Helictite, (2017) 43**:** 15-31

Unusual caves and karst-like features in sandstone and conglomerate in Thailand

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Abstract

Caves are common, significant and widespread in Thailand; over 5,000 are recorded. Probably no other country has a closer human association with caves, largely based on Buddhist occupation, traditions and culture. About 90% are in limestone, but about 400 sites in sandstone are known from northeast Thailand, most are of significance to local communities although of limited scientific or speleological significance. A number known to contain running water are discussed in the context of favourable bedding planes or inceptions and other characteristics. Numerous authors have demonstrated that limestone caves develop along a restricted number of bedding planes within a limestone series but less discussion has occurred about the initiation and development in sandstone and similar non-carbonate caves. Comparisons are drawn with similar caves, karst-like and ruiniform features in India, Czech Republic, Australia and elsewhere, a number of which have received little exploration and research attention until recently. Although advances have been made in the last 25 years, sandstone terrains still remain insufficiently studied.

Prefatory remarks

In 1993 Robert Wray addressed the 19th Biennial Conference of the Australian Speleological Federation in Launceston, Tasmania (Wray 1993). His paper was "Solutional Landforms on Silicates: largely ignored or largely unrecognised?" and commenced:

> *The long held belief that the formation of karst, both the small-scale features superimposed upon a landscape, and the large scale landscapes themselves, can only develop upon relatively water soluble carbonate rocks has only recently been seriously questioned. A terrain may be karstic* sensu stricto *despite a lack of subsurface drainage if solution of bedrock matrix or cement has been critical in the development of the landscape ... given the appropriate environmental conditions, almost any rock can be modelled to karst forms ... This notion challenges the classic view of karst formation being unconditionally restricted to 'soluble' rocks.*

In the years following, Robert earned his PhD from the University of Wollongong with a thesis entitled "Solutional landforms in quartz sandstones of the Sydney Basin" (Wray 1995). He conducted international research and reviews, culminating in updated global reviews of solutional weathering processes and forms in quartz sandstones and quartzites (Wray 1997a; Wray & Sauro 2017). As Wray observed:

> *... limestone and similar highly soluble rocks were long believed the sole host for large karst drainage systems ... Quartzose caves and dolines are similar in size, though, to the vast majority of smaller limestone caves and dolines, and are thus significant, and often very impressive, sandstone karst features.*

Northern Australia possesses vast areas of quartz sandstones, some of which have unusual sandstone cavern systems. Along with their other co-authors, Ken Grimes and Robert Wray prepared an excellent overview of karst-like features in this region (Grimes and others 2011; Jennings 1979) which will be discussed in the context of some in Thailand. Regrettably, Ken Grimes and Robert Wray both died recently (White 2016; Houshold 2017). Ken had a 40-year professional geological interest in pseudokarst, Robert had sandstone landforms as his primary research interests, and in 1997 they contributed neighbouring papers in *Cave and Karst Science* (Wray 1997b; Grimes 1997). Our small contribution in this volume recognises the life of two of Australia's most significant karst scientists.

Introduction

Thailand lies at the eastern edge of one of the world's major structural zones, marking a continental plate boundary where subduction of the Indian Oceanic subplate has occurred at the western edge of the Southeast Asian continental subplate. The geology may thus be regarded as resulting from a series of adjustments to compressive forces from the west in Myanmar acting upon the resistant, stable block (the Indochina plate) immediately to the east in Thailand, Laos, Vietnam and Cambodia. Limestone karst occurs widely along the entire length of western Thailand from the Shan State border with Myanmar to Malaysia, and in north central Thailand immediately east of the Chao Phraya Basin, closely abutting immediately west of the boundary of the Khorat Plateau. The limestones are characterised by Ordovician, Permian, Jurassic and Cretaceous sequences.

Northeastern Thailand encompasses about 400 km by 400 km, mostly 100-500 m in altitude but rising to over 1,600 m, comprising primarily the Khorat Plateau, encircling a geologically stable region made up predominantly of fairly flat-lying terrestrial and marine sedimentary rocks of Mesozoic Age. Some Tertiary and Quaternary volcanic rocks occur along the southern boundaries of the Khorat Plateau. Known as 'Isaan', the Khorat Plateau region is generally more arid and less developed than most of Thailand, and is often covered with low scrub or brush. It is characterised by widespread sandstones, conglomerates, siltstones and lime conglomerates of the Lower Cretaceous to Upper Jurassic Khorat Group.

Caves are common, significant and widespread in Thailand; probably no other country in the world has a closer human association with caves (Dunkley 1995; Vogt 2013). The origins of the Buddhist connection with such speleologically and culturally significant features were described by Dunkley (1995, pp. 19-22) and Munier (1998), while a more recent travel compendium (Vogt 2013) described and photographed their attraction to westerners. Caves associated with the spread of Buddhism in Thailand have been used for at least 1,500 years, spreading from the south, and at least 500, and probably as many as a thousand, such spaces have continuing direct significance and contemporary meaning to the community, ranging from whole underground temples to individual representations of the Buddha in remote passages, and perhaps down to a few candles at a shrine (Figs. 1, 2).

Fig. 1. Rock shelters traditionally sheltered Buddhist monks, who could not ask for accommodation in villages, which donate food. They thereby discovered many caves and lived in some.

Fig. 2. Most "forest monks" used only bare platforms for accommodation and first located many caves. Many still use caves for meditation.

Many are quite small, but most are of considerable local cultural, religious and historical significance, especially to Buddhism, and are treated as focal points for quite large community gatherings, religious observances and spiritual relief, as quiet places of meditation for monks, and in many cases actual living quarters. To that extent they are called caves ('tham') by the community, using the term as a convenient toponymic reference, although the word is sometimes used loosely in the case of sandstone caves and shelters (Figs. 3, 4).

Fig. 3. Tham Pha Mong (Mukdahan) is a typical roofed-over cave used by a small group of 'forest monks'. Several kilometres from the nearest village, this one has been greatly improved by community donations.

The first author of the present paper was consulted by Robert Wray in 1996 in a minor capacity, regarding certain unusual karst-like features in central Thailand, and all three authors have conducted extensive continuing exploration, documentation and field work in the caves and sandstone country of northeast Thailand for over 20 years. Over 400 sites are known from northeastern Thailand, mostly in sandstone and related formations, and not yet well documented. In eastern Thailand particularly are a significant

Fig.4. The most elaborate cave temples like Tham Sumontha Phaowana (Udon Thani) include in this case a large visitor car park and a helicopter pad.

of conglomerate, lime conglomerate and conglomeratic sandstone, with corresponding hydrologic systems grading from wholly or partly karstic to nonkarstic.

The bulk removal of silica and lime – the 'flushing' rate – is critically dependent not only on solubility and kinetics, but also on the rate at which water moves through the rock. The purpose of this paper is to draw attention to several such active sites in Thailand.

number of the so-called 'forest monks' living in or attached to caves, sometimes alone. Ellis (2017a) has catalogued over 5,000 sites in the country, releasing well-illustrated catalogues with numerous maps on a provincial basis, and is a highly recommended source of documentation, most recently Ellis (2017b) dealing with the speleology of Eastern Thailand.

Sandstone caves

Caves in sandstone and conglomerate are scattered widely in many small areas across the world, albeit in smaller numbers compared to limestone and similar more soluble rocks. Very few sandstone caves have been reported from western Europe, for example, though somewhat more from the sandstone landscapes of Poland, the Czech Republic, Turkey (Değirmenci and others 1994) and further afield in South Africa and Venezuela. Northern Australia possesses vast areas of quartz sandstones, some of which have unusual sandstone cavern systems (Grimes and others 2011, Jennings 1979). Gulden (2017) maintains an international catalogue of the longest and deepest caves in sandstone, quartzite and conglomerate, the most extensive in sandstone and quartzite measuring 18 km, the longest in conglomerate being even longer, 58 km.

Many geologic formations are mixtures of beds or packages of beds of clastic and soluble rocks, grading in the case of eastern Thailand from mostly sandstone sequences to interbeds, often quite thin,

Active stream caves and karst-like features

Tham Din Phieng, Nong Khai Province

Wat Tham Din Phieng (also called Wat Tham Si Mongkhon) (NK0007, 17°57'39.13"N, 102°18'07.92"E) is located in Sangkhom District, Nong Khai Province, Northeast Thailand, near the village of Ban Dong Tong (*wat* = temple, *tham* = cave) (Dunkley 2011). Visited in 1938 by a travelling forest monk Luangphu Hom, it was extended since 1960 by Luang Song who oversaw building of a hall. It is listed as NK0007 in the catalogue of M. Ellis who first made a speleological visit with T. Bolger in 2009. A modest donation to the wat is expected of visitors, and a small refreshment shop has recently appeared. Geological maps suggest the cave is in sandstone quartzite probably of the Early Cretaceous Sao Khua Formation of the Khorat Group, consisting predominantly of sandstone with some siltstone, and lime conglomerate and possibly punching through to the more resistant Phu Phan Formation encountered in the cave. Of Jurassic and Cretaceous age, the Khorat Group outcrops widely throughout Northeast Thailand, almost encircling the Khorat Plateau on the south and west, and along much of the 500 km length of the Phu Phan Range in the north.

The cave is only 4 km downstream from a prominent low escarpment to the west separating the Khorat Group, which dips about 15° to the east, closely equivalent to the drainage from the cave to a rising 200 m away. The cave is advertised along nearby roads, attracts a modest flow of regional visitors, is electrically lit and has featured on Bangkok television programs despite its relative isolation (Figs. 5, 6). The site is Buddhist community property, and as with numerous sandstone caves in the region, the cave and associated sacred rocks and some karst-like morphologies (sometimes artificial) form an integral part of Buddhist traditions as well as providing a focus for religious ceremonies.

Fig. 5. Entrance adjacent to wat, Tham Din Phieng showing modern additions.

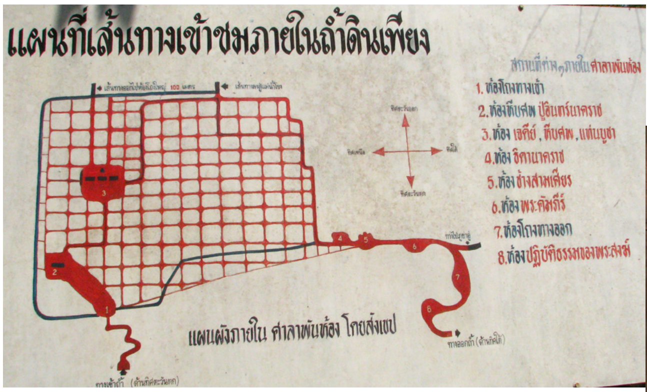

Fig. 6. Diagrammatic sketch outside entrance, Tham Din Phieng.

Above the entrance, for example, a gold-painted *naga* (sacred snake) appeared three or four years ago as tourist income increased, sited to protect the cave (the *naga* is a mythical creature, usually resembling a hooded cobra, believed to guard the border between the human world and the netherworld, often living underground, and frequently depicted in Thai folklore as mythical serpent-like creatures, and at wats where they bring rain and good crops) (Fig. 7). In NE Thailand, particularly, it is believed by locals to live in the Mekong River or estuaries. The cement steps up to and into numerous caves are traditionally flanked by a guarding *naga*. There are a few small Buddhas in the first chamber of Tham Din Phieng and more in a monk's retreat further inside.

Fig. 7. Monk at entrance to Tham Din Phieng.

Cave Description

A small stream sinks in its bed upstream of a shallow 4 m deep doline, cemented at the base for visitors. Within 20 m of the cave entrances a few shallow sandstone collapse features were examined, evidencing on-going subsurface excavation. Steps then lead down about 4 m from the small entrance where, after a narrow triangular section with knee deep water, the cave opens into a small chamber containing a few small images of Buddha. Adjacent to this chamber several rock slabs have detached from nearby walls, suggesting ongoing erosion (Figs. 8, 9). To the east and south an extensive network of maze passages is then encountered, encompassing an area about 60 x 40 m and totalling over 500 m of passages. The passages develop between two harder beds in a calcareous coarse bed about 1.5-2 m thick, liberally furnished with coarse grained, unsorted conglomerate pebbles up to 2-3 cm in diameter (Fig. 10). Smoothly planed maze passages are typically 1-2 m high and usually narrower, some partially blocked by back-flooding and breakdown. There is clear evidence of wet

Fig. 8. Characteristic network maze passages, Tham Din Phieng (Terry Bolger).

Fig. 9. Side passages at 1-2 m intervals in maze section, Tham Din Phieng.

Fig. 10. Typical lime conglomerate wall, Tham Din Phieng.

season flooding throughout and in profile the maze passages appear smoothly epiphreatic. Although their combined surface catchment is only 2-3 sq.km., two small streams flow through the cave, joining in the maze section to a narrow, wet and increasingly low crawl. The conditions support Palmer (1975) who concluded that concentrated, highly variable floodwater recharge, especially through sinking streams, tends to promote maze caves. Such caves require simultaneous enlargement of many competing paths, achieved by water with either a steep hydraulic gradient and/or short flow paths from where solutionally active water first encounters soluble rock; specific patterns being controlled by the mode of groundwater recharge and by local structural conditions. Periodic floodwaters delivered by allogenic recharge can pond in such caves under pressure, injecting water into surrounding openings and enlarging them all simultaneously (Fig. 11).

The western passage is low and may follow a dip or strike slope of about 2-3° on top of the harder underlying bed, where it displays small-scale, presumably calcitic gours (Fig. 12). The junction of the two streams suggests possible ponding by the still-aggressive water, thereby promoting mixture corrosion, and their junction could itself promote additional solution. Further, a slight change in passage orientation close to the junction of the two streams suggests minor faulting, and possibly has directed minor seepage and mixture corrosion.

Four or five risings are recorded in the valley below a rubber plantation, up to 20 m lower than the entrances. Depending on outflow, one is just large enough to enter for a few metres; another has a short shaft to running water, and two more are seasonal risings in tributaries further upstream to the south at about the elevation of the cave entrance. These may represent successive rising wet-season levels of water temporarily impounded within the cave.

Numerous large spiders (possibly *Sinopoda* sp. (Sparassidae) Peter Jäger, pers. com.) and other biota have been encountered in the cave (Figs. 13, 14). At the time of a visit in 2012 at the passage leading east of the maze, just past the junction of the streams, some cave-adapted bioluminescent creatures on silk or similar lines were encountered. A poor photograph was obtained of the site showing glow along each line. The location in a 1 m high wet passage was certainly subject to wet-season

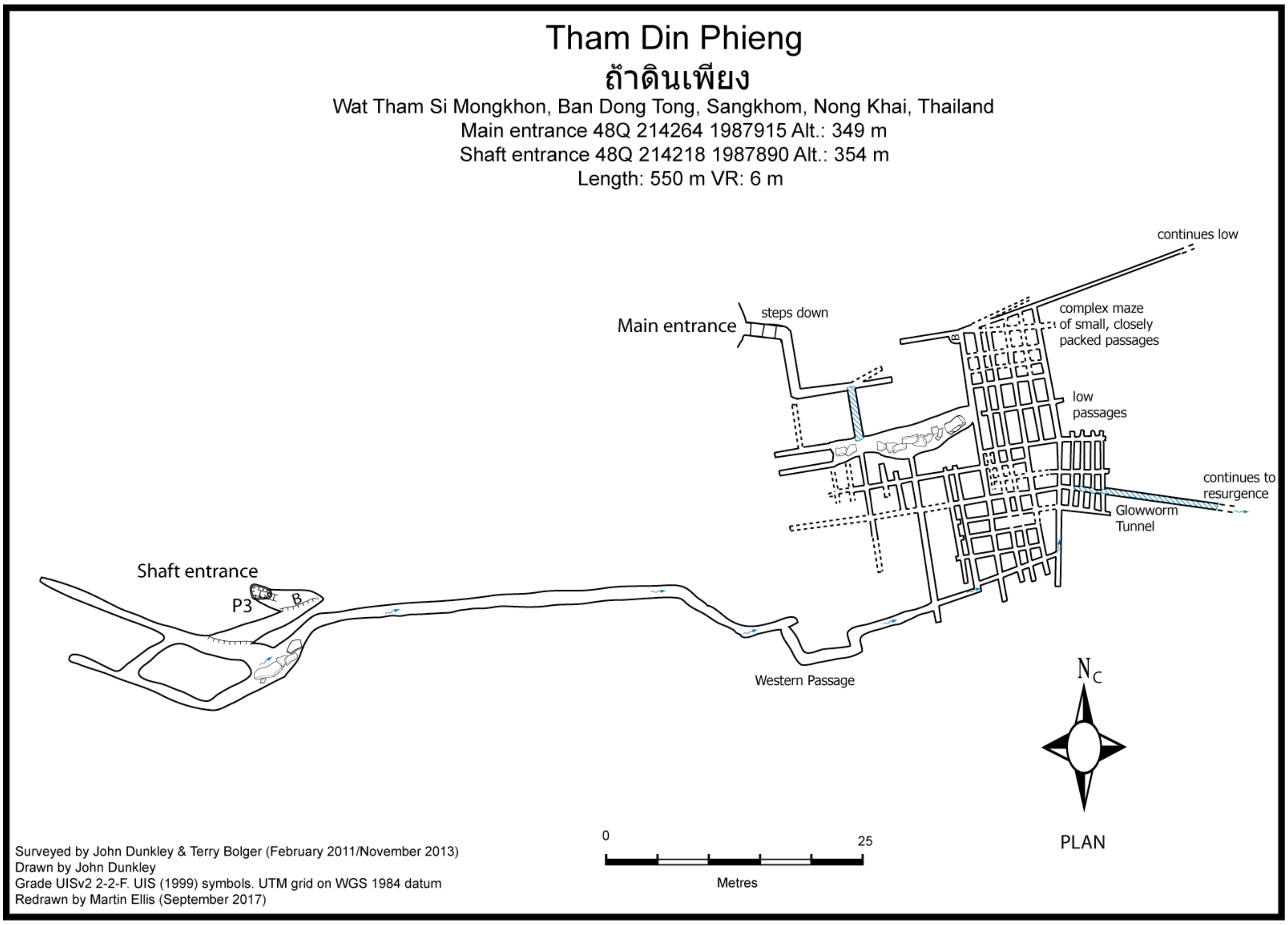

Fig. 11. Plan of Tham Din Phieng (John Dunkley, Martin Ellis).

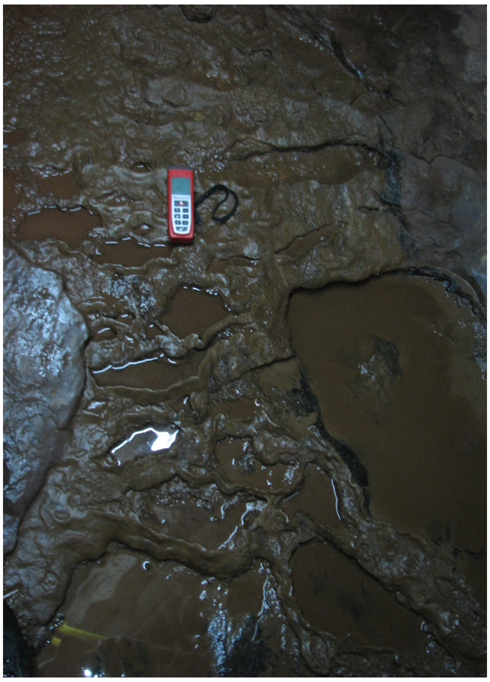

Fig. 12. Small calcitic gours on sandstone passage floor, Western Passage, Tham Din Phieng.

Fig. 13. Small spider colony Tham Din Phieng.

flooding. David Merritt (School of Biological Sciences, University of Queensland, pers. comm.) thinks these may be species of Keroplatinae, perhaps *Chetoneura*, recorded as a troglobiont with vertical lines but is not bioluminescent and is found in many parts of Asia. Unfortunately they were not encountered on a further visit, so the question of bioluminescence remains; because of the electric light and general disturbance from visitors they may have retreated into more remote passages (Fig. 15) The familiar glowworm of Australia and New Zealand *(Arachnocampa)* is the only recorded species exhibiting all three of cave adaptation, hanging lines to trap prey, and bioluminescence.

At the far end a dark, barred private monk's retreat can be seen (very typical of Thai caves),

*Fig. 14. Large spider (*Sinopoda *sp.?), Tham Din Phieng (Terry Bolger).*

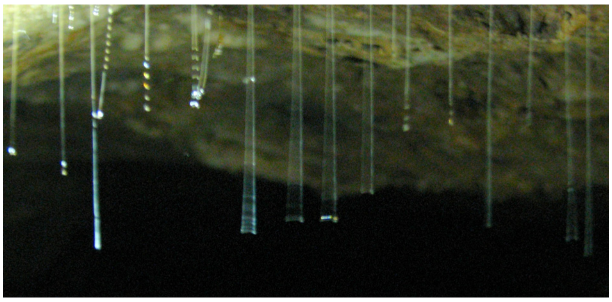

Fig. 15. Bioluminescent glowworms (?) above stream, Tham Din Phieng.

near which a collapse chamber leads upwards to an exit ladder. Within 20 m of the cave entrances a few shallow collapse features were examined, evidencing on-going subsurface excavation.

Crevice caves and karst of Phu Hin Rong Kla National Park, Phitsanulok Province

Phu Hin Rong Kla National Park (307 sq.km) 17°00’25.73”N, 100°59’20.73”E is a prominent plateau mainly in Nakhon Thai District, Phitsanulok Province of central Thailand, rising abruptly over 1,000 m from surrounding farmland and extending eastwards into Loei and Phetchabun provinces, surrounded on the east and west by steep escarpments. Geologically the Khorat Group dominates with a layer of Phu Phan Formation on top in places. This layer gradually slopes down to the north where the Khok Kruat Formation overlies it. Parts of the plateau have thin laterite soils but in the area discussed much is essentially bare.

Crevice caves and karst are narrow features of natural origin, mostly developed on or near cliffs or steep slopes, developed in quartzitic sandstone in the case of Phu Hin Rong Kla, but local terminologies are common in other rocks (see, for example, Halliday (2004) who identified 26 English language synonyms in the literature, describing varying genetic processes, while not including giant grikes or foreign terms such as kluftkarren).

The crevice karst occurs at a high point on the plateau, at an elevation of 1,100-1,250 m, characterised by long, narrow rectilinear widened cracks or networks of natural origin, possibly produced by stresses in the earth’s crust, and running parallel to the western escarpment on a slope about 3-5° to the northwest. Dissolution is not the major agent in forming such caves, but can help enlarge crevices originally formed by mechanical processes from a combination of processes (Figs. 16, 17). The guiding fractures are typically steeply inclined to vertical with irregular floors formed of fallen rocks, soil and vegetal debris. The crevices are sub-parallel, undercut and well vegetated, trending SSE to NNW down a slope of 3-5° and

Fig. 16. One of many crevice caves, Lan Hin Taek.

Fig. 17. Deep crevice cave about 1m wide, 15+m deep, compare with sketch (Fig. 19).

totalling a few kilometres (Fig. 18). Typically separated by closely spaced joints 10-12 m apart, each rift is from 5-15 m deep - some reaching 25-30 m vertically - with most usually less than a metre wide, widening downwards before narrowing again, and leading drainage down dip to the sharp edge of the plateau. The features have not been well known until recently and are named Lan Hin Taek and Lan Hin Pum. During communist insurrections in the 1970s the caves were used by insurgents for shelter against aerial bombardment, and interpretation trails can be visited, including to caves.

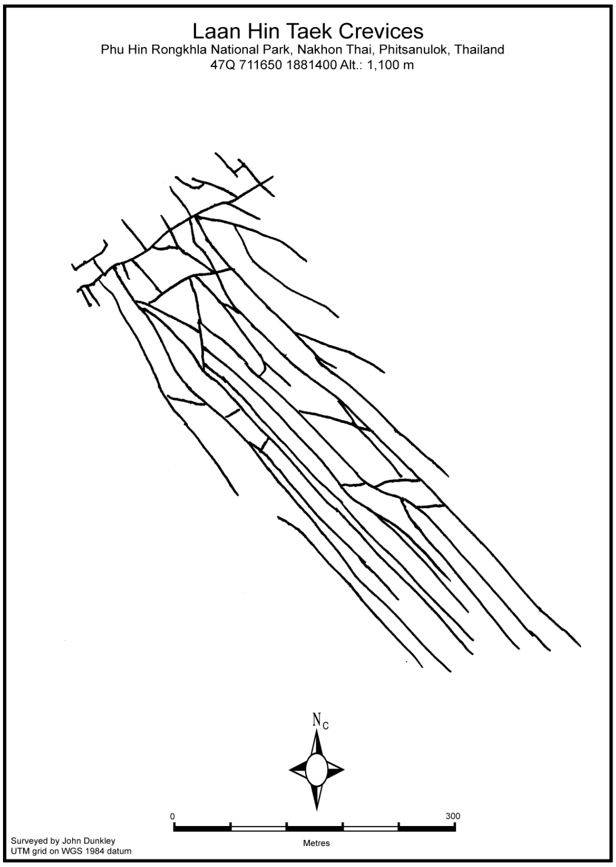

Fig. 18. Sketch of Lan Hin Taek crevices (John Dunkley, Martin Ellis).

A form of giant grikes, they were first described professionally by Odell (1985), who implied that the features were in limestone and used the Slavic term 'bogaz'. J. Dunkley visited in 1991 and recognised the host rock as quartzitic sandstone, as did Doerr (2000). Embedded pebbles are sized up to 4 cm, well rounded and of chert and quartz. The formation was a result of deposition from a braided stream, but cross-bedding is hard to discern.

Two main exposures of the feature are readily accessible to visitors. Lan Hin Taek has more developed crevices physically, covering an area of about 700 m x 200 m wide, the total length of accessible rifts possibly totalling several kilometres. Lan Hin Pum is in two sections separated by low surface vegetation, each approximately 200 x 200 m. Several small caves occur within the crevices but few have been visited, the presence of some being inferred or observed from above. The crevices probably act as refugia for a variety of sheltered vegetation and biological communities. During the wet season water can be heard traversing the crevices (Figs. 19, 20).

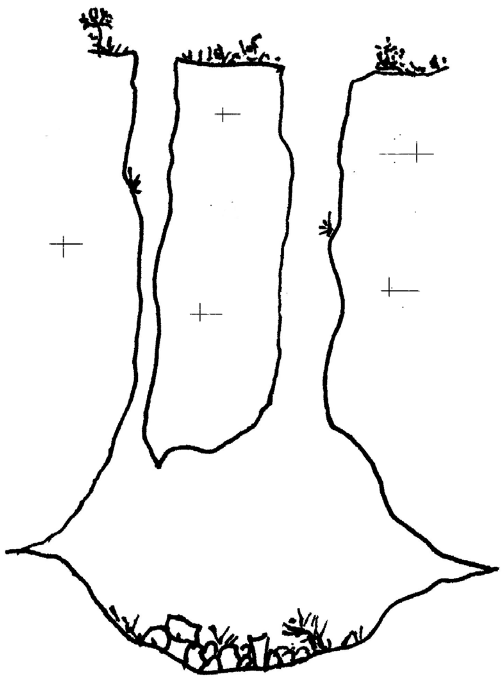

Fig. 19. Sketch of typical crevice cave, Lan Hin Taek (after Odell) (Jeanette Dunkley).

Fig. 20. Vegetation at base of crevice, Lan Hin Taek.

There are suggestions that piping may be a factor in developing this form of karst; certainly cross-sections suggest they widen at depth, but this seems very unlikely. Others have suggested pressure relief because of its location adjacent to a steep escarpment. There is little evidence of this in the field but it may be a factor in the development of Air Raid Shelter No. 1 Cave (below). Odell (1985) supported the early development of very thin solutional lineaments at depth, followed by gravitational or solutional removal of material downwards. It seems much more likely that the crevices are simply and primarily karst-like features enlarged *in situ* by on-going mechanical and solutional activity, as with giant grikes or kluftkarren, and capable of removing debris (Fig. 21). Morphologically similar but more rugged surface karst in dolostone occurs in Judbarra/ Gregory National Park and elsewhere in northern Australia where numerous caves have in time degraded into an assemblage of karst: giant grikes, ruiniform and karst corridors (Grimes 2012).

Fig. 21. "Bollards", Lan Hin Pum.

Meandering surface channels (runnels) similar to solution pans (kamenitsa) in limestone occur, along with other karren features similar to rillenkarren. Rundkarren, commonly 50-500 mm deep and wide and separated by rounded ridges are common. Such features are usually accepted as being created below superficial soil material or plants, which may explain its occurrence in some adjacent thinly vegetated areas such as between Lan Hin Pum and Lan Hin Taek. Similar features have been noted by J. Dunkley in several part of eastern Thailand, along with polygonal crack patterns near the base of such rocks. Doerr (2000) described surface features he termed 'bollard-like rocks', pedestal-shaped rocks up to 0.8 m high, but it is difficult to distinguish these from forms of rundkarren (Figs. 22, 23). Nearby a field of pentagonal and hexagonal cracking is exposed, probably not of solutional origin, more likely of tensile stress cracking (Fig. 24).

Air Raid Shelter Cave No. 1 (PS0038, 16°59'41.31"N, 101°00'48.92"E) (so named after its occupation by communist insurgents at times of aerial bombardment in the 1970s) is similar and at shallow depth, but more network-like in plan with a number of narrow side passages from a pathway winding 200 m through the bottom of the cave system (Fig. 25). Here there is some evidence of gravitational sliding of near-surface rock masses on sloping mountain sides, as an intermediate stage of breakup of the competent rock masses seen in the main karren field nearby (Figs. 26, 27).

Air Raid Shelter Cave No. 2 (PS0039) has a few low passages totalling 60 m, while a further shelter cave No. 3 (PS0064) is only 8 m long, and other caves are known.

Conglomerate cave, Tham Maa / Tham Yang, Nan Province

Tham Maa (NA0147, 19° 15'20.36"N, 101°06'11.33"E) is located in Doi Phu Kha National Park, Nan Province, in the Luang Prabang Range close to the border of Laos. Access is from the village of Ban Nam Phutthana and although it had been developed for tourism with the construction of a gate and steel stairs at the entrance, the cave is not maintained or run as a show cave.

The Shepton Mallet Caving Club has documented over 40 caves in the area between 2009 and 2016 (Ellis 2016), mostly at higher elevations ranging to 1,406 m. Further north near Tham Pha Phueng there are two distinct bands of limestone dipping west at about 40-45°, between which is a band of sandstone, possibly due to a thrust fault. All the caves are in limestone except Tham Maa / Tham Yang, the only one in conglomerate or similar.

Fig. 22. Lan Hin Pum - bollards or runnels?

Fig. 23. Runnels, Lan Hin Taek, Phu Hin Rong Kla.

Fig. 24. Polygonal cracks in sandstone, Lan Hin Pum (probably not a karst feature).

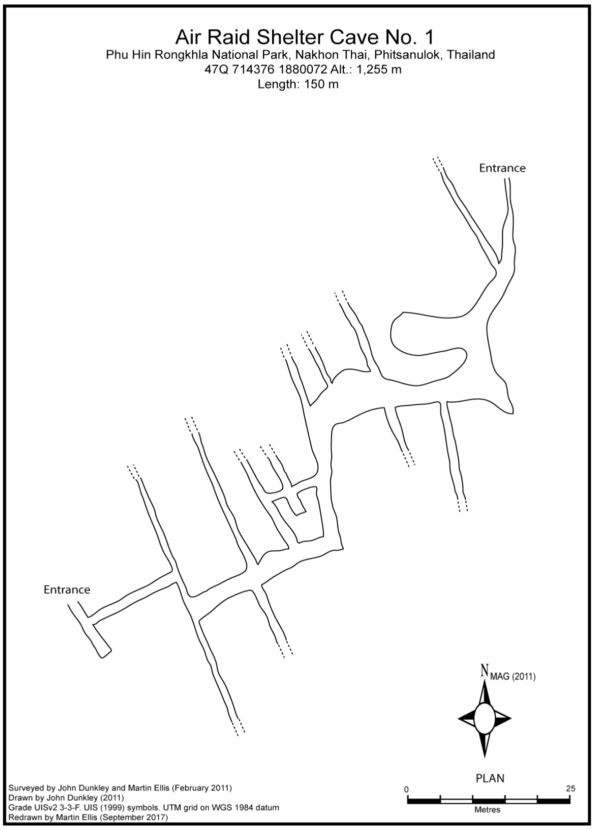

Fig. 25 Plan, Air Raid Shelter Cave No. 1 (John Dunkley & Martin Ellis).

Fig. 26. Air Raid Shelter Cave No. 1, Phu Hin Rong Kla.

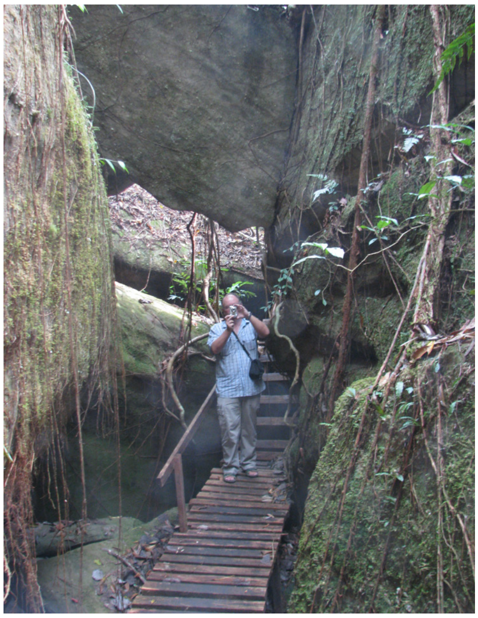

Fig. 27. Air Raid Shelter Cave No. 1, Phu Hin Rong Kla.

This is the only cave in the region formed in conglomerate and it appears to follow the strike, with the bedding dipping 45° to the north, passing beneath a low ridge between the two entrances. The downstream entrance (Tham Yang) caries a small seasonal stream into a small doline about 20 m across. The larger entrance (Tham Maa) is a collapse doline, probably intersected by the valley at some point. A gate leads to a substantial steel staircase descending 25 m, opening to a large 20 m x 20 m chamber. Climbing down fixed ladders and boulders allows access to a medium-sized active stream appearing from the northeast. An inlet floored with gours can then be followed northwards for 50 m to a choke. Upstream to the east there is a drop into a large passage (20 m high x 8 m wide) leading to a boulder fall after 40 m. The stream turns right and can be followed through boulders for 15 m into a small passage (4 m x 3 m) with easy walking on a gravel and cobble floor for 60 m to a hands and knees crawl in water. Once past this crawl the passage can be followed for a total of 300 m to end in a boulder choke. The two leads in the northern series were not fully explored; it could be that these take water sinking in the older limestone but topographically higher to the north, as photos show rounded (predominantly limestone) clasts in the reddish-brown matrix (Fig. 28).

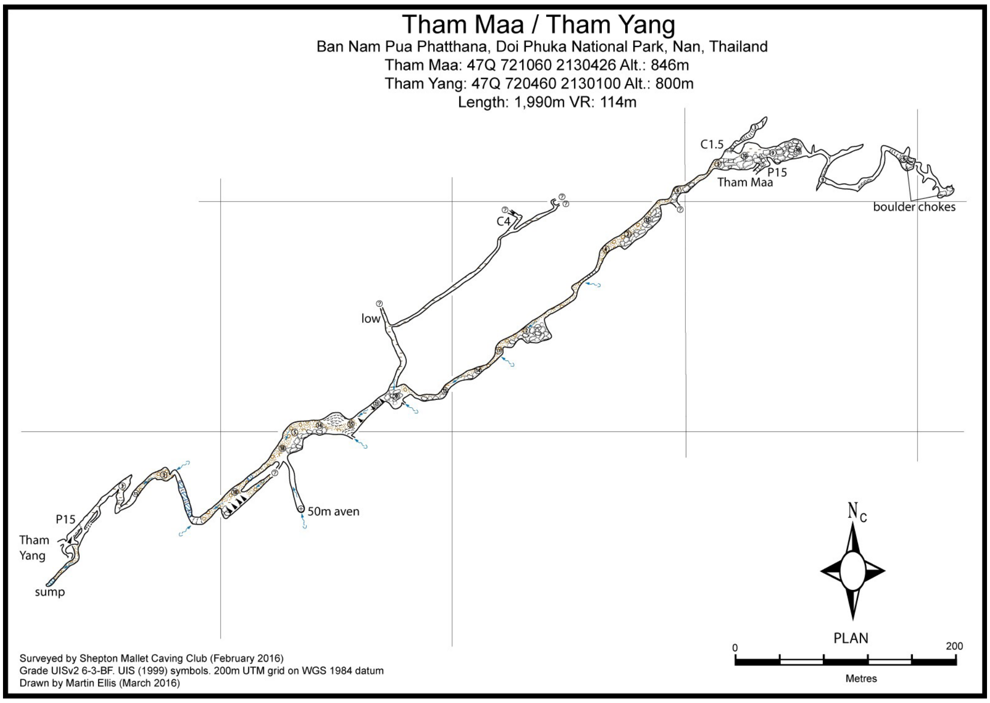

Fig. 28. Plan of Tham Maa / Tham Yang, Nan Province (Martin Ellis).

Heading downstream from the entrance chamber along the streamway requires occasional crawling, but typically follows a high rift varying from 3 to 18 m, probably controlled by the dip of the beds; as in some places the passage clearly slopes upwards to the left, facing in a downstream direction. After 350 m a chamber is reached where a 50 m high rift enters from the north. This was explored for over 200 m, but not pushed to a conclusion. Another high-level passage was surveyed over mud-coated boulders, ending after 150 m. At least six other very low or narrow tributaries feed water to the main streamway which continues through a couple of chambers to a second entrance from Tham Yang by a 15 m pitch from a shallow depression. The Tham Yang entrance in a shallow depression is 2 m by 4 m, dropping through boulders to a dry, 4.5 m wide by 4.5 m high square stream passage which can be followed 20 m down dip on a 25° slope to a 4 m climb and a further 4 m of passage which ends at the lip of a 20 m pitch into the lower streamway from Tham Maa, just upstream from a sump. The stream sumps about 60 m past the Tham Yang pitch and may be either perched or the resurgence hidden in vegetation near the river. In some areas there are ‘hanging boulders’, as if they were part of the bedding that had been undermined, in places bridging the passage leaving an abandoned upper level and lower active stream level. Photographs emphasise mechanical erosion of the cave walls and show rounded clasts in a reddish-brown matrix (predominantly limestone), suggesting that the matrix is less calcareous than the limestone clasts and that the source of the clasts was clearly a limestone area. There was evidence of secondary mineralisation and stress fractures cutting through some of the clasts and matrix (Andy Goddard pers. comm.) (Fig. 29).

The cave is probably formed in either the Early Cretaceous Phra Wihan or Sao Khua Formation of the Khorat Group, all of which Group is younger and mostly lower topographically than the Permian limestone which is considerably folded and faulted in contact with the younger sequences. Based on surveying by Shepton Mallet Caving Club, the main cave appears to follow a gentle slope across the strike of about 3%, similar to that observed in crevice karst of Phu Hin Rong Kla , and in Tham Seri Thai and Tham Si La At (see below).

Fig. 29. Mechanical erosion of conglomerate cave walls, Tham Maa (Andy Goddard).

Other notable pseudokarst areas with active streams

About 400 minor caves are widespread in the Khorat Series sandstone (Ellis 2017b). Many are quite extensive but mostly open to daylight, associated more with undercutting of clay and siltstone beds, leaving space for the construction of temples, meeting or sleeping quarters. A significant number have had roofs constructed over narrow passages between sandstone pillars, or extended outwards, and are of limited significance to scientists or speleologists, though still of considerable local cultural importance. As described above, as many as a thousand such 'caves' occur in both limestone and sandstone in Thailand. Tham Din Phieng is one of six or seven recorded in the sandstone country of Northeast Thailand as containing a stream that is at least seasonally active.

(Wat) Tham Patiharn (UB0018) 15°36'04"N, 105°34'24"E is well-known but in a desolate, infertile area some distance from villages, in a remote part of Ubon Ratchathani Province 5 km west of the Mekong River, in a landscape dominated by mostly bare Phu Phan Formation sandstone and shallow, thinly vegetated 'gallery forest' streams in a large field of joint networks, dipping mostly west from cliffs overlooking the Mekong River. A small entrenched stream draining a few square kilometres leads to a slightly depressed (4 m) and abrupt collapse doline about 10 m wide, with water sinking a short distance upstream of the 20 m wide by 5 m high entrance, falling through a rockfall below an impressive *naga*-lined cement staircase which leads to several underground shrines (Fig. 30). At the base of the staircase, 40 m into the cave, some steps lead down to the active streamway which is about 100 m long by 15 m wide and 2 m high. Straight on the dry upper passage is 140 m long, 20 m wide and 4.5 m high, the floor is tiled and has several shrines. A small active inlet is piped away. There are two more large chambers, about 350 m long, beyond the tiled shrine section which are home to a large number of bats. The second chamber is as big as the first, but only 2 m high. The cave was surveyed by Claude Mouret and Philippe LeClerc in 1994 to give a length of 776 m, but unfortunately the survey has not been published. Geological maps suggest it may have formed at the eastern end of a synclinal trough in the Khok Kruat Formation, possibly punching through to the underlying Phu Phan Formation; the trough bearing about 300° from the entrance. The resurgence is unknown, but is probably in the deep, forested gorge 500 m WNW of the entrance (Fig. 31).

Fig. 30. Naga-flanked staircase leading into Tham Patiharn, above and beside underground stream.

Fig. 31. Bare sandstone surface above Tham Patiharn.

Tham Seri Thai (Sakon Nakhon), (SN0002), 17°06'00"N, 103°58'22"E is marked by a nearby monument and interpretation sign, celebrating its use as a shelter by the Free Thai movement to hide weapons in World War II. Little evidence remains of this event but commemorative candles are maintained in the cave (Fig. 32). Behind a small collapse entrance a small active stream follows its 150 m length, narrowing inwards beneath a very distinctive surface slope, possibly down dip (Fig. 33). A short diversion from the access path can be made to somewhat smaller caves or fissures further downstream from Tham Seri Thai, in which running water can be encountered.

Fig. 32. Entrance to Tham Seri Thai.

Fig. 33. Tham Seri Thai rock fall leading to stream.

Tham Phung (Mukdahan) (MU0035), 16° 27’54”N, 104°33’36”E is a resurgence enterable in the dry season in which three local people drowned in 2014. Known to local villagers for many years, it is said to be capable of holding 60 people.

Tham Nam Lot (UB0068), 15° 44' 48"N, 105° 12'14"E in Ubon Ratchathani has been recently explored and surveyed for 181 m by Romanian cavers. The cave is a joint controlled, straight, 5 m wide by 3 m high passage orientated NE to SW. At the NE end the cave drops down to water level and an upstream sump. In the main passage there are two other windows dropping into the flooded passage and the stream resurges only a few tens of metres from the end of the cave (Valenas 2016).

(Wat) Tham Si La At (CH0048) 15°54’58”N, 102°03’38”E in Chaiyaphum is a single straight 64 m long rift cave below a low rise in the grounds of a wat. A few steps lead from the entrance in the shape of a *naga*’s mouth to a 2 m wide x 3.5 m high passage to a small muddy lake with variable water levels (Figs. 34, 35).

Fig. 34. Entrance to Tham Si La At, Chaiyaphum.

Fig. 35. Cave art and typical thin bed of claystone or siltstone.

Tham Nam (KL0028) 16°32’49”N, 104°08’02”E in the Phu Pha Phueng Forest Park, Kalasin is a seasonally active resurgence cave part way up the slopes of a sandstone mountain. Although not entered, the cave is reported to be long, but very low and a small concrete basin has been built at the entrance to collect water (Fig. 36).

Fig. 36. Spring leading to unexplored cave, Tham Nam, Kalasin (Martin Ellis).

DISCUSSION

Sandstone terrains still remain insufficiently understood although significant advances have been made in the last 25 years (Grimes 1975, 1997; Jennings 1983; Wray 1997b; Young and others 2009). Numerous authors have demonstrated that limestone caves develop along a restricted number of bedding planes within a limestone series but less discussion has occurred about the initiation of some sandstone caves. The term ‘inception horizon’ was introduced by Lowe (1992a, 1992b) to describe stratigraphic discontinuities along inception horizons particularly susceptible to solution, sometimes dating back to diagenesis:

> *... lithostratigraphic horizons that are especially favourable to karstification by virtue of physical, lithological or chemical deviation from the prominent carbonate facies. It passively or actively favours the localised inception of dissolutional activity, marking the transition from 'rock with no caves' to 'rock with caves' and extending through whatever time interval is required for gravitational laminar flow conditions to be established in a given situation.*

Lowe's term included origins in diagenesis, although others have since annexed the term to describe microprocesses in speleogenesis. For example, Filipponi (2009) conducted a detailed analysis of 18 horizons in six cave systems, identifying inception horizons of some centimeters to decimeters, concluding that 10% of existing bedding partings guided more than 70% of phreatic conduits, so the basic concept appears accepted as being relevant to speleogenesis. As Lowe (2000 p. 75) concluded:

> *Whether these bedding/rock combinations are referred to as inception horizons or simply as favourable beds, their role and importance are the same... These arguments relate primarily to speleogenesis in carbonate rock sequences ... Other subtle lithologic differences related to the lithostratigraphy may also influence early conduit development in less obviously karstic rocks, such as sandstone and quartzite.*

Thus it appears likely that even a partly calcareous and/or conglomerate sequence confined in sandstone between two relatively harder impermeable rocks would be favoured as a conduit.

In Tham Din Phieng, Tham Patiharn, Tham Seri Thai, Tham Maa and Tham Nam Lot the evidence suggests that a surface stream or other entrance has broken through overlying sandstone into a cave of modest dimensions in a calcareous bed. Some writers have annexed the word 'inception' to refer to more recent manifestations of clearly favourable beds, but Grimes (1997) thought that dissolution should be regarded as the "initiating process" to allow for the possibility of other processes becoming dominant in later stages of the evolution of the landform. This appears similar to what Odell (1985, p. 28) had called a 'lineament' below water table level, later extending laterally due to weathering and erosion.

Case studies from other countries

The evidence of low-angle cave development between harder beds is also supported from examples in India, Czech Republic and Australia. For example, the Caving in the Abode of the Clouds Project in India has had remarkable success in a range of network maze caves, mostly all quartzose with a siliceous cement, or with thin limestone interbeds. First reported by Breitenbach and others (2010) as two short sandstone caves, an updated poster describing more recent work in the area was displayed at the 2017 ICS Congress in Australia (Tringham pers. comm; Yokx Burgers pers. comm.). Krem Puri ('krem" = 'cave' in the local Khasi language), Mawsynram, India is a dense 2D network cave formed in the middle part of the Late Cretaceous Mahadek Sandstone Formation in Meghalaya, India. Encompassing an area of up to 2 km x 200 m wide, the surveyed length is 12.5 km including a new branch. The cave appears to have formed over a narrow stratigraphic interval (ca. 20 m) in a relict inception 2D network just a few metres thick, where the sandstones contain a calcareous cement. Abundant joint sets and faults are located along which many passages are aligned. Nearby Krem Lum Shken appears to run along an inception in a thin (ca. 0.5 m) limestone bed with rift and collapse into the surrounding sandstones. Largely parallel to beddings, it follows a gentle 2° structural dip. Several other underground streamways were found draining from nearby sinks to a SSW direction. Lum Shken is one of several caves formed mostly in sandstone; exploration and scientific investigation is continuing. As with Tham Maa, above, the relative importance of solutional versus mechanical erosion remains to be investigated.

In the Czech Republic, Mljenek and others (2009) described a more extensive system of underground spaces in sandstone called Poseidon, in the Teplicky Skaly Cliffs, Broumovsko Protected Landscape Area, part of the Bohemian Cretaceous Basin extending into Poland and Germany. Largely inaccessible before 2006, exploration has revealed a total humanly accessible passage length reaching to 27 km within a surface area of 740 m north to south and 550 m west to east. Deep crevices, vertical shafts and open gorges define a labyrinthine rectilinear network of crevices and caves developed around the edges of the sandstone plateau. Many crevices are 1 to 3 m wide but sometimes barely 50 cm wide, and some pits descend 50 to 70 m, the deepest to 105 m. Some open crevices carry small perennial streams; close to the edge of the plateau they change to deep vertical pits. While some of the complex is open to at least filtered daylight, wedged blocks of stone and other debris have created multilevel, wholly dark caverns in places.

Similar networks are reported from northern Australia. A maze cave at Kakadu, Northern Territory, is apparently restricted to a specific susceptible sandstone bed (Grimes and others 2011, p. 8). The cave is a dense horizontal network with branches every 3-5 m and narrow passages several metres high and a metre wide, shrinking to crawlways away from grike entrances. Walls and ceiling are smoothly rounded giving a “phreatic” appearance. A water mark indicates wet season flows of 10-20 cm deep in places. A large chamber has formed as a result of coalescence of several passages. Passage length was estimated from a memory sketch only, but is of the order of 400-500 m with numerous unexplored leads. Other sites are reported nearby. The description is very similar to Tham Din Phieng.

Although not a maze cave, Hilltop Cave near Mittagong, NSW, is one of the few sandstone caves containing water in New South Wales. Consisting of a gently sloping 90 m long passage, it may have developed within a series of thin beds (each about 0.5 m thick but up to 10 m total thickness in a resistant bed in the Mittagong Formation of the Wianamatta Group, which could explain upstream migration of three roughly equidistant knick-points, the last a 3 m waterfall at its lower end where it meets the underlying Hawkesbury Sandstone. The widespread Sydney Sandstones contain numerous small caves (Dunkley 2013), mostly 3-10 m or so in size, but interbeds are primarily thin clay or shale within the main sequence, giving rise to often quite wide but not long caves.

Numerous pinnacles of the kind illustrated in Grimes and others (2011) may be found, for example, in Phu Phra Bat National Park (Munier 1998, ch. 2), west of Udon Thani. These sometimes occur as quite high remnants of sandstone beds underlain by eroded clay and siltstone beds, and again sometimes used as places for meditation by Buddhist monks; some also contain prehistoric paintings. All are similar to those in sandstone throughout NE Thailand where, of course, they are known as ‘tham’ (cave) and very frequently are roofed over as part of a Buddhist temple or priests’ camp property (see Fig. 3 above); they are also known from sites such as Cape Crawford, Northern Territory, Australia, in passages barely a metre apart but 20 m high. Most such sites are of little speleological interest, but do illustrate the process of breakdown of sandstone landforms following the descriptions of Mljenek and others (2009), analogous to the breakdown respectively of limestone and sandstone karst as described by Grimes (2012) and illustrated in Grimes and others (2011), using similar terminology such as karren zones, giant grikefields, stone city and isolated stone forest blocks.

CONCLUDING REMARKS

This review has concentrated on sandstone and related caves and karst-like features containing water, including some receiving only meteoric water. Although many dry caves are culturally very significant in Thailand, active sites in sandstone are not common in Thailand or in Australia, but are of unusual geomorphological and speleological interest. In most cases there is evidence of the significance of favourable beds in directing water flow.

While sandstone terrains remain little understood, much less do we know about landforms and landscapes in conglomerates. Migon & Wray (2013) contrasted erosional landscapes in sandstone and conglomerates. Conglomerates in particular feature coexistence of clasts of different size and cement of different composition, and bedding is not as distinct as in sandstones with jointing typically sparse. Conglomerates and weak sandstones result in cement dissolution and disintegration, then by clast-after-clast release and grain-by-grain disintegration. In strong sandstones weathering focuses on joint and bedding planes, resulting in angular shapes and subsequent surface weathering.

Summarising it as a ‘ruiniform’ product, Grimes and others (2011) have drawn together an understanding of the stages of degradation of sandstone landscapes and related karst-like features and caves, describing processes and terminology of sandstone karst morphology, and especially its decay into giant grikes, stone city ‘streets’ and ‘blocks’, stone forest and pinnacles, small caves and rockshelters.

ACKNOWLEDGMENTS

We wish to acknowledge the helpful contributions of Andy Goddard, Jeanette Dunkley, David Merritt, Cathy Plowman, Mark Tringham, Shepton Mallet Caving Club, National Library of Australia map collection and numerous pleasant assistants in hotels and restaurants we met when when seeking directions.

Photographs, unless otherwise attributed, are by John Dunkley.

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EDITORIAL NOTE

Sadly, on 1 February 2018, during the review process for this paper, the senior author, John Dunkley, passed away, following a brief illness. The final text was settled with the other authors. An obituary, together with what will be John's last published paper, will appear in the next issue of *Helictite* – GJM.
