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Karst development, breccias history, and mammalian assemblages in Southeast Asia: A brief review

Développement des karsts, histoire de brèches et des assemblages de mammifères d'Asie du Sud-Est

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ABSTRACT

Karst processes typically occur in carbonate rocks, such as limestone or dolomite. They occur all over the world everywhere where carbonate rocks are exposed and submitted to rain and/or water circulation. The karstification of carbonate rocks-bearing landscapes leads to a variety of surface and subsurface features. In tropical and sub-tropical areas as it is the case in Southeast Asia, the mature karst landscapes display a typical morphology called tower karst. Beneath the surface, the complex underground drainage systems contribute to an extensive network of caves and caverns, which may be filled with breccia. The history of sedimentary cave infilling is often complicated due to alternating cycles of infilling/removing phases through time, driven by climate/tectonic/eustatic changes. We present results from our research in Vietnam and Laos. We emphasise that both modern and fossil alluvial terraces and cave entrances/exits, evolve together, and that the caves at progressively higher elevations also have older periods of formation. The oldest breccias and sedimentary deposits are on the upper part of the network, whereas the youngest ones are often close to the modern alluvial plain. These processes of formation are in many respects very similar to those of the fluvial terraces formed during the drop of the alluvial plain, showing a stair-like morphology. Additionally, the alternation of infilling and erosion is strongly linked to the progressive downcutting of the alluvial plain that leads to a major change in both, water circulation and sedimentary deposits. The bone-bearing breccias, formed by typical sedimentary processes, yield vertebrate assemblages, often essentially composed of isolated teeth from middle- to large-sized mammals (Artiodactyla, Perissodactyla, Proboscidea, Carnivora, Rodentia, Primates). In terms of zoogeography, the continental Southeast Asian mammals belong to the Indochinese Subregion. After a brief review of the evolution of the faunas throughout the Pleistocene, we present a

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biochronological framework of the transition between the Middle Pleistocene and the Late Pleistocene, on the basis of our research in the karsts of Vietnam (Duoi U'Oi and Ma U'Oi sites) and Laos (Tam Hang site).

Mots clés :
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R É S U M É

Les karsts se développent principalement sur les calcaires et les dolomies. On en rencontre partout dans le monde où les roches carbonatées sont soumises aux précipitations et/ou à la circulation de l'eau. Les processus de karstification conduisent à une grande variété de morphologies aussi bien en surface qu'en profondeur. En condition tropicale ou subtropicale, comme c'est le cas en Asie du Sud-Est, se développent des reliefs abrupts sous la forme de tours appelée « tower karsts ». Dans le même temps se développe sous la surface un réseau très dense de cavernes, conduits et galeries qui peuvent se remplir de dépôts sédimentaires bréchiques. L'histoire de ces remplissages karstiques est souvent compliquée en raison d'une alternance, au cours du temps, de périodes de remplissages et de phases de remaniements en fonction des changements climatiques/tectoniques/eustatiques. Nous présentons ici une synthèse de nos recherches au Viêt Nam et au Laos. Nous mettons l'accent sur le fait que les entrées/sorties des grottes connectées aux terrasses alluviales évoluent ensemble au cours du temps et que les grottes situées plus haut dans la falaise sont ainsi progressivement plus anciennes. Les brèches de cavernes les plus anciennes sont donc situées dans les parties les plus hautes du réseau karstique, alors que les plus jeunes sont souvent localisées à proximité de la plaine alluviale actuelle. La localisation des brèches selon des niveaux successifs à l'intérieur du réseau karstique est, à plusieurs titres, similaire à la morphologie en étages des terrasses des plaines alluviales, formées par incision successive de la plaine d'épandage. L'alternance de phases de dépôts et de phases d'érosions à l'intérieur des grottes est directement liée à l'abaissement progressif du niveau de la plaine alluviale, lié directement à un changement de la circulation de l'eau à l'intérieur du réseau karstique. Les brèches fossilifères formées par des processus sédimentaires classiques contiennent des assemblages de vertébrés souvent essentiellement composés de dents isolées de mammifères de taille moyenne à grande. En termes de zoogéographie, les mammifères de cette région continentale d'Asie du Sud-Est appartiennent à la sous-région indochinoise. Après une brève synthèse sur l'évolution des faunes pléistocènes, nous présentons une échelle biochronologique à la limite Pléistocène moyen/Pléistocène supérieur, sur la base de nos recherches dans les sites karstiques du Viêt Nam (Duoi U'Oi et Ma U'Oi) et du Laos (Tam Hang).

1. Introduction

Here we present results from 10 years of exploration and research in fossil-bearing karstic breccias principally in Vietnam and Laos (Fig. 1). During the decade of research, we visited almost two hundred caves and galleries in these countries. Several of them presented very interesting infilling and sedimentary histories, but only a half dozen were investigated further for their palaeontological assemblages. The limestone (massive micritic to sparitic in nature) displays an intricate network of caverns and galleries generally located in small hills, cones or tower karsts. The tower karsts rarely exceed 150 m in height. Compared to the level of the modern alluvial plain, the elevation of the fossil-bearing breccias is generally low, located several tens of meters above the modern water table. The karstic network is gradually opening up, while the amount of breccias progressively decreases and disappears at the same time due to erosional processes.

On the uppermost part of the limestone mountains, galleries, caves and caverns are wide open, with breccias partially preserved or absent. This is particularly true for the smaller hills of less than 50 m in height (especially in South Cambodia). In contrast, the caves at progressively higher elevations represent generally older periods of formation, including older breccias. The fossil assemblages they contain increase in age from the base to the top of the cliff. This observation has been made by several authors in previous studies (e.g. Stock et al., 2005; Wang et al., 2007, and others). It is one of the biggest geological paradoxes for researchers looking for old fossil-bearing breccias: the higher they are, the older they are. They are correlatively less well-preserved and correspondingly more difficult to find. Moreover, they are often well-cemented and occur in very discontinuous layers leading to difficulties in interpretation of the processes of sedimentation.

The research on karstic breccias during the last ten years has highlighted that the majority of the fossil-bearing sedimentary infillings are the result of normal sedimentary processes, and not the result of an anthropic concentrations (Bacon et al., 2004, 2006, 2008a, 2008b, in press). Generally, the breccias display a complicated sedimentary history, comprising a continuous alternation of deposits/reworking of deposits, often interrupted by speleothem crystallisation (stalagtite, stalagmite, flowstone...). These typical sedimentary dynamics lead to the formation of mature fossiliferous breccias containing mammal teeth in the majority of cases.

The complexity of the karst depositional processes, as well as the difficulty of estimating the age of the breccias,

Fig. 1. Map of continental Southeast Asia with location of Nam Lot cave and Tam Hang rockshelter (Laos), and Duoi U'Oi and Ma U'Oi caves (Vietnam).
Fig. 1. Carte de l'Asie du Sud-Est. Situation de la grotte de Nam Lot et de l'abri-sous-roche de Tam Hang (Laos), et des grottes de Duoi U'Oi et Ma U'Uoi (Viêt Nam).

does not facilitate the study of their mammalian assemblages. For these reasons, these assemblages have simply be referred to as "*Stegodon-Ailuropoda*" faunas, since the 1940s – a reference to the two key-taxa which are the most common and typical species found historically in the Middle Pleistocene sites of southern China (Kahlke, 1961; Pei, 1957). The term is still used today in the literature for historical reasons, to describe the "large mammals faunas from the Middle Pleistocene to the beginning of the Late Pleistocene that characterize the Indochinese Subregion" (Corbet and Hill, 1992).

Even if the faunal assemblages from karst breccias may possibly represent a significant period of accumulation time, they remain the most frequently encountered, and therefore important, sources of data for the Indochinese area. Within the last decade, a better understanding of sedimentary process and stratigraphy in the caves, and the improvement of various dating methods (such as Optically Stimulated Luminescence, Uranium/Thorium, Cosmogenic methods) have allowed geochronologists the opportunity to place the fossils-bearing breccias deposits in a more precise chronological frame (Rink et al., 2008; Shen et al., 2002; Westaway et al., 2007).

Here we present a brief review of the processes of breccia cave deposits characteristic of Southeast Asia, illustrating by examples drawn from our own research into the karstic sites we discovered in Vietnam (Duoi U'Oi, Ma U'Oi) and Laos (Nam Lot). We also present a brief review of the state of knowledge concerning the evolution of Pleistocene mammals from the same area, by discussing key well-documented mammalian assemblages.

2. What is a karst?

The karst landscapes constitute about 20% of the Earth's exposed land surface (Ford and Williams, 2007). The karst topography is a landscape shaped by the dissolution of sedimentary formations of soluble bedrock, usually carbonate rock, such as limestone or dolomite. The karst processes occur almost all over the world: everywhere where carbonate rocks are exposed and submitted to rain and/or water circulation including melt-water (De Waele et al., 2009). The karst processes can also develop in other rock types, such as gypsums/salt-rich-evaporitic formations or, less commonly and much harder, in quartzites of tropical areas (Piccini and Mecchia, 2009). The topography is essentially related to the subterranean drainage, geomorphology and hydrology being closely related (De Waele et al., 2009). The karst processes, especially the network development, are more common in thick formations of dense and massive limestones or marbles. The history of karst geology research over time is abundantly described in the literature giving a good overview on both morphology and dissolution/precipitation processes (Bögli, 1960; Culver and White, 2004; Ford, 2006; Ford and Williams, 1989, 2007; Gunn, 2004; Jennings, 1985; Sweeting, 1981; Trudgill, 1985; White, 1988).

Fig. 2. Karst morphology and alluvial terraces in North-West Vietnam. a: general view of tower karst morphology in the Man Duc area; b: location of the lower (LW) and upper (UM) Ma U'Oi caves/terraces couplets through time from the base to the top of the hill; c: view of the Man Duc area from the upper Ma U'Oi terrace, about 60 m above the modern alluvial plain; d: example of karstic dissolution after disappearance of soil and vegetation on small karst peaks; e: location of the oldest alluvial terrace (upper Ma U'Oi) situated on the same level as a succession of cave entrances/exits. This deposit formed by a mixing of typical exokarstic alluvial pebbles (conglomerate), and endokarstic angular clasts (breccia) supported by a matrix of sandy clays.

Fig. 2. Morphologie karstique et terrasses alluviales au Nord-Ouest du Viêt Nam. a : vue générale de la morphologie en « tower karst » de la région de Man Duc ; b : localisation des grottes inférieure (LW) et supérieure (UM) de Ma U'Oi. Les deux entrées de grottes sont associées à des terrasses alluviales. L'âge des dépôts augmente de bas en haut de la falaise ; c : vue du site de Man Duc depuis l'entrée de la grotte supérieure de Ma U'Oi à environ 60 m au-dessus de la plaine alluviale actuelle ; d : exemple de dissolutions karstiques (lapiaz) sur de petits « tower karst » débarrassés de la végétation ; e : brèche alluviale à l'entrée de la grotte supérieure de Ma U'Oi affleurant en terrasse, exactement à l'entrée de la grotte. Le dépôt est formé par un mélange de galets fluviatiles et de clastes anguleux provenant de l'intérieur de la grotte (origine endokarstique). La matrice est sablo-argileuse.

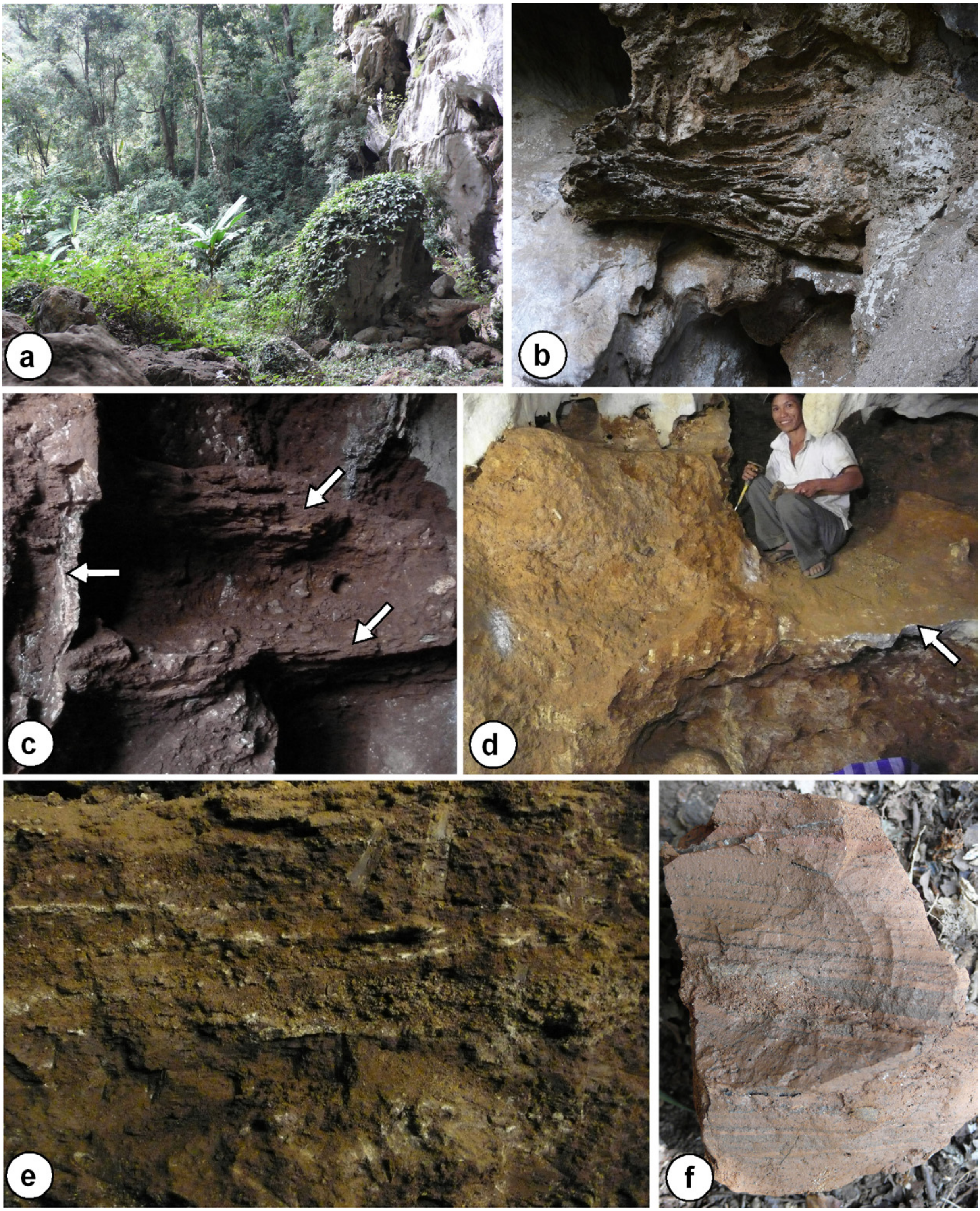

Fig. 3. Karst morphology and breccias in North-East Laos. a: general view of the outcrop in the Pà Hang site, with numerous caves along the limestone cliff; b: example of breccias plastered on the walls of the cliff at a cave outlet; c: breccias from Tam Hang rockshelter consist of argillaceous sandy breccias interrupted by two horizontal and one vertical flowstones (indicated by arrows); d: breccias removed for paleontological studies above and below a limestone blade (indicated by arrow) in the Nam Lot cave; e: argillaceous sandstone and (f) laminated clays removed from the lower part of the Nam Lot cave.

The karstification of a landscape leads to a variety of large- and small-scale features, both on the surface and beneath. On the exposed surfaces, the small features include: flutes, solution runnels, karrens and many others roughly summarised by the term “lapiez” (Fig. 2d) (De Waele et al., 2009). The medium- to large-sized surface features include: dolines, poljes, sinkholes, disappearing streams, and reappearing springs, carbonate pavements, and so forth, in the tropical to sub-tropical areas (Drogue and Bidaux, 1996; Maire et al., 1991; Quinif and Dupuis, 1985; Rossi, 1974; Sweeting, 1995) such as Southeast Asia. The mature karst landscapes display a typical morphology of vertical towers, sometimes similar to the inselberg morphology called tower karst, peak karst or cone karst (Fig. 2a–c), depending on their shape (De Waele et al., 2009; Drogue and Bidaux, 1996; Tang, 2002). Beneath the surface, the complex underground drainage system develops into an extensive network of caves and caverns (Fig. 3a).

Water is central to both the beginning and continued evolution of the geological processes related to karsts. Karst landforms result from mildly acidic water acting on weakly soluble carbonate bedrocks. In the first stage, the rain falling through the atmosphere picks up carbon dioxide, which dissolves into the water, forming carbonic acid. In a second stage, as the water percolates down through the soil, it is further enriched with carbon dioxide, forming a weak solution of carbonic acid able to dissolve more or less rapidly most of the carbonate, depending on the strength of the acid. The rate of the carbonate dissolution, ranging from thousand to hundreds of thousands of years, depends on various factors, all roughly linked to the climate and the available water. This mildly acidic water begins to dissolve the limestone or dolomite commonly along restricted vertical and horizontal pre-existing fractures, joints, bedding planes or along discontinuities (Palmer, 1989; Rauch and White, 1970). Over time, these fractures enlarge as the bedrock continues to dissolve. The openings in the rock increase in size, and an underground drainage system begins to develop, thus also allowing more water to pass through the area. This further accelerates the formation of the underground karst features, creating networks of caves, caverns and galleries. All these mechanisms are called “speleogenesis”, referring to karst development, as reviewed by Klimchouk et al. (2000), Klimchouk (2007) and Palmer (2007).

3. From karst to breccia

As soon as the underground cave network is created, at least two main types of sedimentary deposits begin to form inside. The first and most common type is referred to as speleothems. This constitutes the chemical/biochemical part of the cave deposits. The term encapsulates a wide range of calcitic concretions such as stalactites, stalagmites, flowstones (Fig. 3c) and rimstones. When reappearing springs occur, calcareous tufa can develop locally, possibly associated with plant interbedded or planar flowstones. The second important type of deposits inside the caves is made by various sedimentary particles, grains and clasts forming a true sedimentological deposit. The most common cave deposit is called “breccia” (Fig. 2e and Fig. 3b–f). The term refers to several sedimentary products comprising true sedimentary breccias (Fig. 4b) made of immature or poorly rounded rock clasts, or reworked speleothems including coarse to fine-grained sandstones (Fig. 3e) and sandy to silty argillaceous sediments (Fig. 3c, Fig. 4c, d). Light to shadow brown clays (Fig. 4c, d), possibly mixed with fine to coarse-grained particles and clasts (Fig. 5a), including gastropods shells (Fig. 5b) and iron-rich pisoliths (Fig. 5c, Fig. 6a), are usually the most commonly encountered deposits in the caves. These are typically carried and deposited by water inside the cave network. Most of the breccias have an autochthonous origin (endokarstic processes) created principally by reworked carbonate clasts and clays, whereas some breccias show allochthonous material (exokarstic origin) introduced into the karstic network from adjacent reliefs. The vertical alternation of silty/sandy clays to fine to coarse-grained sediments, sometimes including true gravels which form conglomerates (Fig. 4a) similar to the fluvial deposits, suggests a dynamic of alternating periods of little or no deposition and flood phases. Pure clays or silty clays are generally deposited during slack water periods in drowned caves (Fig. 4c, d). During long quiet or dry periods, the speleothems concretions, especially flowstones, can separate the clastic deposits, by creating capping or basal flowstones (Fig. 4c) which allows the interpretation of the stratigraphy and dating of the calcite (by means of the U/Th methods).

4. From breccia to fossil-bearing breccia

The majority of caves contain breccias on the floor, or plastered as relics on the walls and roofs (Fig. 3b–d, Fig. 4b). Commonly, the volume of the breccias decreases from the base to the top of the tower kart due to the erosion during the Late Quaternary. Generally, the sedimentary infilling of the cave network consists of argillaceous-rich breccias separated or/and covered by flowstones. Caves completely empty of sedimentary deposits are rare, and in these cases, the infilling consists of thin residual films on the walls of the network. From our experience in Vietnam, Laos and Cambodia, we have observed that about 5% (one cave in twenty) contains more or less bones remains, but less than one-tenth contains sufficiently rich sediments to merit further scientific investigation. The quantity of vertebrate remains in the breccias is highly variable in the caves. The concentration of fossils appears also highly variable laterally or vertically in a same breccia due to their accumulation in the stream placers formed by running water.

Fig. 3. Morphologie karstique et brèches de cavernes au Nord-Est du Laos. a : vue générale du site de Pà Hang montrant l’escarpement calcaire constitué de nombreuses grottes ; b : exemple de brèche de caverne cimentée à l’entrée d’une grotte ; c : brèche de l’abri-sous-roche de Tam Hang constituée de dépôts argilo-sableux entrecoupés par des placages de concrétions calcitiques (spéléothèmes) horizontaux et verticaux (flèches) ; d : image montrant l’exploitation de la brèche de la grotte de Nam Lot, de part et d’autre d’une lame de calcaire (flèche) du substratum carbonaté ; e : grès argileux et argiles laminées (f) de la partie inférieure de la grotte de Nam Lot.

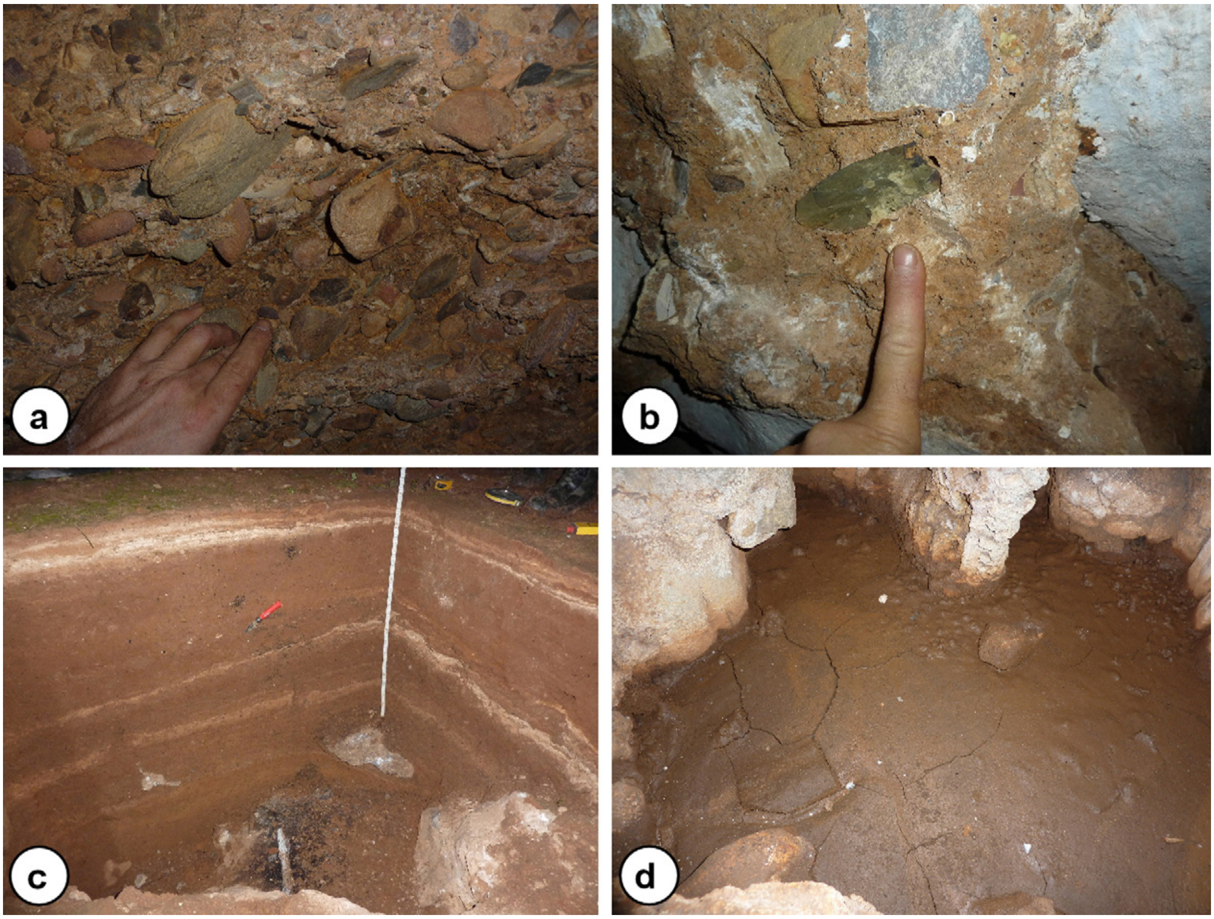

Fig. 4. Conglomerates and clays infilling in North-East Laos. a: alluvial conglomerate in Nam Lot cave. The imbricated pebbles suggest a water paleoflow direction from left to right, i.e. from outside to inside the cavity. During this stage of infilling, the alluvial plain and cave entrance were at the same level; b: breccias in the lower part of Nam Lot cave. Most of vertebrate remains come from this layer; c: example of well-laminated clays and silty clays from the Tam Pà Ling cave not far from Nam Lot cave. Note the white horizontal layers of laminar flowstones and the blocks at the base of the section; d: photo showing the present deposit of argillaceous sediments after a flooding in a cave. Clays and silty clays materials are deposited only during slack water periods that span at least several weeks or months.

Fig. 4. Conglomérats et argiles des remplissages karstiques au Nord-Est du Laos. a : conglomérat fluviatile dans la grotte de Nam Lot. Les imbrications de galets montrent des écoulements de la gauche vers la droite, c'est-à-dire de l'extérieur vers l'intérieur de la grotte. Pendant cette phase de dépôt, la plaine alluviale était située au même niveau que l'entrée de la grotte. La rivière alimentait la grotte ; b : brèche de la partie basse de la grotte. La plupart des restes de vertébrés proviennent de ce dépôt ; c : exemple de dépôts argilo-silteux bien laminés de la grotte de Tam Pà Ling située à proximité de celle de Nam Lot. Les parties horizontales blanches représentent des arrêts du remplissage. Elles sont constituées de planchers calcitiques (« flowstones »). Les blocs de calcaire de la base de la coupe sont des morceaux tombés du plafond ; d : l'image montre un exemple de dépôt argilo-silteux actuel, formé pendant une phase éphémère d'ennoyage de la grotte.

The processes of bone and teeth accumulation, sometimes associated with artefacts, can result from human activities at typical living sites. After 10 years of survey and exploration of hundreds of caves in Vietnam, Laos and Cambodia, we were unable to locate such an *in situ* bone-bearing accumulation, apart from the Holocene to Late Pleistocene cave infilling, mainly from the Hoabinhian epoch. Bone accumulation can also be due in some cases to carnivore accumulators, such as hyaenas (*Hyanea brevirostris*, *Crocuta crocuta*), but one principal agent of accumulation is the porcupine (*Hystrix*). However, despite the activities of carnivores and rodents, all the fossil-rich accumulations we have studied unambiguously suggest that these were formed by sedimentary processes. In fact, the bones and teeth remains included in the sedimentary bedding and sequences showing vertical grading, sometimes concentrated into small runnels, channels or concentrated in typical stream placers, sometimes mixed with pebbles and imbricated as any other clasts in a normal sedimentary habitus. This condition might explain the absence of large and complete bones and skulls, as well as several elements from a single individual in the breccia. The predominance of isolated teeth suggests a long transportation process through the subterraneous cave networks. Such teeth concentrations strongly suggest that the vertebrate remains, like in river processes, are continuously transported, deposited, reworked, from cave to cave, in a *per descensum* processes, over long time-scales, several thousands of year and more. In summary, longer the transportation, the higher the concentration of fossil remains, such as teeth.

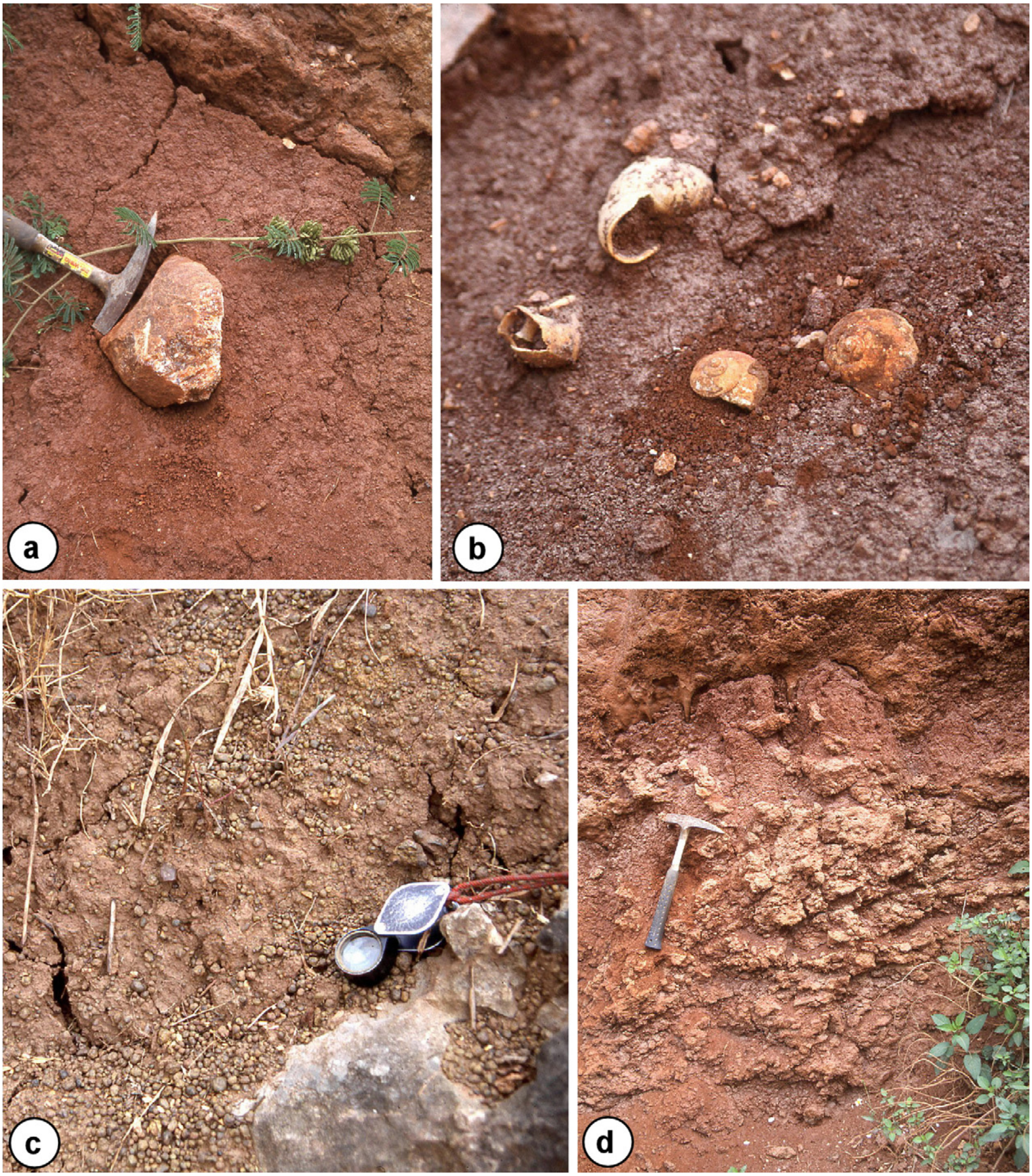

Fig. 5. Example of argillaceous karstic infilling with (a) isolated clasts, (b) continental gastropods, (c) iron-rich pisoliths, and (d) calcitic concretions.
Fig. 5. Exemple de remplissage à dominante argileuse contenant des (a) clastes isolés, (b) des gastéropodes terrestres, (c) des pisolithes de fer et (d) des concrétions calcitiques.

5. Karst and breccia examples in northern Vietnam

5.1. Location and geological setting

The three karstic caves from North Vietnam (Blondel, 1929; Glazek, 1965; Khang, 1991), that have been investigated belong to a series of a half dozen tower karsts about 100 m high, that emerge from the alluvial plain over a surface area of about 10 km^2 (Bacon et al., 2004, 2006, 2008b). The Duoi U'Oi cave and Lower and Upper Ma U'Oi caves are located in the Man Duc village (Tan Lac District, Hoa Binh Province) about 85 km southwest of Hanoi, and 25 km south-southwest of Hoà Binh city (Fig. 1). This area forms part of the northeastern extremity of the Annnamitic

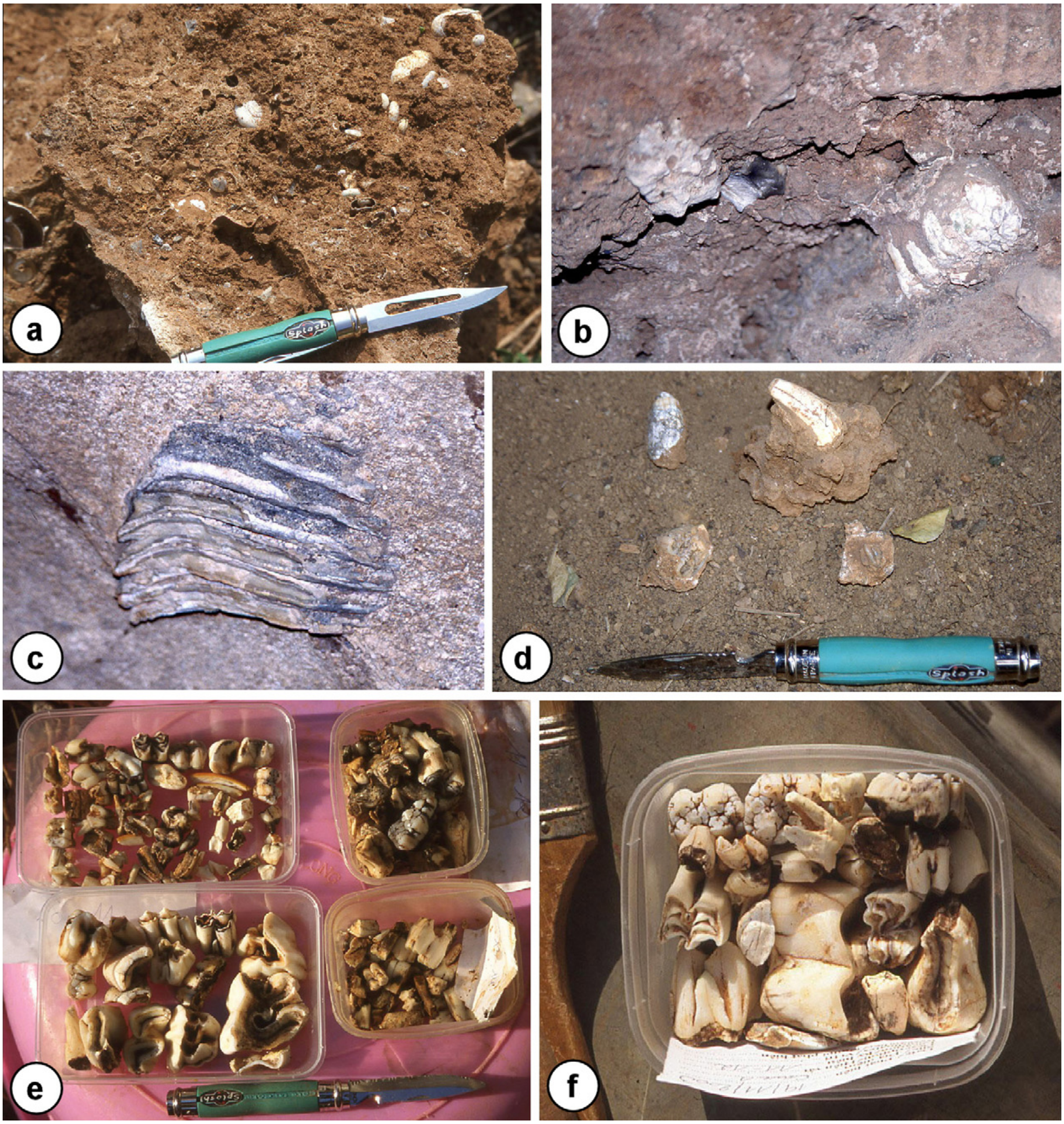

Fig. 6. Fossil-bearing breccia with (a) continental gastropods, (b) unidentified bones and teeth, (c) tooth of proboscidea, (d) canine from carnivore. Example of sampled teeth after sorting (e and f).

Fig. 6. Brèches fossilifères contenant (a) des gastéropodes terrestres, (b) des dents et os indéterminés, (c) une dent de proboscidien, (d) une canine de carnivore. Exemple de matériel récolté après extraction (e et f).

Mountain chain and the western border of the Red River fault zone (Deprat et al., 1963; Ky et al., 2001; Long and Du, 1981; Luong, 1978a, 1978b; Zuchiewicz et al., 2004). The landscape of Tan Lac District is characterised by a typical and spectacular morphology of karst peaks (tower karst) overhanging a mainly argillaceous alluvial plain level (Fig. 1a). The caves are located within monotonous Carboniferous and Triassic limestone formations several hundred metres thick (Deprat et al., 1963; Luong, 1978a, 1978b).

In the study sites, the bedrock consists of poorly fossiliferous dark grey micritic marine limestone dated from the Lower to Middle Triassic (Luong, 1978a; Martini et al., 1998). A dense network of caves, galleries and fissures developed in limestone resulting from faults and fractures. Around Man Duc village, there are at least a hundred caves with exposed sections, which may be of great interest for understanding these karstic networks and their sedimentary infillings. Most of the caves are partly-filled with brown to red-brown argillaceous breccias, containing numerous iron oxide pisoliths, as well as bones and teeth. About 20% of the caves in the Man Duc area have this type of sedimentary infilling (mainly dated from the Late Pleistocene to the Holocene), and more a half contain fossil remains, even if most of the bone-bearing deposits are only partly preserved as relics on the floor, walls and roof. The majority of the breccia was removed as part of historic phosphate mining (Holocene bat guano accumulation) which complicates the understanding of the sedimentary history. The description of the cave infilling and its interpretations, as well as the faunal descriptions, can be found in Bacon et al. (2004, 2006, 2008b).

5.2. *Karstic breccias and alluvial plain: what are their relationships through time?*

Our initial observation that first sparked our interest is the observation that in the largest cliffs, the caves entrances/exits seemed to be aligned on a same horizontal plane. Along the walls of the high cliffs, we observed that the aligned cave entrances are separated vertical by tens of meters without caves. Under good outcrop conditions, such alignment of cave entrances can be traced over kilometres on a same horizontal level sometimes up to 100 m over the plain. In the Man Duc area, the entrances are characterised by well-rounded conglomerates made of allochthonous pebbles (sandstones, grauwackes, quartzites) of fluvial origin. Some conglomerates associated with the cave entrance/exit can be traced on same levels, 10 to 100 m high (Fig. 2e). What is surprising is that these conglomerates occur exactly at the entrance of the cave but do not penetrate more than one or two metres into the interior of the cave network. In fact, the conglomerates are rapidly replaced by typical karstic breccias in the interior of the caves. The conglomerates display typical alluvial features such as cross beds, channels fills, ripple laminations, whereas the breccias appear as immature deposits made of badly-rounded or sub-angular clasts. It is obvious that the outcrop displays an important boundary between endokarstic (breccia) and exokarstic (conglomerate) processes. The outcrop from Upper Ma U'Oi, plastered on the walls of the cliff at the same level than that of cavern entrance/exit, represents a typical example of such mixing between rounded alluvial pebbles and angular clasts of an endokarstic origin (Fig. 2e).

The horizontal alignment of the cave entrances, closely associated with typical alluvial conglomerates passing laterally to breccias into the network, is not coincidental. The observation in the same area of the modern water table level showing similar combinations of river and cave entrances, suggests that endokarstic (cave breccias) and exokarstic (alluvial conglomerates) developed together over time. Most parts of the karstic network are connected to the river. Thus, each alluvial terrace corresponds to an old alluvial plain, which gradually lowered over the time. The entrance of the galleries was therefore automatically readjusted to the new position of the alluvial plain. In fact, each conglomerate/cave entrance corresponds to higher alluvial plain in increasing age from base to top.

Several U/Th dating samples were taken on calcitic flowstones sampled inside the breccias from the Duoi U'Oi cave as well in Lower and Upper Ma U'Oi caves (Bacon et al., 2004, 2006, 2008b). Some speleothems were dated twice. The flowstones from Duoi U'Oi give an age estimate of 66 ± 3 ka (Bacon et al., 2008b). Similar calcite from Lower Ma U'Oi reveals an age of 193 ± 17 ka (Bacon et al., 2006). The laminar speleothems from Upper Ma U'Oi suggest an age of around 600/800 ka or more, but due to some argillaceous pollution, this date has never been published, even though the result is coherent with the increasing ages from base to top of the tower karst. The stair-like geometry of the terraces, associated with cave (terrace/cave combination) summarized in Figs. 7 and 8, indicates at least three successive lowering of alluvial plain during the Late Quaternary: Upper Ma U'Oi (60 m), Lower Ma U'Oi (12 m) and Duoi U'Oi (4 m). The present-day alluvial plain corresponds to the last lowering of the water-table since the infilling of the Duoi U'Oi cave. According to the dating results, the last lowering of the alluvial plain since Duoi U'Oi (66 ka for 4 m), represents about 1 m every 16,500 years. If we apply this rate of lowering of the alluvial plain to the Lower Ma U'Oi terrace situated at 12 m over the alluvial plain, we obtain an age estimate of about 198,000 years which corresponds to the effective U/Th age (193 ± 17 ka). This suggests that the dating is coherent. The U/Th estimate from the Upper Ma U'Oi cave was unsuccessful partly due to detrital thorium pollution. Based on the average speed per meter, the age could be around 990 ka years what is not far from the estimation of the U/Th dating which gives a general estimate of 600/800 ka.

5.3. *Discussion*

When the water table dropped due to tectonic uplifts and/or eustatic variations, a new alluvial terrace formed below the older terrace level by down cutting (Figs. 7 and 8). The karstic networks as well as the entrance/exit of the caverns are progressively adjusted to the new water table level (Figs. 7 and 8). It results a stair-like morphology, consisting of superposed alluvial terraces (Figs. 7 and 8). Such adjustments have been described in the literature (Palmer, 1991; Stock et al., 2005; Wang et al., 2007, and others). In particular, these studies describe similar features on cave development within an incising landscape. Over the time, the bedrock incision and network development result in progressively older cave levels perched higher up canyon walls (Stock et al., 2005). Wang et al. (2007) describe and analyse the fossils contents of Chinese Plio-Pleistocene to Holocene cave infillings. According to these authors, long periods of uplift and river downcutting created new caves at different elevations. At the end of each phase of cave development, the sediments were introduced into the cavities through floodplain runoff and downward movement through openings in the limestone (Wang et al., 2007). Therefore, the caves at progressively higher elevations reflect progressively older periods of cave formation and infilling, and preserve fossil assemblages of increasing age, as we have also observed in Vietnam (Figs. 7 and 8).

One of the best examples about the spectacular water circulation inside the karst during the Messinian Salinity Crisis (MSC) is given by Mocochain et al. (2006). In this case study, the Mediterranean Sea was characterised by

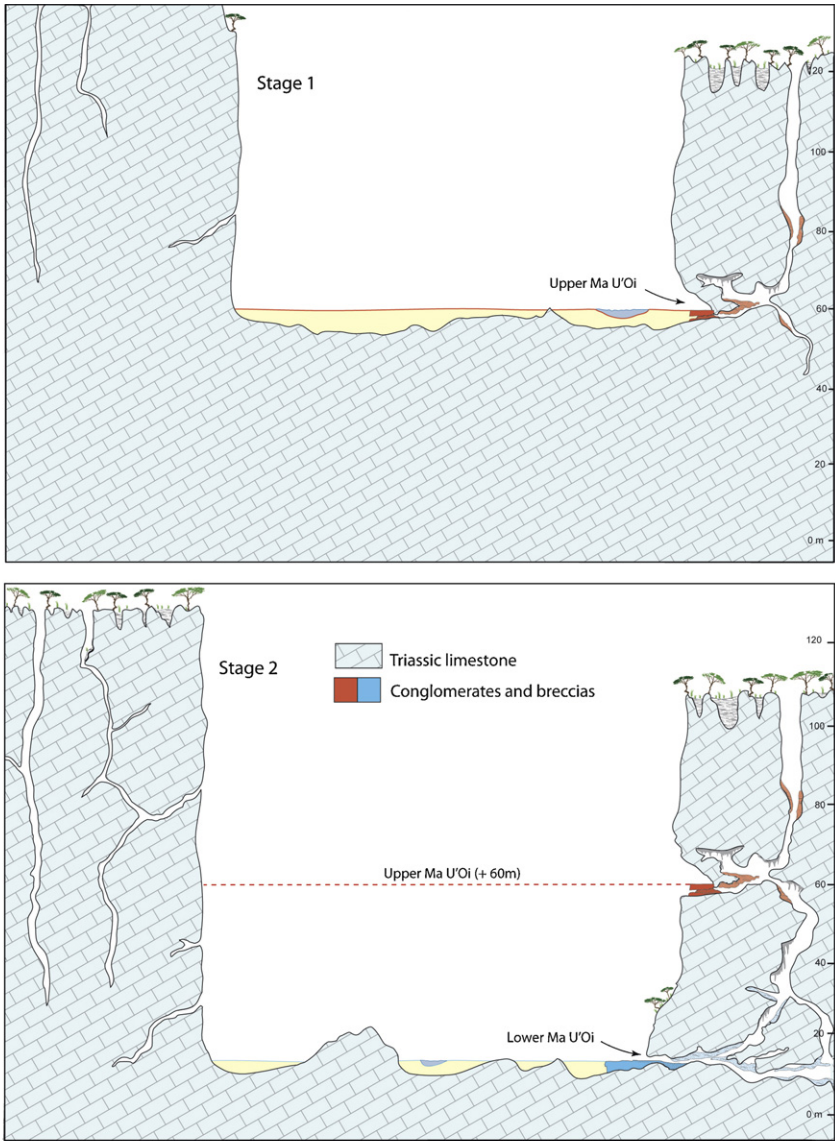

Fig. 7. Sketch showing the drop of the alluvial plain from upper (stage 1) to lower (stage 2) Ma U'Oi caves (Vietnam) forming a two-tiered stair-like morphology. As a consequence, the upper cave/terrace association is older than the lower cave/terrace association. Note that at each stage, the karstic network would have been connected to the river, and so both evolved together over time.

Fig. 7. Dessin montrant l'abaissement du niveau de la plaine alluviale du niveau 1 à 2 avec l'étagement des terrasses entre la grotte supérieure et inférieure de Ma U'Oi (Viêt Nam). L'âge des dépôts augmente de bas en haut de la coupe. À chaque phase, les sorties de grottes sont connectées avec le niveau zéro de la plaine alluviale, les deux évoluant ensemble.

a short-lived (5.95–5.32 Ma) sea-level fall which reached 1500 m in some areas, before returning to current levels. During this alluvial plain lowering, new networks and new cave outlets were progressively developed inside the limestone. Surprisingly, Mocochain et al. (2006) note that cave outlets and general networks were also adjusted during the increasing rise of water-table, resulting from rising sea-levels. The flooding of the caverns led to the creation of incredible vertical galleries formed by strong upward groundwater flows called "chimney-schafts".

In fact, the mechanisms of formation of the karstic terraces in Vietnam are similar in many respects to the fluvial terraces formed during the dropping of alluvial plains. Yang et al. (2011) report the development of at least four well-formed terraces dated to 239 ka in close relation to the adjacent karst. The referred rate of uplift/incision fluctuates between 0.1 and 0.5 m per ka, which is 2 to 10 times higher than those estimated for the Vietnamese examples (Figs. 7 and 8). In comparison, the terraces described in the border of the Maoxi River (China) by Yang et al. (2011) have exactly the same rate of alluvial plain lowering as what we have proposed here: that is around 0.06 m per ka. With respect to the sedimentary cave infilling, during each alluvial plain lowering, the breccias are partly (sometimes completely) eroded. If the amount of water is sufficient, each new lowering can rework the part of the remaining

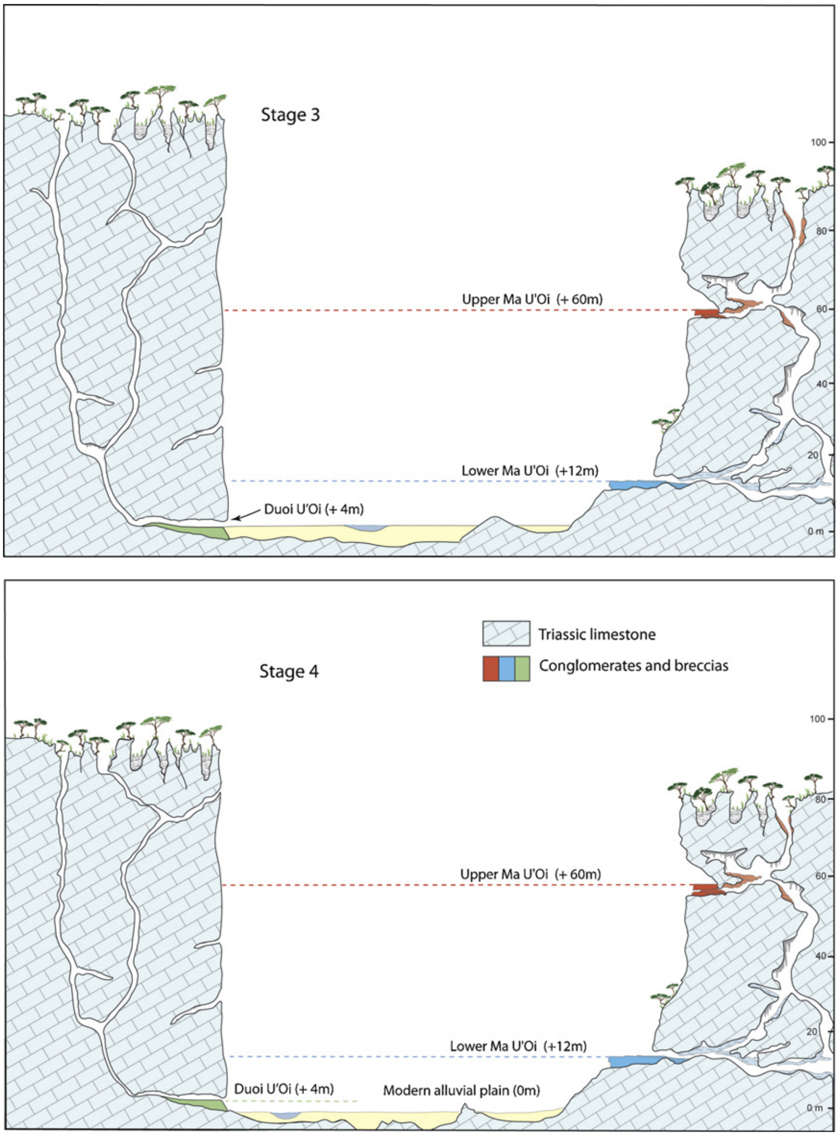

Fig. 8. Sketch showing the drop of the alluvial plain from lower Ma U'Oi (stage 3) to Duoi U'Oi (stage 4) caves (Vietnam) forming a three-tiered stair-like morphology of terraces increasing in age from the base to the top of the cliff. In each stage, the karstic network would have been connected to the river, and both evolved together over time.

Fig. 8. Dessin montrant l'abaissement du niveau de la plaine alluviale entre la grotte inférieure de Ma U'Oi et celle de Duoi U'Oi, exposant ainsi trois terrasses successives correspondant à trois niveaux de plaine alluviale (Viêt Nam). À chaque phase, les sorties des grottes sont connectées à la plaine alluviale. Exutoires karstiques et positions de la plaine alluviale évoluent ensemble au cours du temps.

breccias leading to progressive disappearance. This may explain why the upper networks in the tower karsts are so often empty of sedimentary infilling. The presence of larger amounts of acidic water close to the soil covering the karsts, means that the speleothems are often badly developed in the upper part of the limestone (De Waele et al., 2009).

One important question remains regarding the main processes for the origin of the water table dropping. The influence of tectonics and neotectonics on the morphology of the cone and peak karsts from the Ha Long Bay, has been well-documented (Fenart et al., 1999). In surrounding areas (i.e. Dien Bien Phu basin, 150 km WNW from the studied area), the effects of a recent tectonic activity has been emphasised by Zuchiewicz et al. (2004), who described perched alluvial deposits dating to the Late Pleistocene and the Holocene. The combination of the sea level oscillations with an active tectonic background is considered as the most likely combinations of factors to explain the creation of the architecture of terrace deposits (stair geometry). Moreover, the proximity of Man Duc site to the Red River delta plain (less than 30 km apart) suggests that the Pleistocene sea level oscillations may have controlled the base level, and subsequently also the karstic and alluvial dynamics. The sea level pattern proposed by Molodkos and Bolikhovskaya (2002) for the last 600 ka, in northern Eurasia, allows us to establish a good correlation between the Middle Pleistocene rise and the high stand of sea level (240/180 ka) and the development of lower Ma U'Oi terrace (dated to 193 ka).

In conclusion, the origin and preservation of the fossil-bearing breccias are controlled in over shorter time-scales by the hydrology inside the karsts (Bacon et al., 2004; Roussé et al., 2003). However, over longer time-scales, the deposit and preservation of the cave breccias or other fillings are directly linked to the combined effects of variations in tectonic uplift and sea level oscillations (Molodkos and Bolikhovskaya, 2002; Roussé et al., 2003; Zuchiewicz et al., 2004).

6. Karst and breccia examples in north-eastern Laos

6.1. Location and geological setting

The studied limestone crops out in the form of a tower karst called Pà Hang, on the southeastern side of the P'ou Loi Mountain. It is located in the northeastern part of Laos about 260 km NNE from Vientiane, in the Huà Pan Province (Fig. 1). The P'ou Loi Mountain belongs to the septentrional Annamitic Chain oriented broadly NNW-SSE. The basement consists of Palaeozoic granite and diorite (Saurin, 1961). These rocks are covered with a widespread sedimentary formation characterised by a grey to yellow argillaceous poorly cemented arkosic sandstone attributed to the Silurian, or perhaps partly Devonian (Saurin, 1961). This well-developed arkosic sandstone is capped by a thick limestone unit (Fig. 3a), which is badly dated at present, but which has been attributed by Saurin (1961) to an interval between the Late Carboniferous (Moscovian) and the Permian. This thick limestone unit forms a wide range of discontinuous tower karsts that emerge from the present rain forest. The region is dissected by numerous vertical faults that often create lateral contacts between the thick limestone unit and the arkosic sandstone, in the form of a major unconformity (arkosic sandstones at the base of the horizontal limestone unit are folded).

The limestone unit consists of a pluri-decametric massive sparitic dark-grey carbonate without marl intercalation. It crops out in the form of large to small tower karsts on a scale of hectometres to kilometres. Most of the mountain displays widespread karstic networks (Fig. 3a), in which bone-rich breccias can be found (Fig. 3b–e, Fig. 4b). The Nam Lot cave shows an interesting sedimentary history. The cave is a large cavity of about 60 m long divided by 5 to 6 superposed galleries all connected together, and with at least half of dozen entrances. The sedimentary deposits, located in both lower and upper part of the network, present a wide range of sediments (Fig. 9) comprising true conglomerates (Fig. 4a), conglomeratic sandstones (Fig. 3e), sandstones, limestone-rich breccias (Fig. 4b), sandy and silty clays (Fig. 3f). The conglomerates consist of rounded basement pebbles and cobbles up to 20 cm (Fig. 4a). The cave breccias contain mainly limestone clasts, in size from centimetres to decametres (Fig. 4b). Conglomerates occur only on the upper part of the cave, where they are plastered on the relics of the walls, whereas the breccias, clays and sandy/silty clays are present on the lower part. Except for the conglomerates, most of the sedimentary facies are rich in vertebrate remains, in particular, teeth. The majority of the remains derive from the lower part of the cave from the breccia and from the silty/sandy clays. Their distribution appears to be random, especially in the argillaceous facies.

6.2. Karstic breccias: a polyphasic infilling within the same cave

The cavity reveals a complicated depositional history, consisting at least of three types of deposits, roughly superimposed above each over (Fig. 9). The oldest sedimentary layers consist of conglomerates (Fig. 9b) overlying sandy/silty clays (Fig. 9a), and covered by coarse-grained sandstones (Fig. 9c). The outcrops are discontinuous in the cave and mainly plastered on the floor and walls. From base to top, the deposits lie more than 10 m thick. The conglomerate displays an obvious pebble imbrication (Fig. 4a) suggesting a water flow from outside to inside, suggesting an infilling by the river. Moreover, the pebbles are made of basement rocks, thereby excluding an intra-karstic origin. The second deposit is formed by alterning sandstone and argillaceous sandstone. A major erosional surface separates the latter from the sandy/silty clays. The third deposit, made of coarse to very coarse-grained breccias, overlies the aforementioned sandstone (Fig. 9d). Both deposits, sandstone and breccias, display cross bedding and imbricated limestone clasts in several places, suggesting paleostreams from inside to outside, and thus an obvious endokarstic origin for the sediments.

The history of the sedimentary deposits in the cave can be presented as follows: in the first stage, the cavity is filled with three well-stratified units: sandy/silty clays at the base, followed by a plurimetric conglomerate that passes vertically to a coarse-grained sandstone (Fig. 10). The presence of this argillaceous layer without coarse-grained particles and clasts, suggests a very low water circulation inside the karst before the conglomerate deposition. The deposition of such a thick unit of fine-grained argillaceous materials strongly suggests that the cave was flooded, or had at least a highly reduced water circulation, that permitted the slow decantation of such sediment. The cave was undoubtedly situated under the level of the water-table (i.e. under the alluvial plain) (Fig. 10).

The excellent imbrication of the flattened pebbles (orientated inwards the cave) in the conglomerate suggests a cave infilling directly from the adjacent alluvial plain (Fig. 10). In fact, the cave entrances and alluvial plain are at the same level during this sedimentary stage. The coarse-grained sandstone is interpreted as well. Even if the alluvial infilling in the karsts constituted by rounded pebbles has been described in many caves, the thickness of the conglomerate in this case is very rare.

The second important stage of the cave history is the reworking of more than 90% of these first terrigenous deposits consecutively to a dropping of the alluvial plain. The drop of the latter caused a change in the water flow direction, now from inside to outside, as is demonstrated by the arrangement of the pebbles (Fig. 11). The two superposed sandstone and breccia units reveal at least two successive alluvial plain dropping events, illustrated by an

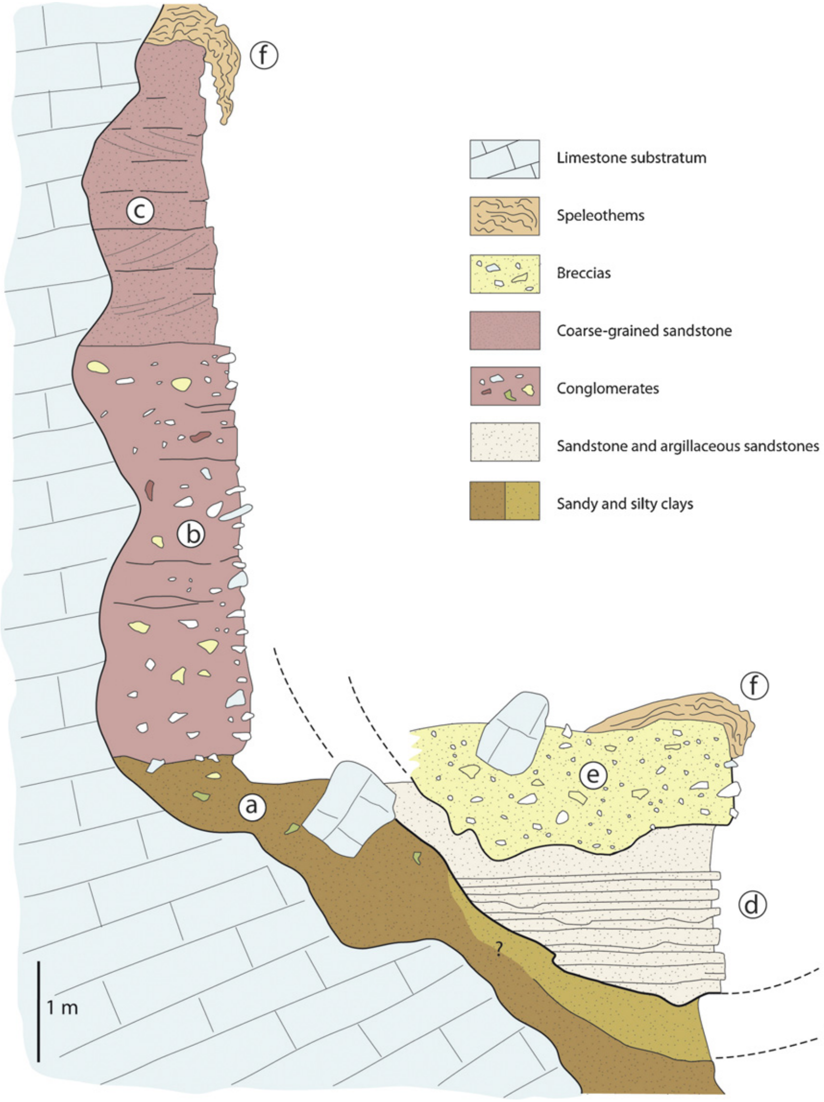

Fig. 9. Synthetic sedimentary column showing the superposition of the main sedimentary facies in the Nam Lot cave in North-East Laos. The sequence from the oldest (a) to the more recent (f) deposits have been noted.

Fig. 9. Coupe synthétique montrant la superposition des dépôts au cours du temps dans la grotte de Nam Lot (Nord-Est du Laos). Les lettres de (a) à (f) caractérisent les âges des dépôts des plus anciens aux plus récents.

obvious erosion surface (Fig. 12). The present-day situation (Fig. 13) displays a new reworking of the greatest part of sedimentary infilling, which remains as a breccias relic, or a remnant, on the floor, wall and roof. The alluvial plain occurs now around 25 m below the entrance of the cavern (Fig. 13).

6.3. Discussion

The history of the Nam Lot cave shows many similarities to other Vietnamese examples. For the discussion about the successive water table changes, we refer the reader back to the depositional model through the time set out in the previous section. What is most remarkable in the Nam Lot cave is the intensity of the erosion between the two main infillings. This is especially true considering the conglomerate deposit, which was characterised by a major change in the direction of water flow (from outside to inside for the conglomerate, but the reverse for all subsequent infillings) (Figs. 10–13). Moreover, each sedimentary erosional surface represents a extended period of time and it is often difficult to quantify its importance in the absence of precise dating. In fact, the alternation infilling/reworking/infilling separated by obvious hiatuses is a frequent specific sedimentary process in the caves. Such mechanisms have been described in many caves, even if it is not so significant for the Nam Lot cave (Bacon et al., 2004, 2006; Latham et al., 2007; Moriarty et al., 2000; Zeitoun et al., 2010). Such alternations are often the result of both water table and climate changes with successive warn and cold periods, which together produce changes to the water supply. In many cases, the sediment

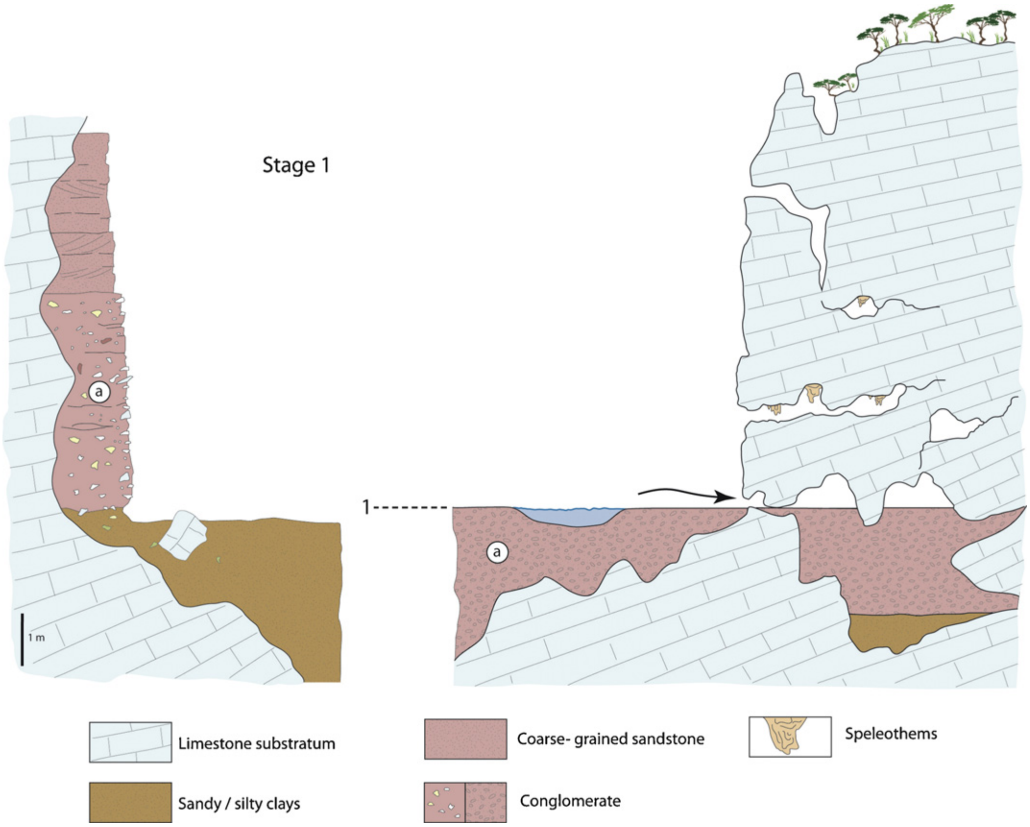

Fig. 10. Stage 1 of the Nam Lot cave history (Laos). The alluvial plain is at the same level as the entrance/exit of the cave. The cave is filling up directly from the river by alluvial gravels and sands forming a conglomerate (a). Note that the drawing on the left side is a synthetic geological section, and that the drawing on the right side represents an interpretation of the whole karstic system.

Fig. 10. Phase 1 de l'histoire du remplissage de la grotte de Nam Lot (Laos). La plaine alluviale et l'entrée de la grotte sont situées au même niveau. La grotte est remplie par la rivière formant un conglomérat (a). Le dessin à gauche représente la coupe géologique synthétique de la grotte et le dessin à droite une interprétation de l'histoire des remplissages.

accumulations are separated by alternating flowstone that allows U/Th dating to provide a chronological framework for the depositional history (Moriarty et al., 2000). Among the numerous caves we have visited, Nam Lot is the only one displaying such a huge conglomeratic infilling directly from the alluvial plain, while showing such clear evidence of flow direction from outside to inside.

7. The difficulties associated with assigning ages to bone-bearing breccias

Assigning a precise age to a karstic deposit is simultaneously straightforward and complicated, for several reasons. Except for the ^{14}C dating for recent deposits, three other methods have advantages/disadvantages for the Late Pleistocene period. The most commonly used in the karstic environments is the U/Th method (Stock et al., 2005). It is very efficient, but requires that at least two conditions are met: the occurrence of interbbeded flowstone inside the breccia and the absence of pollution in the calcite. In fact, in the greater part of studied examples, such flowstones are lacking or/and are not made of pure calcite that would facilitate dating. All dating attempts in Northeast Laos based on this method have failed due to the high detrital thorium contents coming from adjacent granitic mountain. The cosmogenic burial methods ($^{26}Al/^{10}Be$) (Lebatard et al., 2008, 2010), and Optically Stimulated Luminescence (OSL) (Westaway et al., 2007) that have been more recently developed offer real potential in this regard. These methods are performed on the quartz (cosmogenic method) and quartz or feldspar (OSL), and sometimes other minerals, all commonly found in the breccias, making these methods particularly attractive. However, several problems are associated with each method. The U/Th method gives the age of the flowstone but not those of the bone remains. The remains result from a longer history made of a succession of transportation/deposits/transportation from cave to cave, according to the progressive deepening of the karst and the general tectonic/climatic/eustatic evolution. In fact, in all cases, bones and teeth are always older than the age given by the calcitic precipitation in the flowstone. How much older is one of the most important questions, when one bears in mind that vertebrate remains can be reworked from previous breccias, and that this process may occur several times. The cosmogenic burial method and OSL appear to be more precise because quartz/feldspar history follows more or less the same as vertebrate remains i.e., the reworking from cave to cave through time.

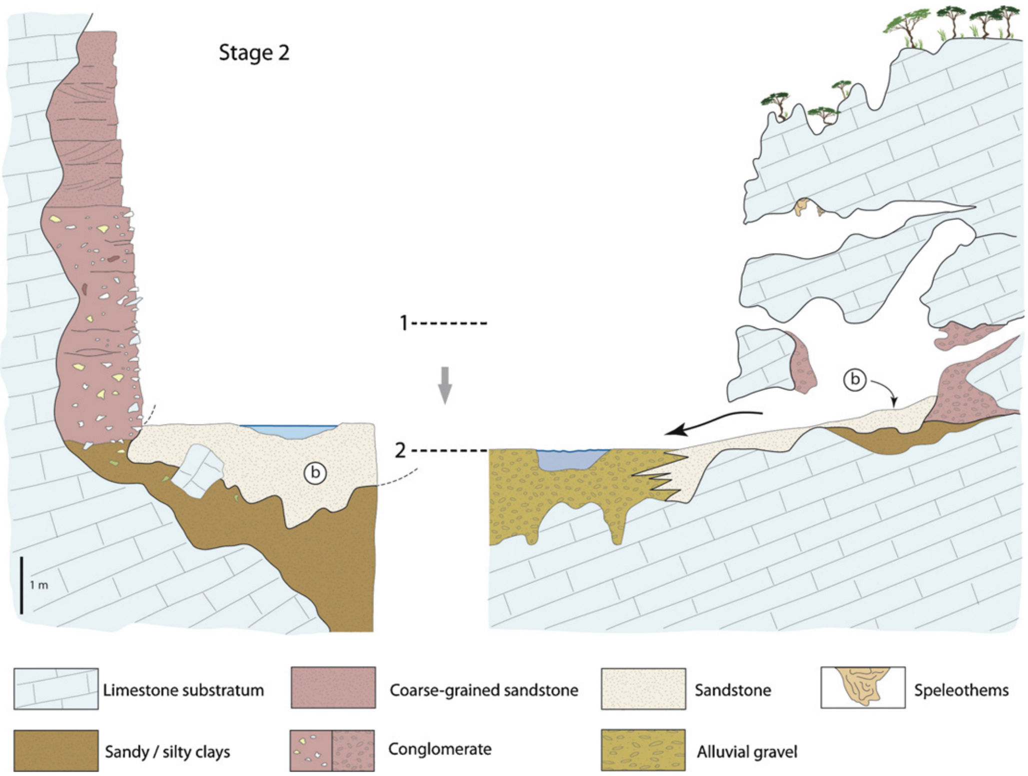

Fig. 11. Stage 2 of the Nam Lot cave history (Laos). The alluvial plain drops below the entrance of the cave leading to an inversion of water circulation inside the cave (from inside to outside). The greatest part of the network is emptied of its deposits. After that, only relics remain plastered on the walls and roof of the cave. A new alluvial plain is formed below the entrance of the cavern partly fed on its border by the reworked endokarstic deposits (b). Note that the drawing on the left side is a synthetic geological section, and that the drawing on the right side represents an interpretation of the whole karstic system.

Fig. 11. Phase 2 de l'histoire du remplissage de la grotte de Nam Lot (Laos). Un abaissement relatif de la plaine alluviale provoque une inversion de l'écoulement général dans le réseau karstique. La plus grande partie des dépôts est remaniée. Il ne subsiste que quelques reliques de dépôts, accrochées sur les parois de la grotte. Les circulations d'origine endokarstique permettent le dépôt de grès selon un écoulement qui va de l'intérieur vers l'extérieur de la grotte (b). Le dessin à gauche représente la coupe géologique synthétique de la grotte et le dessin à droite une interprétation de l'histoire des remplissages.

8. The Pleistocene faunas from Southeast Asia

8.1. Characteristics of the faunal assemblages

The sequence of events from living animals to fossil assemblages in the karstic network is complex, as these events are numerous and diverse in nature. Most of the time, the assemblages are composed of isolated teeth with gnawed roots, deriving from middle to large-sized mammals. Indeed, one of the major selective factors is the post-mortem action of porcupines, which recover bones of carcasses after carnivores have finished (Nowak, 1999). Humans may also have an important role in the accumulation of remains, but that remains to be demonstrated. The deposit of bone and teeth remains is formed under strong to moderate water transport conditions inside the karstic network, as discussed in the previous section regarding the geological context. These characteristics are common to the Pleistocene sites of the Indochinese and Sondaic areas (Bacon et al., 2004, 2006, 2008b, in press; Storm and de Vos, 2006; Storm et al., 2005; Tougard, 1998; Zeitoun et al., 2005).

8.2. The Indochinese Subregion and the zoogeographic subdivision

The Indochinese Subregion is a natural area within the Indomalayan Region (Corbet and Hill, 1992). Today, this Subregion includes three regional divisions: the Indochinese area, southern China, and central China transitional to the northern Palaeartic Region, with a "south-north" gradient from tropical to temperate climates (Fig. 14).

It is increasingly accepted that this division gradually took place at the beginning of the Early Pleistocene (∼2.6 Ma) under the influence of climatic changes, as well as major regional tectonic and geomorphologic events. In the transitional zone of central China, some of the oldest faunas, Renzidong (Anhui province) (Fig. 15) dated to between 2.4 and 1.9 Ma (Jin et al., 2003), reveals a mixed composition with "24 typical species of the Palaearctic Region, 23 species of Oriental Region and 20 widely distributed species" (Jin et al., 2000, p. 240). In central Burma, at the western border of the Indochinese area, one of the other oldest faunas, that of Irrawady also has in part a faunal composition of clear Indian affinity (Colbert, 1943).

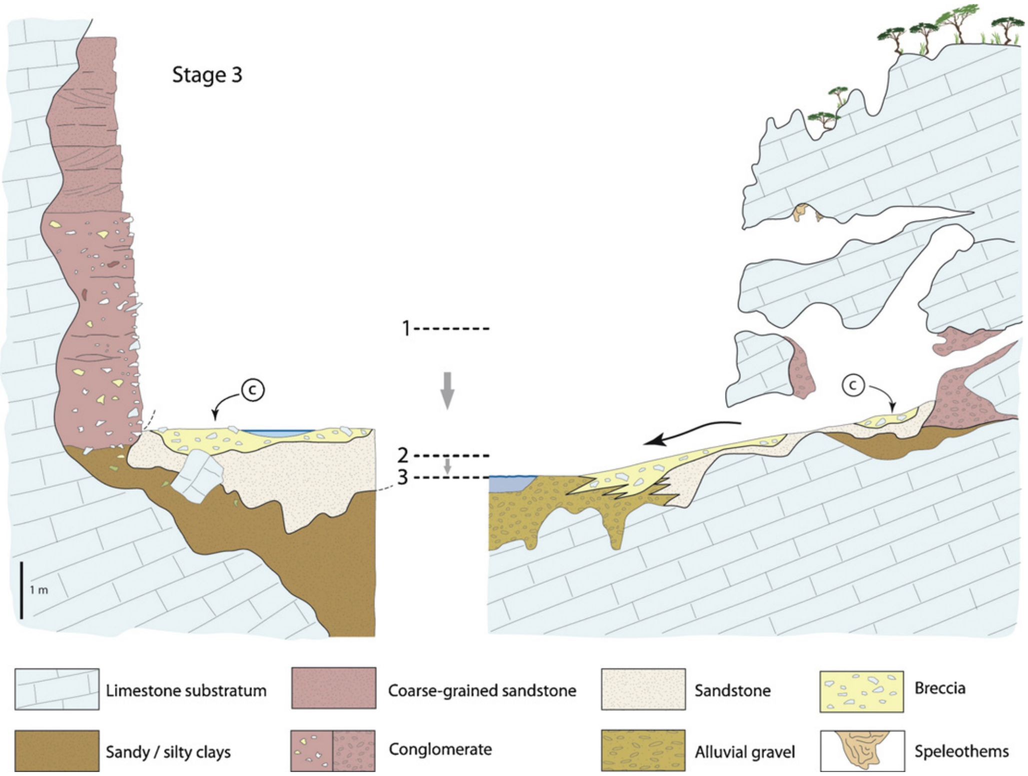

Fig. 12. Stage 3 of the Nam Lot cave history (Laos). A new and lower alluvial plain drop allows the deposit of new sediments inside the cave. Previous sedimentary infilling is partly reworked during this process. Note that the drawing on the left side is a synthetic geological section and that the drawing on the right side represents an interpretation of the whole karstic system.

Fig. 12. Phase 3 de l'histoire du remplissage de la grotte de Nam Lot (Laos). Un nouvel abaissement de la plaine alluviale permet la mise en place d'un nouveau dépôt. Le dépôt gréseux précédent est partiellement érodé. Le dessin à gauche représente la coupe géologique synthétique de la grotte et le dessin à droite une interprétation de l'histoire des remplissages.

The composition of these two mammal assemblages, Renzidong and Irrawady, suggest that the Indochinese area did not yet have its typical faunas at the onset of the Pleistocene. Indeed, both show not only a mixed composition (Indochinese/Palaearctic, Indochinese/Indian) but also the last occurrence of some Tertiary taxa (Fig. 16). In the South of the Indochinese area, Early Pleistocene faunas could also have a sondaic influence, but this period is not documented. The appearance of clearly Indochinese mammalian faunas occurs soon after in the Early Pleistocene, as shows the Liucheng cave assemblage with *Gigantopithecus blacki*, *Pongo pygmaeus*, *Ursus thibetanus*, *Stegodon orientalis*, *Megatapirus augustus* among the most typical species (Kahlke, 1961; Pei, 1957). Southeast Asia was at that time dominated by tropical rain forest.

The boundary between the Indochinese and Palaearctic faunal Regions, formed by the Qinling Moutains and the Huai River, remained fluctuating during the Pleistocene, as demonstrated by Tong (2006, 2007). According to this author, the faunal dispersal events in China, both southwards and northwards, occurred throughout the Pleistocene, in response to climatic fluctuations. The same observation has been made on the basis of Middle Pleistocene faunal compositions, especially for some rodents, throughout the boundary between the Indochinese and Sundaic faunal subregions (Chaimanee, 1998; Tougard, 1998). It seems that the limit, now located at the Isthmus of the Kra, was fluctuating during the Middle Pleistocene. As for the boundary between the Indian and Indochinese Regions, the faunal dispersals are not documented.

8.3. *The Pleistocene Indochinese faunas as a whole*

Reconstructing the history of the faunas of the zoogeographical unit as a whole, including the three subregions, poses several challenges. The first one is the scarcity of well-documented assemblages, as most of them are only known by an inventory of the taxa (Cuong, 1985; Kahlke, 1961; Wang et al., 2007; Wu and Poirier, 1995).

Other factors are linked to the normal practices in systematics of the scientific community. The most striking is the lack of stability in the systematics, especially the creation of species and subspecies of local value. Numerous species of middle to large-sized mammals have only been recorded from one site. The review of Rhinocerotids (Antoine, 2011; Tong, 2001) is one among significant examples, but other groups are equally concerned (suids, cervids, large carnivores). Inversely, the validity of some species considered as a taxonomic "wastebasket" is questioned, and would also require a revision of the diagnosis, as their hypodygms probably encompass at least two species, and possibly even more. These problems in systematics have an

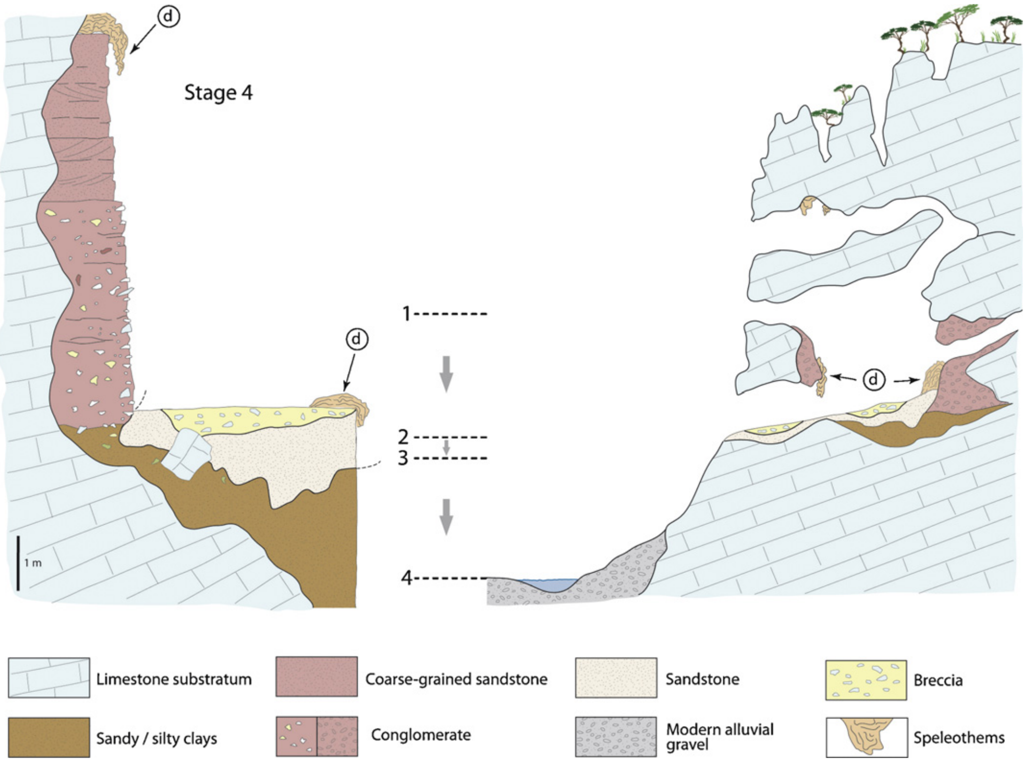

Fig. 13. Stage 4 of the Nam Lot cave history which is the present-day situation (Laos). A new alluvial plain drop allows a new phase of reworking inside the cave. Deposits are only preserved as relics on floor, walls and roof. The speleothems covered almost all the previous deposits. Note that the drawing on the left side is a synthetic geological section and that the drawing on the right side represents an interpretation of the whole karstic system.

Fig. 13. La phase 4 de l'histoire du remplissage de la grotte de Nam Lot (Laos) représente la situation actuelle. L'abaissement de la plaine alluviale a provoqué une nouvelle phase d'érosion des dépôts de caverne. La plupart d'entre eux ne sont présents que sous la forme de plaquages sur les parois de la grotte. Des concrétions calcitiques recouvrent la plupart des dépôts sédimentaires. Le dessin à gauche représente la coupe géologique synthétique de la grotte et le dessin à droite une interprétation de l'histoire des remplissages.

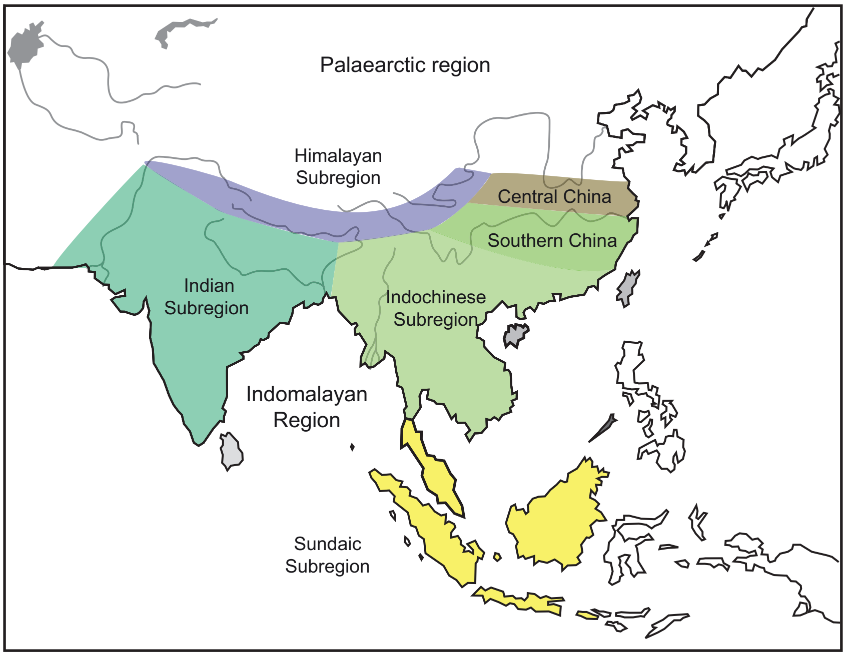

Fig. 14. Zoogeographical subdivisions of the Indomalayan Region according to Corbet and Hill (1992).

Fig. 14. Divisions zoogéographiques de la Région indo-malaise d'après Corbet et Hill (1992).

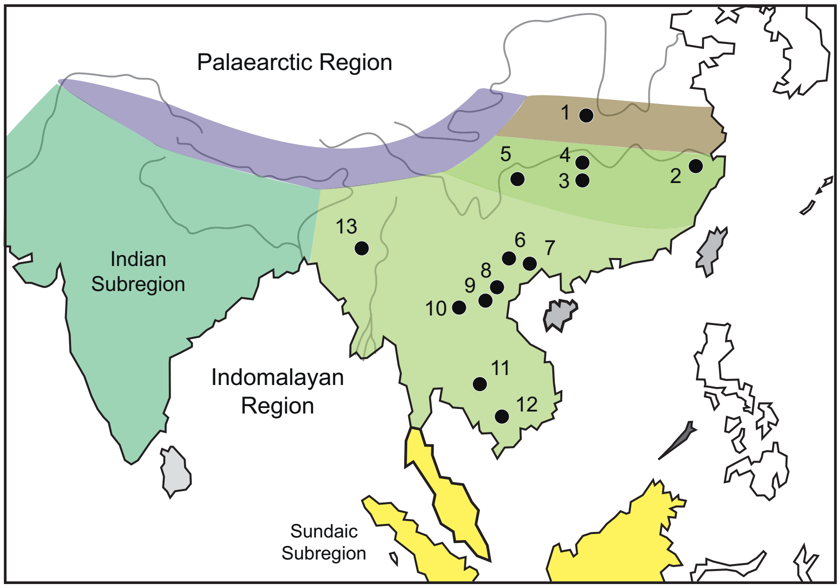

Fig. 15. Location of the sites in the Indochinese Subregion, southern China and central China which yielded the Pleistocene mammal faunas discussed in the text, and used in the brief review of the Pleistocene mammal evolution of the Figs. 16 and 17. In central China: 1. Gongwangling (Lantian). In southern China: 2. Renzindong (Fanchang), 3. Longgudong (Jianshi), 4. Longgupo (Wushan), 5. Yenchingkuo (Sichuan). In the Indochinese Subregion: 6. Liucheng (Guangxi province), 7. Mohui, Wuyun, Lower Pubu, Cunkong (Guangxi province), 8. Duoi U'Oi and Ma U'Oi (Vietnam), 9. Lang Trang (Vietnam), 10. Tam Hang (Laos), 11. Thum Wiman Nakin (Thailand), 12. Phnom Loang (Cambodia), 13. Irrawady (Myanmar).

Fig. 15. Localisation des sites dans la Sub région indochinoise, le Sud de la Chine et la Chine centrale qui ont livré les faunes de mammifères du Pléistocène, citées dans le texte et utilisées pour les brèves synthèses sur l'évolution des mammifères des Fig. 16 et 17. En Chine centrale : 1. Gongwangling (Lantian). Dans le Sud de la Chine : 2. Renzindong (Fanchang), 3. Longgudong (Jianshi), 4. Longgupo (Wushan), 5. Yenchingkuo (Sichuan). Dans la region indochinoise : 6. Liucheng (province du Guangxi), 7. Mohui, Wuyun, Lower Pubu, Cunkong (province du Guangxi), 8. Duoi U'Oi et Ma U'Oi (Viêt Nam), 9. Lang Trang (Viêt Nam), 10. Tam Hang (Laos), 11. Thum Wiman Nakin (Thaïlande), 12. Phnom Loang (Cambodge), 13. Irrawady (Myanmar).

important impact on our understanding of the evolution of the faunas, as we lack a clear view of faunal changes, especially the occurrence of new species and dispersal events, from the Indochinese Region as a whole, throughout the Pleistocene.

Fig. 16 presents the succession in the time of 14 selected mammalian assemblages. This biochronological timescale is far from complete as Pleistocene mammalian fossil records are rare, and their ages often imprecise. Nevertheless, the discontinuous sequence emphasizes that the first lineages of modern species appear during the Early Pleistocene, around 2.0 Ma, as shown by the composition of Liucheng, Mohui and Longgudong faunal assemblages (Kahlke, 1961; Pei, 1957; Wang et al., 2007; Zheng, 2004). A "second wave" of modern lineages appearances occurs later during the Middle Pleistocene, with the Yenchingkuo (Colbert and Hooijer, 1953; Matthew and Granger, 1923), Wuyun (Wang et al., 2007), Tam Hang South (Bacon et al., 2008a, in press), Thum Wiman Nakin (Tougard, 1998) and Lower Pubu faunal assemblages (Wang et al., 2007). The first appearance of the modern lineages is naturally a subject for re-evaluation depending on new Early to Middle Pleistocene data. Indeed, it is highly probable that the modern lineages appear farther in the Pleistocene, considering the marked lacuna between the fossil faunas over this long period. The chronological range (Fig. 16) highlights that, in the Indochinese Subregion and central China, until the Lang Trang fauna, the lineages of modern species evolved together with those of archaic species (*Sus xiaozhu*, *Nestoritherium sinensis*, *Tapirus sinensis*, *Elephas namadicus*, *Megatapirus augustus*, *Stegodon orientalis*, among others). The relationships between these lineages are for the majority unknown.

8.4. *The sequence of faunal changes in well-documented faunas*

Recently, we proposed a refined biochronological framework, using seven faunas dating from the Middle to Late Pleistocene (Bacon et al., in press), among which the faunas recovered during our own research in karstic sites, Duoi U'Oi, Ma U'Oi and Tam Hang. On the basis of the evolutionary stages of some species (subspecies defined on dental dimensions) and the occurrence of new taxa, our Fig. 17 indicates the presence of four distinct evolutionary levels.

Levels 2 and 3 contain diversified faunas with an association of extinct species (*Megatapirus augustus*, *Stegodon orientalis*), and subspecies (*Arctonyx collaris* cf. *rostratus*, *Cuon alpinus* cf. *antiquus*, *Ursus thibetanus* cf. *kokeni*, *Muntiacus muntjak* ssp.1, *Sus scrofa* ssp.1), as those of Tam Hang South (Bacon et al., 2008a, in press), Phnom Loang (Beden and Guérin, 1973), and Thum Wiman Nakin (Tougard, 1998). The latter site is older than 169 ± 11 ka (based on U-series dates) (Esposito et al., 1998, 2002), and this provides a late Middle Pleistocene age estimate for these two levels.

Level 4, although not well documented, nevertheless shows an important change in the faunal composition. The oldest faunas from this level still retain some archaic

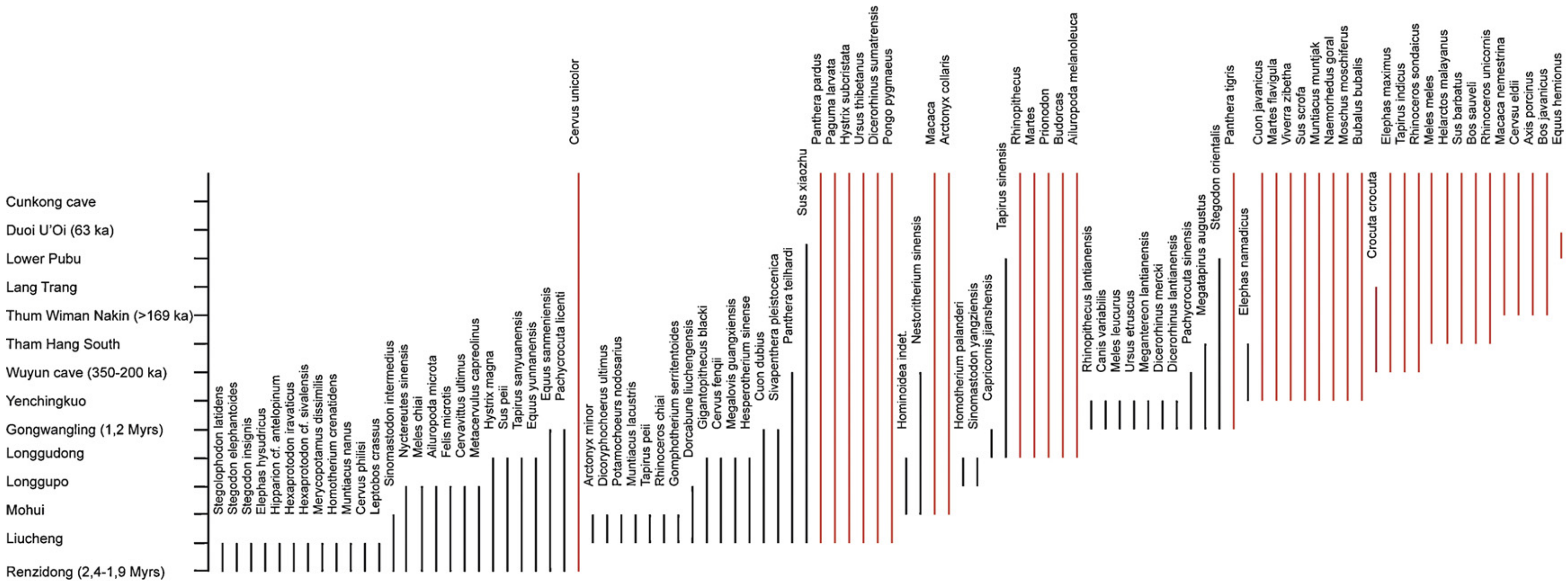

Fig. 16. Chronological range of large mammals based on selected Pleistocene faunas from the Indochinese area (see the Fig. 15 for the site location). The lineages of the modern species are indicated in red. Duoi U'Oi (Bacon et al., 2008b), Tam Hang South (Bacon et al., 2008a, in press), Lang Trang (de Vos and Long, 1993), Thum Wiman Nakin (Esposito et al., 1998, 2002; Tougard, 1998), Renzidong (Jin et al., 2000, 2003), Cunkong, Lower Pubu, Wuyun, Mohui (Wang et al., 2007), Yenchingkuo (Colbert and Hooijer, 1953), Gongwangling (Li et al., 2008), Longgudong (Zheng, 2004), Longgupo (Jin et al., 2000; Wanpo et al., 1995), Liucheng (Kahlke, 1961; Pei, 1957).

Fig. 16. Échelle chronologique des grands mammifères basée sur quelques faunes du Pléistocène de la région indochinoise (voir la Fig. 15 pour la localisation des sites). Les lignées des espèces modernes sont indiquées en rouge. Duoi U'Oi (Bacon et al., 2008b), Tam Hang South (Bacon et al., 2008a, in press), Lang Trang (de Vos et Long, 1993), Thum Wiman Nakin (Esposito et al., 1998, 2002 ; Tougard, 1998), Renzidong (Jin et al., 2000, 2003), Cunkong, Lower Pubu, Wuyun, Mohui (Wang et al., 2007), Yenchingkuo (Colbert et Hooijer, 1953), Gongwangling (Li et al., 2008), Longgudong (Zheng, 2004), Longgupo (Jin et al., 2000 ; Wanpo et al., 1995), Liucheng (Kahlke, 1961; Pei, 1957).

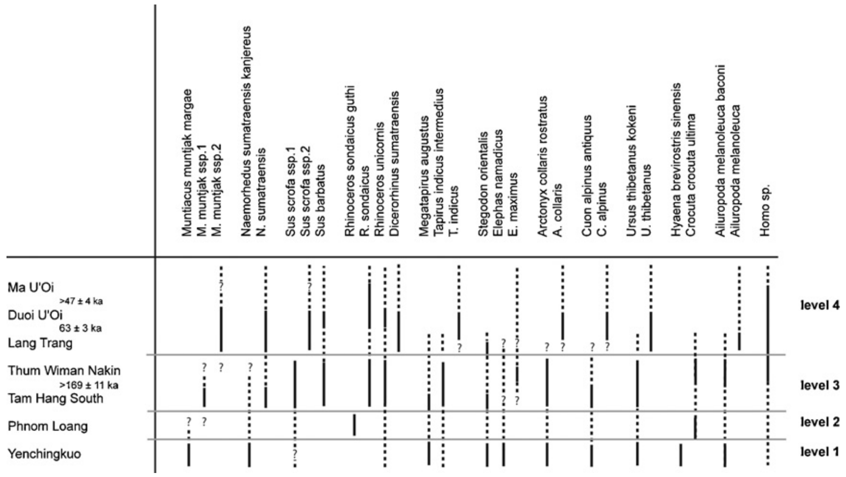

Fig. 17. Chronological range of large mammals based on the seven well-documented faunas from the Indochinese area, at the transition between the Middle and Late Pleistocene (after Bacon et al., in press) (see the Fig. 15 for the site locations). Ma U'Oi (Bacon et al., 2004, 2006), Duoi U'Oi (Bacon et al., 2008b) and Tam Hang South (Bacon et al., 2008a, in press) studied by the present authors; Lang Trang (de Vos and Long, 1993), Thum Wiman Nakin (Tougard, 1998), Phnom Loang (Beden and Guérin, 1973), and Yenchingkuo (Colbert and Hooijer, 1953).

Fig. 17. Échelle chronologique des grands mammifères, basée sur les sept faunes les mieux documentées de la région indochinoise, au passage Pléistocène moyen/Pléistocène supérieur (d'après Bacon et al., in press) (voir la Fig. 15 pour la localisation des sites). Ma U'Oi (Bacon et al., 2004, 2006), Duoi U'Oi (Bacon et al., 2008b) et Tam Hang Sud (Bacon et al., 2008a, in press) étudiés par les auteurs ; Lang Trang (de Vos et Long, 1993), Thum Wiman Nakin (Tougard, 1998), Phnom Loang (Beden et Guérin, 1973), et Yenchingkuo (Colbert et Hooijer, 1953).

species. This has been observed for the Lang Trang fauna (100–80 ka) with *Stegodon orientalis*, the possible *Elephas namadicus*, and the probable extinct forms of *Tapirus indicus*, *Cuon alpinus* and *Rhinoceros sondaicus* (de Vos and Long, 1993; Long et al., 1996) showing that some archaic taxa could have persisted during the beginning of the Late Pleistocene between around 130 ka and 70 ka. Numerous other Chinese sites also have these faunal compositions with a mixture of modern and archaic species (Chen et al., 2002; Jin et al., 2009; Liu et al., 2010; Wang et al., 2007; Wu and Poirier, 1995), but for most of them the ages are only rough estimations. The Duoi U'Oi (Fig. 18) and Ma U'Oi assemblages in northern Vietnam (respectively 66 ± 3 ka and $> 47 \pm 4$ ka) (Bacon et al., 2004, 2006, 2008b; Demeter et al., 2004, 2005) are devoid of any archaic component marking the end of the "*Stegodon-Ailuropoda* era" around 70 ka in the region.

A major shift in the Duoi U'Oi fauna can be observed, in particular we note the extinction of the two last archaic species *Stegodon orientalis* and *Megatapirus augustus*, which were adapted to forested environments and warm climates. This, combined with the appearance of new subspecies in the lineages of modern middle to large-sized mammals, suggest an adaptation to new environmental and climatic conditions (Bacon et al., in press) (concerning the extinction of species in Southeast Asia, a possible combination of human induced and climatic factors is also proposed by Louys et al. (2007). The U/Th dating associated to the Duoi U'Oi fauna corresponds to the onset of the Late Pleistocene cooling period MIS4 (71–59 ka) (Imbrie et al., 1984). From the same period, located in the same area (Fig. 15), the Lower Pubu fauna is also characterised by the absence of *Stegodon* and *Megatapirus*, and documents the dispersal event of *Equus hemionus* recovered in South China so far (Fig. 16). Wang et al. (2007, p. 376) state that: "*This extant species is, at present, distributed broadly in northern China, Mongolia, and central and western Asia; fossils of this species have been recovered in late Pleistocene contexts of Gansu, Inner Mongolia, in northern China* (Deng and Xue, 1999), *and also at 20–40 ka in Nanshan Cave, Guangxi, southern China* (Wang and Mo, 2004). The shift in the faunal composition, together with the southwards dispersion of *Equus hemionus*, reveals the presence of increasingly open vegetation conditions and, as hypothesised by Wang et al. (2007, p. 376), the settlement of a temporary corridor between northern and southern China, which facilitated the migration of this horse species. Since the drop of the temperatures continued during MIS3 (59–24 ka), until the drier climatic conditions of MIS2 (24–12 ka) characterised by the Last Glacial Maximum (~18 ka), one can wonder if this open environment around 70 ka, in South China and northern Vietnam may be the first local sign of the rain forest decline. Sun et al. (2000) observed from the cores of the South China Sea, during the Last Glacial Maximum, "*an alternation of two types of pollen assemblages, namely herb-dominant and montane conifers-marked*". For the moment, as no Late Pleistocene faunas are known in the Indochinese Peninsula (Malaysia, Cambodia, Thailand, Vietnam), we have no idea of the southwards extent of the dispersion of *Equus hemionus* on the mainland. It is not possible as well to document, on the basis of the fossil faunas from the mainland, the hypothetical savannah-corridor passing "*through the center of the Sunda Shelf, extending in an arc from south-Thailand to eastern Java*" (Bird et al., 2005; Heaney, 1991, p. 57). This question, far from being unresolved, is nevertheless essential as it is associated to the dispersion of modern *Homo sapiens* to Australasia during the Late Pleistocene (Barker et al., 2007; Bowler et al., 2003; Mijares et al., 2010; Storm, 2001; Storm and de Vos, 2006).

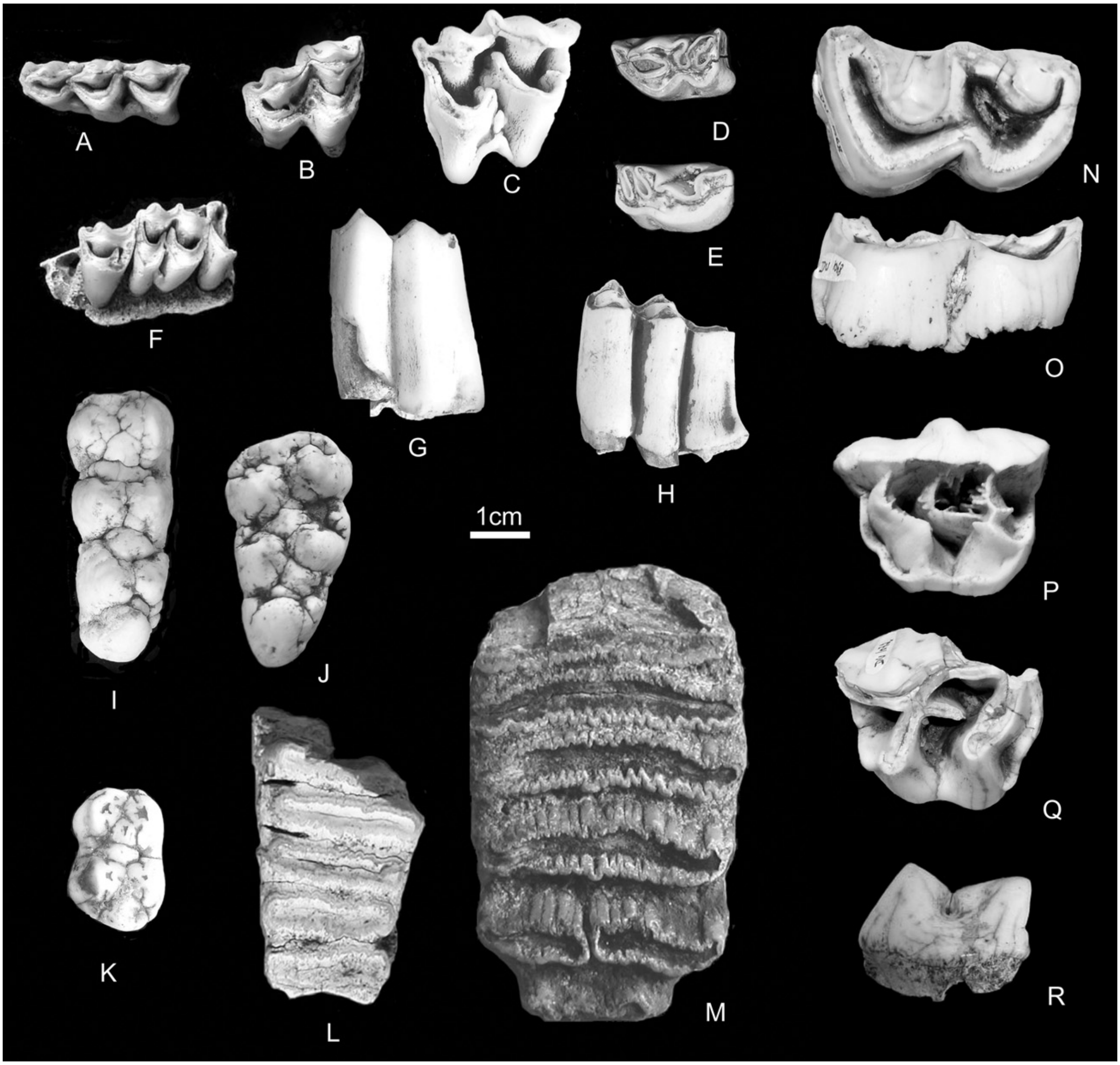

Fig. 18. Some isolated teeth from Duoi U'Oi, Vietnam (after Bacon et al., 2008a). *Cervus unicolor*: A. Left d4; B. Left D3; C. Left M1/M2; D. Left p4; E. Right p3. *Muntiacus muntjak*: F. Left maxilla with P4/M1. *Naemorhedus sumatrensis*: G. Right M3; H. Left m3. *Sus scrofa*: I. Left m3; J. Left M3; K. Left m2. *Elephas* sp.: L. D2; M. Molar. *Rhinoceros sondaicus*: N and O. Right m3; P. Left D2; Q. Right D3. *Panthera tigris*: R. Right m1.

Fig. 18. Quelques dents isolées de Duoi U'Oi, au Viêt Nam (d'après Bacon et al., 2008a). *Cervus unicolor* : A. d4 gauche ; B. D3 gauche ; C. M1/M2 gauche ; D. p4 gauche ; E. p3 droite. *Muntiacus muntjak* : F. Maxillaire gauche avec P4/M1. *Naemorhedus sumatrensis* : G. M3 droite ; H. m3 gauche. *Sus scrofa* : I. m3 gauche ; J. M3 gauche ; K. m2 gauche. *Elephas* sp. : L. D2 ; M. molaire. *Rhinoceros sondaicus* : N et O. m3 droite ; P. D2 gauche ; Q. D3 droite. *Panthera tigris* : R. m1 droite.

9. Conclusion

Cave breccias deposits are the most frequently encountered fossiliferous records of the mammals in the Indochinese area. In certain cases, these breccias are the only fossil records and so we need to improve our understanding of the sedimentary processes, and karst stratigraphy. Over the last decade, improvements in various dating methodologies (Optically Stimulated Luminescence, U/Th, Cosmogenic) have allowed geochronologists to better estimate the ages of the fossils-bearing breccia deposits. While certain problems relating to karst complexity remain, we have demonstrated that the study of such fossiliferous deposits is essential to refine and increase the knowledge of the evolution of Indochinese mammals.

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