



Morphology, hydrochemistry and genesis of water pits in quartzite sandstones of northeastern Thailand

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Abstract: The water pits of northeastern Thailand are typical karst phenomena on sandstones in this part of the Country, where they play an important role as local water supplies and contribute to the ecological balances of their areas of occurrence. They comprise vertical tubes, commonly 1 to 5m deep, some of which have not yet been measured precisely, but appear far deeper. As a step towards explaining their genesis, some precise measurements of their depth and shape have been carried out; additionally, stagnant waters from these natural tubes have been subjected to chemical analysis. They appear to have no connection with the groundwater table but are formed and fed exclusively by rainwater during the wet monsoon season. Their formation is the result of four factors. The primary factor is the process of quartz sandstone arenization, whereas secondary factors are calcium carbonate dissolution within the sandstones, mechanical erosion processes, and biocorrosion related to vegetation and animal activities. A graphic model of the main factors that formed these natural water-filled tubes is presented for the first time.

Keywords: Quartz sandstones; arenization, water pits; vegetation-induced corrosion; hydrogeology in quartz sandstones; silicate karst; Phu Pom.

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Introduction

Water pits should not be confused with potholes. Karst landscapes formed on quartz sandstones in northeastern Thailand (Fig.1) include many forms resembling those seen on limestone and dolomite karsts elsewhere: karren, karren fields, sinkholes, blind valleys, water sinks (ponors), karst springs (some with notably high flows) and large caves of various types (e.g. Dunkley *et al.*, 2018, 5–31; Ellis, 2017; Valenas, 2019, 40–41; 2020, 13–18; 2023a, 66–70; 2023b, 76–83; 2024a, 30–41, 2024b, 30–41, 2025a, 49–55, 2025b, 32–34, 2025c, 147–148, 2025d, 105–106, 2025e, 27–43; Grootaerd, 2024, 25–27).

Additionally, these karst areas include examples of a natural phenomenon that does not appear to have been observed and described in limestones and dolomites: water pits. Whereas a 4.2m-deep water pit in the Jurassic limestone of the Velebit massif of Croatia was described by Perica and Marjanac (*in Ginés et al.*, 2009, 372–373), neither its shape/morphology, its apparent mode of genesis, nor its pH (8.42) are similar to those of the water pits observed in the sandstones of northeastern Thailand, which display an almost perfectly circular entrance above a bell-shaped cavity. These latter features comprise vertical shafts, generally up to 5m deep, which are commonly water-filled, especially during the rainy monsoon season.



Figure 1: Areas with water pits studied to date in northeastern Thailand.



Figure 2: Water pit on the Phu Pom quartz sandstone plateau.

These water pits should not be confused with potholes (rock basins, pots or, in French, *marmites*) that appear at the base of waterfalls and are created by erosion driven by eddy currents. In Ubon Ratchathani Province, at Sam Phan Bok, there are tens of thousands of such potholes, created by the Mekong River. In the local language, these water pits (Fig.2) are called “*bok nam san hin*”, which translates to “*stone pots with water*”. Whereas the local people of northeastern Thailand define this karst phenomenon clearly, geologists from the Department of Mineral Resources in Bangkok, in their 920-page book “*Caves and Karst of Thailand*”, ignore this type of karst formation completely. In the two small chapters dedicated to karst on sandstones in Thailand, there is neither mention nor a photograph of these water pits (“Various”, 2021, 108–119; 176–187). Karst in the sandstones of northeastern Thailand was researched several decades ago by John Dunkley and Claude Mouret, but they do not describe these water pits, either because they did not discover them or because they chose to ignore their potential importance (Mouret and Mouret, 1994; Mouret, 2004; Dunkley *et al.*, 2018). It is paradoxical that, whereas water pits in the sandstones of northeastern Thailand have not previously attracted the attention of karstologists, similar forms developed on granite, are relatively well studied (Twidale and Vidal Romani, 2005; Dominguez-Villar, 2006; Migón, 2006; Aguilera *et al.*, 2014; Vidal Romani *et al.*, 2014; Timms and Halse, 2020; Perez, 2023; Wang *et al.*, 2023). Known either as *gnammas* or as weathering pits, they are described by these authors as having a complex genesis, through the effects of erosion and chemical dissolution processes (including biocorrosion). That is, closely analogous to the water pits of northeastern Thailand. There is one difference, however: the depth of the weathering pits in granite is far less than that of the forms described here, in the sandstones of Thailand.

It is noted and stressed here that these water pits are not *kamenitza* (Cucchi, 2009, 139–150), circular water-filled karren that are especially typical on the limestone karst of Slovenia. The karst on quartz sandstones in Thailand certainly contains many *kamenitza*, but these karst phenomena, spread across all rock-types, are not the subject of this article. Water pits have played, and continue to play, an important role at human and ecological levels. Previously, local populations used them as natural reservoirs of drinking water during the dry season. Currently, they are used in many places for irrigation of small areas and can even provide “mini-farms” for fish culture. They have another highly important role during the dry season, with its extremely high temperatures, when various animals, especially reptiles, take shelter in them. But on occasions a water pit may also become a fatal trap (Fig.3) for the unlucky or unwary.

This article sets out to explain for the first time the genesis of the water pits in the quartz sandstones of northeastern Thailand, based on lithological, climatic, hydrogeological and hydrochemical research data. Whereas the research, which began in 2015, has so far identified 7 areas with water pits, in the provinces of Amnat Charoen, Ubon Ratchathani, Mukdahan, Udon Thani and Nong Khai, it is certain that additional parts of northeastern Thailand also contain these karst forms. As far as possible (considering that northeastern Thailand covers

approximately 150,000km²) the research described here will be widened by identifying and studying water pits in other areas. Because no other scientific study of these water-filled shafts has been carried out and described, the work and results presented here are considered a first step. Hence, some aspects of the origin and genesis of the phenomenon, currently studied only in northeastern Thailand, still require more investigation and clarification.

Materials and methods

The water pits in the Mount Phu Pom area were surveyed and positioned using a Suunto compass, inclinometer and a fibreglass tape. The water depth in these water pits was measured with a graduated ballast wire.

Photographs of the water pits were taken using a Nikon D5200 camera, Tamron 18–155mm lens and UV filter. The sections of sandstones from Phu Pom were photographed first using a reflected light microscope and then rephotographed using double-polarized light.

Temperatures and pH values were determined at the sampling locations using a HQ40D digital dual-channel multimeter from Hach Lange GmbH. The pH electrode (Hach Lange GmbH) was calibrated with pH buffer solutions with pH values of 4.01 ± 0.02 , 7.00 ± 0.02 and 10.01 ± 0.02 (25°C). All water samples were collected exclusively during the dry season (no precipitation), March–April 2023–2025. They were collected between 8:30am and 11am on clear, cloudless days. Outdoor air temperatures ranged between 32°C and 38°C.

Silica concentrations were measured photometrically by DR890 colorimeter from Hach Lange GmbH, using the silicon molybdate method (measuring range: 1.0–100.0 mg L⁻¹ SiO₂). Determinations of the main cations and anions were carried out by ion chromatography. A Metrohm 850 Professional IC ion chromatograph was used for the cations; flow rate: 0.9 mL min⁻¹; oven temperature: 35°C; sample loop: 10 µL; measurement time: 20 min. Ion separation was realized using a Metrosep C 6 - 250/4.0 column with an eluent composition of 4.0 mM nitric acid and 1.0 mM pyridine-2,6-dicarboxylic acid. A Metrohm 881 Compact IC pro ion chromatograph was used for the anions; flow rate: 0.7 mL min⁻¹; oven temperature: 45°C; sample loop: 20 µL; measurement time: 30 min. Ion separation was performed with a Metrosep A Supp 5 - 250/4.0 column. The eluent consisted of 1.0 mM sodium hydrogen carbonate and 3.2 mM sodium carbonate.

Analyses with the inductively coupled plasma optical emission spectroscopy (ICP-OES) were performed with 5900 SVDV spectrometer (Agilent Technologies); rf power: 1.2 kW, coolant gas flow: 12 L min⁻¹; auxiliary gas flow: 1.0 L min⁻¹; nebulizer gas flow: 0.7 L min⁻¹; pumping rate: 12 rpm. Unless otherwise specified, the wavelength (see below) was measured both axially and radially.



Figure 3: A relatively large bird remained trapped and died in a water pit at Phu Pom. This dead bird is directly responsible for a high concentration of ammonium in the water in this water pit. [Photo: Liviu Valenas.]

Measured wavelengths (sorted alphabetically):

- Al** 167.019nm (axial only), 237.312 nm, 396.152nm;
- As** 188.980nm (axial only);
- Ba** 230.424nm (axial only), 233.527nm (axial only), 493.408nm;
- Bi** 190.171nm (axial only), 223.061nm (axial only);
- Cd** 226.502nm, 228.802nm;
- Co** 230.786nm, 238.892nm;
- Cr** 205.560nm, 267.716nm;
- Cu** 213.598nm, 327.395nm;
- Fe** 238.204nm, 239.563nm, 259.940nm;
- Li** 460.289 nm, 610.365nm, 670.783nm;
- Mn** 257.610nm, 260.568nm;
- Ni** 216.555nm, 230.299nm;
- Pb** 217.000nm, 220.353nm;
- Sr** 407.771nm, 421.552nm, 460.733nm (axial only);
- Tl** 190.794nm (axial only), 351.923nm (axial only);
- Zn** 202.548nm, 206.200nm, 213.857nm.

The chemical analyses and the capture of the rock section photomicrographs were carried out in the laboratories of the Technical University of Freiberg, Institute of Geology, Germany.

Areas studied

Mount Phu Pom

This small table-mountain, which reaches a maximum height of 265m (Figs 4, 5 and 6), displays the highest density of water pits yet observed in Thailand. At altitudes between 235–240m a small (14,980m²) plateau of quartz sandstone includes 18 water pits within its length of 214m and width of 70m (Fig.7).

Almost all of the pits have a round opening, some of which are close to being perfect circles, and most of the pit openings are between 1m and 3.5m in diameter, although a few of them are only 50–70cm across (Fig.8). Their probed depths range between 1m and 4.1m (Valenas, 2023b, p.78). Broadly, these 18 water pits (Fig.9) are aligned along two major west–east fault lines. Whereas there is a relatively large maze cave, Tham Phu Pom (Figs 7, 8), nearby (Valenas, 2023b, p.79), the water pits have developed independently and there are no connections with the cave.



Figure 4: General view of part of the small plateau formed on quartz sandstone at Phu Pom. [Photo: Liviu Valenas.]

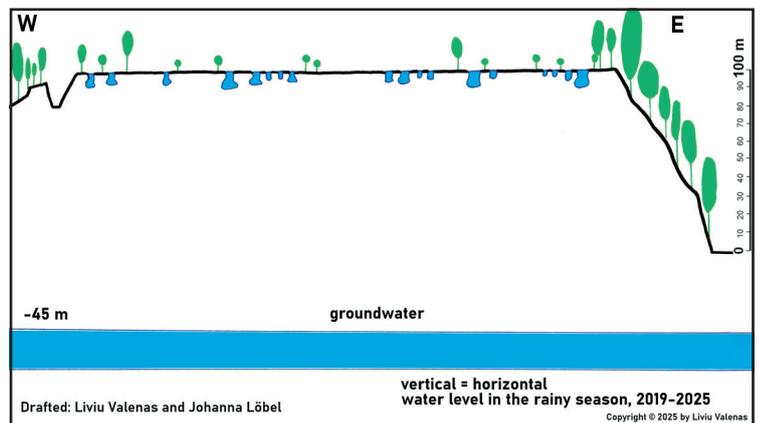


Figure 5: Profile of Mount Phu Pom. Note that the water pits at Phu Pom lie some 145m above the groundwater table. [Cartography: Liviu Valenas.]

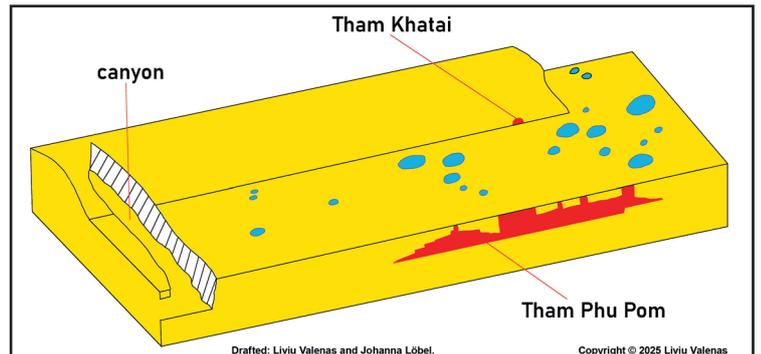


Figure 6: Block diagram of the Phu Pom plateau with water pits.

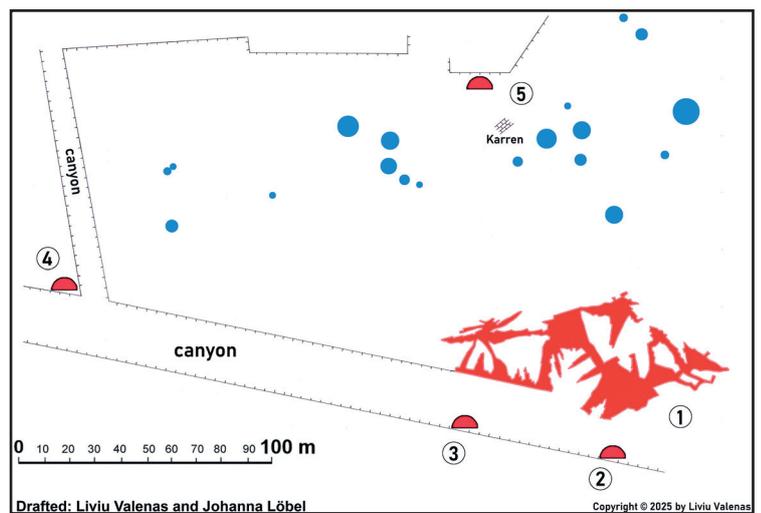


Figure 7: Map of the Phu Pom plateau with the 18 water pits. 1: Tham Phu Pom (284m total length), 2: Tham Phu Pom II (12m length), 3: Tham Phu Pom III (4m length), 4: Tham Phu Pom II (11m length), 5: Tham Khatai (3m length). The largest water pits of Phu Pom are aligned along west–east-oriented fault-related fractures, as are the main galleries of Tham Phu Pom. [Cartography: Liviu Valenas.]

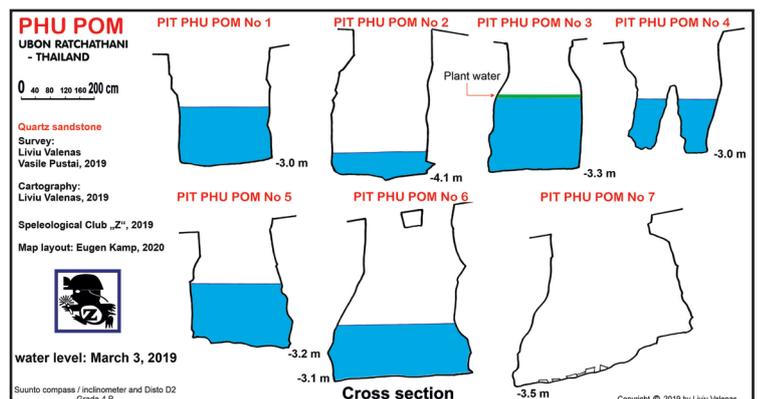


Figure 8: Sections through the 7 most important water pits at Phu Pom. [Cartography by Liviu Valenas.]

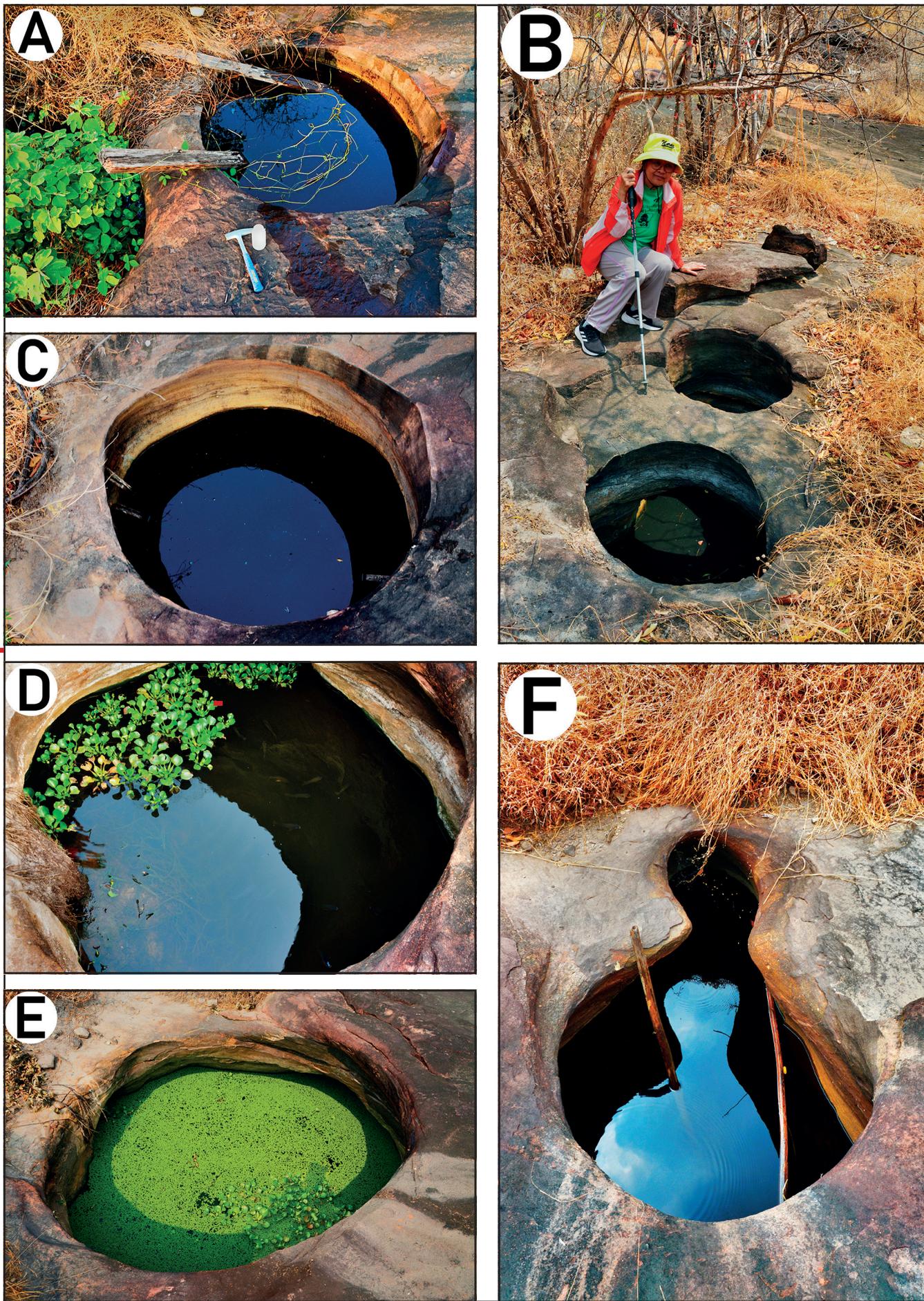


Figure 9A and 9C: Two typical water pits at Phu Pom with almost perfectly circular openings.
 Figure 9B: A water pit at Phu Pom with two separate openings. Through the arenization process they coalesced underground.
 Figure 9D: A water pit at Phu Pom, used by Buddhist monks in 2024 as a small fish farm.
 Figure 9E: Water pit at Phu Pom already invaded by aquatic vegetation. Such vegetation plays an important role in the biocorrosion process.
 Figure 9F: Water pit at Phu Pom, where two originally separate openings have joined through the arenization process. [Photo: Liviu Valenas.]



Figure 10: Three aligned water pits in the Phu Phanom Di plateau. [Photo: Liviu Valenas.]

Phu Phanom Di and Phu Noy

These table-mountains, which lie in the same area as Mount Phu Pom, reach maximum altitudes of 300m (Phu Phanom Di) and 260m (Phu Noy). On a lateral plateau of Mount Phu Phanom Di there are 5 water pits (Fig.10), with diameters between 0.8m and 1.5m. As yet their depths have not been probed, but they appear to be far shallower than those in Mount Phu Pom but, clearly, they are fully formed water pits. A single water pit with a diameter of 1.5m and a depth of about 2.2m was identified on Mount Phu Noy in 2023.

Phu Sa Dok Bua

On the small plateau of the Phu Sa Dok Bua table-mountain, which rises 200m above the surrounding area, are two of the strangest water pits. When found, during the 2018 and 2019 explorations, they were completely dry. Small, irregularly shaped entrances are followed by descents into small, egg-shaped, chambers (Valenas, 2020, 13–18). Two small, hourglass-shaped, potholes at depths of -1.5m and -1.0m in the two cavities (Figs 11–13 helped provide a better understanding of water-pit genesis. In the same area, three more water-filled pits are in the process of formation.



Figure 11: Pothole (originally a water pit) in the upper plateau of Mount Pha Sa Dok Bua. [Photo: Liviu Valenas.]



Figure 12: Pothole (originally a water pit) in the upper plateau of Mount Pha Sa Dok Bua. [Photo: Liviu Valenas.]

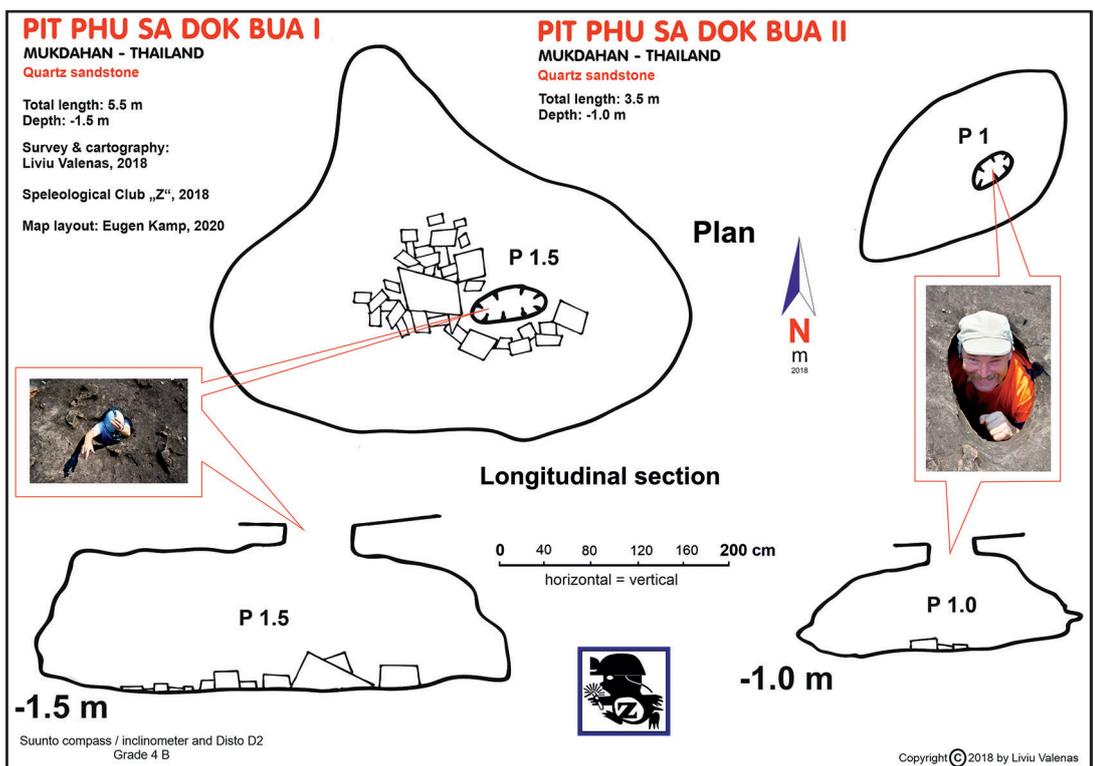


Figure 13: Plan and sections through the two potholes (originally water pits) on the upper plateau of Mount Pha Sa Dok Bua. [Cartography: Liviu Valenas.]

Wat Tham Saeng Phet.

During the 2015 exploration of the upper plateau of this table-mountain, several other water pits were identified, one of which is typical (Fig.14).

Phu Prabat

Megaliths, rock-cut shelters (used by hermits), ancient Buddhist temples, various statues and 54 wall paintings have been identified in the Phu Prabat National Historical Park, which is located on a large quartz sandstone plateau. Whereas 3 or 4 potential water pits have been observed on the plateau, some were dug further by hermits, and it is now impossible to confirm whether all of them were originally natural phenomena. A 2m-diameter hole, of 2.1m depth (Fig.15) is, however, almost certainly a natural water pit.



Figure 14: Water pit at Wat Tham Saeng Phet. [Photo: Liviu Valenas.]



Figure 15: Water pit in Phu Prabat Historical National Park. [Photo: Liviu Valenas.]



Figure 16: The gigantic water pit with a system of arches and a natural bridge in Mount Phu Pha Dak, invaded by aquatic vegetation. [Photo: Liviu Valenas.]

Phu Pha Dak

Another spectacular site with water pits, on Mount Phu Pha Dak in Nong Khai Province, was identified in 2025. Rising some 200m above the surrounding area, the highest part of this table-mountain is at an altitude of 500m. Seven water pits have been identified, with depths between 2.2m and 3.7m and widely different pH values, between 6.49 and 9.09. Conversely, surprisingly, SiO₂ concentrations are extremely low in all seven water pits. One huge pit, with a diameter of 9m, also includes several arches (natural bridges) above the water surface (Fig. 16). This area represents a priority target for follow-up research in 2026.

Lithology

Although some opinions conflict, most Thai and foreign geologists agree that the sandstones that host the studied water pits belong to the Cretaceous Phu Phan Formation (Figs 17 and 18), the outcrop of which extends from Ubon Ratchathani Province to Nong Khai Province (Dunkley *et al.*, 2018, 5–31). According to the “*Thailand Lexicon of Stratigraphic Units*” [<https://thailix.geolex.org/>] the generalized lithology of the Formation includes “...greyish-white medium- to coarse-grained cross-bedded sandstones and thin lenses of grey siltstone and mudstone with subordinate conglomerate.” This generalization is based upon the more-detailed accounts, discussed below, within Ridd *et al.* (2011).

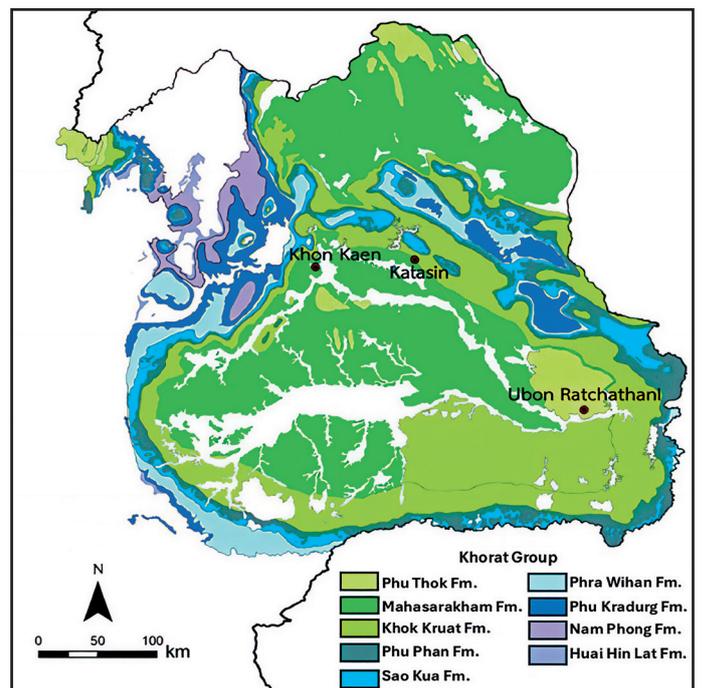


Figure 17: Geology of the Khorat Plateau. [from Wongklo *et al.*, 2019.]

Figure 18:
Mesozoic stratigraphical column of north-eastern Thailand. [After Meesook, 1999.]

In a book chapter that is dedicated to the Cretaceous rocks of Thailand, Meesook (2011) describes the Phu Phan Formation as follows:

“... The rocks generally consist of greyish white, medium- to coarse-grained, cross-bedded sandstones and thin lenses of grey siltstone and mudstone with subordinate conglomerate. In the northern and central parts of the Phu Phan Range, the formation overlies the reddish-brown claystones of the Sao Khua Formation with a distinctively sharp but conformable contact. Sandstone conglomerates are locally exposed...”.

Another view, presented in a book chapter provided by Booth and Sattayarak (2011), describes the same formation as follows:

“The Phu Phan Formation consists of a stacked series of thick-bedded to massive, medium- to very coarse-grained, often pebbly, cross-bedded white sandstones, interbedded with minor, thin, red-brown siltstones and claystones. Where this formation crops out in breached anticlines of the Phu Phan Uplift and around the edge of the Khorat Plateau, its resistant sandstones locally form distinctive cuestas. Generally the formation is 75–150m thick”.

In the Phu Pom plateau area, the Phu Phan Formation is represented both by quartz-rich sandstones and conglomerates, which are well exposed in Tham Phu Pom. The water pits occur only within the upper quartz sandstone horizon; the conglomeratic horizons are not intersected by the vertical tubes.

Other minerals that are represented – in smaller percentages – within the sandstones of the Phu Pom plateau include magnetite, haematite, tourmaline, zircon, calcite, and muscovite (Figs 19C, 19D).

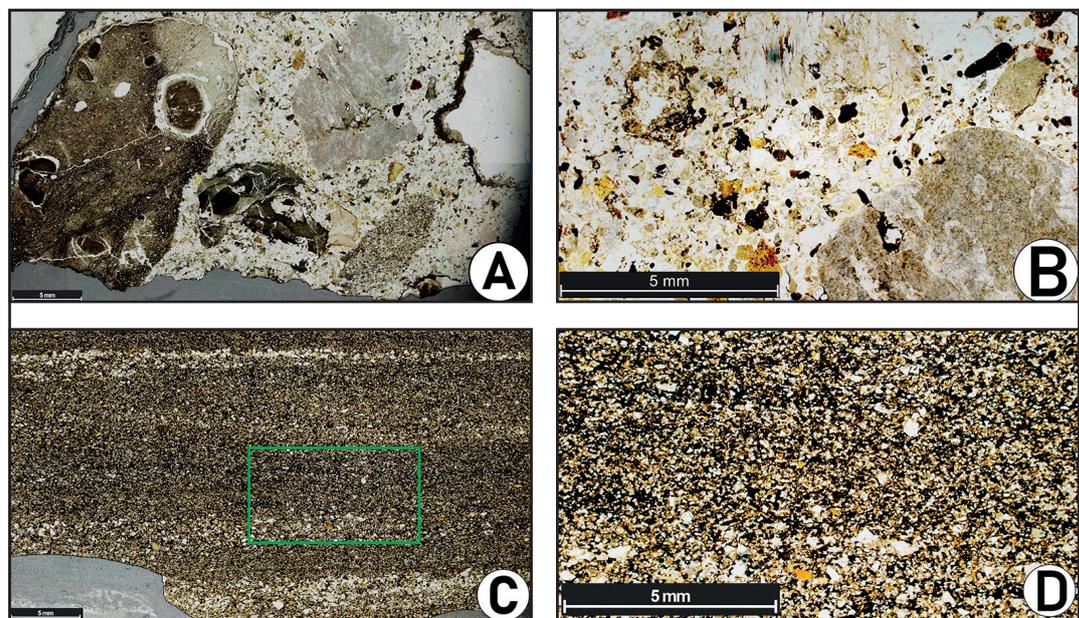
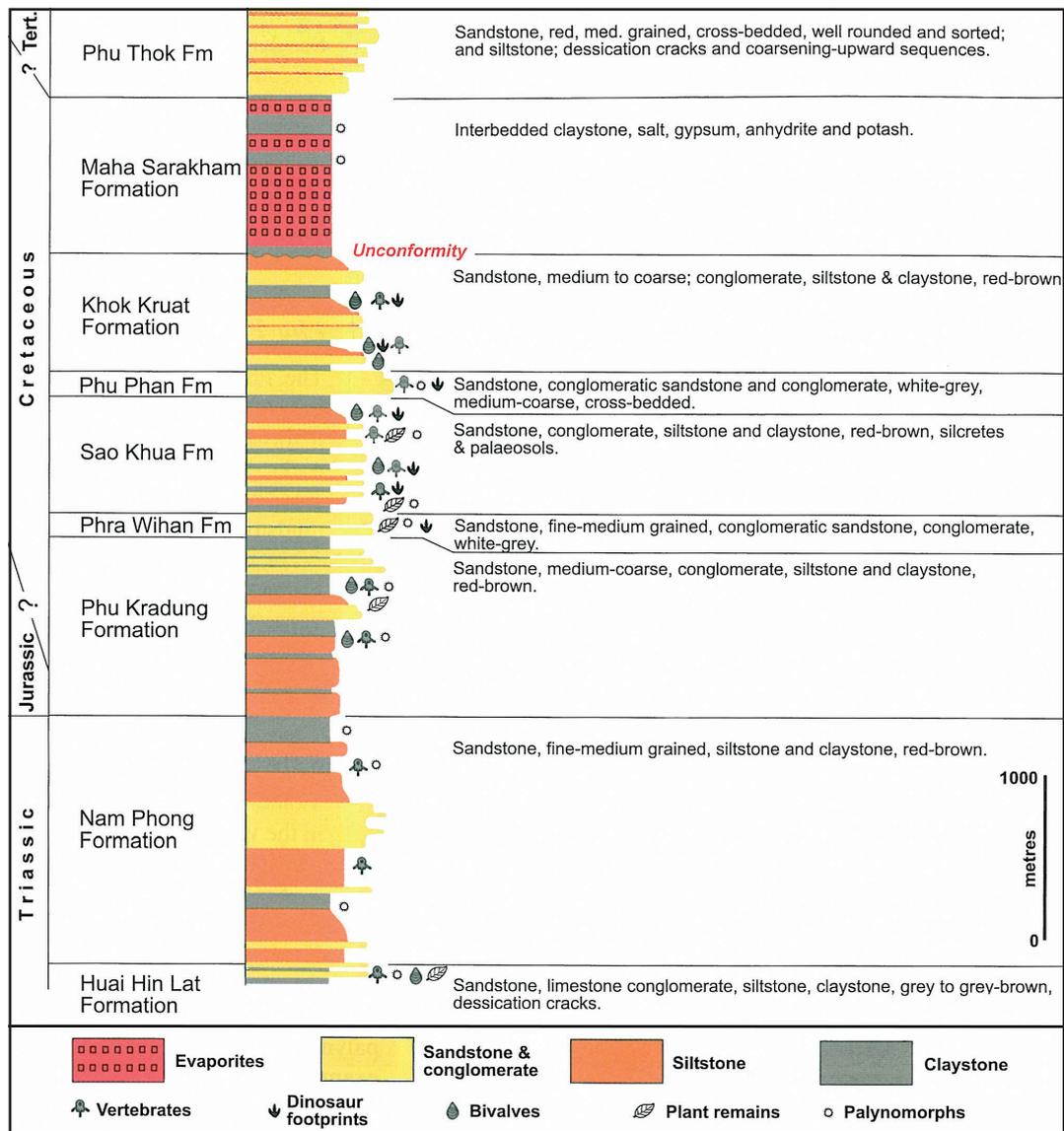


Figure 19 A–D:
Photomicrographs of conglomerate and sandstone samples collected from the Phu Phan Formation on Mount Phu Pom.
A; B: examples of two conglomeratic lithologies, both bound by a calcareous matrix/cement.
C; D: a typical example of the quartzite sandstone within which the water pits occur. The rectangle drawn on image C indicates the approximate area that is shown at higher magnification on image D. Identified minerals include: quartz, feldspar, magnetite, haematite, tourmaline, zircon, calcite, and muscovite, cemented by syntaxial mineral overgrowths.
Note: the scale bars on each of the four images represent 5mm. [Photos by TU Bergakademie, Institute of Geology, Freiberg.]

Whereas none of the authors cited above mention calcium carbonate within the binding matrix that ensures the competence of the Phu Phan Formation sandstones, such carbonate cement is clearly present. This is confirmed not only by the results of chemical analyses of the cave-river water flowing through the formation, but also by the calcium carbonate speleothems (drapes, stalactites, rimstones, etc.) that occur in large caves in the Phu Phan Formation. Concentrations of calcium carbonate in the main karst spring and underground rivers in the sandstone cave Tham Dien Pieng (Valenas, 2025) exceed those of waters emerging from some limestone resurgences elsewhere. Whereas calcium carbonate concentrations are generally lower in the Mount Phu Pom water pits, they are not insignificant. Calcium carbonate within the sandstone matrix has a notable role in the development of water pits.

Climatic data

Climate has played – and still plays – a major role in the formation and functioning of the water pits. The areas studied lie between 16° and 17°50' north, within the tropical zone, but in recent decades dramatic climatic changes have led to northeastern Thailand developing to a more subtropical climate. Nonetheless, characteristics of a climate influenced strongly by monsoon cycles remain. Average climate data for Ubon Ratchathani and Udon Thani provinces have been considered for the 2003 to 2013 period (Figs 20–23). The Phu Pom and Phu Pha Dak areas, both with water pits, lie just a few hundred metres from the administrative border with those provinces, and global climatic change has also manifested itself in areas with water pits in northeastern Thailand.

December to April, which were formerly *relatively* dry months, have now become *extremely* dry, with hardly any rainfall. For example, during the research activities in Ubon Ratchathani Province between 19 January and 08 April 2025, it rained for only 2–3 hours, all of it in one night. Global climatic conditions, characterized in the northeast of Thailand by 4–5 extremely dry months, lead to the transformation of the plateaus with water pits into areas similar to African savannas at these times. In contrast, during the monsoon season, starting at the end of May, there is extremely heavy rainfall, which is the driving factor in the formation of water pits.

In the past, average precipitation in northeastern Thailand was never high, with only 1399mm in Khon Kaen Province and 1515mm in Surin Province (Pfeffer, 2013, p.79). In comparison, the average precipitation in the Chanthaburi Province of Eastern Thailand was 3235mm, with 2466mm in the Phuket Province of Southern Thailand, (Pfeffer 2013, p.79). Similar, or even higher, values of average annual precipitation are also found in several parts of Europe, for example in the Pyrenees, the Alps, or in the Western Carpathians of Romania. There is, however, an essential difference, which can be summed-up as the combination of heavy precipitation with high average annual temperatures in northeastern Thailand – such high temperatures do not occur in Europe. This climatic combination appears to be essential not only for the formation of water pits, but also for development of similar landforms (such as gnammas – or gnamma holes – panholes, or weathering pits) on granitic and related rock types in other tropical or subtropical areas.

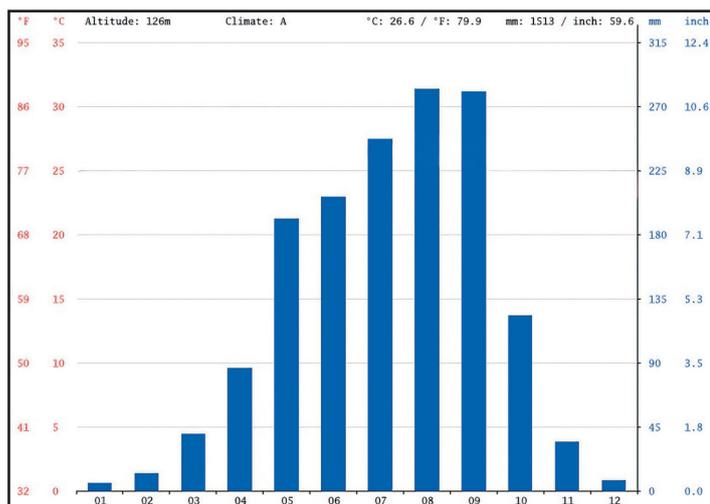


Figure 20: Average precipitation during 2003–2013 in Ubon Ratchathani Province (according to CLIMATE-DATA.ORG).

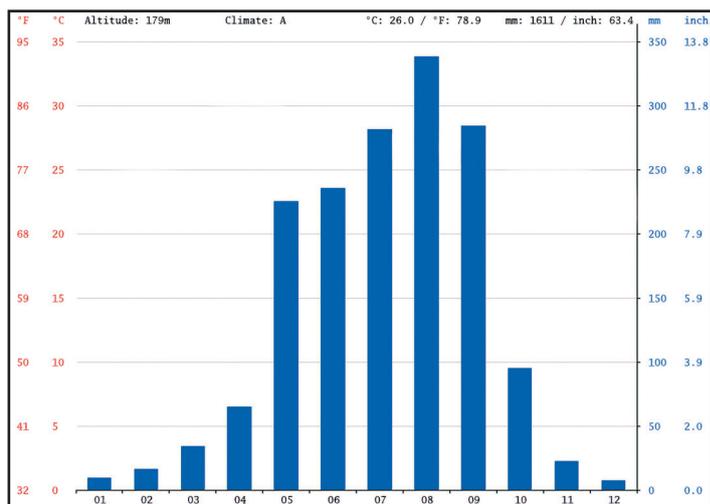


Figure 21: Average precipitation during 2003–2013 in Udon Thani Province (according to CLIMATE-DATA.ORG).

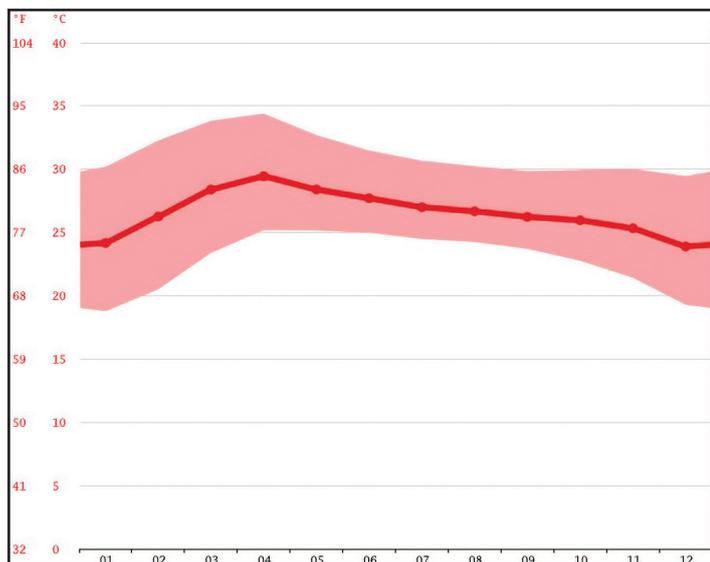


Figure 22: Average temperatures during 2003–2013 in Ubon Ratchathani Province (according to CLIMATE-DATA.ORG).

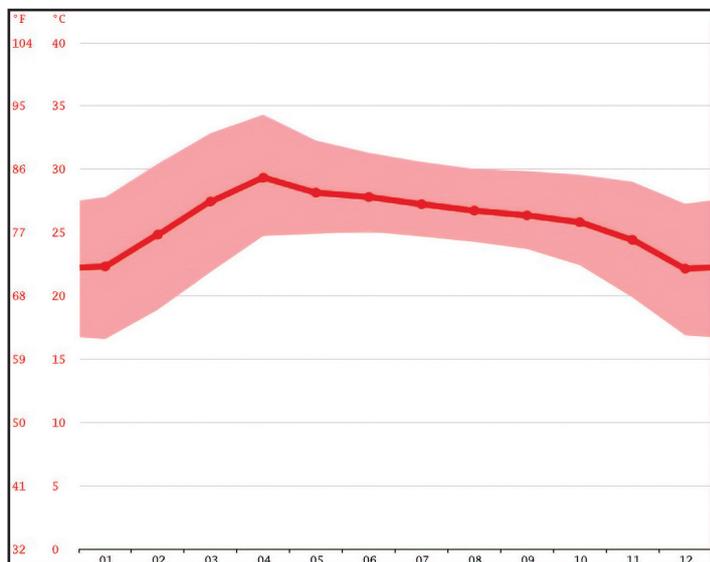


Figure 23: Average temperatures during 2003–2013 in Udon Thani Province (according to CLIMATE-DATA.ORG).

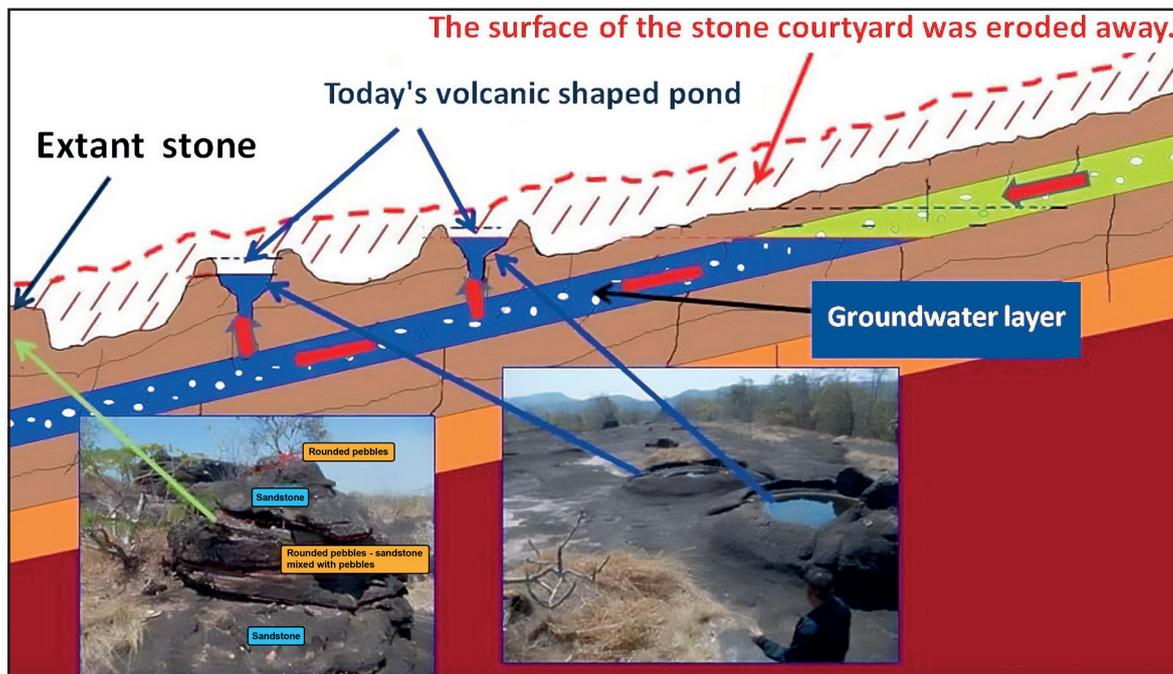


Figure 24: Model developed by the Department of Mineral Resources (DMR) Bangkok, to explain relationships at the Dong Luang water pits in Mukdahan Province.

[Source: Facebook: Literal translations into English of the original Thai labelling are by Paradee Jinawan and Darin Gowland.]

Note: The original figure includes the following text (translations as in the drawing) under the main panel:

“The present remains can be seen that the surface of the stone courtyard has decayed. And was corroded and lost a lot until the shape was changed from the past.”

Hydrogeology and hydrochemistry of the water pits

All of the water pits discussed here are fed exclusively by the rainwater that is abundant during the May to October monsoon season. During the dry season (November to April), mainly through evaporation, but also through infiltration, the water levels drop to between 15% and 75% of the initial volume. Water pits examined during the wet monsoon season were all completely water filled. Whereas water pits on Phu Pom Mountain are 145m above local groundwater table level, and other water pits on the Phu Sa Dok Bua and Phu Pha Dak plateaus are more than 250m above their local water table, geologists from the Department of Mineral Resources (DMR) in Bangkok have reached the unlikely conclusion that they are fed by groundwater (e.g. Fig.24). Proof that these water pits are unrelated to the water table was provided by results of chemical analyses of the groundwater in the Phu Pom area. Chemical values differ appreciably between the two situations.

Regional groundwater displays high concentrations of silica, whereas silica concentrations measured in the Phu Pom water pits are far lower. This is as would be expected if the water recharging the water pits comes only from precipitation.

On-site measurements and chemical analyses provide strong evidence that the water pits are not connected to the regional groundwater system. The reference groundwater sample (Drill –45m, Ban Kham Mae Mui, 2024) exhibits the highest pH value (7.29) among all samples (Table 1). In contrast, the water pits show lower pH values, consistent with rainwater being the dominant source (Thepanondh *et al.*, 2005). Furthermore, the measured SiO₂ concentrations support this interpretation. The groundwater sample contains 18.2 mg L⁻¹ SiO₂, a significantly higher value than in the water pits. Because silica originates primarily from the weathering of silicate rocks (Drever, 1997, 197–214), the low SiO₂ levels in the water pits suggest that there is only limited rock–water interaction, indicating short residence times and absence of aquifer connections.

Sample Name	On-site measurements		Results of water sample analyses with ion chromatography											Carbonate hardness ^a [mmolL ⁻¹]	Ion balance error ^b (%)
	Temperature [°C]	pH	SiO ₂ [mgL ⁻¹]	NH ₄ ⁺ [mgL ⁻¹]	Na ⁺ [mgL ⁻¹]	K ⁺ [mgL ⁻¹]	Mg ²⁺ [mgL ⁻¹]	Ca ²⁺ [mgL ⁻¹]	Cl ⁻ [mgL ⁻¹]	NO ₂ ⁻ [mgL ⁻¹]	NO ₃ ⁻ [mgL ⁻¹]	PO ₄ ³⁻ [mgL ⁻¹]	SO ₄ ²⁻ [mgL ⁻¹]		
Tham Pathaem National Park, 2023	28.3	6.68	–	0.41	2.65	3.03	2.45	28.90	3.00	< 0.5	< 0.5	< 0.5	< 0.5	1.64	3.7
Phu Pom No 1, 2023	31.2	4.96	–	0.65	1.57	1.63	2.93	12.25	1.27	< 0.5	< 0.5	< 0.5	< 0.5	0.85	4.6
Phu Pom No 2, 2023	30.8	5.96	–	0.78	2.59	1.32	2.62	11.64	1.77	< 0.5	< 0.5	< 0.5	< 0.5	0.80	7.9
Phu Pom No 3, 2024	31.7	6.83	4.4	1.04	3.48	5.02	1.58	5.63	4.57	0.17	0.50	0.11	0.83	0.41	13.7
Phu Pom No 4, 2025	34.0	6.05	4.2	< 0.1	1.61	0.54	1.52	9.27	2.48	< 0.1	0.12	< 0.1	< 0.1	0.59	1.0
Phu Pom No 5, 2025	26.6	5.98	< 1.0	< 0.1	1.34	4.26	1.19	7.87	3.45	< 0.1	< 0.1	0.62	0.93	0.49	4.1
Phu Pom No 6, 2025	28.0	4.50	< 1.0	2.62	2.56	2.88	1.44	10.72	4.56	< 0.1	< 0.1	0.66	0.23	0.65	12.7
Drill (–45m) Ban Kham Mae Mui, 2024	31.1	7.29	18.2	< 0.1	14.04	1.93	6.47	68.66	12.09	< 0.1	0.46	0.18	3.25	3.96	3.0

Table 1: On-site measurements and the results of the ion chromatography analyses of water samples collected from the water pits and from groundwater (Drill –45m Ban Kham Mae Mui), together with the determined carbonate hardness and ion balance error (IBF)

^a Carbonate hardness was calculated from the sum of the mass concentrations of calcium and magnesium divided by their molar masses: calcium (40.08 g mol⁻¹); magnesium (24.31 g mol⁻¹).

^b The ion balance error was calculated using the formula $IBF = \frac{\sum c(\frac{1}{z}cations) - \sum c(\frac{1}{z}anions)}{\sum c(\frac{1}{z}cations) + \sum c(\frac{1}{z}anions)} \cdot 100$; c is the molecular concentration; z is the charge number.

Molar concentrations of Ba and Sr determined with ICP-OES were included in the ion balance calculation. Results of the ICP-OES analysis are in Table 2.

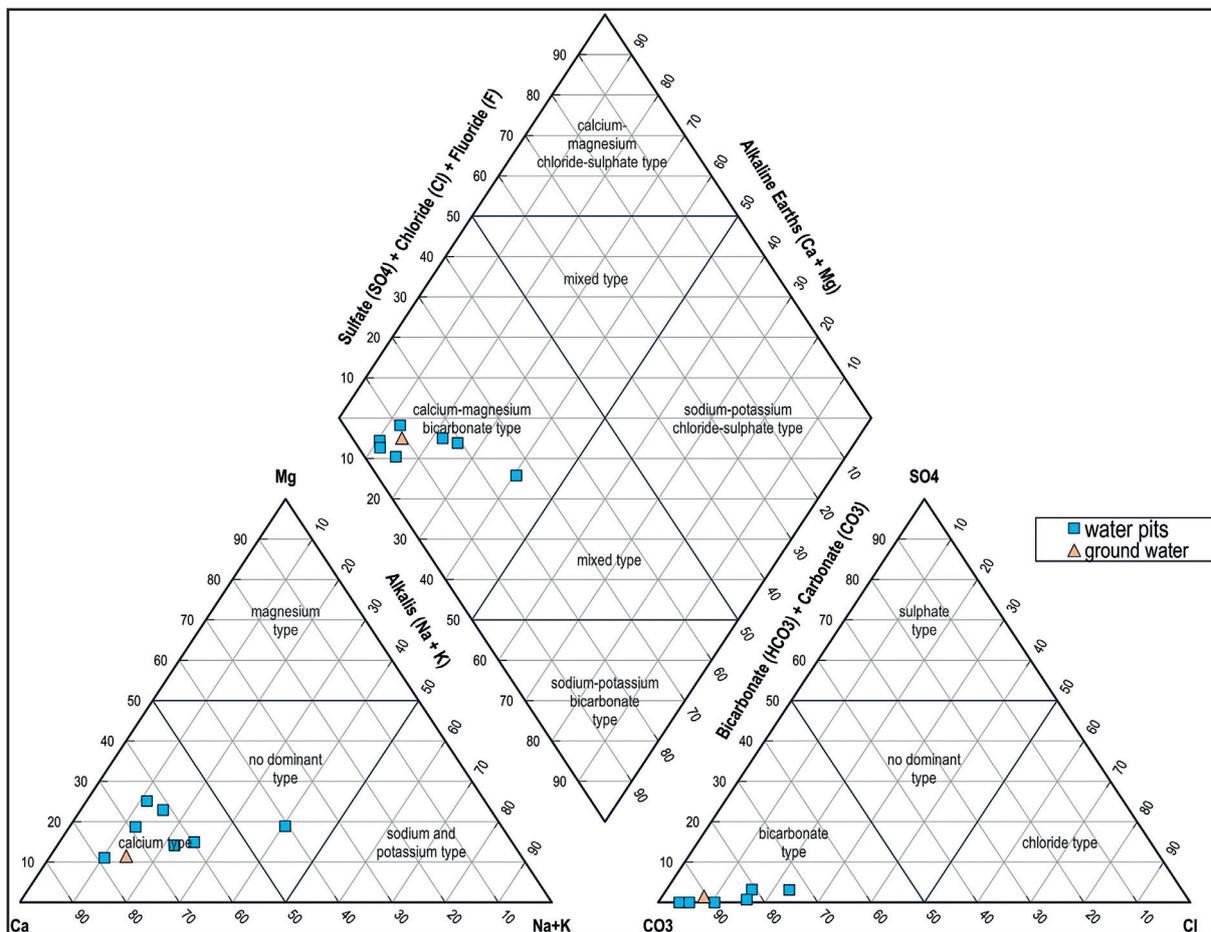


Figure 25: Piper diagram – prepared using the Excel template by Stosch (Version 1.1, 2022 – illustrating hydrochemical data of water samples from water pits (blue squares) and groundwater (orange triangles) in the study area. The cationic ternary plot (left) shows the relative proportions of calcium (Ca^{2+}), magnesium (Mg^{2+}), and the combination of sodium and potassium ($Na^+ + K^+$), expressed as percentages of the total cations. The anionic ternary plot (right) similarly represents the relative proportions of chloride (Cl^-), sulphate (SO_4^{2-}), and the combined bicarbonate and carbonate ($HCO_3^- + CO_3^{2-}$) ions. Data points from both ternary plots are projected onto the central diamond field, which displays the overall hydrochemical facies of the water samples.

As demonstrated by Laonamsai *et al.* (2025), surface waters in northern Thailand exhibit the typical Ca– HCO_3 signature that is common in karst regions. Piper diagrams (Piper, 1944; Stosch, 2022) provide a useful means of classifying water samples into water types; Figure 25, constructed from ion chromatographical data from the current research, confirms this classification (Table 1). Water samples from the water pits are depicted by blue squares, with the groundwater sample indicated by an orange triangle. All but one of the water pit samples, plus the groundwater sample, belong to the calcium type in the cationic ternary plot and to the bicarbonate type in the anionic ternary plot. Water sample Phu Pom No.3 falls in the *no dominant type* region in the cationic ternary plot. In the diamond projection all samples belong to the calcium–magnesium bicarbonate type. Calcium concentrations are, however, higher in the groundwater sample than in the water pit samples, which again supports an assumption that there is no aquifer connection. The main source of Ca^{2+} in these waters is the weathering of limestone, as described for example by Drever (1997, 41–68). In general, higher mass concentrations of the main cations and anions were determined for the aquifer water than for the water from the pits.

Several water pits contain measurable concentrations of ammonium, ranging from 0.4 to 2.6 $mg L^{-1}$ (Table 1). In addition to atmospheric input via rainwater (Paramee *et al.*, 2005), the microbial decomposition of organic material within the water pits plays a key role in ammonium accumulation (Edwards *et al.*, 2024). In contrast, no detectable concentrations of ammonium were found in the groundwater sample from the aquifer (Table 1), further supporting the development hypothesis presented here.

Moreover, the dense aquatic and marginal vegetation observed in many water pits indicates that nutrient availability is generally sufficient to support plant growth (Paramee *et al.*, 2005). The ICP-OES results (Table 2) also confirm that there is no connection between the aquifer and the water pits. Elevated levels of barium ($924 \mu g L^{-1}$), lithium ($18 \mu g L^{-1}$) and strontium ($413 \mu g L^{-1}$), which are of geogenic origin, were detected in the groundwater sample. Similar levels were not present in the water pit samples. In contrast to the aquifer water, iron ($0.04\text{--}0.6 \text{ mg L}^{-1}$) and zinc ($0.01\text{--}0.02 \text{ mg L}^{-1}$) are detectable in the water pits.

Sample Name	Al [$\mu g L^{-1}$]	As [$\mu g L^{-1}$]	Ba [$\mu g L^{-1}$]	Bi [$\mu g L^{-1}$]	Cd [$\mu g L^{-1}$]	Co [$\mu g L^{-1}$]	Cr [$\mu g L^{-1}$]	Cu [$\mu g L^{-1}$]	Fe [$\mu g L^{-1}$]	Li [$\mu g L^{-1}$]	Mn [$\mu g L^{-1}$]	Ni [$\mu g L^{-1}$]	Pb [$\mu g L^{-1}$]	Sr [$\mu g L^{-1}$]	Tl [$\mu g L^{-1}$]	Zn [$\mu g L^{-1}$]
Tham Pathaem National Park, 2023	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Phu Pom No 1, 2023	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Phu Pom No 2, 2023	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Phu Pom No 3, 2024	< 24.3	< 5	31	< 27.1	< 5	< 5	< 5	< 5	17	< 10	< 5	< 6	< 19	14	< 25	12
Phu Pom No 4, 2025	< 50	< 21.1	10.2	< 50	< 2.5	< 28.2	< 2.5	< 2.7	39.7	< 50	< 2.5	< 6.6	< 50	4.6	< 50	20.6
Phu Pom No 5, 2025	69.5	< 21.1	22.4	< 50	< 2.5	< 28.2	< 2.5	< 2.7	567.0	< 50	16.4	< 6.6	< 50	3.5	< 50	13.3
Phu Pom No 6, 2025	< 50.0	< 21.1	31.4	< 50	< 2.5	< 28.2	< 2.5	< 2.7	88.3	< 50	34.1	< 6.6	< 50	7.3	< 50	20.0
Drill (–45m), Ban Kham Mae Mui, 2024	< 24.3	< 5	924	< 27.1	< 5	< 5	< 5	< 5	< 10	18	6	< 6	< 19	413	< 25	< 5

Table 2. Results of ICP-OES analyses of water samples taken from the water pits and from groundwater (Drill –45m Ban Kham Mae Mui).

Genesis

In suitable settings, water pit formation takes place in several distinct stages:

1) Under favourable conditions – requiring particularly a slightly inclined plateau, with a maximum surface slope of 5% (less than 3°) – precipitation from the typically violent rain showers during the monsoon intersects cracks in the bedrock and begins to enlarge incipient depressions (Figs 26A and 26B). Weathering by the process of arenization results in quartz grains and small rock fragments being released from the sandstone's matrix.

Whereas it is also applied to weathering of granitic and other coarse-grained rocks, the term “arenization” was first used by Martini (1979), based on study of karst on sandstones in the Eastern Transvaal of South Africa. Subsequently, the term gained international approbation. It is a concept that attempts to explain the dissolution of rocks normally considered as being insoluble. The concept aims to “reconcile” two seemingly contradictory concepts, related to the occurrence of well-developed karst in rocks characterized by their low solubility and slow dissolution kinetics. Slow dissolution along crystal and grain boundaries reduces the coherence of the rock and increases its porosity. Subsequently, the loose particles and crystals are eroded and transported by surface- and subsurface-flowing water. In other words, a mechanical erosional process.

According to the concept developed by Martini (1979), dissolution is not responsible for the removal of a significant mass of rock but has a crucial preparatory role (De Waele and Gutiérrez, 2022, 115–117). The violent monsoonal rainfall generates circular currents in relatively small depressions (no wider than 0.4m – 0.8m) and the quartz grains, rock fragments and even small boulders (Figs 26C and 26D) are driven into a circular motion, and the classic physical erosional processes of abrasion and attrition, still reinforced in these sandstones by (dominantly matrix) dissolution, begin to excavate the water pits.

2) By minuscule increments a column of water begins to accumulate in the incipient water pits as erosion continues. As stated above, dissolution of calcium carbonate in the rock matrix (ubiquitous as a small percentage in the sandstones of the Khorat Plateau) continues in parallel with the physical erosion, and the excavation of vertical tubes continues. During the dry season the water level in the developing water pits is lower, such that the dissolutorial component continues only in the lower part. This explains the bell-shaped profiles of these cavities. Additional indications that development of the bell-shaped profile reflects ongoing dissolution that acts only within the lower part of the vertical tubes during the dry season are provided by water pits in the Phu Pom plateau. Here, the lower parts of two separate but adjacent water pits were widened by arenization until, eventually, they merged. At one site a small natural bridge is preserved.

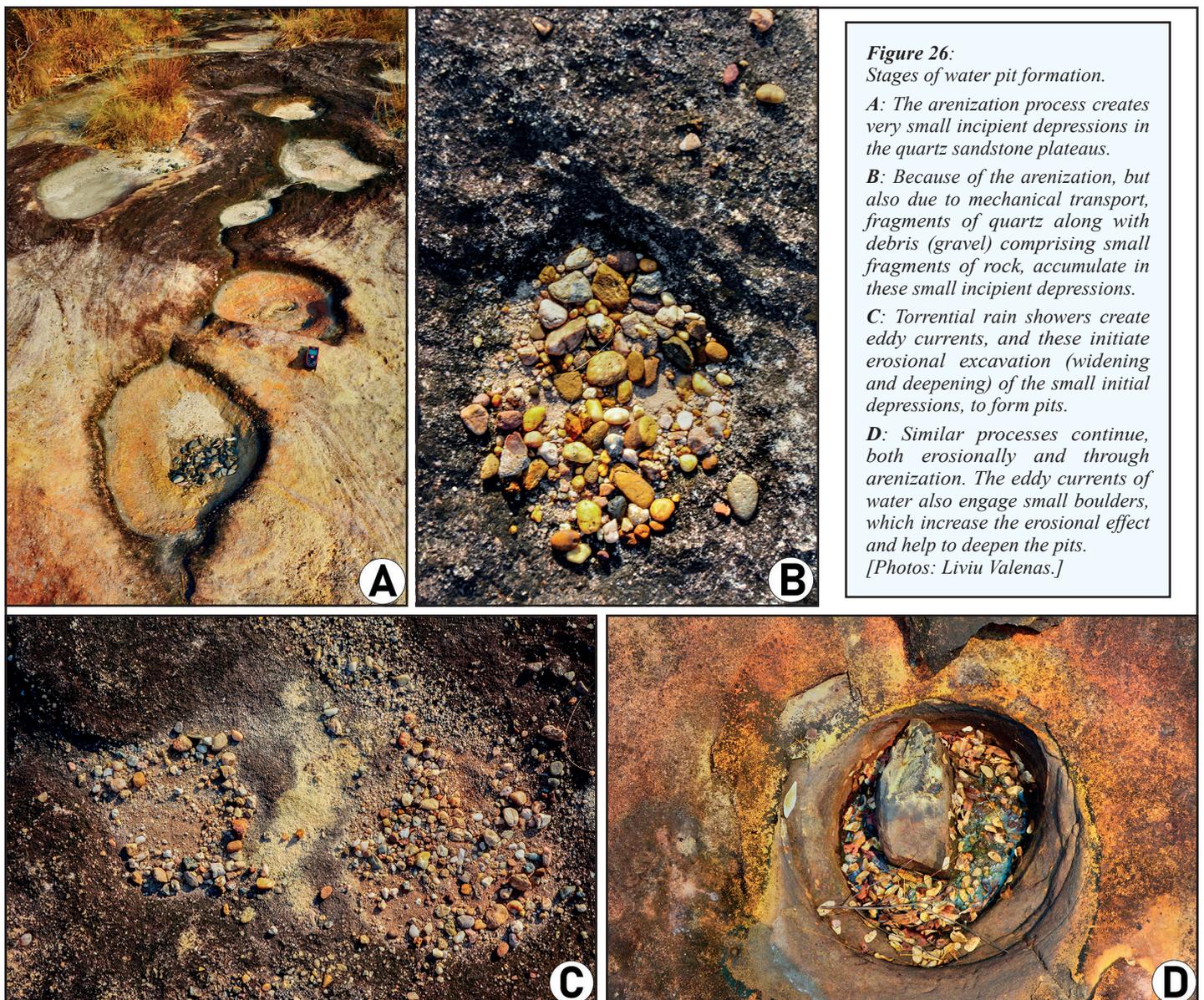


Figure 26:
Stages of water pit formation.

A: *The arenization process creates very small incipient depressions in the quartz sandstone plateaus.*

B: *Because of the arenization, but also due to mechanical transport, fragments of quartz along with debris (gravel) comprising small fragments of rock, accumulate in these small incipient depressions.*

C: *Torrential rain showers create eddy currents, and these initiate erosional excavation (widening and deepening) of the small initial depressions, to form pits.*

D: *Similar processes continue, both erosionally and through arenization. The eddy currents of water also engage small boulders, which increase the erosional effect and help to deepen the pits.*

[Photos: Liviu Valenas.]



Figure 27: Large, fossilized water pit in Phu Pha Mai, Mukdahan Province. It is similar in size to the water pits at Dong Luang in the same province. [Photo: Liviu Valenas.]

3) At least in some cases, the final stage of water pit formation is a senility phase. This is because, in some pits, aquatic plants typically appear on the water surface. Remains of dead plants are deposited on the floor of the pits, where a layer of detritus forms. This layer retards the arenization process by blocking (or reducing) downward advance of water, thus arenization is no longer possible and the water pits cannot deepen further (Fig.27).

Currently the age of the water pits is not clear. Whereas it is certain that some are forming now, development of the oldest observed examples is estimated to have begun in the Mid Pleistocene, with others starting in the Late Pleistocene.

Here a spatial model (Fig. 28) of the four main factors that contributed to the formation of these water-filled pits is presented for the first time. It is interesting that other researchers (e.g. Twidale and Vidal Romani, 2005; Dominguez-Villar, 2006; Migón, 2006; Aguilera *et al.*, 2014; Vidal Romani *et al.*, 2014; Timms and Halse, 2020; Wang *et al.*, 2023; Perez, 2023) who have dealt with granite weathering pits (gnammas) in tropical and subtropical areas have reached practically the same conclusions as those drawn here: the formation of these vertical tubes is driven by erosional and chemical processes, accelerated by biocorrosional effects related to plants and animals. These relationships apply only under tropical or subtropical climatic conditions accompanied by high volumes of precipitation.

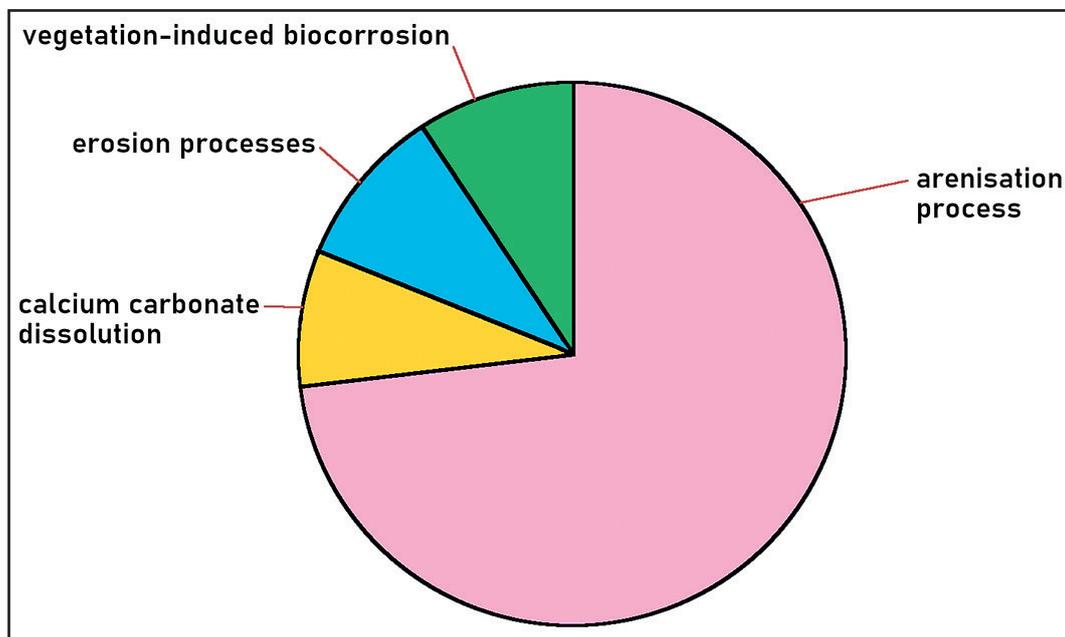


Figure 28: Model of the natural factors involved in the formation of the water pits on Mount Phu Pom.

Some additional clarification must now be provided. Almost all authors report direct relationships between silica (quartz) dissolution, high and extremely high temperatures, and alkaline pHs (e.g. Wray and Sauro, 2017; De Waele and Gutiérrez, 2022). This observation relates, however, to mineral silica, not to the erosion of quartz sandstones comprising cemented silica grains. Water samples collected in Tham Din Pieng Cave (Valenas, 2025, 49–55) in 2023–2025 as part of the current research, were exceptional in displaying an alkaline pH. Dozens of other water samples from quartz sandstones in northeastern Thailand display lower pH values, with the waters ranging from acidic to extremely acidic. Under these conditions, why are quartz sandstones dissolved? The explanation lies in the nature of the matrix that provides chemical cementation of the quartz grains, ensuring the initial induration of the sandstones. Specifically, the quartz sandstones of the Phu Phan Formation contain a significant percentage of calcium carbonate, forming at least part of the rock matrix, and acidic waters interact predominantly with this component of the cement.

Concluding remarks

Water pits in northeastern Thailand do not represent pseudokarst but are part of a karst landscape typical of the sandstones in this country, which is the so-called silicate karst or sandstone karst discussed by Mouret and Mouret (1994, 6–9), Mouret (2004, 55–56) and Mouret (2017, 174–179). During the past three decades, more and more karstologists have repudiated the view that sandstone karst is pseudokarst. In 1993 Robert Wray (Dunkley *et al.*, 2018) addressed the 19th Biennial Conference of the Australian Speleological Federation in Launceston, Tasmania (Wray, 1993, 1995). His paper was entitled “*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 ...”

As was observed by Wray (*in* Wray and Sauro, 2017, 520–557):

“... 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”
(Dunkley *et al.*, 2018).

Slightly more recently, Brazilian researchers and the French karstologist Joel Rodet (Pereira *et al.*, 2022, 259–262) wrote that karst on sandstones is not pseudokarst but true karst. A similar conclusion had previously been reached by Pfeffer (2010, 85–90).

The genesis of these water-filled vertical pits might also give rise to other interpretations, but it is clear that neither their formation nor the source of their water supply has any connection with deeper groundwater. Relatively recently, landforms that partially resemble the water pits of northeastern Thailand have been described in the Northern Harz (Saxony Anhalt, Germany), also in quartz sandstones (Fricke, 2023, 110–118), and they are described clearly as “silicate karst”, not pseudokarst. There is, however, a major difference between the forms described by Fricke and those in Thailand – the dimensions of the German examples described are tiny. A possible explanation for the differences in dimensions is that the monsoon climate existing in northeastern Thailand, with its abundant heavy rain showers and high water-temperatures, is absent in North Germany. It has not yet proved feasible to assess exactly what the effect of global climate change will be upon the type of water pits described here, but it is assumed that there will be a profoundly negative impact.

Finally, it must be emphasized that many aspects regarding the genesis and development of these water pits remain unclear. For example, in some plateaus in northeastern Thailand, located at the same relative height, with the same relief and apparently the same rocks, why do these karst formations not appear at all? A mystery still exists regarding some water pits (described by the Department of Mineral Resources in Bangkok) in the Dong Luang area (Fig.29) of Mukdahan Province; not only do these pits have large diameters, but they also have sandstone “collars” that appear to be of natural origin. Perhaps for these large-diameter water pits, the genetic model developed above for pits with smaller diameters is only partially valid. One more conclusion appears to be inevitable – in the future, multidisciplinary research into the water pits of northeastern Thailand must continue.

Figure 29:

The three photographs to the right illustrate water pits on the Dong Luang plateau in Thailand’s Mukdahan Province. There are three water pits with “collars” on the plateau. Details of the genesis of these “collars” are currently unclear, but it appears certain that they have a natural origin. These examples are developed at the same quartzite sandstone horizon that hosts the other water pits described above.

[Photos: Liviu Valenas.]

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References

- Aguilera, E Y, Sato, A M, Llambias, E, and Tickyj, H, 2014. Erosion surface and granitic Morphology in the Sierra de Lihuel Calel, Province of La Pampa, Argentina. Book Chapter, in: Rabassa, J and Ollier, C (eds), *Gondwana Landscapes in southern South America*. [Springer Earth System Sciences.] [https://doi.org/10.1007/978-94-007-7702-6_14]
- Booth, J and Sattaryarak, N, 2011. Subsurface Carboniferous – Cretaceous geology of NE Thailand. 185–222 (Chapter 9) in Ridd, M E, Barber, A J, and Crow, M J (eds), *The Geology of Thailand*. [London: Geological Society.]
- Cucchi, F, 2009. Kamenitzas. 139–150 (Chapter 12) in Ginés, A, Knez, M, Slabe, T, and Dreybrodt, W (eds), *Karst rock features - Karren sculpturing*. [Ljubljana: ZRC Publishing.] 561pp.
- De Waele, J and Gutiérrez, F, 2022. *Karst Hydrogeology, Geomorphology and Caves*. [Wiley Blackwell.] 888pp.
- Doerr, S H, 2000. Morphology and genesis of some unusual weathering features developed in quartzitic sandstone, North-Central Thailand. *Swansea Geographer*, Vol.35, 1–8.
- Domínguez-Villar, D, 2006. Early formation of gnammas (weathering pits) in a recently glaciated area of Torres del Paine, southern Patagonia (Chile), *Geomorphology*, Vol.76, 137–147. [https://doi.org/10.1016/j.geomorph.2005.10.006]
- Drever, J I, 1997. *The Geochemistry of Natural Waters. Surface and Groundwater Environments*. 3rd Edition. [Upper Saddle River, New Jersey: Prentice Hall.] 450pp.
- Dunkley, J R, Ellis, M, and Bolger, T, 2018. Unusual caves and karst-like features in sandstone and conglomerate in Thailand. *Helictite*, Vol.43, 5–31.
- Eberhard, R and Sharples, C, 2013. Appropriate terminology for karst-like phenomena: the problem with “pseudokarst”. *International Journal of Speleology*, Vol.42(2), 109–113.
- Ellis, M, 2017. *The Caves of Thailand, Volume 1, Eastern Thailand*. [Somerset: Shepton Mallet.] 311pp.
- Edwards, T M, Puglis, H J, Kent, D B, Durán, J L, Bradshaw, L M, and Farag, A M, 2024. Ammonia and aquatic ecosystems – A review of global sources, biogeochemical cycling, and effects on fish. *The Science of The Total Environment*. 907, 167911. [https://doi.org/10.1016/j.scitotenv.2023.167911]
- Fricke, U, 2023. Zur Genese der Napfkarren im Unterkreidesandstein bei Langenstein im Nordharzvorland (Sachsen-Anhalt) – ein Beitrag zur Silikatverkarstung. *Mitteilungen des Verbandes der deutschen Höhlen- und Karstforscher*. Vol.69(4), 110–118.
- Ginés, A, Knez, M, Slabe, T, and Dreybrodt, W (eds), 2009. *Karst rock features – Karren sculpturing*. [Ljubljana: Založba ZRC.] 561pp.
- Grab, S W, Goudie, A S, Viles, H A, and Webb, N, 2011. Sandstone geomorphology of the Golden Gate Highlands National Park, South Africa, in a global context. *Koedoe*, Vol.53(1), 14pp. [https://doi.org/10.4102/koedoe.v53i1.985]
- Grootaerd, D, 2024. Zandsteengrotten verkennen in Thailand. *Spelerpes*, 2024/1, 25–27.
- Halliday, W R, 2004. Pseudokarst. 604–608 in Gunn, J (Editor), *Encyclopedia of Caves and Karst Science*. [New York & London: Fitzroy Dearborn.] 902pp.
- Knight, J and Grab, S W, 2022. Basalt pseudokarst development in the Lesotho Highlands, southern Africa. *Quaternary International*, Vols. 611–612, 29–40.
- Laonamsai, J, Patsinghasanee, S, Kamdee, K, Inseepong, N, Pakoksung, K and Chuenchum, P, 2025. Hydrogeochemical evaluation of water supplies across Thailand. *Water Research*, Vol.284. [https://doi.org/10.1016/j.watres.2025.123980]
- Martini, J E J, 1979. Karst in black reef quartzite near Kaapsehoop, eastern Transvaal. *Annals of the South African Geological Survey*, 13, 115–128.
- Meesook, A, 2011. Cretaceous. 169–184 (Chapter 8) in Ridd, M E, Barber, A J, and Crow, M J (eds), *The Geology of Thailand*. [London: Geological Society.] 626pp.
- Migoñ, P, 2006. *Granite Landscapes of the World*. [Oxford UK: Oxford University Press, Oxford.]
- Mouret, C, 2004. La spéléogénèse des grès: quelques principes fondamentaux. *Actes de 14ème Rencontre d'Octobre, Florac, Spéleo-Club de Paris*, 55–56.
- Mouret, C, 2017. Some fundamental features of speleogenesis in sandstone. *Proceedings of the 17th International Congress of Speleology, Sydney*, Vol.2, 174–179.
- Mouret, C and Mouret, L, 1994. Prospection des karsts gréseux du nord-est de la Thaïlande (Esarn). *Spelunca*, Vol.55, 6–9.
- Nakhiya, T, 2020. Geological and speleological surveys in Pha Cham Samphan Bok Geopark. *Academic Report Sor. Thor. Khor*. 3/2563, Department of Mineral Resources, Bangkok, 79pp.
- Paramee, S, Chidthaisong, A, Towprayoon, S, Asnachinda, P, Bashkin, V N, and Tangtham, N, 2005. Three-year monitoring results of nitrate and ammonium wet deposition in Thailand. *Environmental monitoring and Assessment*, Vol.102(1–3), 27–40. [https://doi.org/10.1007/s10661-005-1593-9]
- Pereira, M C, Vasconcelos, A M, Rodet, J, Biazini Mendes, J, Catarucci, A F M, Souza (de), M E S, Oliveira Rodrigues (de), P C, Coelho, V V, and Araujo, R S, 2022. Overview of cave studies in quartzites, itabirites and granitoids in Southern Brazil. *Proceedings of the 18th UIS Congress*, III, 259–262.
- Pérez, F L, 2023. Geoecology of a granite dome: Spatial interactions between gnammas, rills, soils, and plant cover, Enchanted Rock (Texas, USA), *Catena*, Vol.223,106938. [https://doi.org/10.1016/j.catena.2023.106938]
- Pfeffer, K-H, 2010. *Karst – Entstehung-Phänomene-Nutzung, Studienbucher der Geographie*. [Stuttgart: Borntraeger Sciences Publishers.]
- Pfeffer, K-H, 2013. *Thailands vielfältige Landschaften*. [Stuttgart: Gebrüder Borntraeger.] 194pp.
- Ridd, M E, Barber, A J, and Crow, M J (eds), 2011. *The Geology of Thailand*. [London: Geological Society.] 626pp.
- Stosch, H-G, 2022. Excel template to plot hydrochemical data into a Piper diagram (1.1). Zenodo. [https://doi.org/10.5281/zenodo.5994293]
- Thepanondh, S, Ayers, G, and Hooper, M, 2005. Analysis of precipitation chemistry in northern Thailand. *Clean Air and Environmental Quality*, Vol.39(4), 43–47.
- Timm, B V and Halse, S H, 2020. Rock pools (gnammas) in the Gibson Desert of Western Australia: unique formation and reasons for their limited biological diversity. *Journal of the Royal Society of Western Australia*, Vol.103, 103–110.
- Twidale, C R and Bourne, J A, 2018. Rock basins (gnammas) revisited. *Géomorphologie : relief, processus, environnement*, Vol.24(2), 139–149. [https://doi.org/10.4000/geomorphologie.11880]
- Twidale, C R and Vidal Romani, J R, 2005. *Landforms and Geology of Granite Terrains*. [Leiden, The Netherlands: A A Balkema.]
- Valenas, L, 2019. Speleological exploration in Thailand 2009–2019. *13th Eurospeleo Forum, Sofia, Bulgarian Federation of Speleology*, 40–41.
- Valenas, L, 2020. Speleological explorations in the North-East of Thailand. *Cave Exploring*, Vol.16(1), 13–18.
- Valenas, L, 2023a. Geomorphology and hydrogeology of genuine karst in the quartzitic sandstones of northeast Thailand. *14th International Symposium on Pseudokarst, Karlow*, 66–70.
- Valenas, L, 2023b. Silikatkarst in den quarzitischen Sandsteinen Nordost-Thailands. *Mitteilungen des Verbandes der deutschen Höhlen- und Karstforscher*. Vol.69(3), 76–83.
- Valenas, L, 2024a. Geomorphology and hydrogeology of siliceous karst in the sandstones of northeast Thailand. *International Union of Speleology, Pseudokarst Commission Newsletter*, 31, 30–41.
- Valenas, L, 2024b. Karst geomorphology on sandstones in the area of Ban Dong Tong (Nong Khai), Thailand. *Helictite*, Vol.49, 19–26.
- Valenas, L, 2025a. Geomorfologie und Hydrogeologie der Tham Din Pieng, der längsten Sandsteinhöhle Thailands. *Mitteilungen des Verbandes der deutschen Höhlen- und Karstforscher*, Vol.71(2), 49–55.
- Valenas, L, 2025b. Thaïlande: le Système Seri Thai – Une exploration particulièrement difficile. *Spéleo Magazine*, 132, 32–34.
- Valenas, L, 2025c. Internationale Höhlenforschung – Expedition EXPLO THAILAND 2025. *ACAMONTA*, Vol.32, 147–148.
- Valenas, L, 2025d. Internationale Höhlenforschung – EXPLO THAILAND 2025. *Thailand-Rundschau*, Vol.3/2025, 105–106.
- Valenas, L, 2025e. Tham Phu Pom Cave, een labyrint in de kwartsiet zandsteen van Thailand, *Spelerpes*, 2025/2, 40–46.
- Valenas, L, Ellis, M and Valenas, M, 2025. Seri Thai System, a large cave in the quartz sandstones of North-east Thailand, geology, morphology and genesis, *Helictite*, Vol.50, 27–43.
- “Various”, 2021. *Caves and karst of Thailand*. Department of Mineral Resources, Bangkok. 108–119, 176–187.
- Veeravinantakul, L A, Kanjanapayont, P, Sangsompong, A, Hasebe, N, and Charasuri, P, 2018. Structure of Phu Phan Range in the Khorat Plateau: its apatite fission track ages and geological syntheses. *Bulletin of Earth Sciences of Thailand*, Vol.9(1), 8–16.
- Vidal Romani, J R, Vaquero, M, and Sanjurjo, J, 2014. Granite landforms in Galicia. 63–69 in Gutiérrez, F and Gutiérrez, M (eds), *Landforms and Landscapes of Spain*. [Dordrecht: Springer.]
- Wang, W, Feng J, and Qui, M, 2023. Mineral weathering and element migration in granite weathering pits (gnammas): a case study in Eastern China. *Minerals*, Vol.13(1), 70. [https://doi.org/10.3390/min13010070]
- Wongklo, K, Buffetaut, E, Khamha, S, and Lauprasert, K, 2019. Spinosauridtheropod teeth from the Red Beds of the Khok Kruat Formation (Early Cretaceous) in Northeastern Thailand. *Tropical Natural History*, Vol.19(1), 8–20.
- Wray, R, 1993. Solutional landforms on silicates: largely ignored or largely unrecognised? *Proceedings of the 19th Biennial Conference, Australian Speleological Federation, Launceston*. 32–43.
- Wray, R, 1995. Solutional landforms in quartz sandstones of the Sydney Basin. PhD thesis, School of Geosciences, University of Wollongong. [http://ro.uow.edu.au/theses/19]
- Wray, R A L and Sauro, F, 2017. An updated global review of solutional weathering processes and forms in quartz sandstones and quartzites. *Earth Science Reviews*, Vol.171, 520–557.