



# Development and structure of karstification of the Dong Van Karst Plateau UNESCO Global Geopark, North Vietnam based on cave survey data

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## Abstract

This paper presents a quantitative study of the relationship between the cave system and the tectonic and karst evolution of the Dong Van Karst Plateau based on analysis and statistics of geometric parameters and orientation of cave passages. The region is located in northern Vietnam and belongs to the extended part of the South China karst belt (Yunnan karst plateau), which is composed mainly of carbonate rocks. Cave classification based on cave conduits geometric parameters shows that caves developed mainly in the vadose zone (27 vadose branchwork caves, 10 mixed caves developed under the control of fault systems, and 12 water-table caves). The degree of correlation between cave levels and planation surfaces suggests that the development of horizontal cave passages is related to two levels of planation surfaces, including one at 1250–1450 masl (equivalent to cave level at 1350–1450 masl), and at 1000–1250 masl (corresponding to cave level at 1200–1250 masl). Additionally, cave passage orientation shows that the cave system formed and developed under the influence of tectonic activities in the Cenozoic. The dominant orientation trend is roughly in the East–West direction and occurred in the early phase (Eocene–Miocene). Next is a trend roughly North–South that occurred in the late phase (Pliocene–Quaternary). The last orientation trend follows the NW–SE direction due to the reactivation of paleo-fault systems in the same direction. Although there are limitations due to accessibility and the level of cave exploration, this research suggests that analysis and statistics of the geometric parameters and orientation of cave passages based on cave survey data can be one of the effective approaches used to identify the development and structure of karstification in the karst region.

**Keywords** Speleogenesis · Geometric analysis · Cave passage orientation · Dong Van Karst Plateau UNESCO Global Geopark · Karstification

## Introduction

Dong Van Karst Plateau is located in northern Vietnam and belongs to the extended part of the South China karst belt (Yunnan karst plateau) (Fig. 1b). Besides its geological, geomorphologic, stratigraphic and paleontological features and values, this area is also characterized by extensive and varied karst and cave development. Karst and cave systems are not only valuable in terms of landscape, tourism and subsurface biodiversity, but caves are also places where information about paleoclimatic conditions and tectonic evolution can be recorded (Goldscheider 2019).

In this area, the average altitude is about 1500 m, up to 1800 m at some places, whereas the local erosional base is rather low, only about 200–300 m at the Nhiem River in the south or 400–500 m along the Nho Que River in the north and east (Fig. 1c). The topsoil layer is rarely conserved

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and surface streams are mostly short, becoming dry soon after the rainy season, most of them sink underground at cave entrances or sinkholes (Van et al. 2004). Several studies (Van et al. 2010, Hai et al. 2013) have shown that the distribution of cave systems, planation surfaces, and stream terraces/valleys at different elevations in this area depend on tectonic movements combined with geomorphologic development processes that occurred in cycles during the Cenozoic period. However, two major research questions that need to be clarified are: (1) When and how did the main phases of karst evolution occur? (2) How are these phases related to the tectonic and geomorphologic development of the wider region? We used cave survey data, along with topographic and geologic data, to answer these questions.

Studying caves is a challenge because, except for entrance areas, caves are largely hidden from view, so using systematic documentation of cave survey data is the main key to provide a basis for this kind of research (Kambesis 2007). In recent years, many studies have shown that the formation of karst and cave systems is chiefly controlled by a complex combination of tectonic activities, geomorphic evolution, climatic and hydrologic processes. From the tectonic point of view, Palmer (1991) showed that 42% cave passage of his data set was controlled by faults/fractures, while Littva et al. (2015), Shanov et al. (2015) mention the relationship between cave passage orientation and the neotectonics stress field. Several previous studies (Ford 1971; Palmer 1991, 2009; Klimchouk 2009, 2016; Wagner et al. 2011; Audra and Palmer, 2017) indicate that the conduit network has close relations with landscape evolution and local geology, which are controlled by several factors, such as lithology, tectonics and stratigraphic boundaries. Palmer (1991) classified geomorphologic cave patterns based on speleogenetic context, while Jouves (2017) and Collon (2017) determine these cave patterns through quantitative statistics of morphometric parameters of cave conduits. In addition, the studies of Palmer (1987), Filipponi (2009), Piccini (2011) and Labib (2019) indicate that the occurrence of horizontal levels of cave passages is caused by hydrological factors when the cave passage acted as an underground water conduit in a relatively stable tectonic period. Analysis of the horizontal cave passages can be used to identify the cave levels as a consistent indicator of tectonic periods and karst evolution phases. Thus, analysis and statistics of the geometric parameters and orientation of cave passages are one of the effective approaches used to identify the relationship between the cave system and the tectonic and geomorphologic development processes based on cave survey data.

In this study, by applying the above approach, through analysis and statistics of geometric parameters and orientation of cave passages, cave survey data were used to clarify the development and structure of karstification of the Dong Van Karst Plateau.

## Overview of the study area

The study area is located in Dong Van, Meo Vac district, covering an area of about 620 km<sup>2</sup>, which is composed mainly (more than 60%) of carbonate rocks. The boundary of this area is delineated by Ma Le Stream and North Dong Van fault zone in the north, Nho Que River fault zone in the northeast, Na De–Meo Vac fault zone in the south, and Nhiem River fault zone in the southwest (Fig. 2b, 3).

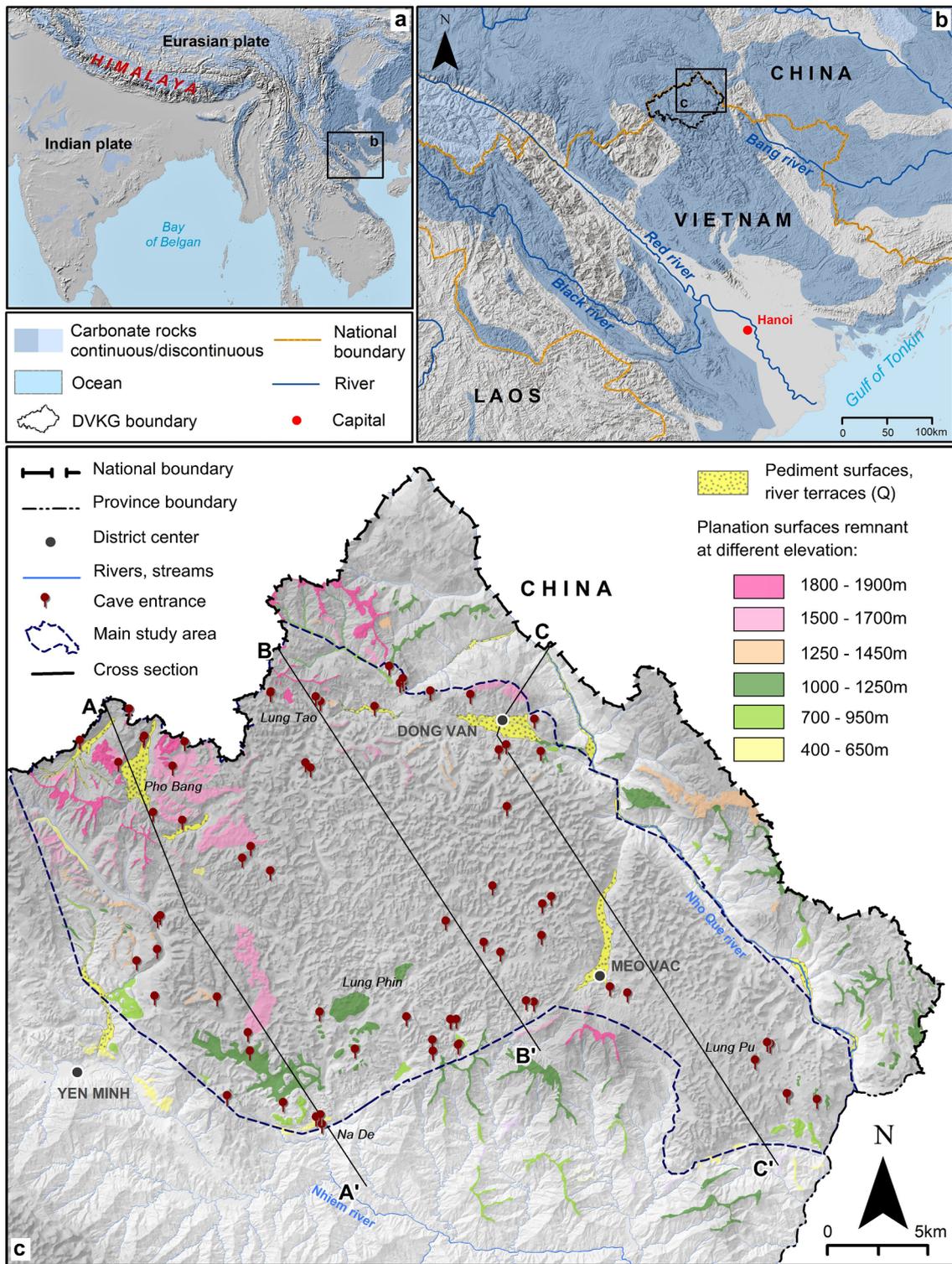
To provide a more general view of the main study area, basic information on geological setting, planation surfaces, and cave systems will be presented and analyzed based on published research, digital elevation models (DEM), unpublished cave data (provided by University of Leuven's caving club, Belgium-SPEKUL), and personal fieldwork.

## Geological setting

According to previous and recently updated geological maps, the study area is composed of sedimentary formations from Paleozoic to Mesozoic, and local outcrops of Triassic gabbro and diabase along deep faults (Fig. 2). Carbonate rock formations, including Bac Son (C–P *bs*), Dong Dang (P<sub>2</sub> *đđ*) and Hong Ngai (T<sub>1</sub> *hn*), are widely distributed in the central part of karst plateau, and caves are mainly developed in these formations. The Devonian formations including Mia Le (D<sub>1</sub> *ml*), Si Phai (D<sub>1–2</sub> *sp*) and Toc Tat (D<sub>3</sub> *tt*) occur in narrow bands, located along the north and northeast. In addition, Triassic formations, including Song Hien (T<sub>1</sub> *sh*) and Yen Binh (T<sub>2a</sub> *yb*), are distributed in the South and SW of this area.

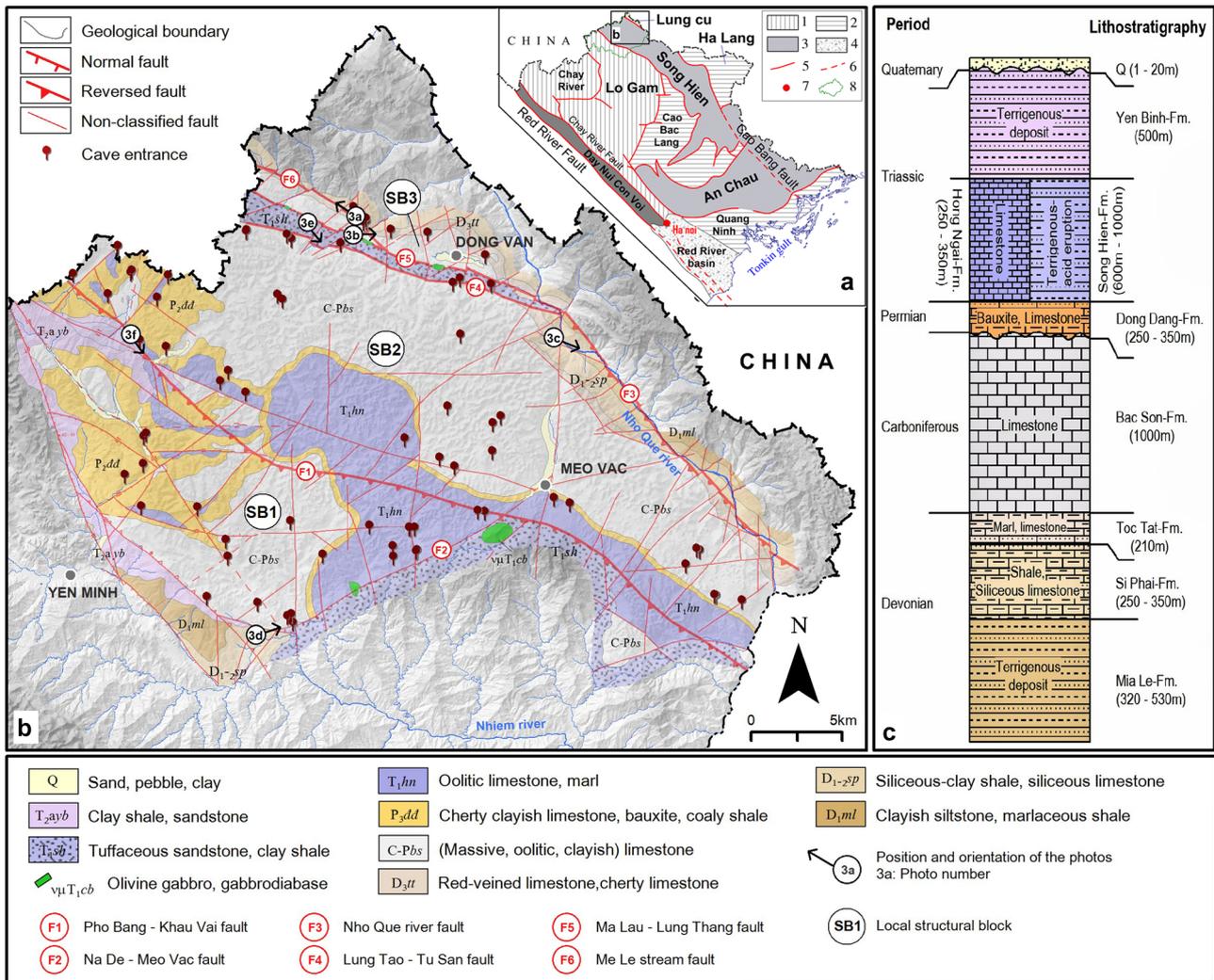
Dong Van Karst Plateau belongs to three tectonic structural zones, including from SW to NE Lo Gam Zone, Song Hien Zone and Lung Cu Zone (Tri et al. 2009) (Fig. 2a). Together they form a large structure shaped like a synclorium extending in the NW–SE direction. The main study area is entirely located in Song Hien zone, mainly composed of Carboniferous–Permian–Triassic carbonate rock and Early Triassic terrigenous acid eruption deposits.

Northeast Vietnam has a long history of tectonic development from Mid-Paleozoic to Cenozoic; however, only two tectonic phases occurring in Mesozoic and Cenozoic have been recorded in the study area. In the Mesozoic, the late Triassic Indosinian orogeny phase occurred consisting in large scale folding and faulting in an overthrust (Hai et al. 2013) (Fig. 3b). In the Neotectonic period two types of tectonics developed according to the two-phase deformation model due to the collision between the Indian and Eurasian plates occurring in Paleogene (Molnar et al. 1993; Tri et al. 2009; Hai et al. 2013). In the first phase (Eocene–Miocene), the geodynamic regime was characterized by a tectonic stress field with sub-latitude compression and sub-meridian



**Fig. 1** Map of the investigation area. **a** Location map of Northern Vietnam illustrating the physiographic impact of the collision between the Indian and Eurasian plates; **b** Location of Dong Van Karst Plateau in the Northern Vietnam and South China karst belt

(based on the World Karst Aquifer Map, Goldscheider et al. 2020); **c** Location map of the main study area shows the distribution of cave entrances, planation/pediment surfaces, and river terrace remnants at different altitudes on top of a DEM (After Tuy in Van et al. 2010)



**Fig. 2** Geological setting of the study area. **a** Study area position in the main structural zone in NE Vietnam (After Tri et al. 2009) (Legend: 1-Viet Bac fold system; 2-Dong Bac fold system; 3-Mesozoic riftogenen superimposed depression; 4-Neogene-Quaternary basin;

5-Accurate fault zone; 6-Supposed fault zone; 7-Capital position; 8-DVKP UGG boundary); **b** Geological map (After Tinh et al. 1976; Updated by KaWaTech project); **c** Lithostratigraphic profile

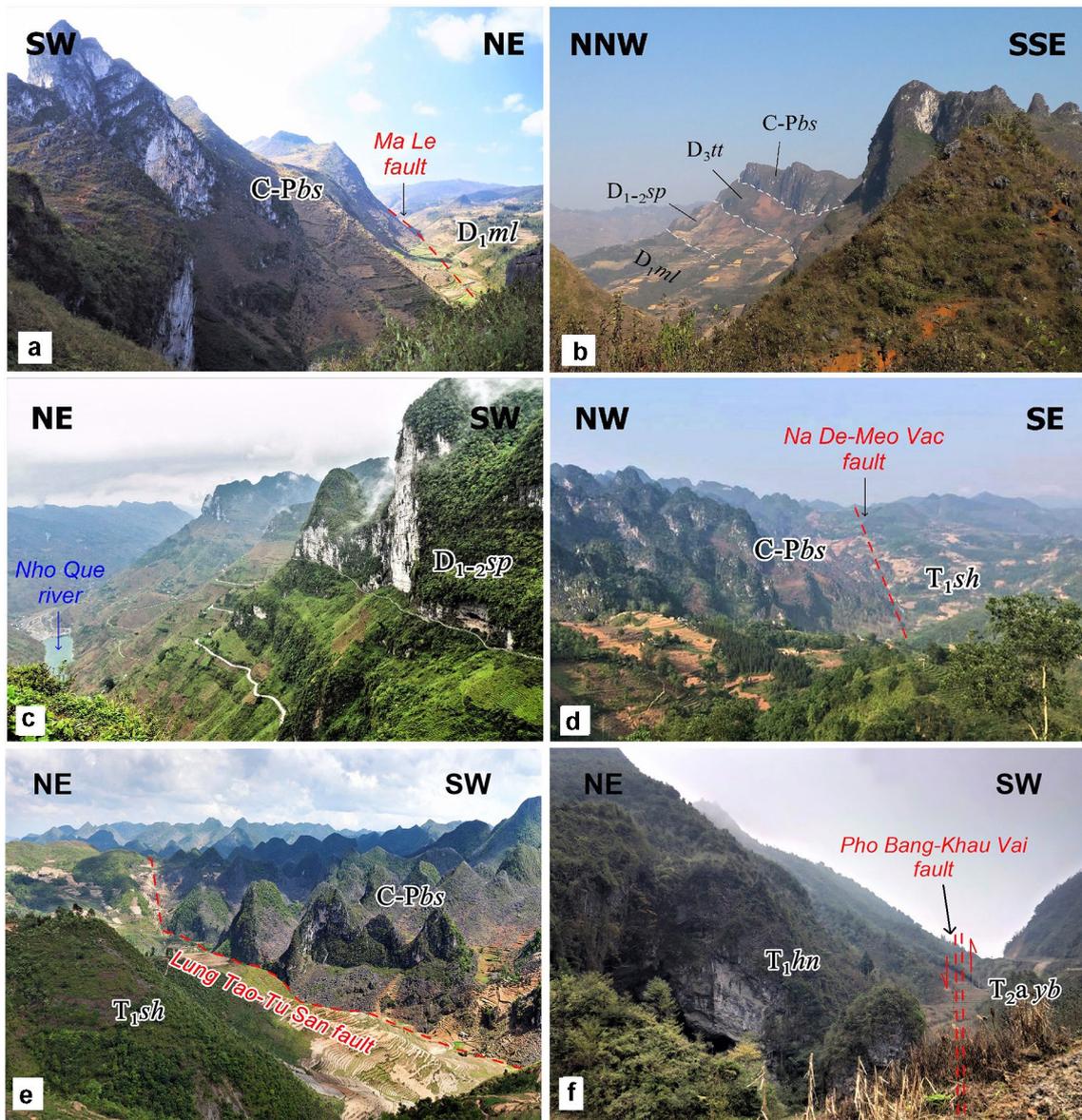
extension (Tapponnier et al. 1990). In the later phase (Pliocene–Quaternary), the tectonic stress field changed into sub-meridian compression and sub-latitude extension (Wang et al. 1998). In summary, if the Indosinian tectonic process plays an important role in shaping geologic structure, the strong activities of fault systems in Neotectonic is considered a factor controlling the formation and development of the topographic landscape, especially karst and cave systems in the Dong Van Karst Plateau.

The study area is dissected by many fault systems (Fig. 2b), but the main one is the NW–SE fault system, include Pho Bang–Khau Vai fault (F1), Nho Que river fault (F3), Lung Tao–Tu San fault (F4), Ma Lau–Dong Van–Lung Thang fault (F5) và Ma Le stream fault (F6) and some of them are in a structural fault zone (F1, F4). In addition, there

is the appearance of fault system with NE–SW direction such as Na De–Meo Vac fault (F2), especially sub-latitude and sub-meridian fault systems formed in the Neotectonic period such as Meo Vac fault with sub-meridian direction.

**Planation surfaces**

There are a number of studies on karst geomorphology-related denudation planation surfaces in Dong Van Karst Plateau and surrounding areas. A study by Chen (1993) determined that the 1600–2000 masl planation surface in Guizhou and the > 2000 masl surface in East Yunnan (belonging to the Guizhou-Yunnan karst region, South China) are of Paleogene age, while the 1700–1900 masl karst forest in East Yunnan is Pliocene in age. After that, An et al. (2008) when



**Fig. 3** Photos showing the karst landscape and important geological structures in the study area; **a** Ma Le stream fault zone; **b** Overthrust fault zone North Dong Van; **c** Nho Que River fault zone, **d** Na De-

Meo Vac fault zone; **e** Lung Tao–Tu San fault zone; **f** Pho Bang–Khau Vai fault zone

studying the Dong Van Karst Plateau, identified five levels of planation surface that can be compared with planation surfaces in South China–North Indochina blocks. The planation surface at an altitude of 1800–1900 masl corresponds to Middle Paleogene; the 1500–1600 masl planation surface corresponds to Early–Middle Miocene; the 1200–1300 masl surface corresponds to Late Miocene; the 800–1000 masl surface corresponds to Pliocene; and the 400–600 masl surface corresponds to Quaternary. Tuy in Van et al. (2010) has established the geomorphological map of the DVKP area showing six planation surfaces distinguished on the basis of previous studies. Accordingly, the planation

surfaces in DVKP are the result of the cyclical activity of Neotectonic movements. At the beginning of each cycle, the terrain was uplifted and dissected. The end of each cycle corresponded to a tectonically stable period, which favored the processes of erosion, transportation, and accumulation, leading to the formation of a fairly flat surface at the local erosion level. Specifically, six planation surfaces include: (1) Paleogene ( $E_2$ – $E_3$ ) at 1700–1900 masl; (2) Early–Middle Miocene ( $N_1^{1-2}$ ) at 1500–1700 masl; (3) Late Miocene ( $N_1^3$ ) at 1300–1500 masl; (4) Late Miocene ( $N_1^3$ ) at 1000–1300 masl; (5) Early–Middle Pliocene ( $N_2^{1-2}$ ) at 750–950 masl; and (6) Late Pliocene ( $N_2^3$ ) at 400–650 masl. The relative

age of the planation surfaces is determined by the presence of Neogene deposits ( $N_1^3$ ) in the southern Dong Van valley at 1000–1300 masl.

In this study, to accurately identify the elevation of the planation surfaces, a morphological analysis was performed by means of a series of topographic cross-sections, based on earlier studies concerning the evolution and classification of planation surfaces (An et al. 2008; Tuy in Van et al. 2010). As a result, six planation surfaces are identified (Fig. 1c, 4):

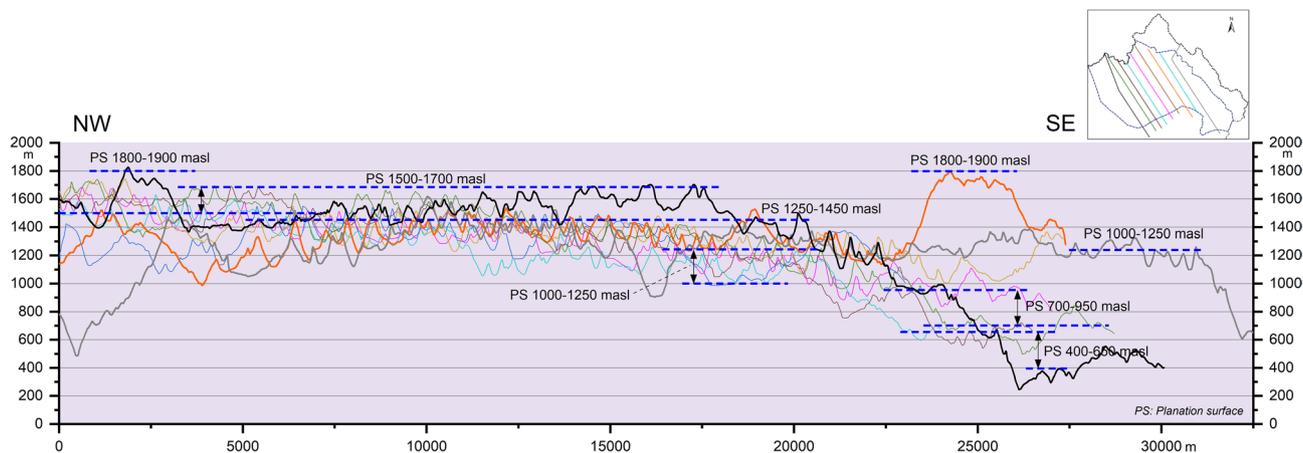
- The Paleogene planation at 1800–1900 masl ( $E_2$ ) approximates the original surface atop the massif, which remains only at the top of the mountains on the west of the study area;
- The Early–Middle Miocene planation at 1500–1700 masl ( $N_1^{1-2}$ ) is present as incomplete planation surface divided by valleys in the southwestern part of the study area and north Dong Van;
- The Late Miocene planation at 1250–1450 masl ( $N_1^3$ ) remains as flat areas on the drainage divide zone of the limestone area east of the study area, south of Dong Van, and the flat areas along the Pho Bang, Pho Cao valleys in the western part of the region;
- The Late Miocene planation at 1000–1250 masl ( $N_1^3$ ) consists of flat areas on the drainage divide zone in the karst and non-karst area, or areas with karst towers of similar altitudes;
- The Early–Middle Pliocene planation at 700–950 masl ( $N_2^{1-2}$ ) is distributed in narrow areas, mainly in form of incomplete planation surfaces on mountain shoulders in limestone areas and along drainage divides in terrigenous rocky areas south of study area;
- The Late Pliocene planation at 400–650 masl ( $N_2^3$ ) is distributed in narrow flat areas with shallow slopes along

the river valleys in the south area (Na De, Mau Due). In addition, high river terraces (river erosion) at different altitudes with Early Pleistocene age ( $Q_1^1$ ) also appear on the pediment surfaces (Nhiem, Nho Que river valley).

### Cave systems

According to the survey data, more than 135 caves were explored with a total of up to 39 km of cave passage mapped so far on Dong Van Karst Plateau (Masschelein et al. 2007; Bontridder et al. 2010). In which, 73 caves were discovered in the main study area, and most of them are developed in three carbonate rock formations including Bac Son ( $C-P_{bs}$ ), Dong Dang ( $P_2_{dd}$ ) and Hong Ngai ( $T_1_{hn}$ ).

Due to different petrographic properties, caves developed in each formation have different characteristics. Bac Son formation is composed of homogeneous, massive, partly dolomitized limestone, totaling in thickness 700–1000 m, so the mapped caves in this unit are usually deep and long. Dong Dang formation consists of layers of limestone, clay-rich limestone, siliceous limestone, medium to thin-bedded in the upper part which is a favorable environment for the formation of caves. However, the bottom part comprising siltstone, claystone, bauxite, shale, is insoluble, so most of the caves are stopped or develop horizontally here. Therefore, in Dong Dang formation, caves are short, horizontal, or in the form of sinkholes with the bottom filled by rockfall blocks and sediment. Hong Ngai formation is composed of layers of argillaceous limestone, siliceous limestone, and medium-to-thick-bedded limestone. Hence, in the Hong Ngai formation, caves developed not only along the faults/cracks but also followed the bedding planes.



**Fig. 4** Distribution of low-gradient surfaces related to planation surfaces as revealed from topographic cross sections in Dong Van Karst Plateau

## Data and methodology

### Cave database

To perform this study, the digital database of 49 caves from 73 caves in the main study area was used for analysis and interpretation. These are caves with length and depth measurements large enough to meet the requirements of analyses. Unused caves are usually in the form of shallow sinkholes, or simply developed, short caves that are not valuable for analysis.

In general, the original cave survey data consisted in survey stations connected to each other by a baseline (Jeannin et al. 2007; Pardo-Iguzquiza et al. 2011). Between two survey stations, the recorded data are length, azimuth, the inclination from horizontal of the line joining these two stations, as well as the local width and height that is provided through left, right, up, and down measurements from each station.

Recently, the development of measuring devices has made the precision and validity of field measurements greatly improved. However, there are some survey errors that can still appear in the surveying process such as back-sight measurements; cycle closure errors; missing connections; fictive data that connect several entrances, survey stations; artificial cycles that correspond to loops acquired in a huge conduit or a room; etc. (more details in Collonet et al. 2017; Jouvès et al. 2017). For this reason, the data set needs to be cleaned before computation. In this study, based on existing cave survey data, the preprocessing step was performed manually following the knowledge of cave surveying techniques (Jeannin et al. 2007).

The data set was carefully evaluated and cleaned and then imported into the speleological software On Station 3.2 (Taco van Ieperen 1990) which enables common survey formats to be read, as well as displaying cave profiles and cave maps. Then the cave entrance (as a survey station) is precisely positioned (location, altitude) in the field by using GPS to calculate the coordinates  $(x_i, y_i, z_i)$  of each station  $(S_i)$ . These are the basic databases used to carry out the calculations in this study.

### Methodology

According to the approach mentioned in the Introduction, the analysis process includes the following steps:

- Perform geometric parameters analysis to identify and classify cave patterns;
- Apply the “Cave passages statistics” method to identify the altimetric distribution of horizontal cave passages as well as cave levels, and divide cave classes according to the elevation of planation surfaces;

- Divide cave groups by local structural blocks (horizontally) and cave classes (vertically);
- Perform geometric parameters analysis and cave passage orientation analysis for each cave group.

The obtained results can be used to interpret and identify the relationship between the cave system and tectonic and geomorphologic development periods in the study area.

The morphometric analysis of cave conduits was used to describe the condition that existed within the cave. It provides valuable information on geometries of karst conduits which are wide enough to be accessible by humans. In this study, geometric characteristics were computed following the approach by Jouvès et al. (2017): (1) the conduit cross-section shape (the width–height ratio), (2) the sinuosity (the curvature and the tortuosity), and (3) the vertical index. The parameters computed locally (per node or per branch) were averaged over the cave network to obtain one value per cave sample. The definition of these parameters is presented in Table 1 and Fig. 5 (more detail in Collonet et al. (2017); Jouvès et al. (2017)). The results obtained from this analysis are one of the bases for cave classification, and explain the relationship of influencing factors in the development of cave passages such as lithology, fault tectonics and geological structures. Following this classification, the vadose branchwork cave (VB) type is mainly delimited by  $WH < 1.5$  with high variability for  $K$  and  $V$ ; The water-table cave (WTC) and looping cave (LC) type is roughly located where  $WH > 1.5$ ,  $K < 0.2$ , and  $V < 0.2$ ; The angular mazes (AM) type is mostly confined to where  $WH > 1$  and  $K > 0.2$ .

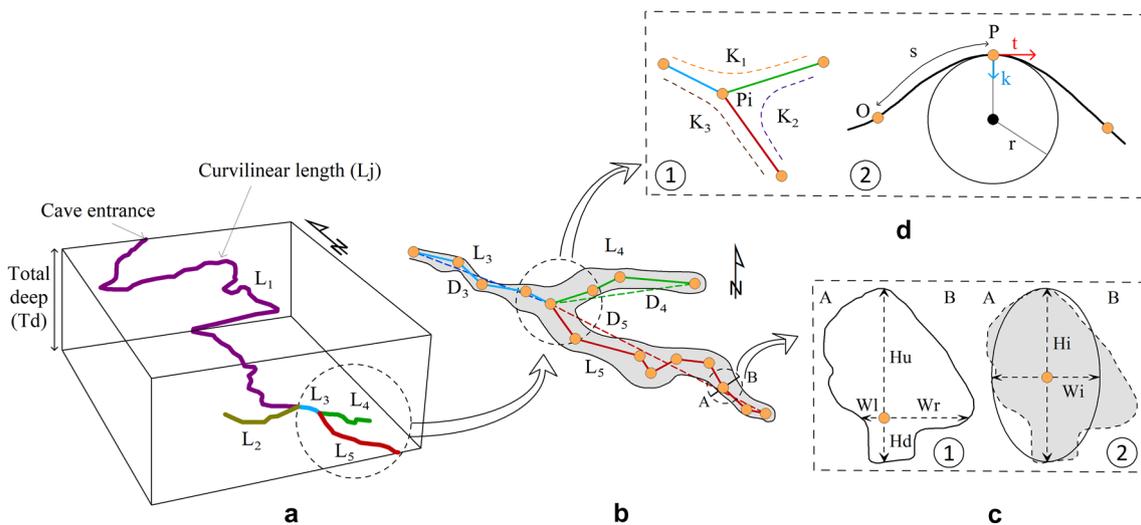
As mentioned by Palmer (1987), Filipponi et al. (2009), Piccini (2011), the “Cave passages statistics” method is implemented through statistical analysis of the altimetric distribution of the horizontal parts of cave passages to identify the cave levels in the study area. In this study, cave survey data and the longitudinal cave profiles are used to identify horizontal and/or low-gradient cave passages (i.e., conduits with Vertical Index  $V < 0.2$  or angle of inclination between two survey stations  $\alpha < 12^\circ$ ; for details see Jouvès et al. 2017), so that these cave passages are statistically at different elevation classes. The obtained frequency graph reflects the vertical distribution of horizontal cave passages and furnishes a database to distinguish cave levels.

Fractures/faults are considered as one of the main geologic features that have a strong influence on the development of karstic conduits (Palmer 1991). Therefore, the frequency distribution of cave passage directions is an interesting parameter that can be used to compare with the geological development periods, as well as to achieve a better understanding of the speleogenetic processes that have locally dominated (Collonet et al. 2017, Piccini 2011). As mentioned by Littva et al. (2015), to perform the cave passage orientation analysis, the plan cave map was used to

**Table 1** Cave passage morphometry

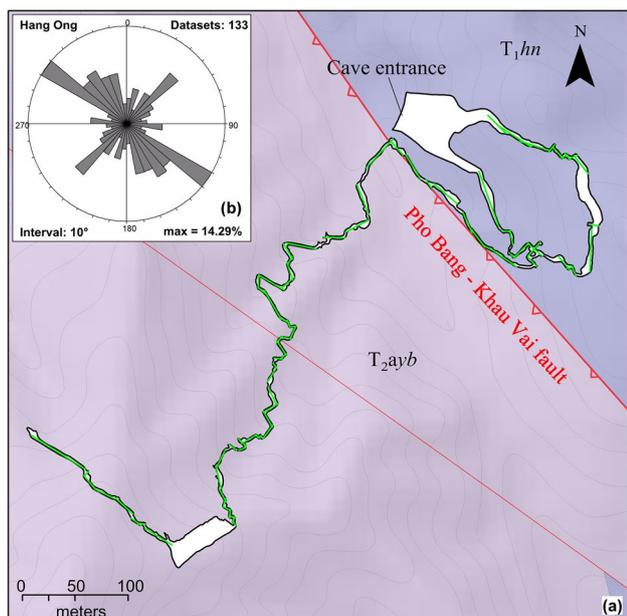
Geometric parameter	Method	Symbol	Calculation formula locally (per node <i>i</i> or per branch <i>j</i> )	Averaged value over the cave network
Curvilinear length	Taken from the data by using OnStation 3.2 software	$L_j$	$L_j$ is all segments between two branch extremities	
Euclidean length	Taken from the data by using OnStation 3.2 software	$D_j$	$D_j$ is the straight distance between two branch extremities	
Width length	Taken from the data by using OnStation 3.2 software	$W$	$W_i = W_l + W_r$	
Height length	Taken from the data by using OnStation 3.2 software	$H$	$H_i = H_u + H_d$	
Total depth	Taken from the data by using OnStation 3.2 software	Td	Td is the straight distance between highest and deepest survey station	
Average elevation	Taken from the data by using OnStation 3.2 software	$E_a$	$E_a$ is the average elevation between highest and deepest survey station	
Modal elevation	Taken from the data by using OnStation 3.2 software	$E_m$	$E_m$ is the elevation of highest survey station	
Real length	Taken from the data by using OnStation 3.2 software	$L_r$	$L_j$ is all segments between two branch extremities	$L_r = \sum_{j=1}^{n_b} L_j$
Width–Height ratio	Calculated from W and H data	WH	$WH_i = \frac{W_i}{H_i}$	$WH = \frac{1}{n} \sum_{i=1}^n WH_i$
Tortuosity	Calculated from $L_j$ and $D_j$ data	$T$	$T_j = \frac{L_j}{D_j}$	$T = \frac{1}{n_b} \sum_{j=1}^{n_b} T_j$
Curvature	Calculated by from coordinates ( $x_i, y_i, z_i$ ) of each survey station	$K$	$K(P) = \frac{1}{r} = \left\  \frac{dt}{ds} \right\  = \left\  \frac{d^2(OP)}{ds^2} \right\ $	$K = \frac{1}{n'} \sum_{i=1}^{n'}  K_i $
Vertical index	Calculated from total deep (Td) and real length ( $L_r$ ) data	$V$		$V = \frac{T_d}{L_r}$

$n$  the number of cave passage nodes,  $n_b$  the number of branches of the cave passage,  $n'$  the number of 3-point combinations along the passage



**Fig. 5** Geometric parameters computation. **a** The vertical index  $V$  on a 3D cave sample. Different color lines represent the different cave branch curvilinear length ( $L_i$ ); **b** Sketch of a karst sample divided into three branches. The curvilinear length  $L_j$  and the Euclidean length  $D_j$  can be computed along each branch  $j$ . Then, the tortuosity of each branch is calculated; **c** Processing of width–height ratio for a cave survey station  $i$ : ① In-situ measurement of width ( $W_i = W_l + W_r$ ) and height ( $H_i = H_u + H_d$ ) at survey station  $i$ ; ② WH-ratio  $WH_i$  calculated

from the in situ measurement for an idealized shape of karst conduit; **d** Curvature parameter computation: ① Possibilities of curvature values computed at an intersection node  $P_i$ ; ② The curvature at a point  $P$  of a curve  $C$ , where the point  $O$  is the origin of the curvilinear abscissa  $s$ . The parameter  $k$  is the curvature vector and  $t$  designates the tangent vector at  $P$ . The value  $r$  is the radius of the osculating circle at  $P$ . ( Modified from Jouves et al. 2017)



**Fig. 6** An example to illustrate the cave passages orientation analysis. **a** The grid displaying general cave passage azimuths is constructed based on Hang Ong cave map on the geological background. **b** Rose diagram of cave passage orientations (number %, 10° classes)

construct a grid displaying the general cave passage azimuths. Cave passages were excluded which had no clear general orientation (e.g., cave chambers and/or halls), and cave passage length was not considered in this analysis. In the next step, rose diagrams were made displaying the overall orientation of cave passages of each cave by using Tectonics FP software written by Franz Reiter and Peter Acs

in 1996, updated in 2020 (Reiter and Acs 1996) (Fig. 6). The individual results obtained are merged into different combinations for interpretation, including the overall cave passage orientation rose diagram which shows the major development direction of cave conduits in the study area; the rose diagram of cave passage orientation of cave groups that divided by local structure blocks and the cave levels show the main development direction of the cave passages of each group.

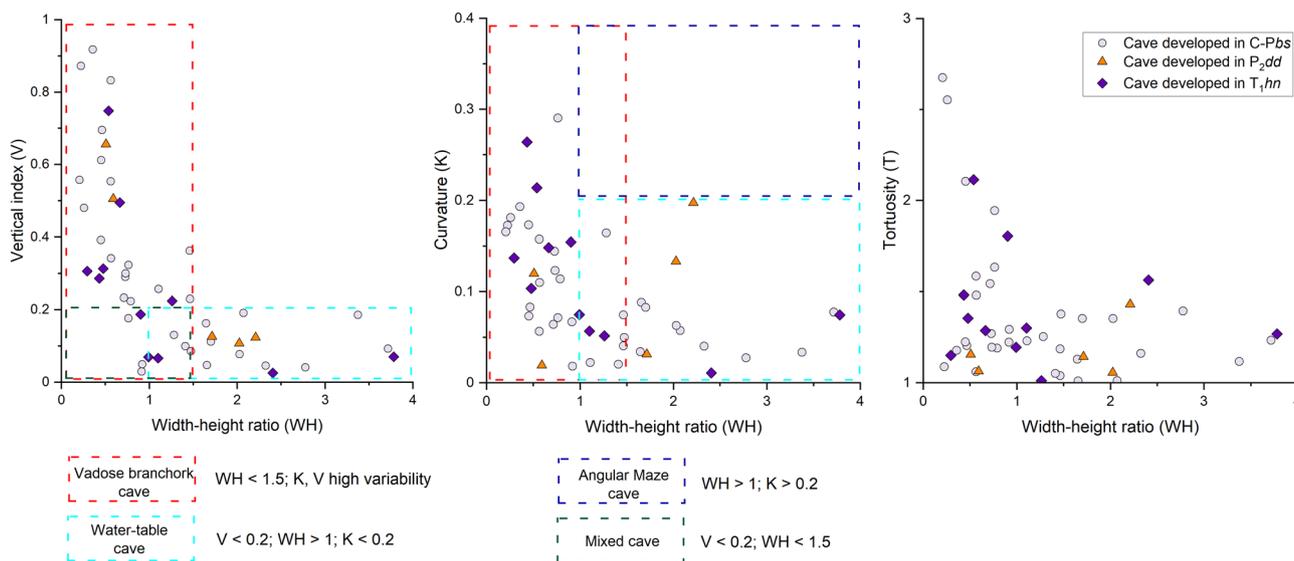
## Results and discussion

### Results

#### Cave classification based on speleomorphologic features of cave conduits

The complete results of the computation of geometric parameters for 49 caves which developed on different carbonate formations in the study area are shown in Appendix 1. The plots nicely show the relations between these parameters (WH, T, K, V) (Fig. 7). Then, the classification of cave types based on geometric parameters features was performed (As mentioned by Jouvès et al. 2017 in Sect. 3.2).

The results of cave classification show that there are 27 vadose branchwork caves (VB), 12 water-table caves (WTC), without the presence of angular mazes. The results also show that there is a cave type that has a low Vertical index ( $V < 0.2$ ) with conduit sections ranging in shape from circular to vertical ( $WH < 1.5$ ) including 10 caves. These caves are not only by definition developed horizontally but



**Fig. 7** Graph showing the distribution of geometric parameters (WH, T, K, V) and classification for the 49 cave conduit systems in Dong Van Karst Plateau

also have steeply sloping passages. However, the passages that develop laterally are dominant throughout the entire cave. Field observations show that the horizontal passages of these caves can be formed by flow beneath the water table or developed under the control of a bedding plane or stratigraphic contact but still can be influenced by tectonically induced discontinuities. This result is supported by several studies (Jaskolla and Volk 1986, Osborne 2001, Littva 2015) which discovered that many caves formed along the intersection of a fault system with discontinuity surface, and these cave passages are usable for tectonic analysis. In this study, we propose to call this type of cave “Mixed cave” (MC).

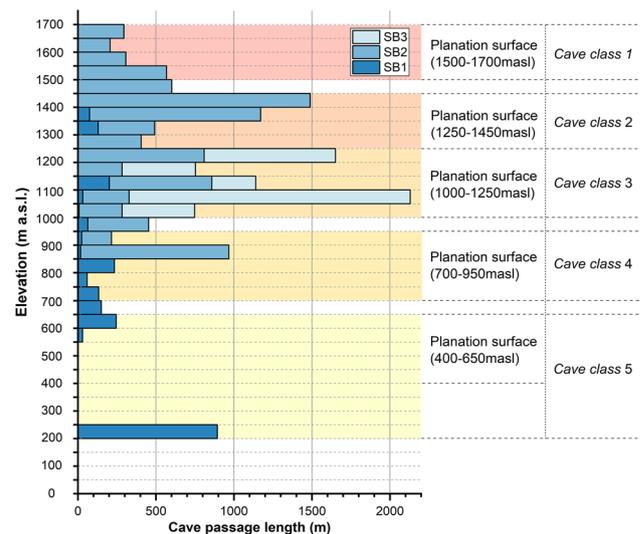
Figure 7 also shows that the VB caves have vertically elongated conduit sections ( $WH < 1$ ). The range of the vertical index is highly variable with caves developing almost vertically ( $V > 0.8$ ) to caves developing less steeply ( $0.13 < V < 0.8$ ). Actual observations show that the Vertical index decreased when the horizontal cave passages appeared in VB cave systems. These cave passages developed in Carboniferous carbonate unit (C-Pbs) during stable tectonic periods, while forming under the control of bedding planes in Dong Dang (P<sub>2</sub>dđ) and Hong Ngai (T<sub>1</sub>hn) formations.

#### Cave levels, speleomorphologic features and cave passage orientation in different cave groups

Based on the geological data, the study area can be divided into three different “local structural blocks” (Fig. 2b) with the boundary delimited by major fault zones including: structural Block 1 (SB1) which is located SW of the F1 fault, limited by the F7 fault (NE–SW direction) and Nhim River fault zone (NW–SE direction); Structural Block 2 (SB2) which is limited by F1 fault and F4 fault, the Western boundary is F3 fault zone; Structural Block 3 (SB3) which is located NE of the F4 fault, which is limited by F6 fault and overthrust fault North Dong Van.

A statistical analyses of the elevation of horizontal cave passages was performed to identify the cave levels in the various local structural blocks and in the entire study area. Within each structural block, the cave group was divided by cave classes to conduct an analysis of the geometric parameters and cave passage orientation. Details of the cave groups are shown in Appendix 1.

**Statistical analysis of horizontal cave passage and division cave classes** The frequency graph (Fig. 8) obtained from the 50 m elevation group of caves shows the vertical distribution of cave passages in the entire study area and in each structural block. Throughout the study area, horizontal cave passages were formed and distributed at different elevations from 200 to 1700 masl. Specifically, Fig. 8 shows five peaks of cave passage lengths ranging in the following groups: 200–250 masl, 850–900 masl, 1050–1150 masl, 1200–1250



**Fig. 8** Elevation distribution of horizontal cave passages and cave level division

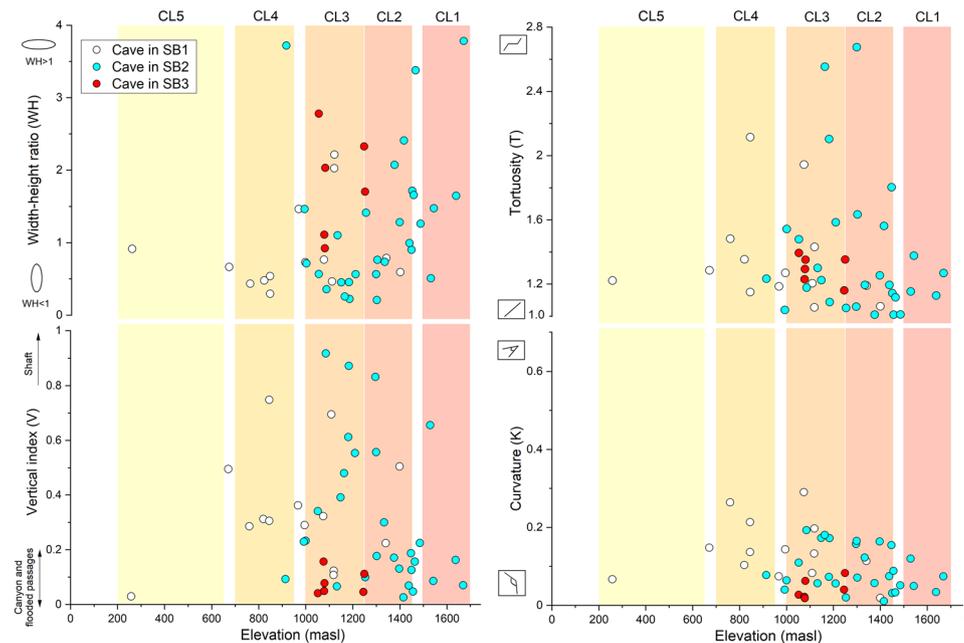
masl, and 1350–1450 masl. In passage length, these peaks range from 890 to 2130 m. (Details of the statistics of horizontal cave passage length are shown in Appendix 2a).

Considering the different structural blocks, the results also show that there is a variation in the distribution of cave levels. In SB1, the horizontal cave passage has rather limited development. They are distributed at scattered elevations from 200 to 1400 masl, with a peak at 200–250 masl reaching 894 m of passage length. The SB2 has strong cave development with a total of 9184 m equivalent to 59.9% of horizontal cave passage length in the entire study area. They are distributed nearly continuously at altitudes from 850 to 1700 masl, with three peaks at 850–900 masl (950 m of passage length), 1200–1250 masl (809 m of passage length), and 1350–1450 masl (ranging from 1096 to 1487 m of passage length). Horizontal cave passages in SB3 develop quite concentratedly at elevations from 1000 to 1250 masl with two peaks. The first peak at 1000–1050 masl reaches 1802 m of passage length and another peak at 1200–1250 masl reaches 842 m of passage length.

On the basis of the obtained results on the degree of development of horizontal cave passage and the elevation of planation surfaces on the DVKP identified in Sect. 2.2, we propose dividing the cave classes according to the elevation of their corresponding planation surfaces as a basis for calculations in the next following sections. In particular, due to rather limited development, we also propose combining the cave passages that have developed at altitudes lower than 650 masl into a single class. As a result, there are five cave classes in the study area (Fig. 8) divided as follows:

- Cave class 1 (CL1) at 1500–1700 masl;

**Fig. 9** Graph showing the distribution of geometric parameters (WH,  $T$ ,  $K$ ,  $V$ ) in different cave levels and local structural blocks



- Cave class 2 (CL2) at 1250–1450 masl;
- Cave class 3 (CL3) at 1000–1250 masl;
- Cave class 4 (CL4) at 700–950 masl;
- Cave class 5 (CL5) at < 650 masl.

### Geometric parameters of cave conduits in different cave groups

Cave entrances cannot always be used to identify cave levels because they commonly are more abundant in the upper part of a karst system and their distribution depends on many surficial geomorphic factors not linked to groundwater hydrology; this is especially the case for caves that have a large vertical range (VB cave). However, a cave with different horizontal levels linked with distinct evolution stages will have an average elevation that does not represent its real pattern. Therefore, in this study, we propose to use the average elevation ( $E_a$ ) to represent the level where VB caves develop ( $V > 0.2$ ), and the modal elevation ( $E_m$ ) to represent the altitude of MC and WTC caves ( $V < 0.2$ ).

Figure 9 shows the correlation of geometric parameters (WH,  $T$ ,  $K$ ,  $V$ ) with different cave classes and local structural blocks. Based on the cave classification, the speleomorphological characteristics of the cave systems in each group are described as follows.

At class 5 (< 650 m), there is only Na Luong cave developed in SB1. Geometric parameters of Na Luong cave conduit show characteristics of mixed cave type which is developed horizontally at the lowest altitude (238 masl) in the limestone of Bac Son formation (C–Pbs).

At class 4, caves are developed in SB1 and SB2. Caves in SB1 are in the type of VB cave that develop in both

Carboniferous–Permian (C–Pbs) and Triassic carbonate rocks (T<sub>1</sub>hm). In this group, cave passages are not very steep ( $V$  ranges from 0.29 to 0.362), with conduit sections varying from circular to longitudinally elongated (WH ranges from 0.294 to 0.665). Only Lung Chinh Cave formed with steeply sloping passages ( $V = 0.75$ ), with a sinuous pattern ( $T = 2.114$ ,  $K = 0.21$ ), and circular conduit sections (WH = 0.54). These parameters show the features of a cave developed in the Vadose zone that was controlled by fracture system. In the SB2, there is Tia Sang cave, developed in Carboniferous–Permian carbonate rock (C–Pbs), with a total length of 1154 m. This cave developed almost in the horizontal plane ( $V = 0.093$ ) with horizontally elongated conduit sections (WH = 3.719). These indicators of a WTC cave, combined with geologic information show that the horizontal development of this cave was formed along the contact of lithologically contrasting rocks.

At class 3, caves develop in three local structural blocks, in which caves in SB3 differ from the other groups. In this group, cave passages are mostly horizontal ( $V$  ranges from 0.041 to 0.256), with conduit sections varying from circular to horizontal elongate (WH ranged from 0.921 to 2.778). These geometric values indicate that there are 3 cave types in this group, including 4 WTC caves, one MC cave (Ma Le 2), and one VB cave (Ma Le 1).

Also in class 3, caves appear scattered on SB1 (4 caves), mainly on SB2 (9 caves), and developed in different Carboniferous–Permian–Triassic carbonate rocks. It can be seen in these groups there are caves that have a low Vertical index ( $V$  from 0.07 to 0.12), including 2 WTC caves (Pho Cao 1, Pho Cao 2019) with horizontally elongated conduit sections

(WH from 2.03 to 2.21) and one MC cave (Meo Vac 1) with circular conduit sections (WH = 1.1). In addition, there are also caves that develop slightly inclined ( $0.23 \leq V \leq 0.34$ ), with vertically elongated conduit sections (WH ranged from 0.57 to 0.76) in the type of VB cave (Kho Thong 1, Pai Lung, Sung Ta). In SB2, caves mainly develop vertically, starting with a sinkhole entrance, followed by passages with variable verticality, interspersed with horizontal passages ( $V$  ranged from 0.391 to 0.917) and often ending at siphons (lake) or small cracks which are difficult to enter by a human or a horizontal section filled by rockfall blocks and sediment. These caves developed a winding (meandering) pattern ( $0.06 \leq K \leq 0.19$ ;  $1.59 \leq T \leq 2.68$ ) with vertically elongated conduit sections (WH ranged from 0.21 to 0.56) (this was seen in Xa Lung 1, Xa Lung 2, Pa Ca 1, Quan Si 1, Lung Pu 1, in which, Xa Lung 2 and Pa Ca 1 are the deepest caves in the study area). These features indicate tectonic and structural factors that contributed to the development of cave systems in the vadose zone.

At class 2, caves appeared mainly on SB2 (11 caves), scattered on SB1 (2 caves), and developed on the carbonate rock of three formations including  $T_1hn$ ,  $P_2\ddot{a}\ddot{a}$ , and  $C-Pbs$ . In the SB1 cave group, slightly inclined caves developed ( $V$  ranged from 0.22 to 0.50), with vertically elongated conduit sections (WH ranged from 0.59 to 0.79) in the type of VB cave. Meanwhile, most of the caves develop in the SB2 have a low Vertical index ( $0.03 \leq V \leq 0.22$ ), a high variation in Curvature index ( $0.01 \leq K \leq 0.16$ ) while the Tortuosity index changes slightly ( $1.01 \leq T \leq 1.80$ ), including five MC caves (Dong Nguyet, Rong TL, Hang Ong, Hang May, Lung Pu 3) and three WTC caves (Xa Phin B, Rong ST, Sang Tung 2). Especially, Hang Ong is evaluated as one of the deepest caves in the study area (341 m depth), but the Vertical index is very low ( $V=0.19$ ). The survey data show that this is a long and multilevel cave (1679 m length), developed over a long time under variable hydrodynamic conditions due to climate and/or tectonic evolutions (WH = 0.90).

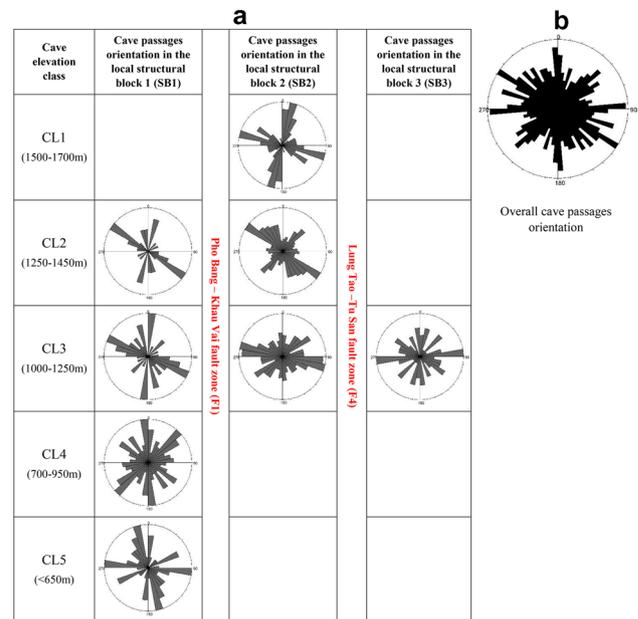
Sparse cave development at class 1, mostly fossil caves, developed horizontally ( $V$  ranges from 0.07 to 0.16), with horizontally elongated conduit sections (WH from 1.47 to 3.78). Only Sung La Tren 3 cave has the form of a sinkhole ( $V=0.66$ , WH = 0.51).

In summary, these results show the diversity of speleomorphologic characteristics of cave systems in each cave group. There are significant similarities between group SB2–CL2 and SB3–CL3 where these cave groups have a low vertical index, most of the caves are in the type of WTC and MC. Meanwhile, the geometric parameters of cave conduits in groups SB1–CL4, SB2–CL3 show the features of caves developed in the Vadose zone. The cave system has developed strongly in structure block 2 (29 caves in total) and contains the deepest and longest caves in the study area.

**Orientation of cave passages at different cave classes and structural zones** Before performing the cave passage orientation analysis, water-table caves were removed from the dataset due to unclear conduit orientations. The results of the cave passage orientation analysis of overall caves and each cave group at different cave classes and local structural blocks are shown in Fig. 10. Accordingly, the rose diagram displaying the overall orientation of all measured cave passages (Fig. 10b) shows two main passage orientations develop in approximately NW–SE and sub-latitude direction and there are two subsidiary orientations developed in the sub-meridian and NE–SW direction.

Figure 10a shows the rose diagrams of cave groups SB1–CL2, SB1–CL3, SB2–CL1, SB2–CL2 display the main passage orientation in an NW–SE direction and the SB2–CL1 cave group also displays the second main orientation in the NNE–SSW direction. In the cave groups SB1–CL5, SB2–CL3, and SB3–CL3, the main cave passage orientation follows the W–E direction, in which, SB1–CL5 group has the second main orientation in the NNW–SSE direction. In addition, the rose diagram of the SB1–CL3, SB1–CL4 cave groups displays the main passage orientation which is in an approximately N–S direction. And there are two cave groups SB1–CL4 and SB2–CL3 have the second main cave orientation is present in the NE–SW direction.

To sum up, the rose diagram displaying the passage orientation of all cave groups reveals that there are striking similarities in the main orientation of each group regardless



**Fig. 10** Rose diagrams display **a** the cave passage orientation in different cave groups and **b** the overall cave passages orientation in the study area

of their position. Two distinctive maxima are present at NW–SE and W–E orientations, with two less distinctive maxima at NE–SW and N–S to NNW–SSE orientations.

## Discussion

In this study, geometric parameters and the orientation of cave conduits were computed from a database of 49 caves in order to characterize the structure and development of karstification in the Dong Van Karst Plateau. In the following, we summarize and discuss these results.

### Cave passage orientation in relationship to the geological structure and tectonic periods

Caves are usually young features, so it is possible to link them to Neotectonic activities occurring in the study area. The main passage orientations in cave groups SB1–CL2, SB1–CL3, SB2–CL1, SB2–CL2 are in an approximately NW–SE direction (Fig. 10a), which is similar to the direction of the main fault systems in Dong Van Karst Plateau. This result can be explained by the tectonic activities occurring in the Cenozoic that reactivated the NW–SE fault systems, resulting in creating spaces or favorable channels for water to flow and corrosion to dissolve the host rock forming caves that follow this direction. In addition, the SB1–CL4 and SB2–CL3 cave groups also are aligned along the second main orientation in the NE–SW direction. Besides fault control, this result could be because some cave passages develop under the control of the bedding plane of Triassic siliceous limestone ( $T_1hn$ ) which is medium bedded and dips in NE direction.

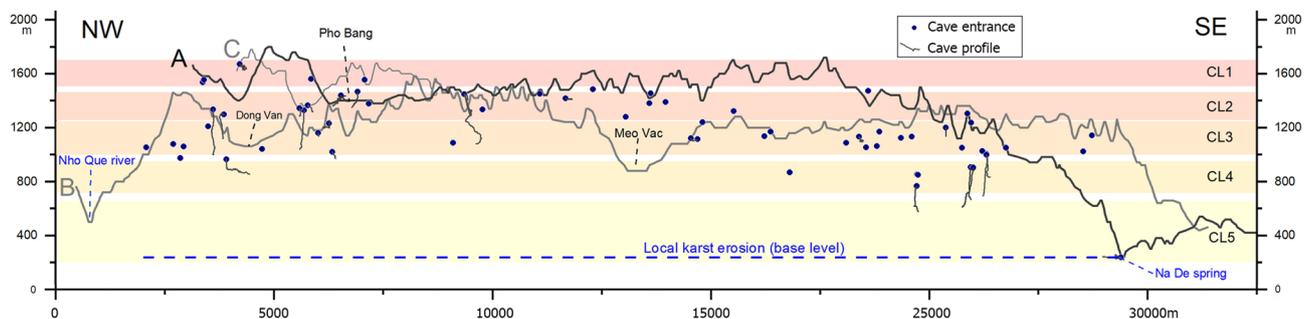
Littva et al. (2015) used the “Cavitonics” method to explain the relationship between Neotectonics and cave passage orientation which suggests that the orientation of cave passages is perpendicular to the extensional component ( $\sigma_3$ ) of the tectonic stress field, which means the same direction

as the maximum compressive stress axis ( $\sigma_1$ ). Applying this approach to the cave system on Dong Van Karst Plateau, it can be seen that, if Neotectonic faulting is considered a factor controlling the formation and development of a cave system, then the cave passage orientation will have the same direction as the maximum compressive stress fields. In the Neotectonic period, the geodynamic regime in Dong Van Karst Plateau developed according to the two-phase deformation model, sub-latitude compression in the early phase (Eocene–Miocene), and sub-meridian compression in the later phase (Pliocene–Quaternary), therefore, cave passages will be oriented mainly in these two directions.

It is clear that, in the remaining cave groups, the main passages orientation in cave groups SB1–CL5, SB2–CL3, and SB3–CL3 are in an approximately W–E direction, which are similar to the direction of the maximum compressive stress axis in the early phase (Eocene–Miocene). In addition, SB1–CL5 group display the second main orientation in the NNW–SSE direction, SB2–CL1 group also has the second main orientation in NNE–SSW direction and the main passage orientations in cave groups SB1–CL3, and SB1–CL4 is in an approximately N–S direction, which are similar to the direction of the maximum compressive stress axis in the late phase (Pliocene–Quaternary).

### Relationship between cave levels and planation surfaces on Dong Van Karst Plateau

As mentioned by Palmer (1987), Filipponi et al. (2009), there are some limitations in using horizontal cave levels as an indicator to interpret the karst evolution process because of limited field data analysis, combined with uncertainty as to what constitutes a true cave level such as cave passages developing under the control of a stratigraphic boundary or bedding plane or litho-structural as in the case of an inception horizons. Therefore, cave levels can be correctly



**Fig. 11** Cross sections (in Fig. 1) showing the development and structure of cave systems and the karstification features on Dong Van Karst Plateau

interpreted only where an accurate morphologic and structural analysis is performed to exclude such cave passages.

To combine actual observations with geological data, as well as geometrical parameters of cave conduits in the study area, it should be mentioned that there are many caves developed along bedding planes in the Permian ( $P_2d\bar{d}$ ) and Triassic ( $T_1hn$ ) carbonate units, such as Hang Rong ST, Sang Tung 2, Pho Cao 2, Tru Lia. In addition, in the Carboniferous ( $C-Pbs$ ) carbonate unit, there are caves such as Tia Sang, Xa Phin B, Hang Ho, Sang Ma Sao, Bo Doi, and Ma Le 1, 2 which are mainly developed along the stratigraphic boundaries. In fact, these results are limited by the accessibility of caves and the level of cave exploration, because there could be many other cave passages that are not yet discovered. In addition, varied interpretations may have resulted from different experiences and evaluations of speleologists. Therefore, in this calculation, we suggest excluding caves that our study has shown to have developed laterally under the influence of horizontal bedding and/or stratigraphic boundaries.

According to the data in Appendix 2b, there are significant changes in horizontal cave passages at different elevation classes after the questionable caves were removed. As a result, the cumulative passage length decreased greatly at altitudes of 850–900 masl, 1000–1150 masl, 1400–1500 masl, and 1550–1700 masl. Most significant was a decrease in cave passage length to 1315 m at 1050–1100 masl. Next, at elevation class 850–900 masl, the cave passage length decreased strongly, with a decrease of 950 m. In the remaining altitude classes, the passage length slightly decreases from 88 to 410 m.

Appendix 2b also shows that the horizontal cave passages are distributed at different elevation classes from 200 to 1550 masl with three peaks. The passage length reaches 894 m at 200–250 masl. At 1200–1250 masl the passage length reaches a maximum is 1651 m, and at 1350–1450 masl the passage length reaches 898–1077 m. In addition, the revised version of the passage distribution in the cave system showed a slight development at 1050–1150 masl with a passage length equivalent to 753–814 m.

The degree of association between horizontal cave passage and planation surface that are formed during tectonically stable periods can be used as a consistent indicator of tectonic periods and karst evolution, as mentioned in the studies of Palmer (1987), Filipponi (2009), Piccini (2011). According to the statistics of elevation distribution of horizontal cave passages after excluding unsuitable caves (App. 2b), it can be seen that in DVKP there are two cave levels that can be related to the planation surface, including cave level with a peak at 1200–1250 masl, equivalent to the planation surface at 1000–1250 masl and cave level with a peak at 1350–1450 masl in comparison to the planation surface at 1250–1450 masl. In addition, there is a peak at the lowest altitude 200–250 masl; however, the cave survey shows that only Na Luong Cave developed at this elevation. This cave is directly connected to Na De spring, a very large karst spring that probably drains large parts of the Dong Van Karst Plateau and forms the upstream end of Nhiem River. These features suggest that this could be the local base level for karst erosion in this area (Fig. 11).

Determining whether a cave level may be related to the planation surface needs to be based on a combination of several factors. However, in this study, due to the small number of caves and their limited development in a large karst region, the results obtained are very encouraging, because they represent an aspect of the relationship between the cave level and the planation surface, as well as karst evolution on the Dong Van Karst Plateau. To prove these points quantitatively, the absolute age analysis of cave sediments, stalagmites, etc. at different cave levels, and a comparison with the results of this paper, should be performed in the future.

## Conclusions

This paper has highlighted the relationship between cave systems and the tectonic and geomorphologic development on the Dong Van Karst Plateau, based on analysis and statistics of geometric parameters and orientation of cave passages. Our work has led us to conclude the following:

- Cave classification based on cave conduits geometric parameters shows that caves developed mainly in the vadose zone (27 vadose branchwork caves, 10 mixed caves developed under the control of fault systems, and 12 water-table caves).
- The degree of correlation between cave levels and planation surfaces suggests that the development of horizontal cave passages is related to two levels of planation surfaces, including one at 1250–1450 masl (equivalent to cave level at 1350–1450 masl), and at 1000–1250 masl (corresponding to cave level at 1200–1250 masl).
- The results of geometric parameter analysis of cave conduits in different cave groups show that the karst evolution in the local structural block 3 is mature. In this group, after corrosion to the local base level, the cave system continues to develop horizontally, expanding into lithologically different rocks. Meanwhile, the karst evolution in local structural blocks 1 and 2 are mostly at a youthful stage, with cave systems formed by dissolution, leaching or erosion which are mainly of the isometric form (developed almost vertically), and not yet deepened to the local base level. In these groups, some caves have developed laterally under the influence of a relatively resistant horizontal layer.
- Passage orientation show that the cave system on the Dong Van Karst Plateau formed and developed under the influence of tectonic activity during in the Cenozoic. In terms of cave passage orientation, there are three main distinct trends. The dominant orientation is roughly E–W, coinciding with the direction of the maximum compressive stress axis in the early phase (Eocene–Miocene). Next is a trend roughly N–S with the same direction as the maximum compressive stress axis in the late phase (Pliocene–Quaternary). The last orientation follows the

NW–SE direction due to the reactivation of paleo-fault systems having the same direction. In addition, there is a minor trend in the NE–SW direction that follows the dip direction of bedding planes.

Although there are limitations due to the accessibility and the level of cave exploration, this research suggests that cave databases could be used in order to clarify the development and structure of karstification in a region of soluble rocks. Specifically, Jouves's (2017) approach for quantitative cave classification based on the geometric parameters of cave conduits is useful for identifying the caves that are usable for tectonic analysis. Additionally, the analysis of cave passage orientation (Littva et al. 2015) represents a simple and useful approach for the study of neo-tectonics. On the other hand, the degree of correlation of cave levels and planation surfaces in this research once again emphasizes the validity of previous studies (Palmer 1987; Filipponi et al. 2009; Piccini 2011) which suggest that cave levels are among the morphological factors that are consistent indicators of karst evolution. Results presented so far have been very encouraging and could quantitatively demonstrate the association between cave systems and the development and structure of karstification on Dong Van Karst Plateau.

## Appendix 1

## See Table 2

**Table 2** Summary of cave survey data and cave conduits geometric parameters in Dong Van Karst Plateau

No.	Cave name	Development [m]	Denivelation [m]	Vertical index (V)	Tortuosity (T)	Curvature (K)	Width–height ratio (WH)	Cave entrance elevation [masl]	Average elevation [masl]	Modal elevation [masl]	Formation	Cave type	Local Structural Block
1	Nia Luong	1113	– 32.7	0.029	1.223	0.067	0.915	238	242	258	C–P bs	MC	SB1
2	Sung Khe 2	389	– 192	0.495	1.286	0.148	0.665	768	671	768	T <sub>1</sub> hm	VB	
3	Sung Khe 1b	183	– 57.1	0.313	1.354	0.103	0.478	849	820	849	T <sub>1</sub> hm	VB	
4	Sung Khe 1a	52	– 15.8	0.306	1.151	0.137	0.294	853	845	853	T <sub>1</sub> hm	VB	
5	Sung Khe 3–4	1030	– 296	0.286	1.482	0.264	0.433	903	758	903	T <sub>1</sub> hm	VB	
6	Ha Su 1	411	– 149	0.362	1.186	0.075	1.463	983	967	983	C–P bs	VB	
7	Lung Chinh	504	– 306	0.748	2.114	0.214	0.538	1006	844	1006	T <sub>1</sub> hm	VB	
8	Sung Dia 2	173	– 50	0.290	1.270	0.144	0.729	1021	995	1021	C–P bs	VB	
9	Phong Tung	92	– 63.7	0.695	1.205	0.083	0.465	1199	1074	1199	C–P bs	VB	
10	Sung Ta 2	162	– 52.3	0.322	1.944	0.290	0.764	1084	1060	1086	C–P bs	VB	
11	Pho Cao 1	94	– 11.6	0.123	1.431	0.197	2.213	1113	1112	1119	P <sub>2</sub> dd	WTC	
12	Pho Cao 2019	164	– 17.6	0.107	1.055	0.133	2.026	1118	1109	1118	P <sub>2</sub> dd	WTC	
13	Pho La	195	– 51	0.224	1.191	0.114	0.789	1365	1340	1365	C–P bs	VB	
14	Ta Lung 0	280	– 141.2	0.504	1.062	0.019	0.592	1470	1399	1470	P <sub>2</sub> dd	VB	
15	Tia Sang	1154	– 107	0.093	1.233	0.078	3.719	963	914	963	C–P bs	WTC	SB2
16	Pai Lung	201	– 47	0.233	1.543	0.064	0.715	1017	1000	1017	C–P bs	VB	
17	Sang Chai 1A	501	– 115	0.229	1.039	0.040	1.464	1050	992	1050	C–P bs	VB	
18	Kho Thong 1	190	– 64.8	0.341	1.479	0.110	0.567	1085	1052	1085	C–P bs	VB	
19	Meo Vac 1	617	– 41	0.066	1.300	0.057	1.102	1132	1112	1132	T <sub>1</sub> hm	MC	
20	Quan Si 1	117	– 107.2	0.917	1.178	0.193	0.357	1139	1085	1139	C–P bs	VB	
21	Hang May 2	65	– 25.6	0.391	1.224	0.173	0.451	1160	1148	1160	C–P bs	VB	
22	Hang May	598	– 57.9	0.100	1.051	0.020	1.411	1230	1224	1253	C–P bs	MC	
23	Lung Pu 1	118	– 102.9	0.872	1.088	0.172	0.225	1235	1183	1235	C–P bs	VB	
24	Xa Lung 1	262	– 178	0.553	1.585	0.056	0.564	1301	1209	1301	C–P bs	VB	
25	Lung Pu 3	181	– 32	0.177	1.633	0.071	0.763	1302	1286	1302	C–P bs	MC	
26	Pa Ca 1	475	– 293	0.612	2.104	0.073	0.455	1328	1181	1328	C–P bs	VB	
27	Xa Lung 2	1951	– 340	0.480	2.553	0.181	0.258	1332	1163	1332	C–P bs	VB	
28	Doan Ket	88	– 73.3	0.832	1.059	0.157	0.564	1333	1296	1333	C–P bs	VB	
29	Hang Ong	1679	– 341	0.187	1.803	0.154	0.902	1446	1274	1446	T <sub>1</sub> hm	MC	

**Table 2** (continued)

No.	Cave name	Development [m]	Denivelation [m]	Vertical index (V)	Tortuosity (T)	Curvature (K)	Width–height ratio (WH)	Cave entrance elevation [masl]	Average elevation [masl]	Modal elevation [masl]	Formation	Cave type	Local Structural Block
30	Pa Ca 2	106	– 59	0.557	2.675	0.165	0.208	1342	1299	1342	C–P bs	VB	
31	Dong Nguyet	1143	– 78	0.069	1.195	0.075	0.993	1438	1400	1438	T <sub>1</sub> hn	MC	
32	Xa Phin B	123	– 33.2	0.191	1.010	0.057	2.073	1375	1359	1375	C–P bs	WTC	
33	Hang Doi TL	300	– 90	0.300	1.195	0.123	0.733	1378	1333	1378	C–P bs	VB	
34	Hang Rong TL	241	– 28.5	0.131	1.254	0.164	1.282	1389	1382	1397	C–P bs	MC	
35	Hang Rong ST	404	– 10.4	0.026	1.562	0.011	2.408	1415	1411	1415	T <sub>1</sub> hn	WTC	
36	Sang Tung 2	262	– 33	0.126	1.143	0.031	1.714	1450	1436	1450	P <sub>2</sub> dd	WTC	
37	Lung Tung 1	172	– 8.1	0.047	1.009	0.088	1.656	1454	1452	1456	C–P bs	WTC	
38	Xa Phin 3	437	– 116	0.186	1.117	0.033	3.377	1464	1407	1464	C–P bs	WTC	
39	Ban Sinh Chau	401	– 90	0.224	1.010	0.051	1.261	1485	1441	1485	T <sub>1</sub> hn	MC	
40	Nhu Sang	926	– 22	0.086	1.377	0.050	1.474	1536	1502	1542	C–P bs	MC	
41	Bo Doi	200	– 12	0.162	1.129	0.034	1.647	1554	1595	1637	C–P bs	WTC	
42	Sung La Tren 3	97	– 63.4	0.656	1.154	0.120	0.509	1561	1529	1561	P <sub>2</sub> dd	VB	
43	Tru Lia	541	– 41.4	0.070	1.269	0.074	3.781	1669	1650	1669	T <sub>1</sub> hn	WTC	
44	Hang Ho	337	– 13.8	0.041	1.394	0.027	2.778	1038	1045	1052	C–P bs	WTC	SB3
45	Ma Le 1	218	– 55.9	0.256	1.230	0.022	1.109	1052	1076	1099	C–P bs	VB	
46	Ma Le 2	899	– 44.2	0.049	1.293	0.018	0.921	1059	1057	1078	C–P bs	MC	
47	Ma Le 5	610	– 47.2	0.077	1.352	0.063	2.030	1077	1059	1080	C–P bs	WTC	
48	Sang Ma Sao	1254	– 140	0.112	1.353	0.083	1.701	1138	1185	1249	C–P bs	WTC	
49	Hang Dot Pha	1540	– 70	0.045	1.160	0.040	2.327	1208	1217	1245	C–P bs	WTC	

## Appendix 2

### See Table 3

**Table 3** Summary of the statistics of horizontal cave passage length in Dong Van Karst Plateau

Elevation class [masl]	(a)				(b)			
	Cave passage length (m)				Cave passage length after excluding unsuitable caves (m)			
	Entire DVKP	SB1	SB2	SB3	Entire DVKP	SB1	SB2	SB3
1650–1700	294.7	–	294.7	–	–	–	–	–
1600–1650	206.6	–	206.6	–	–	–	–	–
1550–1600	307.6	–	307.6	–	–	–	–	–
1500–1550	567.9	–	567.9	–	567.9	–	567.9	–
1450–1500	601.4	–	601.4	–	601.4	–	601.4	–
1400–1450	1488.6	–	1488.6	–	898.3	–	898.3	–
1350–1400	1171.5	75.2	1096.3	–	1077.3	75.2	1002.1	–
1300–1350	492.5	129.4	363.1	–	492.5	129.4	363.0	–
1250–1300	405.5	–	405.5	–	405.5	–	405.5	–
1200–1250	1651.1	–	809.2	841.9	1651.0	–	809.2	841.9
1150–1200	753.5	–	283.4	470.1	753.4	–	283.4	470.1
1100–1150	1140.0	201.4	657.0	281.6	792.8	135.8	657.0	–
1050–1100	2130.2	32.0	296.4	1801.8	814.9	32.0	296.4	486.5
1000–1050	748.4	8.1	275.9	464.4	337.6	8.1	275.9	53.6
950–1000	453.7	63.8	389.9	–	447.7	63.8	383.9	–
900–950	215.4	25.1	190.3	–	127.4	25.1	102.3	–
850–900	967.9	17.9	950.0	–	17.9	17.9	–	–
800–850	234.0	234.0	–	–	234.0	234.0	–	–
750–800	59.5	59.5	–	–	59.5	59.5	–	–
700–750	133.6	133.6	–	–	133.6	133.6	–	–
650–700	150.5	150.5	–	–	150.5	150.5	–	–
600–650	245.6	245.6	–	–	245.6	245.6	–	–
550–600	29.6	29.6	–	–	29.6	29.6	–	–
500–550	–	–	–	–	–	–	–	–
450–500	–	–	–	–	–	–	–	–
400–450	–	–	–	–	–	–	–	–
350–400	–	–	–	–	–	–	–	–
300–350	–	–	–	–	–	–	–	–
250–300	–	–	–	–	–	–	–	–
200–250	893.7	893.7	–	–	893.7	893.7	–	–
Total	15,343.0	2299.4	9183.7	3859.8	10,732.3	2233.8	6646.3	1852.1

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