

**Taphonomic analyses of cave breccia in Southeast Asia: A review
and future directions**

Author

Smith, HE, Morley, MW, Louys, J

Published

2020

Journal Title

Open Quaternary

Version

Version of Record (VoR)

DOI

[10.5334/OQ.75](https://doi.org/10.5334/OQ.75)

Downloaded from

<http://hdl.handle.net/10072/402371>

Griffith Research Online

<https://research-repository.griffith.edu.au>

REVIEW

Taphonomic Analyses of Cave Breccia in Southeast Asia: A Review and Future Directions

Holly Ellen Smith*, Mike W. Morley† and Julien Louys*

Karst-derived breccia is the most analysed deposit in fossil-bearing Southeast Asian caves due to its superior preservation potential for human, faunal, archaeological, and palaeontological data. The study of breccia can provide a better understanding of human and faunal histories, and an opportunity to investigate site taphonomy and insights into environments of deposition and post-depositional processes. We review the literature on approaches used to improve the taphonomic understanding of cave deposits in Southeast Asia and how these deposits fit into a cave's life history. We discuss common methods used to extract taphonomic data retained in Southeast Asian cave deposits and the associated opportunities to discern the mechanisms of cave formation, depositional history, and faunal accumulation. While attempts have previously been made to discern the taphonomic characteristics of Pleistocene vertebrate remains in the region, there has been no comprehensive review outlining methods used to understand taphonomic histories and the biases introduced through these processes. We illustrate the challenges of researching cave breccias in Southeast Asia and the knowledge gaps brought about by conventional methodologies. Uncertainties exist about the extent to which breccia can be examined to infer the taphonomic history of a vertebrate assemblage. These uncertainties exist in part because of dating complexities. This review demonstrates that a taphonomic analysis of breccia in complex long-term accumulations requires a multi-disciplinary approach. We recommend using digital techniques to record spatial distribution data for a thorough interpretation of taphonomic characteristics.

Keywords: taphonomy; speleogenesis; cave; breccia; tomography; micromorphology

1. Introduction

Present research in Quaternary palaeontology, taphonomy and palaeoenvironments has examined various aspects of the mechanisms of vertebrate accumulation, using the exceptional preservation potential in caves as a vital source of data (e.g. Worthy & Holdaway 1994; Auler et al., 2006; Blain et al., 2009; Bountalis & Kuhn 2014; Maldonado et al., 2016; Price et al., 2019). However, a comprehensive assessment of the depositional histories of individual cave breccia deposits is generally lacking, particularly in Southeast Asia, although there are some notable exceptions (e.g. Bacon et al., 2004; Bacon et al., 2008; O'Connor et al., 2010).

Current research in Southeast Asia strongly emphasises breccia as valuable archives for fossil and geochronological data (e.g. Westaway et al., 2007, 2017; O'Connor et al., 2017). However, limitations associated with investigating

breccia as a source of taphonomic information may have repercussions on our understanding of the temporal reconstruction of cave palaeoenvironments and regional chronostratigraphies (Louys et al., 2017). A more detailed understanding of taphonomic data has the potential to inform on the evolution of ecosystems through time, and to consider the emerging complexity of taphonomic modification, future research will benefit considerably from a detailed study of the geochronology of cave sites (Wei et al., 2005; Wang et al., 2007).

Caves host a variety of deposits, including breccia and conglomerates, speleothem and flowstones, tufas and calcretes, organics and anthropogenic deposits (Farrand, 2001; Fairchild and Baker, 2012). We focus on karst breccia as these deposits appear to contain the majority of cultural or faunal material in Southeast Asian cave sites, also often interbedded with flowstone. These materials are often the only surviving remnants in Southeast Asian cave sites, preserving evidence crucial to understanding the chronology of cave deposits and the taphonomy of incorporated fossil assemblages.

Here, we systematically analyse primary studies of breccia histories in Southeast Asia to better synthesize what is known about the depositional and preservational processes that alter cave deposits in tropical climates,

* Australian Research Centre for Human Evolution, Environmental Futures Research Institute, Griffith University, Brisbane, Queensland, AU

† Archaeology, College of Humanities, Arts and Social Sciences, Flinders University, Adelaide, AU

Corresponding author: Holly Ellen Smith
(holly.smith11@griffithuni.edu.au)

challenges associated with identifying the taphonomic agents acting on cave palaeofaunal assemblages, and identify areas for further study. This review critically analyses the conventional methods used in the taphonomic interpretation of naturally accumulated fossil assemblages in Southeast Asian cave deposits. We assess case studies to determine the analytical methods used, highlight the findings, assess the common limitations, and assert how the application of new methods would improve these results. We highlight the potential of novel techniques for a holistic analysis of fossiliferous cave deposits, reconstructing the complex taphonomic history of fossil assemblages and the diagenesis of the sediments in which they are held. In particular, this paper aims to answer the following questions: (1) What taphonomic evidence has been extracted from cave breccia in Southeast Asia and what are the limitations of the methods used?; (2) What are the knowledge gaps in previous taphonomic studies of cave breccia in Southeast Asia and what approach should be used in future research?

Study Location

There has been an expansion in Late Pleistocene archaeological research in caves from tropical climates, particularly in the Southeast Asian region (e.g. Anderson, 1997; O'Connor & Veth, 2005; Aubert et al., 2017; Morley, 2017). However, this hardly approaches the amount of scientific endeavour seen in other parts of the world; particularly

for questions regarding hominin occupation and dispersal (e.g. Brain, 1981; Emslie, 1988; Andrews & Cook, 1990; Heries et al., 2006a,b, 2009; Dirks et al., 2010, 2017; Blain et al., 2009; Adams, 2017; Steinthorsdottir & Håkansson, 2017; Schubert & Mead, 2019). Nevertheless, recent publications that have investigated the taphonomy of palaeontological assemblages in cave sites have increasingly focused on Southeast Asia.

The region of Southeast Asia in this review comprises the eleven countries that lie geographically south of China, east of the Indian subcontinent and north-west of Australia: Indonesia, Malaysia, Singapore, Philippines, Timor-Leste, Brunei, Cambodia, Laos, Myanmar (Burma), Thailand and Vietnam. The geographical distribution of the cave sites in Southeast Asia discussed is shown in **Figure 1**.

Geological Background

Limestone caves form when water percolates through soil using groundwater runoff (Palmer, 2007). Carbon dioxide in the atmosphere dissolves into these waters to form carbonic acid (H_2CO_3). Further carbon dioxide from the soil, which accumulates from root respiration and decay of organic matter, is added as the waters travel through the ground (Palmer, 1991). Carbonic acid solution then builds up in fissures, bedding planes, joints, and faults, which dissolves the calcium carbonate to create a limestone cave (Gillieson, 2009; Fairchild & Baker, 2012). This fluid circulation can assist in guiding the evolution of karstic caves.

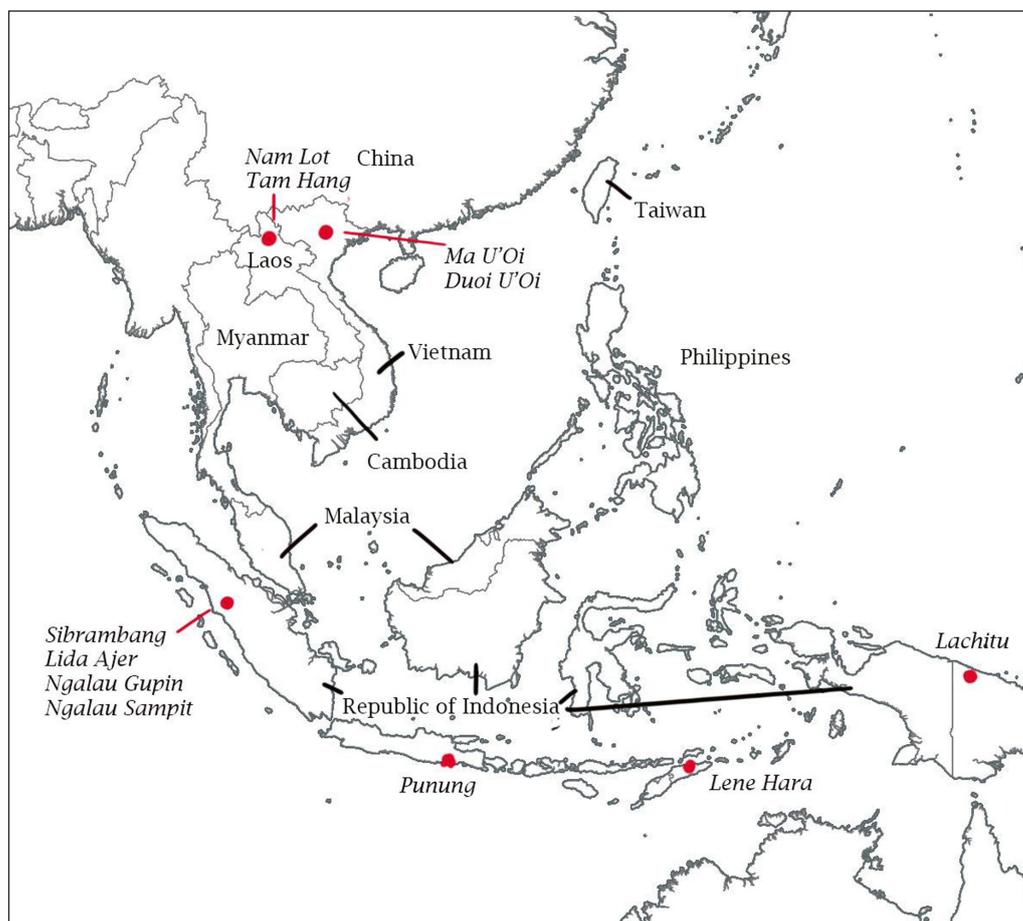


Figure 1: A map of Southeast Asia, highlighting the key cave localities in the research analysed in this review.

Breccias are clastic sedimentary rocks that commonly occur in caves formed in limestone or dolomite. They are composed of angular fragments over two millimetres in diameter, bound together by mineral cement of lesser size (Woodcock & Mort, 2008). Breccia formation is common in limestone caves in Southeast Asia (Dominguez-Bella et al., 2012; O'Connor et al., 2017). Breccia are very dense, well-cemented deposits and so can survive the destructive processes of cave evolution, increasing the preservation potential of geological and faunal aggregates incorporated within. Karst breccia can provide a chronological framework of depositional history as the indurate deposits incorporate aggregates such as speleothem and mammalian teeth conventionally used for direct dating in isolation. We focus on karst breccia as these deposits are the primary source of data in Southeast Asian cave studies, due to being the most frequently encountered and often containing vertebrate assemblages (see supplementary information).

Humid climates increase water levels that allow for carbonate laden solutions to seep through fissures in cave walls and cement the breccia deposits (e.g., Mijares et al., 2010; Morley & Goldberg, 2017). These carbonates

are often interbedded with evaporitic rocks such as anhydrite or gypsum (Klimchouk et al., 2000). Expansion and dissolution of carbonates or evaporitic rocks can cause brecciation of the minerals and adjacent rock (Klimchouk, 1996; Li & Zhou, 2015). The instability created by brecciation typically occurs when the cave is inactive. Subsequent karst collapse can lead to the formation of dissolution-collapse breccia composed of carbonate clasts (O'Connor et al., 2017; Shukla & Sharma, 2018).

The breccia deposits of Southeast Asia are often clay-rich infill with large angular limestone clasts (**Figure 2**). These breccia are thin remnants of much larger, older deposits removed from the cave networks, found cemented to the walls or accumulated on the floor. These relics are likely removed by solution, and mechanical erosion enhanced by significant humidity and increased precipitation levels (Andrews & Cook, 1985; Fernández-Jalvo et al., 2010; Morley & Goldberg, 2017). Allogenic sediment from eroded cave fill can be reactivated and pass through internal waterways. The resulting deposits can be heavily reworked from the original sediments laid down during diagenesis. Exhumation is one such mode of modification, in which filled and covered sediments are removed



Figure 2: (A) Argillaceous chaotic breccia deposit cemented to the limestone cave wall of Lida Ajer; (B) Fractured angular clast protruding from the breccia cement; (C) Cervid tooth specimen incorporated into the breccia matrix.

from a palaeokarst feature; it occurs due to the recommencement of speleogenetic processes after a dormant period (Osborne, 2000, 2003). Sediments can be heavily reworked multiple times by complex processes occurring in situ (Farrant & Smart, 2011). These processes can profoundly alter the type and completeness of incorporated fossils.

2. Methodology

A systematic literature review was performed using a recently developed method that lies between a traditional narrative review and a detailed meta-analysis of relevant scientific research (Pickering & Byrne, 2014). A paper was considered a primary publication if the focus were to elucidate the formation history of breccia deposits in Southeast Asian caves and listed in **Table 1**. Included in our review is literature that investigates early hominin remains in Southeast Asian caves, as the presence of early hominin remains is often regarded as evidence of cave occupation, similarly to that of faunal remains, though evidence suggests that these remains could be allochthonous; ex-situ recycled deposits as part of larger faunal assemblages (e.g. Anderson, 1997; Barker et al., 2007; O'Connor et al., 2010). It is likely that taphonomic literature from Southeast Asia and regions of similar tropical climate has documented scientific knowledge in a language that is not native to any of the authors and thus has not been analysed by this review. This is a noted limitation to this review.

3. Results

The method evolution of the literature we are analysing is summarised in **Table 1** and fully described in the supplementary online database.

General site characteristics

The cave sites were all located in karstified limestone hills or karst towers at elevations from approximate sea-level to over one hundred metres above sea level (e.g. Long et al., 1996; O'Connor et al., 2010, 2017). The elevated karst systems of Island Southeast Asia were instigated as a secondary result of major tectonic activity during the Pliocene and Pleistocene that triggered an increased period of mountain building and elevated the continental Sundaland margin (Drawhorn, 1994; Hall, 2009). 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. Plio-Pleistocene sea-level changes during the region's interglacial periods led to the repetitive inundation of the region's continental shelves during interglacials (Hanebuth et al., 2011; De Bruyn et al., 2014). The elevations in the continental Sundaland margin occurred together with significant intensification in rainfall levels that modified the geochemistry of the geological setting and began the process of cave formation (Verstappen, 1997). Further north, the karst structures of Indochina were predominantly formed by mountain building incurred by non-rigid clockwise shifting past the stresses of the eastern syntaxis of northward-moving India during the Cenozoic (Huchon et al., 1994).

All excavated cave breccia contain comparable diverse vertebrate remains, dominated heavily by a suite of extant and extinct medium to large-bodied mammal teeth and bone fragments (e.g. Schwartz et al., 1994; Mijares et al., 2010; Düringer et al., 2012; Bacon et al., 2018a). The deposits are characterised by the abundance of teeth and a general absence of large or complete bones. It is also possible that fragmentation of bone in the collections are so intense that researchers invest little effort in preparing or identifying the remains, and so teeth dominate the 'taxonomically informative' aspect of the assemblages. This likely results in a bias in publication of dental remains in comparison to that of skeletal remains.

Species identified in Southeast Asian faunal assemblages include herbivorous, omnivorous, carnivorous, and durophagous (bone) feeders. The vertebrate remains and fossil-bearing sediments show a range in age from the early to late Quaternary (e.g. Esposito et al., 2002; Bacon et al., 2018b; Zeitoun et al., 2019). Taken together, most data suggest that mammal remains were initially deposited in the landscape surrounding the caves, then transported into the cave and lithified into consolidated breccia. The fauna inhabits both humid tropical rainforest environments like that of modern Southeast Asia as well as more open savannah environments (Louys and Roberts, 2020).

Geomorphological Processes

Glover (1979) considered the changing nature of archaeological research, shifting to the geomorphological aspects of caves, as there seemed to be recurring issues in forming chronological interpretations of sites. The deposits of greatest scientific interest were deemed to be "ancient intact deposits cemented to cave walls by calcareous groundwater" (Glover, 1979, p. 305). Glover (1979) recorded artefacts recovered from Ulu Leang I as blades, flakes, bones and shells but provided no detailed taxonomic or taphonomic analysis. Nevertheless, his research first highlighted the hidden complexity in post-depositional discontinuities during deposit formation. The rate of occurrence of these dislocations was noted to increase dramatically in tropical sites such as Southeast Asia. The author forewarned future researchers to ascertain that depositional sites are in-situ prior to analysis.

However, it was not until the early 2000s that a critical component of this issue, taking into account the fabric of the deposits, was considered. Burial context is a key factor in a taphonomic analysis and can be informed by fabric descriptions. However, in early studies breccia were simply noted as present, or the principal characteristics described only by general colouration, basic composition or broad type. In geological studies, the fabric of breccia has often been used as the diagnostic signature to determine breccia type. Defining breccia type can provide important information about the depositional conditions and history of the deposit. Thus, classifying a breccia can provide direct indications into the basic mechanisms and time-scale of accumulation of incorporated vertebrate remains, and the interactions with the depositional environment. The classification of karst breccia is determined by conducting a fabric analysis based on their microscopic and

Table 1: A summary of the method evolution used in the taphonomic analyses of Southeast Asian cave sites. A full review is available in the supplementary information.

Theme	Author/Year	Cave site name	Study Location	Methodologies
<i>Breccia Depositional Components</i>	Glover, 1979	Ulu Leang I	Lealleang Valley Maros Sulawesi	Stratigraphic analysis Sediment analysis
	Gilbertson et al., 2005	Subis limestone Niah	Sarawak	Stratigraphic analysis Radiocarbon dating
	Duringer et al., 2012	Nam Lot	Pà Hang Mountain Laos	14C for recent deposits U/Th - detrital content pollution
		Tam Hang	Huà Pan province Laos	Cosmogenical burial - susceptible to reworking OSL
		Duoi U'oi	25 km from Hoà Binh city Man Duc Village Vietnam	Cosmogenical burial - susceptible to reworking OSL
		Ma U'oi	Man Duc village Vietnam	Cosmogenical burial - susceptible to reworking OSL
	O'Connor et al., 2017	Lachitu	S2°38'0.20" E141°08'11.0" Oenake range Papau New Guinea	Carbon dating Bio/chronostratigraphic dating of cultural materials from archives
		Lena Hara	S08°24'51.9" E127°07'21.42" Papau New Guinea	Carbon dating Bio/chronostratigraphic dating of cultural materials from archives
		Laili Cave	S08°54'48" E126°16'40.5" Timor-Leste	Carbon dating Bio/chronostratigraphic dating of cultural materials from archives' into the methodology column for Laili Cave
	Louys et al., 2017	32 sites Talaud	See Supplementary database	14C dating Neutron tomographic imaging ESR dating OSL dating Micromorphology
		4 sites Sangihe		14C dating Neutron tomographic imaging ESR dating OSL dating Micromorphology
		19 sites Alor		14C dating Neutron tomographic imaging ESR dating OSL dating Micromorphology
		19 sites Pantar		14C dating Neutron tomographic imaging ESR dating OSL dating Micromorphology
		13 sites Timor Leste		14C dating Neutron tomographic imaging ESR dating OSL dating Micromorphology

(Contd.)

Theme	Author/Year	Cave site name	Study Location	Methodologies
<i>Vertebrate & Cultural Assemblages</i>		25 sites Sumatra		14C dating Neutron tomographic imaging ESR dating OSL dating Micromorphology
	Celiberti et al., 2018	Doi Pha Kan	Lampang Province N18°26.95' E99°46.62' Thailand	Techno-morphostudy
	Long et al., 1996	Lang Trang	Thanh Hoa Province Vietnam	Faunal Analysis
	Tougard et al., 1998	Thum wiman nakin	Kon San District Thailand	Taphonomic analysis Faunal analysis
	Esposito et al., 2002	Snake cave	Kon San District Thailand	U-series dating
	Bacon et al., 2004	Ma U'oi	Tan Lac Province N20°37'22" E105°16'40" Vietnam	U/Th dating
	Bacon et al., 2006	Ma U'oi	Tan Lac Province N20°37'22" E105°16'40" Vietnam	U/Th dating
	O'Connor et al., 2005a	Pulau Kobroor Liang Nabulei Lisa	Aru Island	Radiocarbon dating Weighting cultural material Faunal analysis
	Ibrahim et al., 2013	Batu caves	Malaysia 13 km north of Kuala Lumpur Batu cave Massif	Luminescence U/Th dating TIMS Gamma spec
	Filoux et al., 2015	Tham Prakia Phet	Chaiyaphum Province Thailand	Faunal analysis
	Suraprasit et al., 2015	Khok sung	Nakhon Ratchasima Province Thailand	Magnetostratigraphy Systematic Palaeontology
	Bacon et al., 2015	Tam Hang	Huà Pan province Laos	Uranium series dating OSL
		Nam Lot	Pà Hang Mountain, Laos	Uranium series dating OSL
		Duoi U'oi	25 km from Hoà Binh city Man Duc Village Vietnam	Uranium series dating OSL
	Punung Fauna	S08°80'30.3" E111°10'58.3" S08°70'33.2" E110°580'58.5" S08°070'33.5" E110°590'15.1" Java	Uranium series dating OSL	
	Simbrambang	Tapisello, west Sumatra	Uranium series dating OSL	
Sutikna et al., 2016	Liang Bua	East Nusa Tenggara Flores	ESR dating Thermoluminescence	

(Contd.)

Theme	Author/Year	Cave site name	Study Location	Methodologies
	Westaway et al., 2017	Lida Ajer	S00°19'11.8" E100°35'12.3" Sumatra	Luminescence U-series dating ESR dating
	Bacon et al., 2018a	Boh Dambang	N22°210'21.54" E106°260'6.12" Cambodia	SG-OSL U-series dating ESR dating
	Setiyabudi et al., 2018	Seropan	Yogyakarta S08°00'55.5" E110°40'56.9" Indonesia	Systematic palaeontology
	Suraprasit et al., 2019	Yai Ruak	Krabi Province N92°78'98" E47°50'10" Thailand	Radiometric dating Systematic Palaeontology
<i>Taphonomic Agents</i>	Schwartz et al., 1994	Tham Khuyen	Lhang Song Province Vietnam	Faunal analysis
	Zeitoun et al., 2005	Cave of the Monk	Chiang Dao Wildlife Reserve Thailand	Taphonomic analysis
	Bacon et al., 2008	Doui U'oi	Tan Lac Province N20°37'12" E105°16'25" Thailand	Palynology
	Mijares et al., 2010	Callao	Cagayan Valley, Northern Luzon, Phillipines	U-Series U- concentration Laser ablation Faunal analysis CT scanning
	Frère et al., 2018	Doi Pha Kan Ban Tha Si	N18°26'55" E99°45'98" Lampang Province Thailand	Taphonomic analysis
		Laang Spean	Battam Bang N12°51' E102°55' Cambodia	Taphonomic analysis
<i>Post-depositional Complexities</i>	O'Connor et al., 2005b	Sungai Dosi Liang Lemdubu	Aru Island	Radiocarbon dating Weighting & distribution of remains
	O'Connor & Aplin, 2007	Lena Hara Matja Kuru 2 Telupunu Jerimalai Uai bobo Bui Ceri Oato	Northeast coast of Timor-Leste Within Baucau Limestone formation	Radiocarbon dating
		Liang Lemdubu Nebulai Lisa	Aru Islands South of New Guinea at 7°S and 134°E	Radiocarbon dating
	Westaway et al., 2007	Punung Fauna	S08°080'30.3" E111°010'58.3" S08°070'33.2" E110°580'58.5" S08°070'33.5" E110°590'15.1" Java	OSL TIMS Thermoluminescence
	O'Connor et al., 2010	Lene Hara	S08°24'51.9" E127°07'21.42" Timor-Leste	Thermoluminescence OSL

(Contd.)

Theme	Author/Year	Cave site name	Study Location	Methodologies
	Morley et al., 2017	Liang Bua	Western Flores, Miocene limestone near Wae Racang	Radiocarbon dating Micromorphology
	Zeitoun et al., 2019	Ban Fa Suai II	Ban Fa Suai Village Thailand	Faunal analysis ESR dating Palaeoecological analysis
	McAdams et al., 2020	Con Moong	Cuc Phuong National Park Vietnam	Radiocarbon dating OSL dating Micromorphology

macroscopic lithological character; the principal types of each breccia are described in **Table 2**.

Gilbertson et al., (2005) was the first to undertake the research suggested by Glover (1979), when he described, analysed, and interpret the geomorphology of Niah cave, Sarawak rather than focussing on dating the vertebrate remains. Comparisons between lithological properties, location, and observed lithostratigraphic positions of all the surviving exposures were made to determine the sedimentary and stratigraphic sequence of the site. Rather than taking on the previous approaches at this site (determining the initial biological, airfall, and human origins of much of the materials in the cave), the investigation focused on depositional and post-depositional sedimentary structures and diagenetic changes. Notably, there was a truly novel approach to document small-scale and microscale sedimentary and structural features to fully understand the depositional and deformational processes. Correlating the principal components of the sequence with those previously analysed revealed a more complex stratigraphy than had previously been described. Important geomorphological processes that formed the sequence were identified as mudflow, colluviation, and fluvial and shallow lake activity. Diagenetic alteration of guano and midden then further modified the in-situ cave sediment.

Speleogenesis is the process that determines the evolution of cave formation and development (Klimchouk et al., 2000; Palmer, 2002). It determines the plan geometry of a cave and directly affects cave entrance morphologies, associated fluvial systems, and the actions of biological accumulators (Andrews & Cook, 1990) that introduce and shape cave deposits and any incorporated fossil assemblages. Numerous factors affect speleogenesis, uniquely determining the evolution of each cave and the nature of the passages into which sediments and fossils accumulate. The energy of streamflow in invading waters determines the size and number of, the degree of dispersal and the configuration of the final assemblage (Voorhies, 1969).

Duringer et al. (2012) were the first to examine speleogenesis at a landscape level. They introduced the idea of comparing the dates of the breccia with the topographic level of alluvial plains to determine if cave formation is determined by water table changes. Their study suggested that the origin and preservation of the fossil bearing breccias are controlled at shorter time scales by the hydrology inside the karsts themselves. However, there is little evidence of direct geomorphological coupling between

breccia formation and the broader landscape hydrology or major zones of sediment storage suggesting localized breccia forming processes. Duringer et al. (2012) highlighted that the fluctuating velocity of natural flowing waters regulates the grade of suspended load that is transported and deposited during cave development. When fossil elements are suspended in these natural flowing waters, the remains are similarly characterised by a systematic gradation in size and the taphonomic mode of occurrence, and transport histories can be evident in the sedimentological context of the host lithofacies (Behrensmeyer & Hill, 1988; Andrews & Cook, 1990; Aslan & Behrensmeyer, 1996).

Fluvial action has long been considered a possible primary taphonomic agent operating in the caves of Southeast Asia. Fluvial transport is particularly likely to act as a prominent taphonomic process in cave environments (Howard, 1964; Palmer, 1987, 2001, 2007; Klimchouk, 1996; Klimchouk et al., 2000). Voorhies (1969), Behrensmeyer & Ak (1975), Hanson (1980) and Koster (1987), focused on theoretical and practical reconstructions of fluvial taphonomic processes that can affect vertebrate remains. Bones are sorted as a function of size and density. The methodologies included in these studies are excellent sources of direct evidence as to the physical and hydraulic processes in complex fluvial environments in caves. Water is also the key agent for most of the major chemical processes that can instigate significant bone and tooth modification within the soil (Behrensmeyer & Ak, 1975; Hedges & Millard, 1995; Hedges, 2002; Turner-Walker, 2008).

The morphometrics and distribution of caves are a natural record of the setting in which the cave formation processes originated and the dynamics of cave development (e.g. Palmer, 2001; Gillieson, 2009; Boggus & Crawfis, 2009; Morley et al., 2017). Thus, a thorough analysis of solution cave characteristics can provide direct evidence of the natural controls of cave formation and origin. The origin and development of caves reflected the influence of speleogenesis as a taphonomic process in the long-term accumulation and deposition of cave deposits, some of which are fossiliferous.

The key characteristics of the breccia studied by Duringer et al. (2012) denoted a similarity in geological, biogeographical, and environmental settings of the deposits, while the complex interactions of hydrology, tectonics and climate determined the evolution of each individual cave. This evolution is highly variable, and so each cave is a unique dynamic system. O'Connor et al.

Table 2: Principal karst breccia types and characteristics. Adapted from Stow (2005) & Tucker (2009).

Major Type	Sub-type	Lithology	Nature/Origin	SE Asian Example
Extra-formational breccia	Polymict	Matrix-supported fabric. Many variable gravel-sized clast origins derived outside the site of deposition	Breakdown of older rocks through erosion and deposition by fluid flow and sediment gravity flow	
	Oligomict	Matrix-supported fabric. Few gravel-sized biogenics/clastics. Clasts with origins likely derived predominantly of contemporaneous limestone or dolomite	<i>See above</i>	Westaway et al., 2007
	Monomict	Matrix-supported fabric. Gravel-sized biogenics/clastics. Clasts of a single rock type, likely a single contemporaneous rock unit	<i>See above</i>	Bacon et al., 2008
Intra-formational breccia	Mainly monomict	Gravel-sized biogenics/clastics derived from the site of deposition, clastics are typically micritic limestone in origin	Fragmentation of poorly consolidated contemporaneous beds, deposited by fluid or gravity flow	O'Connor et al., 2017
Cataclastic breccia	Landslide/slump	Random biogenic/clastic supported fabric. Appear massive	Breakage due to tensile stresses of slumping	Louys et al., 2017
	Solution collapse breccia	Inversely graded fabric. Sharp, flat base. Commonly matrix supported. Insoluble clast fragments	Breakage due to collapse into void created by solution or similar processes	

(2017) demonstrated this concept in in Lachitu, Papua New Guinea and Lena Hara and Laili Cave, Timor Leste, where a significant lateral shift in facies composition over a few metres in the breccia deposits was recorded. Concentrations of fossils can vary considerably laterally or vertically in a single breccia (Westaway et al., 2007; Bacon et al., 2008, 2015; Durringer et al., 2012); though these interpretations of breccia are limited as the deposits were only viewed externally.

Acknowledging the apparent importance in the geomorphological aspects of cave studies in Southeast Asia as an increasing relevant theme in the literature, O'Connor et al. (2010) focused on the lithostratigraphy of the deposits. A depositional history of the breccia was formed suggesting multiple erosional and depositional episodes together with long-term shifts in sedimentary processes. Mylroie & Carew (1990) note that the process by which authigenic cave deposits are originally set down can be further altered by alluviation from freshwater discharge, known in cave environments as allogenic recharge. This can radically alter any interpretation of cave origin and the evolution of a cave system. Erosional processes not only form caves and shape overall morphology but are also the very factors that can infill and permanently destroy the cave (Palmer, 1991, 2001, 2002).

Breccia formation and removal have different causes and mapping of time discontinuities and lateral sequence gaps is informative about the occupation and geomorphic history of the sites. One of the most significant findings from the archaeological sites discussed by O'Connor et al. (2017) concerns sampling. Their results clearly demonstrate that cave deposits in humid tropical regions are stratigraphically complex, reflecting multiple erosional

and depositional episodes together with long term shifts in sedimentary processes. This complexity means that a complete cultural and chronological sequence may not survive as a typical stratigraphic column in any single part of a site. While breccia has excellent potential to act as stores of chrono-stratigraphic data, complicated depositional histories are a significant issue in Southeast Asian cave studies.

Louys et al. (2017) focused on defining formation processes of vertebrate-bearing breccias, their taphonomic histories, and the criteria used to determine whether breccia represent syngenetic or multiple deposits in multiple caves across Asia. Their study also demonstrated that a single breccia can be formed through multiple cementation and dissolution events and yet show no significant lateral movement of fossils incorporated within. These data indicate that depositional histories for individual breccias are potentially highly complex and may result in significant time- or habitat-averaging of fossils. While direct dating may help resolve some of these complexities, Louys et al. (2017) highlighted that events extending beyond radiocarbon dating thresholds require a comprehensive multi-disciplinary approach to interpret complex breccia formation histories. Their research makes a novel attempt to form a critical understanding of vertebrate taphonomy by reconstructing the biogeographic context in which burial data are created. This was also the first study in the region to use neutron tomography to non-destructively analyse the spatial associations and variations of clasts and inclusions within a breccia deposit.

Detailed recording of spatial distribution data in breccia in relation to dating samples may improve the reconstruction of pre- and post-depositional actions in

vertebrate-bearing deposits. High resolution dating and detailed interpretation of localised palaeoenvironmental information has recently been informed using photogrammetry and laser scan surveys (Bates et al., 2010; McFarlane et al., 2013; Oludare & Pradhan, 2016). This methodology can be applied to quickly record three-dimensional models of cave surfaces for realistic high-resolution visualisation and extraction of data at various scales (Lerma et al., 2010). The results of such research may aid in the documentation of the metrics of the cave, to monitor modifications and developments in cave deposition and morphology (Lerma et al., 2010), and hence inform on some elements of the formation history of the cave. Computed tomographic imaging provides the potential to reveal the depositional and three-dimensional relationships of internal breccia structures, correlating breccia formation history with that of the incorporated vertebrate remains.

The recording of spatial information using such methods is, however, limited by not accounting for variable taphonomic processes that alter the formation, preservation, and degradation of complex cave sites at the microscale. Such insights can provide further information on site formation processes. Morley et al. (2017) detailed the microscale component of a multidisciplinary program of research that is entirely focussed upon the geomorphological aspects of Liang Bua, Flores. A robust understanding of site formation, preservation and destruction was described. Death assemblages and their primary or secondary context can be further modified by numerous chemical, physical, and biological processes after decomposition has begun (Behrensmeyer & Hill, 1988; Lyman, 1994). In a novel approach for the region, micromorphological samples were used to study the chronologies and depositional histories of fossil-bearing sediments.

The geomorphic and archaeological context of Con Moong cave, Vietnam was also studied through geoarchaeological and geochronological analyses of excavated sediments by McAdams et al. (2020). Field descriptions combined with micromorphological analyses revealed major stratigraphic changes throughout the deposit. Sedimentological analyses were carried out on bulk samples to form numerical data related to texture, geochemistry, and mineralogy. The destructive effects of sediment transport, bioturbation and guano-driven diagenetic change were visible throughout the sequence. The loss of microstratigraphic relationships and sedimentary constituents means that the environmental histories of the sediments cannot be reconstructed solely from micromorphological analysis. Bulk sediment analysis combined with these sedimentological observations enabled the authors to extrapolate these data across the entire sequence. Radiocarbon, OSL and micro X-ray fluorescence (pXRF) indicate that the sediment ages range from ~74 to ~19 ka. The authors reiterated strongly that the complexity of the processes that commonly affect caves in Southeast Asia ultimately require a diverse combination of a range of complementary macro- and microtechniques and approaches.

Insights from Direct Dating and Biochronology

The focus of Long et al. (1996) was on the faunal composition rather than the geomorphological aspects of several cave sites. The species of Lang Trang in Vietnam, Punung in Java and Lida Ajer in Sumatra were seen to be similar, particularly the distribution of species in Lang Trang and Lida Ajer. Not only was the species content similar but Long et al. (1996) suggested that their taphonomy was also comparable: there was significant evidence of rodent gnawing attributed to porcupines. In Southeast Asian cave deposits, porcupine accumulations are dominated by isolated mammal teeth (Lenoble et al., 2006; Bacon et al., 2008; Bacon et al., 2015; Zeitoun et al., 2019). Porcupine gnawing marks are evident on the enamel and root of isolated teeth and the periphery of long bones. It is very difficult to determine if a fossil assemblage is the result of a single accumulator or multiple agents, and the order in which these agents recycled the deposits (c.f. Behrensmeyer & Hill, 1988). Considerable opportunities surround definitively indicating the presence of a modifier or accumulator in cave environments, should future research focus their intentions upon explicating intense post-depositional fossil disintegration and complex depositional histories (Durringer et al., 2012). However, porcupines are the only definitively identified taphonomic agent acting upon the vertebrate remains in most cave deposits (e.g. De Vos, 1984; Bacon et al., 2006).

Tougard et al. (1998) recorded a huge variation in age in the extracted mammalian teeth of the Thum Wiman Nakin assemblage, spanning between 80–350 000 years old based on biochronology. It was not considered whether the deposit represented a mix of older and younger fauna or just older fauna that had been eroded into a younger deposit. This remains a common challenge associated with interpreting the palaeoenvironmental history of the vertebrate-bearing breccia in Southeast Asian caves.

Esposito et al. (2002) established a chronology of site deposition in Snake cave, Thailand, shifting methodology radically from that of Long et al. (1996) and Tougard et al. (1998) to focus on direct dating. The application of uranium series dating relies on dating individual inclusions within a deposit, including fossil teeth, or bracketing the age of a deposit through the dating of capping flowstones. This approach is, however, susceptible to time averaging processes. As detailed above, complex speleogenic events can rework cave deposits through one or multiple phases of dissolution and cementation. A complicated depositional history can lead to temporal mixing of incorporated fossils (O'Connor et al., 2010; Durringer et al., 2012; Louys et al., 2017). This can lead to inaccuracies in establishing the age of the deposits, as the fossils found within a single stratum may not be contemporaneous (e.g. Louys et al., 2017; O'Connor et al., 2017; Curnoe et al., 2019). The bracketed age derived from capping flowstones can constitute low resolution ages with large errors.

In part to address this, a multi-disciplinary approach was taken by Bacon et al. (2004, 2006) to determine the biostratigraphy of Ma U'O'i cave, Vietnam and determine biocorrelation with other cave sites in the region. A virtual stratigraphy was formed by directly correlating deposits

of similar lithological character throughout the cave. A taxonomic analysis of the mammalian fauna and direct comparison with similar continental sites was used to bracket an age for the remains. In their 2006 study, U/Th dating of calcite and breccia provided a minimum age of late Pleistocene for the in-situ fauna. This age estimation fitted with the biochronological age suggested by earlier site comparisons. However, the initial apparent homogeneity of breccia was not demonstrated, and a finer scaled stratigraphy suggested a multi episodic breccia formation. Multiple dating techniques were also used by Ibrahim et al. (2013) to provide independent age estimates for deposits associated with a diverse faunal assemblage excavated from Batu caves, Malaysia. Luminescence dating was employed to provide a chronology for the breccia sediments and uranium-series dating of flowstones provided a minimum age for the deposition and cementation of the breccia.

The use of multiple dating methods continued to co-occur with efforts to refine biostratigraphic schemes in Southeast Asia into the 2010s. Re-investigations of faunal remains excavated from Tham Prakia Phet in Thailand were undertaken by Filoux et al. (2015) to complement the Pleistocene mammal biostratigraphic framework of the Indochinese sub-region. The mode of accumulation was difficult to establish due to destructive excavation and stratigraphic analysis, although gnawing evidence suggested partial accumulation by porcupine rodents. The new taxonomic data nevertheless revealed a considerably more diverse Pleistocene faunal assemblage than previously documented at this site. The authors indicated that some taxonomic attributions were tenuous due to the natural range in tooth size and concluded that more contextual evidence needed to reconstruct the biostratigraphy and environment of Pleistocene Southeast Asia.

Excavation of Khok Sung cave site, Thailand by Suraprasit et al. (2015) yielded many fossil vertebrate remains, of which the extensive diversity allows the authors to constrain the age of the fauna from the previous estimates between the Early Pleistocene and the Middle Pleistocene to a more definitive Middle Pleistocene age. The faunal comparisons with other Middle Pleistocene assemblages focused on a hyaenid skull and mandible characteristic of Southeast Asian Middle Pleistocene faunas. These new bio-chronological data were coupled with a magnetostratigraphic study of the lithological section, to reinforce the age determination within a multiproxy approach.

The vertebrate assemblages recovered in five mainland and insular karstic sites in Laos, Vietnam and Java were analysed by Bacon et al. (2015) to improve the potential for faunal interpretation by establishing solid chronologies. These mammalian faunas were well-known and had already been discussed in terms of composition, taphonomy, biochronology, evolution, and palaeoecology, but only two solid age estimates of two fauna had been determined. To ensure the accuracy of the new chronologies, independent age estimates were obtained by employing luminescence techniques applied to the sediments/breccias, OSL of quartz grains and U-series dating of flowstone. The previously estimated chronologies of Tam Hang and

Nam Lot were replaced with direct chronological context. The mortality profiles of the remains were also analysed by Bacon et al. (2015) to emphasize the possible selectivity of large predators (carnivores and humans) on ungulate prey.

The multidisciplinary practice that has become standard in Southeast Asian cave studies is well demonstrated by Westaway et al. (2017). Luminescence and uranium-series techniques were applied to bone-bearing sediments and speleothems. Coupled uranium-series and ESR were applied to mammalian teeth. These methods were modelled under a Bayesian framework, and produced estimates of 73 and 63 ka for the age of the breccia. Similarly, to constrain deposition at Coc Muoi cave, Vietnam, Bacon et al. (2018b) undertook a multi-proxy dating approach to contextualise a dental health assessment of the fauna. OSL and post-infrared infrared-stimulated luminescence (pIR-IRSL) dating of the cave sediments and U-series dating of flowstones indicated a potential age range of 148–117 ka for the fauna (MIS 6–5).

Bacon et al., (2018a) also analysed sediments and fauna excavated from Boh Dambang, Cambodia using a standard multi-proxy integrated dating approach; unlike previous studies above, this allowed them to consider multiple phases of deposition within their site. Red thermoluminescence and OSL, ESR and U/Th dating methods were used, with the resulting age estimates suggesting two depositional phases: the younger ranging from 25 +/- 18 ka with sediment that was last exposed to sunlight between 8 and 7 ka, and an older deposit (~100 +/- 80 ka) that they suggested had eroded from the higher caves in the system and washed down and incorporated into the younger deposit. They also conducted a taphonomic analysis of the assemblage but focusing on isolated teeth to determine taxonomic diversity and abundance. Hyenas and porcupines were considered the main bone accumulators.

While the use of multiple direct dating techniques has increased the chronological resolution of the specific material dated, it has so far failed to provide sufficient clarity on the chronology of depositional events that may be present within breccia deposits. This lack of resolution has impacted efforts to refine or expand biochronological schemes based on Southeast Asian cave deposits. This was highlighted by Zeitoun et al. (2019) who studied the vertebrate remains from the site of Ban Fa Suai II using an atypical multidisciplinary approach to form a palaeoenvironmental reconstruction. The authors provided a systematic critique of the issues and assumptions that prevent a consistent regional bio-chronological framework being developed. The study reappraised numerous sites and taxa in the Southeast Asian regional complex associated with the *Ailuropoda-Stegodon* complex, identifying some key issues; namely, the “admixture of faunas, the inadequacy between chronological data and faunal assemblages, the absence of taphonomic work, and the lack of record of remains” (Zeitoun et al., 2019, p 9). Partly because of the insights provided by dating difficulties and attempts to resolve biostratigraphic schemes, attention has shifted towards more detailed taphonomic studies in Southeast Asia.

Taphonomic Agents

The focus of Schwartz et al. (1994) marked the early focus on the taphonomic agents that alter and transport the cave vertebrate remains in Southeast Asia. Schwartz et al. (1994) undertook a taphonomic analysis of the vertebrate remains excavated from the breccia deposits of Tham Khuyen, Vietnam. Zeitoun et al. (2005) also focused almost solely on the taphonomic history of the mammalian fauna excavated from the Cave of the Monk, Thailand, reporting prolific gnawing of porcupines in several phases and intense weathering as the main taphonomic agents that had modified the assemblage. However, they considered their taphonomic approach as 'modest', and indeed, thorough taphonomic analyses of fossil deposits from cave sites in Southeast Asia remain rare.

Bacon et al. (2008) attempted a detailed analysis of a rich mammalian fauna excavated from Duoi U'oi cave, Vietnam to determine local taphonomy and palaeoenvironment. Their sedimentological analysis showed that the fossiliferous deposits represented several thousand years of accumulation. Due to the significant taphonomic modifications that the assemblage had undergone, namely porcupines and water action, led to the faunal material being far from complete.

A taxonomic and taphonomic analysis of vertebrate assemblages from three sites in Cambodia and Thailand by Frère et al. (2018) attempted to determine how taphonomy, preservation, or hunter-gatherer subsistence behaviours can influence the interpretations of archaeological bone quantification studies. Taphonomic biases were recorded at all three sites. The conventional quantification methods of MNI and NISP were used, as well as a less conventional bone weight (mass) quantification approach, that has previously been favoured in Europe. The quantity of meat from each species was correlated with the fragment count as an indicator of bone biomass. This data suggested the meat supply seemed to be specifically based on large grazers, providing potential insights into primary accumulating agents.

The main issue with taphonomic analyses of breccia deposits is the indurated nature of the breccias. The extraction of incorporated aggregates from breccia samples is particularly destructive (Dominguez-Bella et al., 2012). The properties that make excavation difficult are the very properties that resist forces eroding unconsolidated cave deposits, preventing the removal or destruction of incorporated fossils (Pickle, 1985; Smilg & Berger, 2015). The hardness and density of breccia creates resistance to the natural erosive forces produced when a large volume of low-velocity water is trapped within a considerable area of the cave cross-section (Pickle, 1985). Hydrodynamic processes often cause these erosive episodes (Bosch and White, 2004; Gillieson, 2009; Morley et al., 2017). Local features, of course, dictate this within each cave, such as the stability of adjacent cave walls and the mass transfer within the allogenic waters of the host limestone rock (O'Connor et al., 2017). Methods such as acid preparation and mechanical preparation require the disintegration of the breccia; this manual dissection of the breccia matrix disturbs the internal stratigraphical record of reformation

and destruction that may be preserved at the macroscopic and microscopic levels.

4. Knowledge Gaps and Future Approaches

Even the most recent research suffers from the same problems seen throughout the literature: admixture of faunas, the disconnect between chronological data and faunal assemblages, the absence of taphonomic work, and the lack of record of the positions of the remains in the sediment. Many Southeast Asian caves are hypothesised to be composed of interconnected, active, non-active, and reactivated cavities that underwent multiple major depositional processes, thus the hypothesised agents acquired from direct analysis of aggregates may not provide complete evidence of primary processes due to significant overprinting and time-averaging. Within the last decade, a better understanding of sedimentary processes and stratigraphy in the caves, and the improvement of various dating methods have allowed researchers the opportunity to place the fossil-bearing breccias deposits in a more precise chronological frame. 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 archaeological and palaeontological data.

This review has demonstrated that the mechanisms of vertebrate-bearing breccia deposition in Southeast Asian caves is understudied. There is an urgent need for a multiscale and multidimensional contextual approach that cannot be fulfilled by traditional methods alone. In the field, in terms of dynamics, it is difficult to determine lithostratigraphy or mode of deposition if the deposits seem largely homogeneous, as in Lida Ajer, Sumatra (Westaway et al., 2017; Louys et al., 2017). Conventional methods can be valuable when applicable (e.g. McAdams et al., 2020) but can be particularly destructive to delicate structures and may destroy evidence in the surrounding matrix.

Most previous studies of complex depositional histories of individual deposits within Southeast Asia have been limited, hindering palaeoenvironmental analyses (Lenoble et al., 2006; Louys et al., 2017; Zeitoun et al., 2019). Research in recent years has acknowledged the importance of local taphonomic agents, requiring a more thorough examination of the formation, preservation, and degradation of complex cave sites. Multi-disciplinary analyses of vertebrate assemblages in cave environments has led to a greater focus on the chronology of site depositional phases, which has in turn spurred detailed taphonomic reconstructions. An integrated and multidisciplinary approach to analysing breccia deposits is essential for a holistic interpretation of fossiliferous cave deposits.

Future research should aim to establish an understanding of the fossil distributions through three-dimensional studies of the geometrical relationships of breccia, and the attendant vertebrate remains, combined with microstratigraphic analyses to elucidate the depositional and post-depositional histories of the Southeast Asian breccia records. Significant deterioration created by harsh conditions, such as humid tropical sites, promotes particularly

severe post-depositional alterations of fossil assemblages. The complex diagnostic features of geomorphic processes and site formations in tropical climates, as opposed to the more typical signatures in colder climates, are still poorly understood and make the process of determining the taphonomy and palaeoenvironments complicated (Stephens et al., 2005; Gupta, 2011; Morley et al., 2017). For this reason, one method in isolation cannot reconstruct the environmental history of an archaeological or palaeontological site. As highlighted in our review, combining computed tomography and micromorphology might be one way to provide finer resolution than exists using traditional methodologies.

Computed tomography

A relatively new aspect of palaeontological and geoarchaeological studies involves non-destructive thermal neutron computed tomography (CT) scanning. These scans are a non-destructive digital imaging method that allows for quick three-dimensional reconstructions that have the potential to reveal complex internal structures at the macroscopic and microscopic levels. The exact location, orientation, and direction (imbrication) of clasts, including bones, in the deposit can be measured. These data can reveal various characteristics of a bone assemblage, such as overall composition, frequencies of elements and clasts (Schwarz et al., 2005), and size and alignment of coarse elements that can provide information about depositional environments. Tomographic techniques have been used in palaeontology since the 1980s but have become more widely used in modern research as the equipment is now more readily available, and the costs of analysis have been reduced (Sutton et al., 2014; Rahman & Smith, 2014). Imaging contrast of any sample is determined by the differences in the attenuation properties and detection techniques of each tomographic method; thus, the best applicable method is determined by the preservational and material properties of the object in question (Schwarz et al., 2005).

Computed tomographic imaging of vertebrate-bearing breccia deposits provides evidence of complex breccia formation at the macroscopic level that would otherwise have been destroyed. This method can reveal that seemingly homogeneous deposits retain significant geological, sedimentological, and fossil evidence that can inform the chronology of site formation. Previous use of tomographic analysis to determine the taphonomy of vertebrate-bearing deposits has been limited due to the technique's youth and limited instrument availability, especially for investigations in which there is a complicated nature to the depositional environments. However, there are several recently published examples of palaeontological research using tomography techniques, with high-resolution scanning techniques informing on both the complex breccia formation histories and vertebrate remains at the macroscopic level (e.g., Bevitt (2016) and Louys et al. (2017)).

Louys et al. (2017) used the DINGO tomographic imaging station at the Australian Nuclear Science and Technology Organisation, in Sydney, Australia, to render two false-colour volume-rendered neutron computed

tomography images of a single breccia subsample from Matja Kuru, Timor. These data revealed evidence of the overall composition and frequencies of certain aggregates that correlated to younger, unconsolidated deposits nearby. Reconstructed volume data could further provide preliminary evidence of the agents of concentration that have influenced the faunal assemblage. This isolated study of breccia formation processes through three-dimensional analyses of spatial associations or orientations of clasts and inclusions in a singular deposit does not, however, create a stronger chronological resolution of formation history. A more comprehensive tomographic study of multiple samples across individual cave sites, and across multiple cave sites, may offer a holistic analysis of complex depositional cave environments that have removed all other indication of the complex depositional history of the site.

Tomographic analysis is an excellent method with which to determine sediment distribution and interrelationships of clasts, but it is limited regarding observation of depositional and post-depositional alterations of cave deposits (Louys et al., 2017). Furthermore, such analyses are limited to macro-studies and may not relay crucial microstructural information.

Micromorphology

Micromorphology is a microtaphonomic approach that could be used to determine the alteration processes of fossils and sediments during burial or post-deposition. Micromorphology has previously been used for investigations in which there is a complicated nature to the depositional environments of the cave sites (Stephens et al., 2005; Karkanis & Goldberg, 2010; Estévez et al., 2014; Morley et al., 2017). There is significant potential for the use of micromorphology in palaeontological studies to elucidate taphonomy and palaeoenvironmental history in equivalent complex depositional environments.

The study of microstratigraphy (micromorphology) was a technique first used to study soils by Walter Kubiěna in the early 1930s (Kubiěna, 1938). Micromorphology documents formation processes on a microscopic level, detailing timing and modification of the accumulations (Stephens et al., 2005; Berna et al., 2012; Morley, 2017; Morley & Goldberg, 2017; Morley et al., 2017). Most importantly, sediment and inclusions are analysed while retaining their original associations. As such, Goldberg & Aldeias (2016) define the underlying strategy of micromorphology as using intact samples of cave sediment material to reveal internal geometry and microcontext of incorporated components. This methodology conserves the original integrity of excavated cave deposits, allowing depositional and post-depositional alterations to be observed, that can in turn reveal diagenetic episodes (Goldberg & Berna, 2010; Karkanis & Goldberg, 2010; Macphail & Goldberg, 2010; Morley et al., 2017). It is possible to directly observe sediment breakdown and specific stages of alteration through analysis of micromorphology in thin section samples (Stoops, 2003; Estevez et al., 2014; Morley et al., 2017; Stephens et al., 2017). The climatic and environmental conditions of a cave site reconstructed in this way can be

related to different states of faunal preservation (Stephens et al., 2005; Karkanas & Goldberg, 2010).

Micromorphology has not been a popular technique due to the difficulties in interpreting and describing such detailed evidence (Goldberg & Aldeias, 2016). There has been, however, recent increases in the use of micromorphology in geoarchaeology and palaeoanthropology due to the advances from optical viewing through a petrographic microscope to more sophisticated methodologies such as Fourier Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscope (SEM) (e.g. Morley et al., 2017; McAdams et al., 2020). FTIR measures the absorption rates of a range of infrared radiation wavelengths travelling through organic and inorganic compounds to identify functional groups (Smith, 2011; Margaris, 2014; Berna, 2017). Scanning electron microscopy involves an electron microscope in which a concentrated beam of secondary electrons scans a sample, which can be used to determine surface structural or chemical compositions (Wang & Petrova, 2012).

The method is 'microdestructive' in that sample preparation requires only a tiny amount of sediment to perform the technique and is a quick process that allows for on-site sampling and analysis to provide real-time results and guide further fieldwork (Monnier, 2018). One recent example is the study by McAdams et al., (2020) described above. Micromorphological research revealed features indicative of site depositional history and human occupation in Con Moong Cave, Vietnam that was otherwise unobservable in the field. The in-situ sediments in the cave were homogeneous to the naked eye; however, photomicrographs revealed nodules, faunal voids, phosphatization, and combustion features.

After the initial burial of vertebrate remains, physico-chemical agents can significantly broaden the modifications of any biotic agents or transport mediums. Turner-Walker (2008) state that environments of continually flowing water amplifies dissolution processes in comparison to that of saturated soils. Diagenesis is considerably accelerated in the tropics by humid temperatures and high levels of precipitation (Andrews & Cook, 1985; Fernández-Jalvo et al., 2010; Morley & Goldberg, 2017). Most of Southeast Asia is within the commonly used humid tropical climate classification created by Köppen (1923). The high levels of precipitation in Southeast Asia create poor conditions for the preservation of archaeological and palaeontological material (Andrews & Cook, 1985; Fernández-Jalvo et al., 2010; Morley & Goldberg, 2017). Thus, fossil assemblages in the caves of Southeast Asia are exposed to significant deterioration caused by chemical and physical degradation brought about by the high temperatures and precipitation of the region. This can create a considerable bias in fossil preservation. An example of the degradation that can occur in an organic sample taken from a Southeast Asian cave can be seen in **Figure 3**. This image shows the disparity down the midline of an orangutan tooth from unconsolidated sediments of Ngalau Gupin, western Sumatra. The mesial enamel and root that was exposed and has undergone significantly more deterioration than the buried distal side.

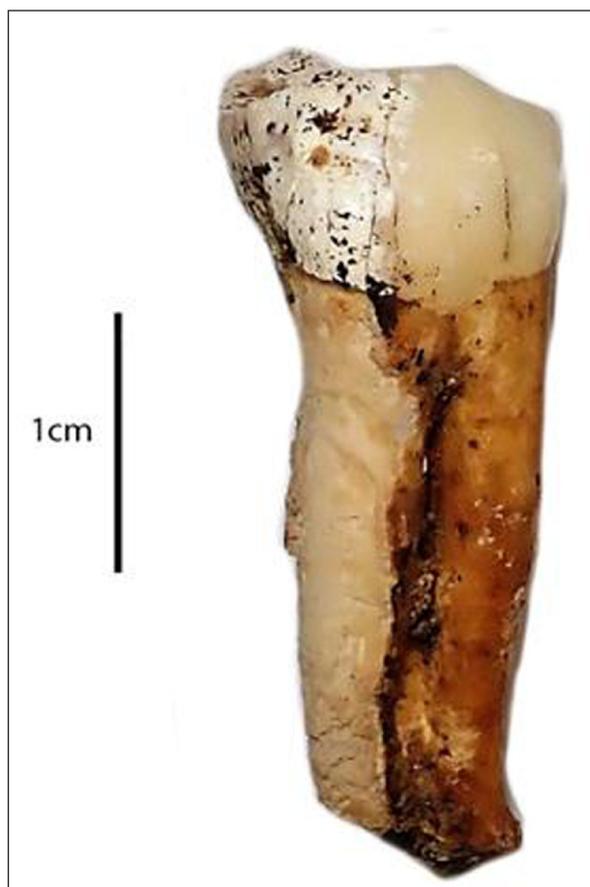


Figure 3: A *Pongo* molar with distinctive weathering on the mesial side, with a distinctive divide down the midline where the tooth was partially buried in the sediments of Ngalau Gupin B, Sumatra.

One example of using micromorphology to identify the processes that can cause this deterioration can be seen in micrograph MM3B, LSU-B from Con Moong cave, North Vietnam. This singular photomicrograph reveals a heavily phosphatised carbonate sand grain (**Figure 4**). This feature is strong indication of considerable microbial action. The characteristics in this photomicrograph are evidence of depositional and erosional processes in a Southeast Asian cave prior to 42 ka. Observing phosphatisation is significant in revealing animal roosting locations, erosion, stabilisation of surfaces and gaps in the stratigraphic record (Morley et al., 2017). Morley et al. (2017, p. 32) also state that phosphatisation may also “signify regions of locally enhanced or reduced radioactivity, which could influence the radionuclide concentrations in sediments and faunal remains sampled for luminescence, electron-spin resonance and uranium-series dating”.

In thin section, several signatures indicate post-depositional alterations of fossil-bearing sediments. Channels and chamber voids allude to bioturbation (Kooistra & Pulleman, 2010; Karkanas & Goldberg, 2010; Estévez et al., 2014), compaction and planar voids represent trampling episodes (Gé et al., 1993; Goldberg & Berna, 2010; Miller et al., 2010), mineral replacement in skeletal tissues or precipitation of phosphates in sediment suggests the dissolution of bone (White & Hannus, 1983; Hedges, 2002; Stoops et al., 2010; Morley et al., 2017), and microscopic

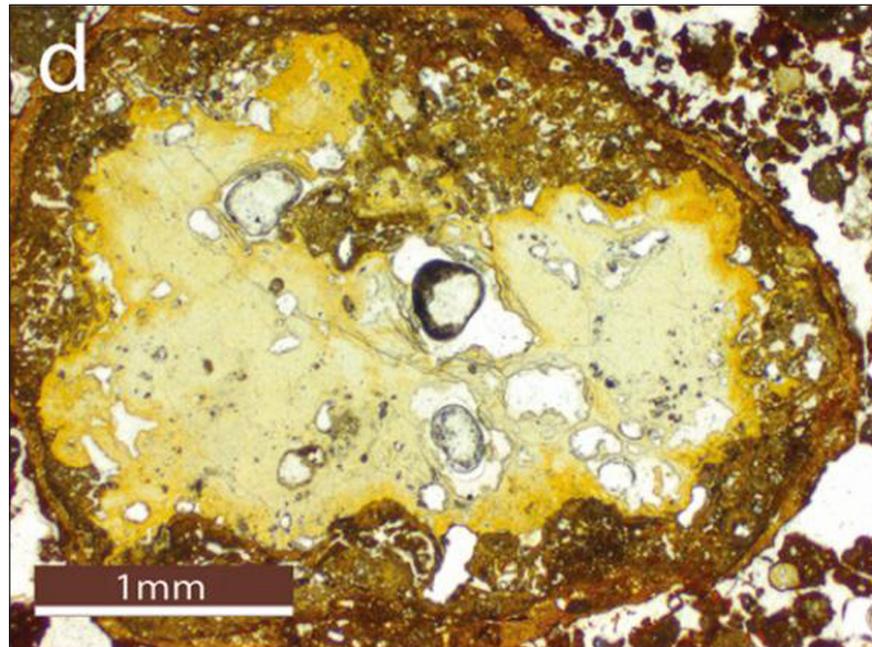


Figure 4: A single photomicrograph (database reference: MM3B, LSU-B) of a heavily phosphatised carbonate grain from Con Moong cave, North Vietnam viewed in plane polarised light McAdams et al.

destruction highlights microbial attacks (Jones, 2000). This methodology has the potential of providing important new insights into site formation processes if applied directly to breccia deposits.

5. Summary

The primary concern of researchers originally studying fossil deposits in Southeast Asia was on the composition of the vertebrate remains. Making faunal comparisons between similar cave sites, museum specimens and common literatures remained the standard approach throughout the 1990s. Other than a few notable exceptions (e.g. Glover, 1979) there was little consideration of the sedimentary context of breccia assemblages until the early 2000s. Understanding the cave fossil deposits suffered due to the biased preservation and excavation strategies, and significant taphonomic alterations. A shift in analyses from just the vertebrate remains to include associated sediments occurred parallel with a shift from faunal analyses to direct dating. The most widely used method of direct dating in cave sites of Southeast Asia began with radiocarbon dating, which continues to be used today where appropriate. For example, O'Connor et al. (2005a) assigned an age to the cultural material in the cave deposits of Pulau Kobroor and Liang Nabulei Lisa in the Aru Islands using radiocarbon dating. While this dating method is the conventional means to determine ages for organic samples from the last 50 ka, the value of radiocarbon dating is often limited in tropical climates due to the increased temperatures and moisture that degrades the bone collagen and plant material (Wood, 2015; Morley, 2017; Becerra-Valdivia et al., 2020).

Throughout the mid- to late 2000s, there was a significant diversification in direct dating approaches made to better constrain the age estimates of the cave sediments and vertebrate remains. At present, common practices

include uranium-series dating, ESR, TL and OSL dating. As the use of these methods has become mainstream, paralleling efforts to refine biochronological schemes, the limitations of direct dating also have become more apparent. All direct dating methods are susceptible to significant risk of time- or habitat-averaging due to natural 'mixing' processes in complex depositional environments such as tropical caves as well as limitation of the techniques themselves. Thus, the standard practice has become to combine several methods to give greater confidence to the results. However, recent research has also highlighted the importance of understanding the modes of accumulation and concentration of the deposits. Nevertheless, while the need to better understand taphonomic processes operating in Southeast Asian caves is recognised, such studies remain comparatively rare.

Part of the problem is that studying indurated breccia deposits is difficult. Nevertheless, comprehensive studies of breccia formation are needed to better understand faunal, archaeological, and palaeoenvironmental histories of complex depositional sites. The progression of the studies considered here has shown a holistic approach to analysing breccia deposits is essential. However, current spatial distribution data collected from cave breccia of Southeast Asia is often limited to two-dimensional assessments, often restricted to the surface of the deposit in the field. Three-dimensional analyses of spatial distribution data using reconstructed volume data can be analysed to assess the spatial location and temporal sequence of sediment layers and inclusions within the breccia laid down during formation, significant evidence in the study of site depositional history and palaeoenvironment. These can be refined with microscopic analyses of the breccia deposits themselves. Such detailed spatial associations of faunal remains and sedimentary structures may provide preliminary evidence of the agents of concentration that

have influenced faunal assemblages incorporated into the breccia.

Additional File

The additional file for this article can be found as follows:

- **Supplementary Information Database.** Method evolution used in the taphonomic analyses of Southeast Asian cave sites. DOI: <https://doi.org/10.5334/oq.75.s1>

Acknowledgements

Sincere thanks to Connor McAdams, Wollongong University for the photomicrographs from the research database for McAdams et al (2019). Thank you to Dr Mike Morley's, Associate Professor, Australian Research Council Future Fellowship FT180100309 & Dr Julien Louys' Australian Research Council Future Fellowship FT160100450. Thank you to the Australian Research Centre for Human Evolution, Griffith University, Brisbane for Ms Holly Smith's Postgraduate & Research Scholarships. Thank you to Kim Newman for your assistance. Thank you to our reviewers for your valuable input.

Competing Interests

The authors have no competing interests to declare.

Authors Contributions

H.E.S. contributed towards the authorship of this review. J.L. & M.W.M. contributed to the editing of this review.

References

- Adams, N.** 2017. Early Pleistocene palaeontology of Westbury Cave, Somerset. *Palaeontology Newsletter*, 94: 79–84.
- Anderson, DD.** 1997. Cave archaeology in Southeast Asia. *Geoarchaeology*, 12(6): 607–638. DOI: [https://doi.org/10.1002/\(SICI\)1520-6548\(199709\)12:6<607::AID-GEA5>3.0.CO;2-2](https://doi.org/10.1002/(SICI)1520-6548(199709)12:6<607::AID-GEA5>3.0.CO;2-2)
- Andrews, P** and **Cook, J.** 1985. Natural modifications to bones in a temperate setting. *Man*, 20(4): 675–691. DOI: <https://doi.org/10.2307/2802756>
- Andrews, P** and **Cook, J.** 1990. *Owls, caves and fossils: predation, preservation and accumulation of small mammal bones in caves, with an analysis of the Pleistocene cave faunas from Westbury-sub-Mendip, Somerset, UK.* Chicago, USA: University of Chicago Press.
- Aslan, A** and **Behrensmeyer, AK.** 1996. Taphonomy and time resolution of bone assemblages in a contemporary fluvial system: The East Fork River, Wyoming. *PALAIOS*, 11(5): 411–421. DOI: <https://doi.org/10.2307/3515209>
- Aubert, M, Brumm, A** and **Taçon, PSC.** 2017. The timing and nature of human colonization of Southeast Asia in the late Pleistocene. *Current Anthropology*, 58(17): s553–566. DOI: <https://doi.org/10.1086/694414>
- Auler, AS, Piló, LB, Smart, PL, Wang, X, Hoffmann, D, Richards, DA, Edwards, RL, Neves, WA** and **Cheng, H.** 2006. U-series dating and taphonomy of Quaternary vertebrates from Brazilian caves. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 240(3): 508–522.
- Bacon, A-M, Antoine, P-O, Huong, NTM, Westaway, K, Tuan, NA, Durringer, P, Zhao, J-X, Ponche, J-L, Dung, SC, Nghia, TH, Minh, TT, Son, PT, Boyon, M, Thuy, NTK, Blin, A** and **Demeter, F.** 2018b. A rhinocerotid-dominated megafauna at the MIS6-5 transition: The late Middle Pleistocene Coc Muoi assemblage, Lang Son province, Vietnam. *Quaternary Science Reviews*, 186: 123–141. DOI: <https://doi.org/10.1016/j.quascirev.2018.02.017>
- Bacon, A-M, Demeter, F, Durringer, P, Helm, C, Bano, M, Long, VT, Thuy, NTK, Antoine, P-O, Mai, BT, Huong, NTM, Dodo, Y, Chabaux, F** and **Rihs, S.** 2008. The late Pleistocene Duoi U'Oi cave in Northern Vietnam: Palaeontology, sedimentology, taphonomy and palaeoenvironments. *Quaternary Science Reviews*, 27: 1627–1654. DOI: <https://doi.org/10.1016/j.quascirev.2008.04.017>
- Bacon, A-M, Demeter, F, Roussé, S, Long, VT, Durringer, P, Antoine, P-O, Thuy, NK, Mai, BT, Huong, NTM, Dodo, Y, Matsumura, H, Schuster, M** and **Anezaki, T.** 2006. New palaeontological assemblage, sedimentological and chronological data from the Pleistocene Ma U'Oi cave (Northern Vietnam). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 230: 280–298. DOI: <https://doi.org/10.1016/j.palaeo.2005.07.023>
- Bacon, A-M, Demeter, F, Schuster, M, Long, VT, Thuy, NK, Antoine, P-O, Sen, S, Nga, HH** and **Huong, NM.** 2004. The Pleistocene Ma U'Oi cave, Northern Vietnam: Palaeontology, sedimentology and palaeoenvironments. *Geobios*, 37(3): 305–314. DOI: <https://doi.org/10.1016/j.geobios.2003.03.010>
- Bacon, A-M, Durringer, P, Westaway, K, Joannes-Boyau, R, Zhao, J-X, Bourgon, N, Dufour, E, Pheng, S, Tep, S, Ponche, J-L, Barnes, L, Blin, A, Patole-Edoumba, E** and **Demeter, F.** 2018a. Testing the savannah corridor hypothesis during MIS2: The Boh Dambang hyena site in southern Cambodia. *Quaternary International*, 464: 417–439. DOI: <https://doi.org/10.1016/j.quaint.2017.10.047>
- Bacon, A-M, Westaway, K, Antoine, P-O, Durringer, P, Blin, A, Demeter, F, Ponche, J-L, Zhao, J-X, Barnes, LM, Sayavonkhamdy, T, Thuy, NTK, Long, VT, Patole-Edoumba, E** and **Shackelford, L.** 2015. Late Pleistocene mammalian assemblages of Southeast Asia: New dating, mortality profiles and evolution of the predator–prey relationships in an environmental context. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 422: 101–127. DOI: <https://doi.org/10.1016/j.palaeo.2015.01.011>
- Barker, G, Barton, H, Bird, M, Daly, P, Datan, I, Dykes, A, Farr, L, Gilbertson, D, Harrisson, B, Hunt, C, Higham, T, Kealhofer, L, Krigbaum, J, Lewis, H, McLaren, S, Paz, V, Pike, A, Piper, P, Pyatt, B, Rabett, R, Reynolds, T, Rose, J, Rushworth, G, Stephens, M, Stringer, C, Thompson, J** and **Turney, C.** 2007. The 'human revolution' in lowland tropical Southeast Asia: the antiquity and

- behavior of anatomically modern humans at Niah Cave (Sarawak, Borneo). *Journal of Human Evolution*, 52(3): 243–261. DOI: <https://doi.org/10.1016/j.jhevol.2006.08.011>
- Bates, K, Falkingham, P, Rarity, F, Hodgetts, D, Purslow, A and Manning, P.** 2010. Application of high-resolution laser scanning and photogrammetric techniques to data acquisition, analysis and interpretation in palaeontology. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38: 68–73.
- Becerra-Valdivia, L, Leal-Cervantes, R, Wood, R and Higham, T.** 2020. Challenges in sample processing within radiocarbon dating and their impact in ¹⁴C-dates-as-data studies. *Journal of Archaeological Science*, 113: 105043.
- Behrensmeyer, AK.** 1975. The taphonomy and paleoecology of Plio-Pleistocene vertebrate assemblages east of Lake Rudolf, Kenya. *Bulletin of the Museum of Comparative Zoology at Harvard College*, 146: 473–578.
- Behrensmeyer, AK and Hill, AP.** 1988. *Fossils in the making: Vertebrate taphonomy and paleoecology*. Chicago Press, University of Chicago Press.
- Berna, F.** 2017. FTIR microscopy. In: Nicosia, C and Stoops, G (eds.), *Encyclopedia of Archaeological Soil and Sediment Micromorphology*. Pondicherry, India: John Wiley & Sons, pp. 411–415. DOI: <https://doi.org/10.1002/9781118941065.ch39>
- Berna, F, Goldberg, P, Horwitz, LK, Brink, J, Holt, S, Bamford, M and Chazan, M.** 2012. Microstratigraphic evidence of in situ fire in the Acheulean strata of Wonderwerk Cave, Northern Cape province, South Africa. *Proceedings of the National Academy of Sciences*, 109(20): E1215–E1220. DOI: <https://doi.org/10.1073/pnas.1117620109>
- Bevitt, J.** 2016. Neutron micro-CT as a non-destructive tool for palaeontology. *Australian Institute of Nuclear Science and Engineering Ltd-Australian Neutron Beam Users Group. Neutron Scattering Symposium*, pp. 29–30.
- Blain, H-A, Bailon, S, Cuenca-Bescós, G, Arsuaga, JL, Bermúdez De Castro, JM and Carbonell, E.** 2009. Long-term climate record inferred from early-middle Pleistocene amphibian and squamate reptile assemblages at the Gran Dolina Cave, Atapuerca, Spain. *Journal of Human Evolution*, 56(1): 55–65. DOI: <https://doi.org/10.1016/j.jhevol.2008.08.020>
- Bogus, M and Crawfis, R.** 2009. Procedural creation of 3D solution cave models. *Proceedings of the IASTED International Conference on Modelling and Simulation*.
- Bosch, RF and White, WB.** 2004. Lithofacies and Transport of Clastic Sediments in Karstic Aquifers. In: Sasowsky, ID and Mylroie, J. (eds.) *Studies of Cave Sediments*. Boston, USA: Springer, pp. 1–22. DOI: https://doi.org/10.1007/978-1-4419-9118-8_1
- Bountalis, AC and Kuhn, BF.** 2014. Cave usage by multiple taphonomic agents: Issues towards interpreting the fossil bearing cave deposits in South Africa. *American Journal of Zoological Research*, 2(4): 55–61.
- Brain, CK.** 1981. *The Hunters or the hunted?: An Introduction to African cave taphonomy*. Chicago, London: University of Chicago Press.
- Celiberti, V, Forestier, H, Auetrakulvit, P and Zeitoun, V.** 2018. Doi Pha Kan, Lampang province, north of Thailand: A new lithic assemblage in the Hoabinhian chrono-cultural context. In: Tan, N. H. (ed.), *Advancing Southeast Asian Archaeology 2016*. Bangkok, Thailand: SEAMEO SPAFA Regional Centre for Archaeology and Fine Arts, pp. 91–99. DOI: <https://doi.org/10.1016/j.jasrep.2019.04.020>
- Curnoe, D, Zhao, J-X, Aubert, M, Fan, M, Wu, Y, Baker, A, Mei, GH, Sun, X-F, Mendoza, R, Adler, L, Ma, S, Kinsey, L and Ji, X.** 2019. Implications of multimodal age distributions in Pleistocene cave deposits: A case study of Maludong palaeoanthropological locality, southern China. *Journal of Archaeological Science: Reports*, 25: 388–399.
- De Bruyn, M, Stelbrink, B, Morley, R, Hall, R, Carvalho, G, Cannon, C, Van Den Bergh, G, Meijaard, E, Metcalfe, I, Boitani, L, Maiorano, L, Shoup, R and Rintelen, T.** 2014. Borneo and Indochina are major evolutionary hotspots for Southeast Asian biodiversity. *Systematic Biology*, 63: 879–901. DOI: <https://doi.org/10.1093/sysbio/syu047>
- De Vos, J.** 1984. Reconsideration of Pleistocene cave faunas from South China and their relation to the faunas from Java. *Courier Forschungsinstitut Senckenberg*, 69: 259–266.
- Dirks, PH, Kibii, JM, Kuhn, BF, Steininger, C, Churchill, SE, Kramers, JD, Pickering, R, Farber, DL, Mériaux, AS, Herries, AI and King, GC.** 2010. Geological setting and age of *Australopithecus sediba* from southern Africa. *Science*, 328(5975): 205–208. DOI: <https://doi.org/10.1126/science.1184950>
- Dirks, PH, Roberts, EM, Hilbert-Wolf, H, Kramers, JD, Hawks, J, Dosseto, A, Duval, M, Elliott, M, Evans, M, Grün, R and Hellstrom, J.** 2017. The age of *Homo naledi* and associated sediments in the Rising Star Cave, South Africa. *Elife*, 6: p.e24231. DOI: <https://doi.org/10.7554/eLife.24231>
- Domínguez-Bella, S, Ramos, J, Bernal, D, Vijande, E, Cantillo, JJ, Cabral, A, Pérez, M and Barrera, A.** 2012. Excavating in breccia: New methods developed at the Benzu Rockshelter. *Antiquity*, 86: 1167–1178. DOI: <https://doi.org/10.1017/S0003598X00048328>
- Drawhorn, GM.** 1994. The systematics and paleodemography of fossil orangutans. Unpublished PhD Thesis, University of California.
- Duringer, P, Bacon, A-M, Sayavongkhamdy, T and Thuy, NTK.** 2012. Karst development, breccias history, and mammalian assemblages in Southeast Asia: A brief review. *Comptes Rendus Palevol*, 11: 133–157. DOI: <https://doi.org/10.1016/j.crpv.2011.07.003>
- Emslie, SD.** 1988. Vertebrate paleontology and taphonomy of caves in Grand Canyon, Arizona (USA). *National Geographic Research*, 4(1): 128–142.

- Esposito, M, Reyss, J-L, Chaimanee, Y and Jaeger, J-J.** 2002. U-series dating of fossil teeth and carbonates from Snake Cave, Thailand. *Journal of Archaeological Science*, 29(4): 341–349.
- Estévez, J, Villagran, XS, Balbo, AL and Hardy, K.** 2014. Microtaphonomy in archaeological sites: The use of soil micromorphology to better understand bone taphonomy in archaeological contexts. *Quaternary International*, 330: 3–9. DOI: <https://doi.org/10.1016/j.quaint.2013.08.007>
- Fairchild, IJ and Baker, A.** 2012. *Speleothem science: from process to past environments*. Hoboken, USA, Wiley. DOI: <https://doi.org/10.1002/9781444361094>
- Farrand, WR.** 2001. Sediments and stratigraphy in rockshelters and caves: A personal perspective on principles and pragmatics. *Geoarchaeology*, 16(5): 537–557. DOI: <https://doi.org/10.1002/gea.1004>
- Farrant, AR and Smart, PL.** 2011. Role of sediment in speleogenesis; sedimentation and paragenesis. *Geomorphology*, 134(1): 79–93. DOI: <https://doi.org/10.1016/j.geomorph.2011.06.006>
- Fernández-Jalvo, Y, Andrews, P, Pesquero, D, Smith, C, Marín-Monfort, D, Sánchez, B, Geigl, E-M and Alonso, A.** 2010. Early bone diagenesis in temperate environments: Part I: Surface features and histology. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 288(1): 62–81. DOI: <https://doi.org/10.1016/j.palaeo.2009.12.016>
- Filoux, A, Wattanapituksakul, A, Lespes, C and Thongcharoenchaikit, C.** 2015. A Pleistocene mammal assemblage containing *Ailuropoda* and *Pongo* from Tham Prakai Phet cave, Chaiyaphum Province, Thailand. *Geobios*, 48(5): 341–349. DOI: <https://doi.org/10.1016/j.geobios.2015.07.003>
- Frère, S, Auetrakulvit, P, Zeitoun, V, Sophady, H and Forestier, H.** 2018. Doi Pha Kan (Thailand), Ban Tha Si (Thailand) and Laang Spean (Cambodia) Animal Bone Assemblages: A New Perception of Meat Supply Strategies for Early Holocene Mainland Southeast Asia? In: Tan, NH (ed.), *Advancing South-east Asian Archaeology 2016*. Bangkok, Thailand: SEAMEO SPAFA Regional Centre for Archaeology and Fine Arts, pp. 100–108.
- Gé, T, Courty, M-A, Matthews, W and Watzetz, J.** 1993. Sedimentary formation processes of occupation surfaces. In: Goldberg, P, Nash, DT and Petraglia, MD (eds.), *Formation processes in archaeological context*. Madison, USA: Prehistory Press, pp. 149–163.
- Gilbertson, D, Bird, M, Hunt, C, McLaren, S, Banda, R, Pyatt, B, Rose, J and Stephens, M.** 2005. Past human activity and geomorphological change in a guano-rich tropical cave mouth: Initial interpretations of the late Quaternary succession in the Great Cave of Niah, Sarawak. *Asian Perspectives*, 44: 16–41. DOI: <https://doi.org/10.1353/asi.2005.0007>
- Gillieson, D.** 2009. *Caves: processes, development and management*. Oxford, Blackwell.
- Glover, IC.** 1979. The effects of sink action on archaeological deposits in caves: An Indonesian example. *World Archaeology*, 10(3): 302–317. DOI: <https://doi.org/10.1080/00438243.1979.9979739>
- Goldberg, P and Aldeias, V.** 2016. Why does (archaeological) micromorphology have such little traction in (geo)archaeology? *Archaeological and Anthropological Sciences*, 10(2): 269–278. DOI: <https://doi.org/10.1007/s12520-016-0353-9>
- Goldberg, P and Berna, F.** 2010. Micromorphology and context. *Quaternary International*, 214(1–2): 56–62. DOI: <https://doi.org/10.1016/j.quaint.2009.10.023>
- Gupta, A.** 2011. *Tropical geomorphology*. Cambridge: Cambridge University Press. DOI: <https://doi.org/10.1017/CBO9780511978067>
- Hall, R.** 2009. Indonesia, geology. *Encyclopedia of Islands*, Univ. California Press, Berkeley, California, pp. 454–460.
- Hanebuth, TJJ, Voris, HK, Yokoyama, Y, Saito, Y and Okuno, JI.** 2011. Formation and fate of sedimentary depocentres on Southeast Asia's Sunda Shelf over the past sea-level cycle and biogeographic implications. *Earth-Science Reviews*, 104(1): 92–110. DOI: <https://doi.org/10.1016/j.earscirev.2010.09.006>
- Hanson, CB.** 1980. Fluvial taphonomic processes: models and experiments. In: Behrensmeyer, AK and Hill, AP (eds.), *Fossils in the Making: Vertebrate Taphonomy and Paleocology*. Chicago: University of Chicago Press, pp. 156–181.
- Hedges, REM.** 2002. Bone diagenesis: An overview of processes. *Archaeometry*, 44: 319–328. DOI: <https://doi.org/10.1111/1475-4754.00064>
- Hedges, REM and Millard, AR.** 1995. Bones and groundwater: Towards the modelling of diagenetic processes. *Journal of Archaeological Science*, 22(2): 155–164. DOI: <https://doi.org/10.1006/jasc.1995.0017>
- Herries, AI, Adams, JW, Kuykendall, KL and Shaw, J.** 2006a. Speleology and magnetobiostratigraphic chronology of the GD 2 locality of the Gondolin hominin-bearing paleocave deposits, North West Province, South Africa. *Journal of Human Evolution*, 51(6): 617–631.
- Herries, AI, Curnoe, D and Adams, JW.** 2009. A multidisciplinary seriation of early *Homo* and *Paranthropus* bearing palaeocaves in southern Africa. *Quaternary International*, 202(1–2): 14–28. DOI: <https://doi.org/10.1016/j.quaint.2008.05.017>
- Herries, AI, Reed, KE, Kuykendall, KL and Latham, AG.** 2006b. Speleology and magnetobiostratigraphic chronology of the Buffalo Cave fossil site, Makapansgat, South Africa. *Quaternary Research*, 66(2): 233–245. DOI: <https://doi.org/10.1016/j.yqres.2006.03.006>
- Howard, AD.** 1964. Processes of limestone cave development. *International Journal of Speleology*, 1: 47–60. DOI: <https://doi.org/10.5038/1827-806X.1.1.8>
- Huchon, P, Le Pichon, X and Rangin, C.** 1994. Indochina Peninsula and the collision of India and Eurasia. *Geology*, 22: 27–30. DOI: <https://doi.org/10.1016/j.yqres.2006.03.006>

- org/10.1130/0091-7613(1994)022<0027:IPATCO>2.3.CO;2
- Ibrahim, YK, Tshen, LT, Westaway, KE, Cranbrook, EO, Humphrey, L, Muhammad, RF, Zhao, J-X and Peng, LC.** 2013. First discovery of Pleistocene orangutan (*Pongo* sp.) fossils in Peninsular Malaysia: Biogeographic and paleoenvironmental implications. *Journal of Human Evolution*, 65(6): 770–797. DOI: <https://doi.org/10.1016/j.jhevol.2013.09.005>
- Jones, B.** 2000. Microbial sediments in tropical karst terrains: A model based on the Cayman Islands. *Microbial Sediments*, pp. 171–178. DOI: https://doi.org/10.1007/978-3-662-04036-2_19
- Karkanas, P and Goldberg, P.** 2010. Site formation processes at Pinnacle Point Cave 13B (Mossel Bay, Western Cape Province, South Africa): resolving stratigraphic and depositional complexities with micromorphology. *Journal of Human Evolution*, 59: 256–273. DOI: <https://doi.org/10.1016/j.jhevol.2010.07.001>
- Klimchouk, A.** 1996. The dissolution and conversion of gypsum and anhydrite. *International Journal of Speleology*, 25(3–4): 21–36. DOI: <https://doi.org/10.5038/1827-806X.25.3.2>
- Klimchouk, AB, Ford, DC, Palmer, AN and Dreybrodt, W.** 2000. *Speleogenesis: Evolution of karst aquifers*. Huntsville: National Speleological Society, Inc.
- Kooistra, MJ and Pulleman, MM.** 2010. Features related to faunal activity. In: Stoops, G, Marcelino, V and Mees, F (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam: Elsevier, pp. 397–417. DOI: <https://doi.org/10.1016/B978-0-444-53156-8.00018-0>
- Köppen, WP.** 1923. *Die klimare der erde, grundriss der klimakunde*. Berlin; Leipzig, Walter de Gruyter & Co. DOI: <https://doi.org/10.1515/9783111491530>
- Koster, EH, Ethridge, FG, Flores, RM and Harvey, MD.** 1987. Vertebrate taphonomy applied to the analysis of ancient fluvial systems. In: Ethridge, FG, Flores, RM and Harvey, MD (eds.), *Recent Developments in Fluvial Sedimentology. SEPM Society for Sedimentary Geology. Rept. 6th Int. Congr. Soil Sci. B*, 241–9. DOI: <https://doi.org/10.2110/pec.87.39>
- Kubiëna, WL.** 1938. *Micropedology*. Ames, Iowa: Collegiate Press, 243.
- Lenoble, A, Zeitoun, V, Laudet, F, Seveau, A and Asa, TD.** 2006. Natural processes involved in the formation of Pleistocene bone assemblages in continental South-east Asian caves: the case of the Cave of the Monk (Chiang Dao Wildlife Sanctuary, Thailand). In: Pautreau, J-P, Coupey, A-S, Zeitoun, V and Rambault, E (eds.), *11th International Conference of the EurASEAA, Bougon, France*. Chiang Mai: Siam Ratana Ltd, pp. 41–50.
- Lerma, JL, Navarro, S, Cabrelles, M and Villaverde, V.** 2010. Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the Upper Palaeolithic Cave of Parpalló as a case study. *Journal of Archaeological Science*, 37(3): 499–507. DOI: <https://doi.org/10.1016/j.jas.2009.10.011>
- Li, G and Zhou, W.** 2015. Karst paleo-collapses and their impacts on mining and the environment in Northern China. In: Doctor, DH, Land, L and Stephenson, JB (eds.), *Proceedings of the Fourteenth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst*. Carlsbad, USA: National Cave and Karst Research Institute, pp. 147–156.
- Long, VT, De Vos, J and Ciochon, RS.** 1996. The fossil mammal fauna of the Lang Trang caves, Vietnam, compared with Southeast Asian fossil and recent mammal faunas: the geographical implications. *Bulletin of the Indo-Pacific Prehistory Association*, 14: 101–109. DOI: <https://doi.org/10.7152/bippa.v14i0.11593>
- Louys, J, Kealy, S, O'Connor, S, Price, GJ, Hawkins, S, Aplin, K, Rizal, Y, Zaim, J, Mahirta, Tanudirjo, DA, Santoso, WD, Hidayah, AR, Trihascaryo, A, Wood, R, Bevitt, J and Clark, T.** 2017. Differential preservation of vertebrates in Southeast Asian caves. *International Journal of Speleology*, 46(3): 379–408. DOI: <https://doi.org/10.5038/1827-806X.46.3.2131>
- Louys, J and Roberts, P.** 2020. Environmental drivers of megafauna and hominin extinction in Southeast Asia. *Nature*, 586: 402–406.
- Lyman, RL.** 1994. *Vertebrate taphonomy*. Cambridge: Cambridge University Press. DOI: <https://doi.org/10.1017/CBO9781139878302>
- Macphail, RI and Goldberg, P.** 2010. Archaeological materials. In: Stoops, G, Vera, M and Mees, F (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam, The Netherlands: Elsevier, pp. 589–622. DOI: <https://doi.org/10.1016/B978-0-444-53156-8.00026-X>
- Maldonado, V, Monteiro, L, Rotti, A, Pereira, C, Araújo Júnior, H and Dos Santos Avilla, L.** 2016. Taphonomic aspects of deer (Mammalia, Cetartiodactyla, Cervidae) remains from a Quaternary cave deposit in Northern Brazil. *Journal of Sedimentary Environments*, 1: 234–248. DOI: <https://doi.org/10.12957/jse.2016.23026>
- Margaris, AV.** 2014. Fourier transform infrared spectroscopy (FTIR): Applications in archaeology. In: Smith, C. (ed.), *Encyclopedia of Global Archaeology*. New York, NY: Springer, pp. 2890–2893. DOI: https://doi.org/10.1007/978-1-4419-0465-2_343
- McAdams, C, Morley, MW, Fu, X, Kandyba, AV, Derevianko, AP, Nguyen, DT, Doi, NG and Roberts, RG.** 2020. The Pleistocene geoarchaeology and geochronology of Con Moong Cave, North Vietnam: Site formation processes and hominin activity in the humid tropics. *Geoarchaeology*, 35(1): 72–97. DOI: <https://doi.org/10.1002/gea.21758>
- McFarlane, DA, Buchroithner, M, Lundberg, J, Petters, C, Roberts, W and Van Rentergem, G.** 2013. Integrated three-dimensional laser scanning and

autonomous drone surface-photogrammetry at Gomantong Caves, Sabah, Malaysia. *Proceedings of the 16th International Congress of Speleology, Borneo*, 2: 317–320.

- Mijares, AS, Détroit, F, Piper, P, Grün, R, Bellwood, P, Aubert, M, Champion, G, Cuevas, N, De Leon, A and Dizon, E.** 2010. New evidence for a 67,000-year-old human presence at Callao Cave, Luzon, Philippines. *Journal of Human Evolution*, 59(2010): 123–132. DOI: <https://doi.org/10.1016/j.jhevol.2010.04.008>
- Miller, CE, Conard, N, Goldberg, P and Berna, F.** 2010. Dumping, sweeping and trampling: Experimental micromorphological analysis of anthropogenically modified combustion features. *Palethnologie*, 2: 25–37.
- Monnier, GF.** 2018. A review of infrared spectroscopy in microarchaeology: Methods, applications, and recent trends. *Journal of Archaeological Science: Reports*, 18: 806–823. DOI: <https://doi.org/10.1016/j.jasrep.2017.12.029>
- Morley, MW.** 2017. The geoarchaeology of hominin dispersals to and from tropical Southeast Asia: A review and prognosis. *Journal of Archaeological Science*, 77: 78–93. DOI: <https://doi.org/10.1016/j.jas.2016.07.009>
- Morley, MW and Goldberg, P.** 2017. Geoarchaeological research in the humid tropics: A global perspective. *Journal of Archaeological Science*, 77: 1–9. DOI: <https://doi.org/10.1016/j.jas.2016.11.002>
- Morley, MW, Goldberg, P, Sutikna, T, Tocheri, MW, Prinsloo, LC, Jatmiko, Saptomo, EW, Wasisto, S and Roberts, RG.** 2017. Initial micromorphological results from Liang Bua, Flores (Indonesia): Site formation processes and hominin activities at the type locality of *Homo floresiensis*. *Journal of Archaeological Science*, 77: 125–142. DOI: <https://doi.org/10.1016/j.jas.2016.06.004>
- Mylroie, JE and Carew, JL.** 1990. The flank margin model for dissolution cave development in carbonate platforms. *Earth Surface Processes and Landforms*, 15(5): 413–424. DOI: <https://doi.org/10.1002/esp.3290150505>
- O'Connor, S and Aplin, K.** 2007. A Matter of Balance: An overview of Pleistocene occupation history and the impact of the Last Glacial Phase in East Timor and the Aru Islands, eastern Indonesia. *Archaeology in Oceania*, 42(3): 82–90. DOI: <https://doi.org/10.1002/j.1834-4453.2007.tb00021.x>
- O'Connor, S, Aplin, K, Pasveer, J and Hope, G.** 2005a. Liang Nabulei Lisa: A late Pleistocene and Holocene sequence from the Aru Islands. In: O'Connor, S and Spriggs, M (eds.), *The Archaeology of the Aru Islands, Eastern Indonesia*. Canberra: ANU Press, pp. 125–162.
- O'Connor, S, Aplin, K, Szabó, K, Pasveer, J, Veth, P and Spriggs, M.** 2005b. Liang Lemdubu, a Pleistocene cave site in the Aru Islands. In: O'Connor, S and Spriggs, M (eds.), *The Archaeology of the Aru Islands, Eastern Indonesia*. Canberra: ANU Press, pp. 171–204.
- O'Connor, S, Barham, A, Aplin, K and Maloney, T.** 2017. Cave stratigraphies and cave breccias: Implications for sediment accumulation and removal models and interpreting the record of human occupation. *Journal of Archaeological Science*, 77: 143–159. DOI: <https://doi.org/10.1016/j.jas.2016.05.002>
- O'Connor, S, Barham, A, Spriggs, M, Veth, P, Aplin, K and St Pierre, E.** 2010. Cave archaeology and sampling issues in the tropics: A case study from Lene Hara Cave, a 42,000 year old occupation site in East Timor, Island Southeast Asia. *Australian Archaeology*, 71(1): 29–40. DOI: <https://doi.org/10.1080/03122417.2010.11689382>
- O'Connor, S and Veth, P.** 2005. Early Holocene shell fish hooks from Lene Hara Cave, East Timor establish complex fishing technology was in use in Island South East Asia five thousand years before Austronesian settlement. *Antiquity*, 79(304): 249. DOI: <https://doi.org/10.1017/S0003598X0011405X>
- Oludare, IM and Pradhan, B.** 2016. A decade of modern cave surveying with terrestrial laser scanning: A review of sensors, method and application development. *International Journal of Speleology*, 45: 71–88.
- Osborne, R.** 2000. Palaeokarst and its significance for speleogenesis. In: Klimchouk, AB, Ford, DC, Palmer, AN and Dreybrodt, W. (eds.) *Speleogenesis, Evolution of Karst Aquifers*. Huntsville, USA: National Speleological Society, pp. 113–123.
- Osborne, R.** 2003. Paleokarst. *Encyclopedia of cave and karst science*. New York: Fitzroy Dearborn, pp. 559–561.
- Palmer, AN.** 1987. Cave levels and their interpretation. *NSS Bulletin*, 49: 50–66.
- Palmer, AN.** 1991. Origin and morphology of limestone caves. *Geological Society of America Bulletin*, 103: 1–21.
- Palmer, AN.** 2001. Dynamics of cave development by allogenic water. *Acta Carsologica*, 30(2): 13–32.
- Palmer, AN.** 2002. Speleogenesis in carbonate rocks. In: Gabrovšek, F (ed.), *Evolution of Karst: From Prekarst to Cessation*. Ljubljana, Slovenia: Založba (ZRC), pp. 43–59.
- Palmer, AN.** 2007. Cave geology and speleogenesis over the past 65 years: role of the National Speleological Society in advancing the science. *Journal of Cave and Karst Studies*, 69(1): 3–12.
- Pickering, C and Byrne, JA.** 2014. The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early career researchers. *Higher Education Research and Development*, 33(3): 534–548. DOI: <https://doi.org/10.1080/07294360.2013.841651>
- Pickle, JD.** 1985. *Dynamics of clastic sedimentation and watershed evolution within a low-relief karst drainage basin, Mammoth Cave Region, Kentucky*. MS Thesis, University of New Mexico.

- Price, GJ, Louys, J, Smith, GK and Cramb, J.** 2019. Shifting faunal baselines through the Quaternary revealed by cave fossils of eastern Australia. *PeerJ*, 6: e6099. DOI: <https://doi.org/10.7717/peerj.6099>
- Rahman, IA and Smith, SY.** 2014. Virtual paleontology: computer-aided analysis of fossil form and function. *Journal of Paleontology*, 88(4): 633–635. DOI: <https://doi.org/10.1666/13-0011>
- Schubert, BW and Mead, JI.** 2019. Paleontology of caves. In: White, WB, Culver, DC and Pipan, T (eds.), *Encyclopedia of Caves*. Third Edition ed. London, UK: Academic Press, pp. 794–805.
- Schwarz, D, Vontobel, P, Lehmann, EH, Meyer, CA and Bongartz, G.** 2005. Neutron tomography of internal structures of vertebrate remains: A comparison with X-Ray Computed Tomography. *Paleontologica Electronica*, 8(2): 30A:1–11.
- Schwartz, JH, Long, VT, Cuong, NL, Kha, LT and Tattersall, I.** 1994. *A diverse hominoid fauna from the Late Middle Pleistocene breccia cave of Tham Khuyen, Socialist Republic of Vietnam*. New York, NY: American Museum of Natural History.
- Setiyabudi, E, Prasthisto, B, Kurniawan, I and Jatmiko, T.** 2018. The early Holocene vertebrate faunas from Seropan Cave, Gunung Sewu, Yogyakarta, Indonesia. *Indonesian Journal on Geoscience*, 5(1): 33–45. DOI: <https://doi.org/10.17014/ijog.5.1.33-45>
- Shukla, D and Sharma, M.** 2018. A new approach for scene-based digital video watermarking using discrete wavelet transforms. *International Journal of Advanced and Applied Sciences*, 5(2): 148–160.
- Smilg, JS and Berger, LR.** 2015. Discovering Hominins – Application of medical Computed Tomography (CT) to fossil-bearing rocks from the site of Malapa, South Africa. *PLoS one*, 10(12): e0145340. DOI: <https://doi.org/10.1371/journal.pone.0145340>
- Smith, BC.** 2011. *Fundamentals of Fourier transform infrared spectroscopy*. Hoboken: CRC Press.
- Steinhorsdottir, M and Håkansson, E.** 2017. Endo- and epilithic faunal succession in a Pliocene–Pleistocene cave on Rhodes, Greece: record of a transgression. *Palaeontology*, 60(5): 663–681. DOI: <https://doi.org/10.1111/pala.12312>
- Stephens, M, Rose, J and Gilbertson, D.** 2017. Post-depositional alteration of humid tropical cave sediments: Micromorphological research in the Great Cave of Niah, Sarawak, Borneo. *Journal of Archaeological Science*, 77: 109–124. DOI: <https://doi.org/10.1016/j.jas.2016.01.015>
- Stephens, M, Rose, J, Gilbertson, D and Canti, MG.** 2005. Micromorphology of cave sediments in the humid tropics: Niah cave, Sarawak. *Asian Perspectives*, 44(1): 42–55. DOI: <https://doi.org/10.1353/asi.2005.0014>
- Stoops, G.** 2003. *Guidelines for analysis and description of soil and regolith thin sections*. Madison, USA: Soil Science Society of America Inc.
- Stoops, G, Marcelino, V and Meers, F.** 2010. *Interpretation of micromorphological features of soils and regoliths*. Amsterdam, The Netherlands: Elsevier.
- Stow, DAV.** 2005. *Sedimentary rocks in the field: A colour guide*. London, Great Britain: CRC Press. DOI: <https://doi.org/10.1201/b15204>
- Suraprasit, K, Jaeger, J-J, Chaimanee, Y, Benammi, M, Chavasseau, O, Yamee, C, Tian, P and Panha, S.** 2015. A complete skull of *Crocota crocota* ultima indicates a late Middle Pleistocene age for the Khok Sung (northeastern Thailand) vertebrate fauna. *Quaternary International*, 374: 34–45. DOI: <https://doi.org/10.1016/j.quaint.2014.12.062>
- Suraprasit, K, Jongautchariyakul, S, Yamee, C, Pothichaiya, C and Bocherens, H.** 2019. New fossil and isotope evidence for the Pleistocene zoogeographic transition and hypothesized savanna corridor in peninsular Thailand. *Quaternary Science Reviews*, 221: 105861.
- Sutikna, T, Tocheri, MW, Morwood, MJ, Saptomo, EW, Jatmiko, Due Awe, R, Wasisto, S, Westaway, KE, Aubert, M, Li, B, Zhao, J-X, Storey, M, Alloway, BV, Morley, MW, Meijer, HJM, Van Den Bergh, GD, Grün, R, Dosseto, A, Brumm, A, Jungers, WL and Roberts, RG.** 2016. Revised stratigraphy and chronology for *Homo floresiensis* at Liang Bua in Indonesia. *Nature*, 532: 366–369. DOI: <https://doi.org/10.1038/nature17179>
- Sutton, M, Rahman, I and Garwood, R.** 2014. *Techniques for virtual palaeontology*. New York, USA: Wiley-Blackwell.
- Tougaard, C, Jaeger, J-J, Chaimanee, Y, Suteethorn, V and Triamwichanon, S.** 1998. Discovery of a *Homo* sp. tooth associated with a mammalian cave fauna of Late Middle Pleistocene age, Northern Thailand. *Journal of Human Evolution*, 35(1): 47–54. DOI: <https://doi.org/10.1006/jhev.1998.0221>
- Tucker, ME.** 2009. *Sedimentary petrology: an introduction to the origin of sedimentary rocks*. Oxford, Great Britain: Blackwell Science.
- Turner-Walker, G.** 2008. The chemical and microbial degradation of bones and teeth. In: Pinhasi, R and Mays, S (eds.), *Advances in Human Palaeopathology*. Chichester: John Wiley & Sons, Ltd, pp. 3–29.
- Verstappen, HT.** 1997. The effect of climatic change on Southeast Asian geomorphology. *Journal of Quaternary Science*, 12(5): 413–418. DOI: [https://doi.org/10.1002/\(SICI\)1099-1417\(199709/10\)12:5<413::AID-JQS324>3.0.CO;2-P](https://doi.org/10.1002/(SICI)1099-1417(199709/10)12:5<413::AID-JQS324>3.0.CO;2-P)
- Voorhies, MR.** 1969. Taphonomy and population dynamics of an early Pliocene vertebrate fauna, Knox County, Nebraska. *Rocky Mountain Geology*, 8(special_paper_1): 1–69. DOI: https://doi.org/10.2113/gsrocky.8.special_paper_1.1
- Wang, W, Potts, R, Baoyin, Y, Huang, W, Cheng, H, Edwards, RL and Ditchfield, P.** 2007. Sequence of mammalian fossils, including hominoid teeth, from the Bubing Basin caves, South China. *Journal of Human Evolution*, 52(4): 370–379.

- Wang, Y** and **Petrova, V**. 2012. Scanning electron microscopy. In: Padua, GW and Wang, Q (eds.), *Nanotechnology Research Methods for Foods and Bioproducts*. Oxford, Great Britain: John Wiley & Sons, pp. 103–126. DOI: <https://doi.org/10.1002/9781118229347.ch6>
- Wei, W, Potts, R, Yamei, H, Yunfa, C, Huaying, W, Baoyin, Y** and **Weiwen, H**. 2005. Early Pleistocene hominid teeth recovered in Mohui cave in Bubing Basin, Guangxi, South China. *Chinese Science Bulletin*, 50(23): 2777–2782. DOI: <https://doi.org/10.1007/BF02899650>
- Westaway, KE, Louys, J, Awe, RD, Morwood, MJ, Price, GJ, Zhao, JX, Aubert, M, Joannes-Boyau, R, Smith, TM, Skinner, MM, Compton, T, Bailey, RM, Van Den Bergh, GD, De Vos, J, Pike, AWG, Stringer, C, Saptomo, EW, Rizal, Y, Zaim, J, Santoso, WD, Trihascaryo, A, Kinsley, L** and **Sulistiyanto, B**. 2017. An early modern human presence in Sumatra 73,000–63,000 years ago. *Nature*, 548 (7667): 322–325. DOI: <https://doi.org/10.1038/nature23452>
- Westaway, KE, Morwood, MJ, Roberts, RG, Rokus, AD, Zhao, J-X, Storm, P, Aziz, F, Bergh, GVD, Hadi, P, Jatmiko** and **De Vos, J**. 2007. Age and biostratigraphic significance of the Punung rain-forest fauna, east Java, Indonesia, and implications for *Pongo* and *Homo*. *Journal of Human Evolution*, 53(2007): 709–717. DOI: <https://doi.org/10.1016/j.jhevol.2007.06.002>
- White, EM** and **Hannus, LA**. 1983. Chemical weathering of bone in archaeological soils. *American Antiquity*, 48(2): 316–322. DOI: <https://doi.org/10.2307/280453>
- Wood, R**. 2015. From revolution to convention: The past, present and future of radiocarbon dating. *Journal of Archaeological Science*, 56: 61–72. DOI: <https://doi.org/10.1016/j.jas.2015.02.019>
- Woodcock, NH** and **Mort, K**. 2008. Classification of fault breccias and related fault rocks. *Geological Magazine*, 145(3): 435–440. DOI: <https://doi.org/10.1017/S0016756808004883>
- Worthy, TH** and **Holdaway, RN**. 1994. Quaternary fossil faunas from caves in Takaka Valley and on Takaka Hill, northwest Nelson, South Island, New Zealand. *Journal of the Royal Society of New Zealand*, 24(3): 297–391. DOI: <https://doi.org/10.1080/03014223.1994.9517474>
- Zeitoun, V, Chinnawut, W, Arnaud, L, Bochaton, C, Burdette, K, Thompson, J, Mallye, J-B, Frère, S, Debruyne, R, Antoine, P-O, William, JR** and **Prasit, A**. 2019. Dating, stratigraphy and taphonomy of the Pleistocene site of Ban Fa Suai II (Northern Thailand): Contributions to the study of paleobiodiversity in Southeast Asia. *Annales de Paléontologie*, 105(4): 275–285. DOI: <https://doi.org/10.1016/j.annpal.2019.03.005>
- Zeitoun, V, Seveau, A, Forestier, H, Thomas, H, Lenoble, A, Laudet, F, Antoine, P-O, Debruyne, R, Ginsburg, L, Mein, P, Winayalai, C, Chumdee, N, Doyasa, T, Kijngam, A** and **Nakbunlung, S**. 2005. Découverte d'un assemblage faunique à *Stegodon*–*Ailuropoda* dans une grotte du Nord de la Thaïlande (Ban Fa Suai, Chiang Dao). *Comptes Rendus Palevol*, 4(3): 255–264. DOI: <https://doi.org/10.1016/j.crvp.2004.11.013>

How to cite this article: Smith, HE, Morley, MW and Louys, J. 2020. Taphonomic Analyses of Cave Breccia in Southeast Asia: A Review and Future Directions. *Open Quaternary*, 6: 13, pp. 1–22. DOI: <https://doi.org/10.5334/oq.75>

Submitted: 17 October 2019

Accepted: 26 October 2020

Published: 14 December 2020

Copyright: © 2020 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See <http://creativecommons.org/licenses/by/4.0/>.

]u[

Open Quaternary is a peer-reviewed open access journal published by Ubiquity Press.

OPEN ACCESS 