Limbert, H., Limbert, D., Hieu, N., Văn Phái, V., Bac, D. K., Phuong, T. H. and Granger, D., 2016. The discovery and exploration of Hang Son Doong. *Boletín Geológico y Minero*, 127 (1): 165-176
ISSN: 0366-0176

# The discovery and exploration of Hang Son Doong

H. Limbert[1], D. Limbert[1], N. Hieu[2], V. V. Phái, D. Kinh Bac[2], T. H. Phuong[2] and D. Granger[3]

(1) British Cave Research Association (BCRA). The Old Methodist Chapel, Great Hucklow, BUXTON, UK.
howard@howardlimbert.plus.com
(2) Faculty of Geography, Hanoi University of Science, Vietnam
(3) Department of Earth, Atmospheric and Planetary Sciences, Purdue University, USA

ABSTRACT

Hang Son Doong is located in the Phong Nha Ke Bang Limestone Massif in Quang Binh Province, Central Vietnam. Cave exploration by British cavers has been continuous in this area since 1990. Hang Son Doong is part of the Phong Nha Cave system which runs from the southern end of the National Park near the Lao border to the final resurgence at Phong Nha Cave.

Key words: British cavers, cave, Hang Son Doong, limestone, Vietnam.

## *El descubrimiento y exploración de Hang Son Doong*

*RESUMEN*

*Hang Son Doong está situada en el macizo calcáreo de Phong Nha Ke Bang, en la provincia de Quang Binh, Vietnam Central. La exploración de cuevas por espeleólogos británicos ha sido continua en esta área desde 1990. Hang Son Doong es parte del sistema cuevas de Phong Nha que se extiende desde el extremo sur del Parque Nacional, cerca de la frontera con Laos hasta la parte final de la cueva Phong Nha.*

*Palabras clave: caliza, cuevas, Hang Son Doong, espeleólogos británicos, Vietnam.*

*VERSIÓN ABREVIADA EN CASTELLANO*

### ***Introducción y metodología***

*La exploración de los sistemas de cuevas de Phong Nha Bang comenzó en 1990 con un equipo de científicos de la Hanoi University of Science, the Faculty of Geography y miembros del British Cave Research Association. Se han descubierto y explorado muchas cuevas, y se han identificado dos sistemas principales. Estos son Phong Nha System y Hang Vom System. Hang Son Dong (o Mountain River Cave), explorado en 2009 y probablemente el mayor pasaje de cueva conocida hasta la fecha, se cree que es una de las mayores cuevas del mundo, es parte del Phong Nha System, y tiene 8950 m de longitud. La cueva pudo ser localizada gracias al guía local Mr. Ho Khanh que la había encontrado por casualidad diez años antes, aunque debido al paso del tiempo fueron necesarios varios intentos hasta que finalmente se encontró. La expedición sintió el viento de la cueva desde una distancia de 500 m lo que indicaba que estaban a punto de encontrar algo muy especial. La entrada de 30 m por 10 m es relativamente pequeña para los estándares vietnamitas.*

*Hang Son Doong está formada en el macizo Ke Bang, el cual expone una sección de calizas desde el Devónico al Permico-Carbonífero que se depositaron en el océano Paleotethys. La cueva pasa a través de las dos formaciones: la formación Phong Nha y la formación Bac Son.*

*Se ha hecho un gran esfuerzo para buscar muestras que pudieran constreñir la edad de la cueva a partir de los sedimentos dentro de ella. Muestras adecuadas para datación de la cueva se encuentran frecuentemente en sedimentos que rellenan los huecos sobre la pared de la cueva o los pasajes más altos. Los*

*espeleotemas de calcita pura que se pueden datar con series de U o U-Pb, no se encontraron. Sin embargo, si se encontraron dos rellenos sedimentarios que son posteriores a la formación de cuevas y se recogieron muestras para su datación. Estas fueron 1) limos laminados detrás del WOFD en el "Hang of Dog", y 2) una becha que rellena los pasajes en "The Alcove".*

*Hay varias observaciones de la geología y geomorfología local que conducen a una teoría general de espeleogénesis para Hang Son Doong. Lo más revelador es un paleo-valle en un nivel alto esculpido a lo largo de la superficie y drenando hacia el oeste (Fig. 1). Este paleo-valle está esculpido en las calizas pero es anterior a la formación de la cueva. Esto implica que no había salida subterránea para el agua de la cuenca, o de otro modo las cuevas se habrían llevado el agua. La cuenca está rodeada al este por rocas metamórficas y cristalinas, y al sur por capas rojas cretáceas. Una porción del borde norte de la cuenca de drenaje también acaba en las capas rojas cretáceas, previniendo la formación de cuevas. El resto del límite de la cuenca de drenaje está rodeado por grandes fallas. Se sugiere que estas fallas sirvieron como acuicludos, lo que previene el paso de agua, obstaculizando la formación de cuevas. En particular la falla en el norte de la cueva habría bloqueado el flujo de agua hacia el Son River. Fue sólo cuando esta falla se brechificó, y la subsiguiente incisión de una corriente superficial de agua, cuando se pudo producir una salida hidrológica de la cuenca de drenaje. En ese tiempo, el agua que drenaba la cuenca Hang Son Doong habría estado colgada en un lecho fluvial sobre el nuevo nivel de base donde la falla estaba brechificada. El agua comenzó a formar rápidamente cuevas hacia su surgencia. El camino más rápido del flujo a la salida era a lo largo de la falla N-S (Paleógeno) preexistente, y también otra falla NO-SE (Neógeno). La cueva se desarrolló rápidamente, tomando toda la descarga de la cuenca de drenaje por la captura del río superficial. La cueva ha persistido durante millones de años, asociado con un lento descenso del nivel de base a un ratio de 22 ± 6 m/Ma.*

***Discusión y conslusiones***

*Hang Son Doong se formó como resultado de la captura de una corriente de agua a lo largo de una falla N-S pre-existente. La captura ocurrió probablemente debido a la ruptura y brechificación de una falla NE que bloqueó el flujo de agua hasta algún momento del Plioceno o del Mioceno superior (2-5 Ma). La cueva hoy lleva una descarga anual máxima estimada de 400 a 450 m$^3$/s, en consonancia con una cuenca de drenaje de 200 km$^2$. El gran tamaño de la cueva es probablemente debido a la convergencia de varios factores. 1) La caliza en esta zona está generalmente estratificada y muy potente, capaz de soportar techos muy anchos. 2) La cueva se ha desarrollado con una anchura bastante uniforme, posiblemente influenciada por la anchura de la zona de brecha de la falla en la que se ha formado. 3) La cueva tiene pocos tributarios que hubieran debilitado el techo. Allí donde las condiciones (1) o (3) no se cumplen, la cueva se ha colapsado. La edad de los colapsos son variables pero "Watch out for Dinosaurs" colapsó probablemente durante los últimos 500 000 años. 4) Los ratios de levantamiento tectónico y de descenso del nivel de base han sido lentos lo que implica que los pasajes se han podido estar agrandando por períodos de hasta varios millones de años. Ha sido la convergencia de todos estos factores lo que ha conducido a las enormes dimensiones de Hang Son Doong y otras cuevas en el sistema Phong Nha.*

## Introduction

Exploration of the cave systems of the Phong Nha Ke Bang Massif began in 1990 with a team of scientists from Hanoi University of Science, the Faculty of Geography and members of the British Cave Research Association from England. Many caves have been discovered and explored, with two main systems being identified. These are the Phong Nha System and the Hang Vom System. Hang Son Doong, explored in 2009 and probably the largest known cave passage, which is believed to be one the largest caves in the world, is part of the Phong Nha System, and is 8950 m long.

Hang Son Doong or the Mountain River Cave was first explored in 2009 after many years of searching for a cave in this area. Our team has been exploring caves in the Quang Binh region of Vietnam since 1990 and we have found 2 major caves with large rivers in close proximity. Hang En and Hang Khe Ry are both extremely large and important river caves. They exit into the same valley and the rivers then unite and sink into a massive boulder choke. We examined this area for over 6 years with no luck in finding the continuation and what we expected to be a major cave. This area is very remote and in the 1990s it was a 3 day trek in difficult forests to reach the furthest sink. Two attempts were made to pass this obstruction without success so we spent a number of expeditions searching the area for other entrances unsuccessfully.

In 2009 our main jungle guide, Mr Ho Khanh, told me about a cave entrance he had found in 1990 when he was searching for rare wood deep in the jungle. He was by himself and was caught in a big thunderstorm and managed to find a cliff to shelter from the heavy rain. At the base of this cliff he found an entrance from which a huge wind was felt and the sound of a river could be heard far below. He never revisited the area and it was only when we asked local jungle people for caves that he mentioned this to our group. However, it was nearly 20 years since he had been to the entrance and it took him a few attempts to relocate the cave.

With Mr Khanh as our guide, a team set out from our base to try and find this elusive cave. Our route took us through the spectacular Hang En, past the junction with Hang Khe Ry and up into the jungle before we reached a cliff from which we could see mist blowing out of an entrance. The wind from the cave could be felt over 500 m away and it was obvious we had come across something special.

The entrance is relatively small by Vietnamese standards, around 30 m by 10 m. Looking down into the cave, a very steeply descending calcite slope leads. This very intimidating entrance had stopped any locals ever entering the cave but to cavers the strong wind and sound of a large river was very exciting. The 80 m descent is achieved by a series of ledges around huge calcite flowstones and leads to a huge passage around 100 m high and 80 m wide. At the base is a lake and a collection of enormous boulders with the roar of water in the distance. A complex route was finally found leading through the boulders to the source of this noise. We had discovered the continuation and what is now known as Hang Son Doong.

**Figure 1:** The first river crossing (photo Ryan Deboodt).
***Figura 1:*** *La primera travesía en el río (foto de Ryan Deboodt)*

## The Exploration of Hang Son Doong

The river here is not a pleasant knee-deep stroll in a river valley, but rather a fast flowing river very deep in places with many noisy fast flowing rapids. After a few failed attempts at crossing the rapids a way was found and we managed to cross to a large flat floored passage safely away from the dangerous river section. However, after only 200 m we again met the river and had to cross back to the other side to find more dry land. This crossing was a little easier and we managed to find our way into a huge passage leaving the river as it cascades down through boulders. This enormous passage, in places 175 m high and 135 m wide, was initially very confusing between many large boulders. We finally reached a large sandy area and to our amazement we could see daylight in the distance. This turned out to be a daylight shaft over 200 m high and 1.5 km away.

The passage here has enormous stalagmites over 75 m high and the river could still be heard flowing fast between the boulders in the lower left hand side of this gigantic passage.

With the faint daylight as a guide the enormous passage continues with a number of climbs up and down and a breath-taking view ahead. Finally, a large sandy area is reached which is on top of huge dry gours with the daylight shaft towering above. This has become the site of our first camp which we used for further exploration into the cave. In this part of the cave we have recently discovered an amazing side passage near the lower river series which contains some stunning and numerous examples of Tetra Coral fossils. In jet black limestone these 300-million year-old fossils confirmed the age of the limestone in this area.

**Figure 2:** Enormous stalactites in the main passage.
***Figura 2.*** *Enormes estalactitas en el pasaje principal.*

**Figure 3:** Looking down from 'Watch out for Dinosaurs'.
***Figura 3.*** *Vista del pasaje 'Watch out for Dinosaurs'.*

**Figure 4:** Looking back to 'Wath out for Dinosaurs' (photo Ryan Deboodt).
***Figura 4.*** *Vista de la sala 'Watch out for Dinosaurs' (foto de Ryan Deboodt).*

Continuing from this easy, sandy flat-floored viewpoint the way on is to cross over the jumble of huge rocks to the other side of the passage, heading up towards the daylight. Two ways lead off from here, one a very steep ascent to the base of the shaft and the other a large oxbow 45m above the river series. This river series was explored for around 1km to end in a terminal sump that has not yet been dived. The oxbow series is the more stable way to reach the base of the daylight shaft which we named 'Watch out for Dinosaurs'. The oxbow exposes some incredible fault breccias with white calcite mineralisation of the fault within the black limestone.

The area around 'Watch out for Dinosaurs' is a truly stunning part of the cave with many sections full of great examples of phytokarst with huge areas of sharp pencil like projections all pointing towards the daylight. The base of the shaft has enormous stalagmites all covered in green, with many small plants and trees and bushes present in this beautiful part of the cave. The shaft is over 200 m high and the opening around 100 m by 50 m and as yet has not been located in the dense jungle above the cave.

From the base of the shaft a steep slope leads down to the continuation passage, crossing a series of giant gours, often active, with the first 300m all covered in green algae. These superb gours, many over 80m wide run for over 500 m. In the distance more daylight could be seen over 1km away. This easy going passage led to the first sighting of the 'Garden of Edam'.

**Figure 5:** Approaching the Garden of Edam (photo Ryan Deboodt).
***Figura 5.*** *Vista central del Garden of Edam (foto de Ryan Deboodt).*

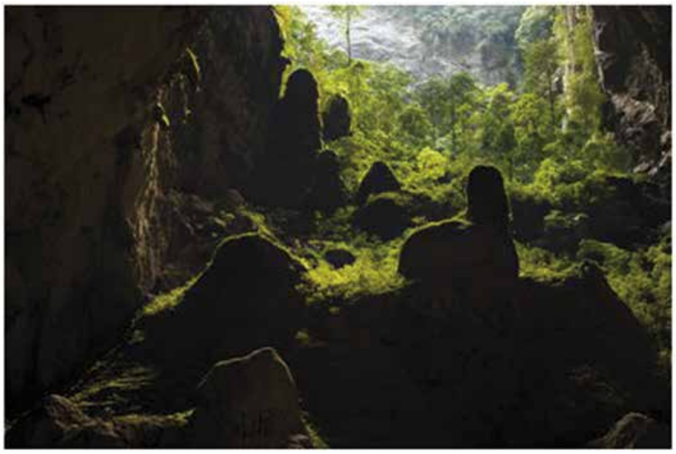

**Figure 6:** The Garden of Edam (photo Ryan Deboodt).
***Figura 6***. *Vista lateral del Garden of Edam (foto de Ryan Deboodt).*

A 120 m ascent up a gour filled passage with stunning small plant life filling the gours leads up to the enormous daylight shaft. The cliffs tower over 250 m high and the width of the passage at the base is 175 m. This section of the cave has very tall trees around 30 m high. This very dense jungle section includes many rare plant species. Many animals seem to visit this doline, including monkeys, snakes, flying foxes as well as birds including hornbills and eagles.

When we first explored this section of cave the path through the jungle was very difficult but now a small path has been made across the centre to make the traverse easier. There is a climb to base of the daylight shaft on top of the vegetation covered rubble cone, and then a descent over 120 m to the huge passage continuing onwards. At the base of the hill is a white sandy beach, one of the most amazing campsites in the world. The view of the jungle and the constant noise of the jungle are truly incredible.

From this camp the passage leads off, passing many enormous large stalagmite bosses. This section is dry and very easy going. After passing sections with huge cave pearls the passage descends to a small river with the walls coated with mud. This is only in the dry season and even then this part of the cave can turn into a huge lake 600 m long after floods. With no water the passage is awfully muddy but when a lake is present the clear blue water-filled passage is superb. This leads to the 'Great Wall of Vietnam'. In 2009 this was our farthest point and in 2010 we returned with National Geographic film and magazine to try and ascend the wall and explore the continuation.

The wall was passed after two very difficult days bolting up a weak calcite wall. The bottom 15 m of the wall consists of a very thin calcite edge covered in mud. The wall was eventually climbed to reach a continuation after a 90 m climb. The height of the passage at the wall is over 200 m. The small river at its base disappears into a very small calcite ringed sump with no passable way on. At the top of the wall a 400 m long passage leads to the final exit of Hang Son Doong. Along this passage an excellent array of cave pearls and calcited bones of some animals are seen. The exit is finally reached deep in the jungle and by obtaining a GPS of this exit we were able to reach it using a very difficult jungle path. No evidence of local people using this exit was found.

Since 2010 we have had the opportunity to take numerous film crews and scientists into Hang Son Doong, including two Japanese teams, the BBC, from Vietnam, Hong Kong and a Brazilian team, which along with the National Geographic team this has led to worldwide recognition of this truly amazing cave.

There is still much work to be done in Hang Son Doong and as yet no tourists have been allowed to visit the cave. The Vietnamese authorities have been excellent in controlling access and hence the cave is still in its pristine condition. The cave is a very fragile environment and despite many investors wishing to make the cave into a mass tourism cave this has been rejected by the local government. We hope this will continue to prevent serious and irreversible damage to the remote area all within the core section of the World Heritage Site.

Hang Son Doong is both remarkable for its size and splendour and its many unique situations. Hang Son Doong, though only just short of 9 km long, at present has a greater volume than any other cave on the planet. It is probably most remarkable that such a place was only first explored in 2009. It is possible larger caves do exist in the Ke Bang Massif in Vietnam which is a very remote area near the Laos border. Our team is returning in 2014 for another expedition into this wild and remote part of the world.

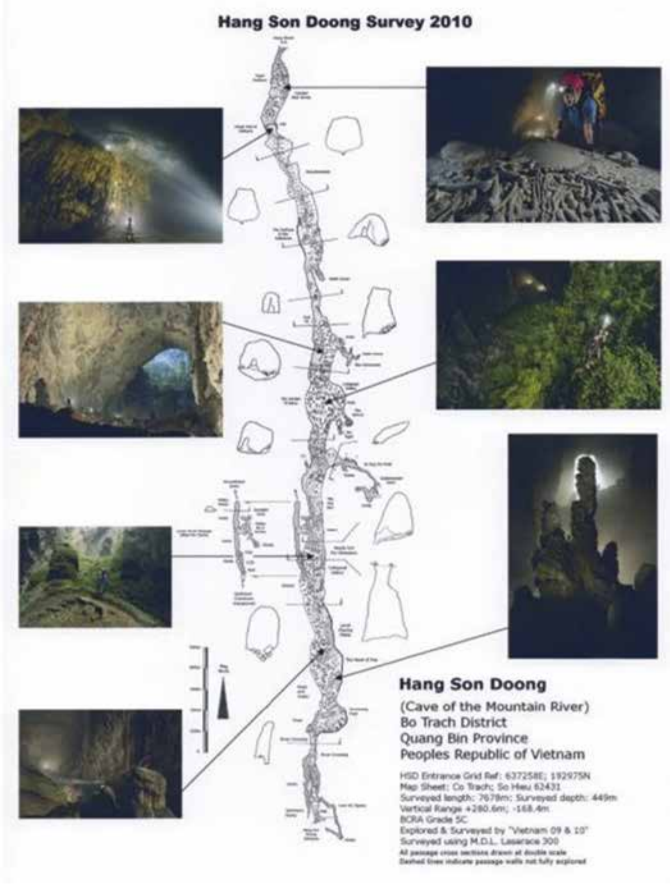


**Figure 7**: Survey of Hang Son Doong.
***Figura 7.*** *Estudio de Hang Son Doong.*

There is some debate as to whether Hang Son Doong has the largest cave passage cross section, partly because accurate measurements of cave passages become very difficult when the caves are so large. Deer Cave, in the Mulu karst in Sarawak (Malaysia), has been very accurately surveyed, and one part of it is 168 m wide and 125 m high (Waltham and Despain, 2012). This is almost certainly larger than any part of Hang Son Doong. However, the largest part of Deer Cave is less than a kilometre long, whereas this cave in Vietnam maintains its extremely large dimensions for more than three kilometres (the quoted length of nearly 9 km is merely the surveyed length of all the passages). So Hang Son Doong can lay fair claim to being the largest cave passage in the world.

## The Geology of Hang Son Doong

### *Bedrock Geology*

Hang Son Doong is formed in the Ke Bang massif, which exposes a section of Devonian (359-416 My) to Permo-Carboniferous (251-359 My) limestone that were originally deposited in the Paleotethys ocean. The cave passes through the carbonate rocks of two formations: the Phong Nha Formation ($D_3$-$C_1$ *pn*) and the Bac Son Formation (C-P *bs*):

1. *Phong Nha Formation* ($C_1$t *pn*): The Phong Nha Fm. has its stratotype in the Phong Nha - Ke Bang area within the Bo Trach and Minh Hoa districts, Quang Binh Province. The formation has extensive outcrops in the My Duc area, Quang Binh Province, and Cam Lo area, Quang Tri Province.
   The stratotype of the formation, exposed in the Phong Nha Cave mouth, is about 100 m thick, composed of : 1) black-grey organic clastic limestone and banded, thinly-bedded cherty limestone with interbeds of red-brown shale, 60 m thick, containing Tournaisian fossils, such as: *Crurithyris urii* (brachiopods); *Bisphaera malevkensis, Parathurammina suleimanovi, Tournayellina beata, T. primitiva, Chernyshinella glomiformis, Septabrunsiina (Septabrunsiina) kingirica, S. Septatournayella evoluta, S. segmentata* (foraminifers), and *Rotiphyllum* sp., *Fedorowskia phongnhaensis*, *Cobaiphyllum* sp. (Rugose corals); 2) dark grey, thin- to medium-bedded organic clastic limestone interbedded with chert or containing small chert nests, 15 m thick, containing the coral *Pseudouralinia* aff. *tangpakonensis*, gastropods and brachiopods; 3) grey cherty shale, cherty limestone, 15 m thick, containing the trilobite *Phillipsia* sp. and ossicles of crinoids.
   The Phong Nha Fm. has been dated as Tournaisian at the base of the Early Carboniferous (347-359 My) on the basis of rugose corals and foraminifera. The formation has a transitional relation upon the Cù Bai Fm and is unconformably overlain by the La Khê Fm ($C_1$ *lk*).
2. *Bac Son Formation* ($C_1$v-$P_2$ *bs*): The Bac Son Fm. [Nguyen Van Liem, 1978] is composed entirely of carbonate sediments exposed in the North Vietnam Basin (Bac Bo) and Viet-Laotian Basin. This formation is largely distributed in both West Nghe An, Ha Tinh and Quang Binh areas of the Viet-Laotian Basin. In these areas, this formation has the sedimentary composition and fauna similar to those described in the Bac Bo region that are light grey, thick-bedded to massive limestone containing an abundance of fossils from the Early Carboniferous, Visean to Middle Permian fossil groups, such as foraminifera, crinoids, tabulates, rugose corals etc. In the Viet-Laotian Basin, the Bac Son Fm. rests conformably upon the Phong Nha Fm. or La Khê Fm.

These limestones are part of the Truong Son Fold Belt that extends northwest across the northern half of Vietnam and into northern Laos. Folding occurred during the Early Triassic Indosinian orogeny (Lepvrier *et al.,* 2004). The limestone of the Ke Bang massif is surrounded by insoluble rocks to the east and south. These include Carboniferous to Triassic metamorphosed crystalline rocks that form mountains to the northeast, and much younger Cretaceous (145-65 My) red sandstone and mudstone largely exposed to the south.

A series of strike-slip faults trending NW-SE are widely observed in north-central Vietnam, as well as regionally, associated with Paleogene extrusion of the Indochina block along the NW-SE trending Red River fault that passes through Hanoi into the Gulf of Tonkin (Rangin *et al.,* 1995). A second, somewhat younger set of strike-slip faults trends N-S, and cuts the older faults. The N-S faults probably date to the Neogene (beginning 23 My ago), and may be associated with opening of the South China Sea (Rangin *et al.,* 1995).

The bedrock geology has had a strong influence on the formation of Hang Son Doong. The Permo-Carboniferous rocks that the cave passes through are generally massive to thickly bedded, and are formed of relatively pure calcium carbonate that is conducive to cave formation. At the cave, the rocks are dipping approximately 20-30 degrees to the north. At only one place in the cave (Watch Out for Dinosaurs) was a section of thinly-bedded limestone observed, and this was associated with passage collapse. Interbedded cherts are generally rare, except in localized bands. Both the Paleogene and Neogene faults control the passage geometry. Hang Son Doong formed primarily along a single N-S fault, with a collapsed passage (The Alcove) extending SE along an older fault.

**Fossils**

The limestone at Hang Son Doong cave contains similar fossils to those of the limestone of Phong Nha and Bac Son Formations in other areas of Vietnam, such as Ha Giang, Lang Son and Quang Ninh Provinces. Some of these fossils are particularly well exposed and worth description.

Near the collapse doline "Watch Out for Dinosaurs", on the surface of the limestone there are many beautiful corals. They are solitary horn-shaped corals, about 3 cm diameter and 10 cm long. According to the preliminary determination of Dr. Nguyen Duc Khoa (a member of the Vietnamese Paleontological and Stratigraphical association) they are rugose corals belonging to the family Dibunophyllidae of Early Carboniferous age. On the rock surface near the stalactites blocks called the "Hand of Dog", there are many segments of crinoids.

Finally, near the exit of Son Doong cave located on a small hill there is a very recent calcite-draped skeleton of an animal. Dr. Vu The Long considers it to be the skeleton of an herbivore, although without the skull the genus cannot be determined with accuracy.

**Cave description**

*Geology*

Besides its size, one of the defining characteristics of Hang Son Doong is that it is profoundly straight due to fault control. The fault is well-exposed in the ceiling and walls, and is almost never out of sight. It is sub-vertical and usually consists of 1-2 major strands. The walls of the cave also often expose a fault breccia that consists of striking black and white cement, predominant CaCO3 over the cave that forms angular, sharply-defined patterns. The patterns tend to be tooth-like near minor faults, merging into an almost kaleidoscopic background. Overall, the fault breccia can be found in a zone approximately 100 metres across, and may have helped to control the width of the cave.

The cave has been subject to two massive collapses to daylight. The southern collapse doline is named "Watch Out for Dinosaurs" (WOFD). It is 110 metres across at the base, and is colonized by thin forest. The walls of the WOFD collapse are the only place in the cave that expose thinly-bedded chert-bearing limestones. The doline collapse almost certainly occurred here due to the weakness of the rocks. The northern collapse doline at the Garden of Edam (GOE) is considerably larger, 163 meters across at the base. A thicker forest covers the collapse pile. The rocks at GOE are thickly bedded, and so collapse here is not due solely to rock strength. Instead, it is apparent that GOE formed at the intersection of two major faults. The main cave is formed along a N-S fault, presumably Neogene in age. A tributary passage that is filled by an earlier collapse formed along a NW-SE trending fault, presumably of Paleogene age. GOE is found at the intersection of these two faults, where the ceiling would have been weakened both by its extra width at the passage intersection, as well as by the presence of two faults in the ceiling which would promote collapse of the unsupported blocks between them.

*Hydrology*

Hang Son Doong can be conveniently broken into three smaller units. The southern section, south of the WOFD, the central section between the WOFD and GOE collapse dolines, and the northern section, north of the GOE.

*a. Southern upstream section*

The southern section of the cave actively takes water today. The passage has many indications of annual flooding, including actively dissolving breakdown, re-dissolving speleothem, and coarse fluvial sediment derived from outside the cave, as evidenced by abundant red sand and mud from the Cretaceous rocks and crystalline fragments from the Triassic rocks.

Base-level flow at the time of our visit was estimated to be about 10 $m^3/s$, although no direct measurements were taken. Peak flow was estimated from scallops widely distributed on the floor and walls at the first river crossing. The scallop dimension can be related to flow velocity, and probably represents conditions under peak annual flow. Scallop lengths were measured at 10 places each on the floor and walls, chosen at random over an area of several square

| Floor | Wall |
|---|---|
| 35 | 35 |
| 25 | 35 |
| 30 | 35 |
| 35 | 28 |
| 24 | 37 |
| 50 | 32 |
| 55 | 34 |
| 60 | 35 |
| 45 | 28 |
| 34 | 40 |

**Table 1:** Scallop dimensions at river crossing, in mm.
***Tabla 1.*** *Tabla 1. Dimensiones de "scallop" en el cruce del río, en mm.*

meters, and are reported in Table 1. The standard method for interpreting scallop dimensions comes from Curl (1974).

For flow velocity calculations, we assume that the flooded passage at the river crossing was 35 metres wide and 10 metres high. Flow velocity is calculated for parallel walls 10 metres apart, with a water viscosity of 1 centipoise, consistent with a water temperature of 20°C. For a weighted average scallop dimension of 35 mm, the calculated water velocity is 1.2 m/s, or 4.4 km/hr. This corresponds to a discharge of approximately 400-450 $m^3$/s.

Active flooding of the southern section of the cave is evident all the way to the WOFD doline collapse. During floods, water is apparently dammed behind the collapse pile, filling the passage approximately to a 100 metres deep to the elevation of the "Level Playing Fields", a flat surface on the top of a gour sequence capped by a layer of sand. The sand is active during the annual flood. Footprints from 2009 were not visible in 2010. There are small channels that are apparently active on this surface, and the sand shows evidence of water flow.

There is evidence that the southern section of the cave has a long history of being filled with ponded water during the rainy season. The lower half of the cave contains a thick deposit of laminated muds and fine sands. These sediments are best exposed underneath the formation called the "Hand of Dog" (HOD). The massive speleothems in the vicinity of the HOD all show evidence of faulting, slipping, and wholesale collapse into the main passage as the formations are undercut by erosion of the mud banks on which they formed. Two samples were taken to ascertain the age of the sediments at HOD: one for paleomagnetism, and another for cosmogenic nuclide burial dating. Dating results are reported in detail in a later section, but the sediments here are likely to be younger than about 500000 years.

*b. Central section*

The central section of the cave is fossil, with no evidence of river flow in the recent geologic past. The area near the WOFD collapse doline has a fantastic set of gours formed from ceiling dripwater. Elsewhere in this section there are speleothems indicative of dripwater, but no externally-derived sediment and no evidence of flooding.

*c. Northern downstream section*

The northern section of the cave is mostly fossil passage. There is some evidence of flooding in the geologic past in the vicinity of "The Alcove" adjacent to the GOE collapse doline. An unconsolidated deposit of large cobbles and small rounded boulders indicate very rapid stream flow through a passage near floor level just to the south of "The Alcove". However, all of the cobbles and boulders are composed of limestone; there is no externally-derived sediment. This indicates that the water is either coming from a different source, or that the sediment has been filtered and is not transported to this part of the cave. This deposit does not represent simply a downstream extension of the same river that entered the southern section. The sediment is also clearly not associated with the time of speleogenesis, when a river would have travelled through the entire length of the cave.

At "Camp II" (north of "The Cormorant") there are several metres of laminated silt indicative of flooding. The source of the water is probably a rising sump. There is no evidence of externally-derived sediment, so this water is either from a local source or it is filtered from the main river below. The silts are of unknown age, but the surface shows signs of active transport, so they are probably flooded episodically today.

Continuing north, the" Passchendaele" section carries water, even under base flow conditions. The presence of cave blindfish indicates persistent stream flow. The sediments here are several metres thick, and consist primarily of wet mud. A bathtub ring extends several metres above the sediments, illustrating the limit of annual flooding. Floodwater here is probably from two sources: a rising sump and drip water. The "Passchendaele" section is beneath a doline on the surface that funnels drip water into the cave, even during the dry season. The "Great Wall of Vietnam" is a muddy flowstone that has accumulated beneath the doline. The main source of water here is probably the same as at "Camp II". There is no evidence of externally-derived sediment.

## Geochronology

A dedicated effort was made to search for samples that could constrain the age of either the cave or the sediments within it. Suitable samples for dating caves are often found in sediments filling pockets on the cave wall, or high-level passages. Speleothem of pure calcite can be dated by U-series or U-Pb under suitable conditions. No such sediments were found. However, two sedimentary fills that postdate cave formation were found and samples were collected for dating. These were 1) laminated silts behind the WOFD at the "Hand of Dog", and 2) a passage-filling breccia at "The Alcove".

### *1. Hand of Dog.*

Laminated silt and mud beneath the speleothem at the "Hand of Dog" were deposited in a quiet water environment, probably in ponded water behind a dam formed by the collapse at the WOFD. The sediments thus postdate the time of doline collapse. They are much younger than the cave itself, and have little bearing on the time of speleogenesis.

Two types of samples were collected. Three cubes of sediment were collected in oriented plastic boxes for paleomagnetic analysis. Each cube consists of a 1 inch (2.54 cm) square pressed into an oriented surface. The cube is 5/8 inch (1.6 cm) deep. Three samples were taken on a vertical face oriented N12°E. Each cube was marked, and oriented using a bubble level. The samples were sent to Josep Pares at CENIEH (Centro Nacional de Investigación sobre la Evolución Humana), Burgos, Spain for analysis. All three samples were determined to be magnetically normal, indicating that they were deposited less than 780 000 years ago.

A sample of silt was also collected for cosmogenic nuclide burial dating. This dating method is based on the decay of cosmogenic $^{26}Al$ and $^{10}Be$ in the mineral quartz after deposition in the cave (Granger and Muzikar, 2001). Successful dating requires that there be a measurable quantity of these nuclides, and that the aluminum concentration in the quartz be low (10-100 ppm). The silt sample was found to contain abundant quartz, however the aluminum content was moderately high (~250 ppm). The measurements were therefore not very precise. Cosmogenic nuclide data are reported in Table 2, and age calculations are reported in Table 3. The age of sediment at "Hand of Dog" was determined to be young, $-0.26\ ^{+0.36}/_{-0.32}$ My. Even though the age is negative (a physical impossibility), it overlaps within error with zero, and is thus statistically normal for a young sample. A sensible maximum age for the sediments is two standard errors older than the calculated age. The age of the sediments is therefore determined at 95% confidence to be younger than 0.46 My.

Both paleomagnetic and cosmogenic data indicate that the sediments at the HOD are young. The best estimate for the timing of collapse at the WOFD is within the past 500 000 years.

### *2. The Alcove*

"The Alcove" is a filled side passage that intersected Hang Son Doong at the "Garden of Edam" collapse doline. The Alcove represents a passage essentially as large as that of the main cave, and would have been a major tributary passage at the time of cave formation. It is possible that the cave carried water sourced from a stream passing through the village along the trail to Hang En (near 17°26.9′ N, 106°18.9′E). At "The Alcove", the passage is entirely filled with a breakdown breccia containing abundant externally-derived sediment. The passage collapse here therefore occurred after the time of speleogenesis, but while the river was still occupying the main passage. (This sediment is distinct from the much younger sediment at floor level that consists entirely of rounded limestone.)

A sample of sediment was collected here for cosmogenic nuclide burial dating. Results are reported in Table 2. This sample also contained a moderately high (~150 ppm) aluminium concentration, precluding very accurate dating. The sediment dates to $2.29\ ^{+0.70}/_{-0.53}$ My, placing it in the middle of the Pliocene. Although the uncertainty in the burial age at "The Alcove" is disappointingly high, the result clearly points to the antiquity of the cave, placing speleogenesis in the Pliocene or late Miocene.

We can use the age of sediments in the cave to learn about the long-term history of river incision. "The Alcove" is approximately 50 metres above the modern base level within the cave, and 80 metres

| Sample | [$^{10}$Be] ($10^6$at/g) | [$^{26}$Al] ($10^6$at/g) | Burial age* (My) |
|---|---|---|---|
| Hand of Dog | 0.055 ± 0.003 | 0.424 ± 0.065 | $-0.26\ ^{+0.36}/_{-0.32}$ |
| Alcove | 0.0214 ± 0.0014 | 0.057 ± 0.018 | $2.29\ ^{+0.70}/_{-0.53}$ |

$^{26}$Al and $^{10}$Be measured at PRIME Lab. $^{10}$Be measured against standard 07KNSTD.
*Burial age calculated using radioactive mean lives for $^{26}$Al and $^{10}$Be of 1.02 and 2.005 My. Production rates are taken as 4.1 and 27.9 atom-s/g/yr for latitude 17.5°N and altitude 0.4 km.
**Table 2:** Cosmogenic nuclide analysis.
***Tabla 2**. Análisis de núclidos cosmogénicos.*

above the resurgence. Dividing the elevation of 50 metres by $2.29\ ^{+0.70}/_{-0.53}$ My yields a water table lowering rate of approximately 22 ± 6 m/My. We can also learn about the paleo-erosion rate of the sediment source area at the time of deposition by correcting the concentrations of $^{10}$Be and $^{26}$Al for radioactive decay. These calculations show that the erosion rate in the mountains surrounding the cave was 37 ± 11 m/My, similar to the rate of river incision and water table lowering. Such remarkably low incision and erosion rates suggest that this area of central Vietnam is uplifting very slowly, in sharp contrast to the Kong Tum block to the south where a pulse of rapid uplift has been inferred. Apatite fission tracks reveal that exhumation rates there increased from 34 m/My to 390-500 m/My in the Miocene (Carter et al., 2000). Our incision and erosion rates are similar to the pre-Miocene exhumation rates of the Kong Tum block of ~34 m/My, suggesting that Miocene uplift may have been confined to the south.

## Speleogenesis

There are several observations of local geomorphology and geology that lead to a general theory of speleogenesis for Hang Son Doong. Most tellingly, a high-level paleo-valley is sculpted across the surface, draining westward (Fig. 1). This paleo-valley is carved into the limestone, but pre-dates cave formation. This implies that there was no subterranean outlet for the water from the basin, or else the caves would surely have carried the water. The basin is surrounded to the east by metamorphic and crystalline rocks, and to the south by Cretaceous redbeds. A portion of the northern boundary of the watershed also abuts onto Cretaceous redbeds, preventing cave formation. The remainder of the watershed is surrounded by large faults. We suggest that these faults served as aquicludes, preventing water from passing through, and stymieing cave development. In particular, the fault to the north of the cave would have blocked water flow towards the Son River. It was only when this fault was breached, probably by incision of a surface stream in the valley to which Hang Son Doong exits to the north, that a hydrologic outlet was available for the watershed. At that time, the water draining the Hang Son Doong watershed would have been perched in a riverbed above the new base level where the fault was breached. Water immediately began forming caves to this outlet. The fastest flow path to the outlet was along a pre-existing N-S (Paleogene) fault, and another NW-SE (Neogene) fault. The cave expanded rapidly, taking the entire discharge of the watershed by wholesale capture of the surface river. Initial cave formation was probably rapid, as suggested by the lack of tributary passages and the volume of water that must have been captured. The cave has persisted for millions of years, associated with a relatively slow base level lowering rate of 22 ± 6 m/My.

## Summary of observations

Hang Son Doong formed as a result of stream capture along a pre-existing N-S trending fault. The capture likely occurred due to breaching of a different NE-trending fault that blocked water flow until sometime during the Pliocene or latest Miocene (2-5 My). The cave today takes an estimated peak annual discharge of 400-450 $m^3/s$, consistent with a drainage area of 200 $km^2$. The massive size of the cave is probably due to several factors. 1) The limestone here is generally thickly bedded and able to support a wide ceiling. 2) The cave has developed to a fairly uniform width, possibly influenced by the width of the fault breccia zone in which it formed. Cave enlargement has thus been primarily vertical rather than horizontal. 3) The cave has few tributaries that would weaken the ceiling. In cases where either conditions (1) or (3) are violated, the cave has collapsed. The age of the collapses is probably variable, but “Watch Out for Dinosaurs” probably collapsed during the past 500 000 years. 4) Slow uplift and water table lowering rates imply that

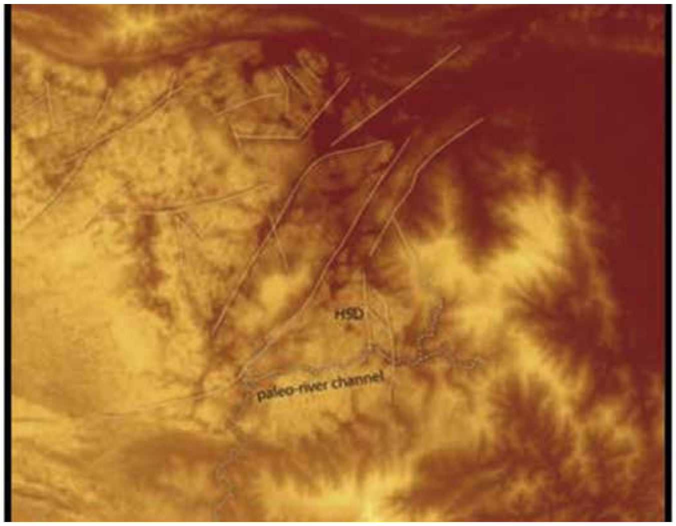


**Figure 8:** Digital Elevation Model showing topography in the Ke Bang massif in the vicinity of Hang Son Doong. Major lineations (faults) are highlighted in yellow. Note the prevailing tendency of N-S and NW-SE trending faults, as well as the younger NE-trending major faults. The valley does not take water today, but predates cave development. Hang Son Doong (HSD) formed near the intersection of a N-S fault with the paleo-valley. At the time of speleogenesis the cave pirated water from the paleo-river and carried it along the N-S fault to discharge ultimately into the Son River.

***Figura 8.*** *Modelo digital de elevaciones mostrando la topografía en el macizo de Ke Bang en las cercanías de Hang Son Doong. Las principales lineaciones (fallas) están resaltadas en amarillo. Hay que tener en cuenta la tendencia prevaleciente de N-S y NO-SE de las fallas, así como la reciente tendencia NE de las fallas mayores. El valle no toma agua hoy, pero es anterior al desarrollo de la cueva. Hang Son Doong (HSD) formado cerca de la intersección de una falla N-S con el paleovalle. En el momento de espeleogénesis la cueva pirateó agua del paleo-río y lo llevó a lo largo de la falla N-S para descargar en última instancia al río Son.*

**Figure 9:** Fossils found within Hang Son Doong. (photo Prof Ta Hoa Phuong. A) Crinoid fossils. B, C y D) Tetracoral fossils. E and F) Herbivore fossils,

***Figura 9****. Figura 9. Fósiles encontrados dentro de Hang Son Doong. (foto del Prof. Ta Hoa Phuong. A) Fósiles crinoideos. B, C y D) Fósiles de tetracoralarios. E y F) Fósiles de herbívoros.*

the main cave passage may have enlarged over a period of up to several million years. It is the convergence of all of these factors that led to the enormous dimensions of Hang Son Doong and other caves in the Phong Nha system.

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Recibido: febrero 2015
Revisado: marzo 2015
Aceptado: abril 2015
Publicado: marzo 2016