.82 m E	132	2/7/2014	31.10	0.23	**8.900**	**0.028**	0.060	Siliceous Limestone-Micrite coarsening to bioclastic wackestone and calcite spar

[1/] MSL - Mean See Level

Table 5. *Summary of rock sample data*

Conclusions

The Hoa Quang karst has developed into a tower karst landscape that overlooks valleys, poljes, and closed basins. The area underlain by limestones is extensive. Rainfall is abundant and the karst's vertical potential exceeds 200 m. Exokarst landforms are well represented by a variety of karrens, tsingi, small- to medium-sized sinkholes, and poljes.

As shown on cross section A-A', the tower karst in Vietnam emerges at the intersection of the land surface with a fault/joint or a bedding plane parting. These structural features appear on the 1:200,000-scale (medium scale) geologic map. More than likely, when a geologic map at a larger scale (1:10,000 to 1:100,000) is prepared, more structural features will be documented.

The base map for the Tuscumbia area is a 1:24,000-scale topographic/geologic map. No fractures or faults are shown and the bedding planes are nearly horizontal. The quality of limestones in Vietnam and Tuscumbia (38.7 percent and 39.6 percent versus 31.10 percent calcium concentration) and the amount of precipitation (1,500 to 2,000 mm/m^2 in Vietnam versus 947 mm/m^2 to 1,960 mm/m^2 per year in Tuscumbia) are comparable.

Thick limestone beds, massively jointed, combined with frequent tectonic uplifts and a complex geologic pattern result in the tower karst landscape in Vietnam versus a leveled landscape in Tuscumbia, Alabama (Figure 2). Tectonics is the primary driver for the formation of tower karst landscape in Cao Bang Province, Vietnam.

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