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# Characterisation of potholes formed on bedrock sandstones at Loei Dun, Phetchabun Geopark, Thailand

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**Abstract**

Phetchabun National Geopark comprises varied geosites; one of the fluvial bedrock landforms distinguished here is Loei Dun. This shows many potholes in Mesozoic sandstone of the Nam Phong Formation (Khorat Group). A genetic study of the occurrence of the Loei Dun potholes lends it a higher geoheritage value. For the present study we did fieldwork and carried out petrographical and geotechnical analyses so as to classify and characterise the potholes and consider geotourism potentials. Petrographically, the bedrock sandstone is a lithic arenite which consists of 82-96 percent very fine to coarse, well-sorted subangular sand with low sphericity and calcite cementation. Our geotechnical analysis of the bedrock sandstone suggests that pothole occurrence may be linked to low rock strength and slake durability index with high rock absorption and porosity at Loei Dun. Field studies confirmed the impact of other factors such as joints/faults, fluvial conditions and biological weathering. There are five types of pothole, viz., simple ones, potholes with external furrows, compound potholes, breached potholes and lateral ones. The present study adds educational value to the Loei Dun geosite at Phetchabun Geoparks and cultural and economic aspects can be further strengthened through the development of geotourism in the area.

**Key words:** geomorphology, landforms, geotourism, lithic arenite, geoheritage, Mesozoic, Nam Phong Formation

## 1. Introduction

A geopark is an area that combines conservation and sustainable use of geological heritage for the furthering of better economic conditions for people living in the area (Mc Keever & Zouros, 2005). Thus, a geopark plays an essential role in protecting natural and geological heritage through geotourism, which currently is developing worldwide and will become an important touristic activity in Thailand (Singtuen & Won-In, 2018; Singtuen et al., 2019; Vivitkul & Singtuen, 2021). In Thailand, there are three ranks of geopark, namely local geoparks (LG), national geoparks (NG) and UNESCO Global Geoparks (UGG). Currently, Thailand has these six geoparks: Satun UGG, Khorat NG, Pahchan-Sampanbok NG, Phetchabun NG, Khon Kaen NG and Tak Petrified Wood LG (Vivitkul & Singtuen, 2021). Phetchabun Geopark is one of four national geoparks in Thailand and is defined as the land of palaeo-sea and two microplates, indicative of subduction. This geopark is located in the province of Phetchabun in the north of the country, and has numerous geoheritage resources that are linked to anthropological, cultural and natural aspects (Paungya et al., 2020). A categorised system for the conservation of geological heritage, geo-education and geotourism comprises geosites at the smallest spatial scale, geotope confines at larger scales and geoparks typically at the largest scale (Gray, 2004, 2005, 2008; Eder, 2008; Ieleniz, 2009; Joyce, 2010; ProGEO, 2011; GSA, 2012; Moufti & Németh, 2013, 2016; Thomas, 2016). A geopark would typically be a nationally protected area covering a number of geological heritage sites of particular importance, rarity or aesthetic appeal and achieves its goals through conservation, education and sustainable development of geological heritage through geotourism (Dowling & Newsome, 2010). A SWAT analysis undertaken after field studies of several geologically important sites in the Kachchh Basin (western India) offered potentially important factors of geopark development and demonstrated how educational institutions in such areas could play an important role in convincing local authorities and architects (Bhosale et al., 2021; Chauhan et al., 2021).

Ranking among outstanding geosites in Thailand is Loei Dun, representing a pothole-dominated fluvial erosional landform along the River Loei. Potholes occur when the bedrock of the river contains joints or fractures with sufficient sediment supply, a flow of water with a gradient or a link to a tectonically active terrain (Thakkar et al., 2006; Sane et al., 2020). Sediment particles, ranging from sand grains aud suspended solids to large boulders are essential for abrasion; in addition, eddy currents and cracks in river beds cause pitting (Elston, 1917, 1918; Alexander, 1932; Álvarez-Vázquez & Uña-Álvarez, 2017; Ji et al., 2018). On both morphological and mechanical grounds, Richardson & Carling (2005) noted three types of pothole: simple ones, potholes with external furrows and compound potholes, while Ängeby (1951) opined that the term pothole referred to any scoured depression on bedrocks. Potholes are also classified according to the complexity of erosion, as breached potholes and lateral potholes (Maxson & Campbell, 1935; Zen & Prestegaard, 1994; Pelletier et al., 2015).

Thailand covers two significant geoheritage sites with potholes. One of these is Loei Dun, for which, however, there is insufficient geological information pertaining to rock characteristics and pothole formation. The other is Sam Phan Bok along the River Mekong in the province of Ubon Ratchathani, the easternmost edge of the region, which represents in excess of 3,000 potholes in the Phu Phan Formation, which comprises sandstone mixed with gravel. These potholes occur in the centre of the large syn-

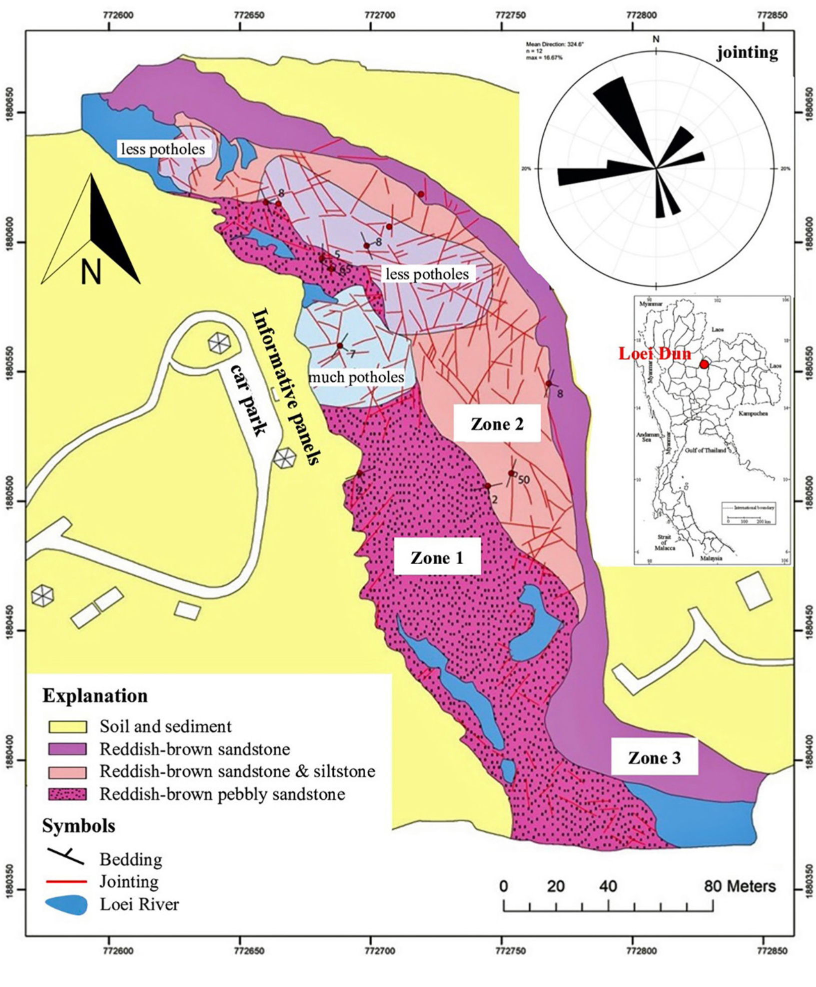


**Fig. 1.** Geological map of Loei Dun, Phetchabun Geopark, Thailand (geological data modified from DMR, 2007, 2020), with three zones of potholes and Stereonet pole plot of joint orientations.

cline in subhorizontally bedded sandstones. Formation of the Sam Phan Bok is primarily related to the fact that the stream eroded the rocks, breaking them down to sand faction and polishing them until becoming a pothole (Udomsak et al., 2021). Therefore, there is a strong need to understand the relationship between pothole occurrence and rock properties, which ultimately will help provide better data to tourists and local people and local guides in the Phetchabun geopark alike. Moreover, this work will benefit geo-eduction at the geopark and help develop sustainable geotourism through systematic geological understanding.

## 2. Geological setting

The Loei Dun geoheritage site represents a unique geomorphological feature that is related to long-term bedrock erosion by the River Loei. This site is located in Ban Huai Kapo (Lak Dan Subdistrict, Nam Nao District, province of Phetchabun) and comprises terraces along the River Loei, mountains and forests that surround it. The total area measures 50 by 200 metres and approximately 9,500 square metres. The Loei Dun geoheritage site comprises sandstone of the Nam Phong Formation of the Khorat Rock Group (DMR, 2007, 2020). Racey et al. (1994, 1996) noted that the lower portion of this formation, which is datek as Late Triassic, was separated from the rest of the Khorat Group by a hiatus. The age of the upper portion of the Nam Phong Formation is poorly constrained by palynological data which merely indicate that it is neither Pliensbachian, nor Late Jurassic. The upper Nam Phong Formation is provisionally dated as Late Jurassic based on the age of the overlying Phu Kradung Formation (Buffetaut et al., 1993; Racey et al., 1994; Racey & Goodall, 2009). The Loei Dun geoheritage is divided into three zones; the first is a reddish-brown, pebbly sandstone with many pothole characteristics, while the second refers to reddish-brown sandstone and siltstone, with a small number of potholes. The third is a reddish-brown sandstone with almost no potholes (Fig. 1). This area presents four joint sets with NW–SE, N–S, NE–SW and E–W directions.

## 3. Methodology

The present study characterises the rocks in the three zones of the Phetchabun Geopark (Loei Dun area) on the basis of the number of potholes. Detailed fieldwork and mapping was carried out, following a study of literature sources on general geology. Our analyses include sampling, rock description, measurements of structures, pothole classification (Maxson & Campbell, 1935; Zen & Prestegaard, 1994; Richardson & Carling, 2005) and evaluation of geotourism. Rock strength was also studied in the field, using a Schmidt Rebound Hammer. Large-scale field investigations and geomorphological analysis by Google Earth Pro 7.3.3.7786 (64-bit) with a NVIDIA Graphics Driver (00027.00020.00100.08681) were integrated in order to determine the area, scope and factors of potholes.

Ten samples were collected for petrographical study at the Department of Geotechnology, Khon Kaen University, using ZEN core Imaging Software, linking ZEISS imaging and polarised light microscope. Petrographical data were used to identify texture, mineral composition and rock names, following Dott (1964) and Pettijohn (1975). Geotechnical studies were carried out to determine porosity, specific gravity and water absorption according to the ASTM C127-15 (2015) standard, as well as durability to weathering (Slake Durability Index) following ASTM D4644-16 (2016) at the geological engineering laboratory, Department of Geotechnology, Khon Kaen University.

Porosity, specific gravity and water absorption were calculated by equations 1, 2 and 3, respectively, where $W_{sat}$ means the weight of the rock when saturated with water, weighed in air. $W_{sub}$ means the weight of the rock saturated with water, weighed in water. $W_{dry}$ means the weight of the dry rock studied. The Slake Durability Index ($Id_n$) was analysed by equation 4, where $W_{mn}$ is the weight of dry rock with the remaining container in each cycle, while $W_d$ is the weight of the container. The weight of dry rock with the remaining container is presented as $W_m$ in the equation.

$$\text{porosity} = \frac{W_{sat} - W_{dry}}{W_{sat} - W_{sub}} \times 100 \qquad (1)$$

$$\text{specific gravity} = \frac{W_{sat}}{W_{sat} - W_{sub}} \qquad (2)$$

$$\text{water absorption} = \frac{W_{sat} - W_{dry}}{W_{dry}} \times 100 \qquad (3)$$

$$\text{Stake Durability Index } (Id_n) = \frac{W_{mn} - W_d}{W_m - W_d} \times 100 \qquad (4)$$


**Fig. 2.** Outcrops of three zone in the study area of Loei Dun, Phetchabun Geopark, Thailand. **A –** Zone 1; **B –** Zone 2; **C –** Zone 3. For locations of the zones, see Figure 1.

## 4. Results

### 4.1. Petrography

Petrographical studies carried out in the three zones determined the number of potholes (Fig. 2). It follows that zones 1 and 2 comprise lithic arenite with pebbly lithic arenite, while only lithic arenite occurs in zone 3 (Fig. 3). All three zones represent similar petrological rock features, including grain size, sorting, roundness, sphericity and mineral composition (grain, matrix and cement). In addition, these lithic arenites comprise reddish-brown, very fine- to coarse-grained sandstones. The lithic arenites studied consist of 92.42 modal% of sediment grain and 7.58 modal% of matrix. Sediment grains comprise quartz, plagioclase, orthoclase, perthite, rhyolite, opaque mineral, epidote, muscovite and zircon (Fig. 4). The matrix consists mainly of quartz and rhyolite fragments with calcite cementation.

Quartz grains (36.20–58.68 modal%) present angular to subangular shapes with a low spherical appearance, measuring between 0.11 and 0.625 mm in size, i.e., very fine to coarse sand (Fig. 4A). Feldspar grains (5.43–10.54 modal%) composed of plagioclase, orthoclase and perthite, exhibit angular to subangular shapes with low sphericity, measuring between 0.06 and 0.3 mm, or coarse silt to medium-fine sand. Feldspar often exhibits a perthitic and myrmekitic texture (Fig. 4B). The rock fragment grains (28.12–49.02 modal%) are composed of rhyolite, opaque minerals, epidote, muscovite and zircon, exhibiting angular to subangular shapes with a low spherical appearance, measuring between 0.03 and 0.21 mm, or coarse to fine sand.

The matrix exhibits very fine-grained sediment, less than 0.05 mm, composed of quartz and rhyolite. Meanwhile, anhedral calcite crystals act as cement between sedimentary grains and matrix.

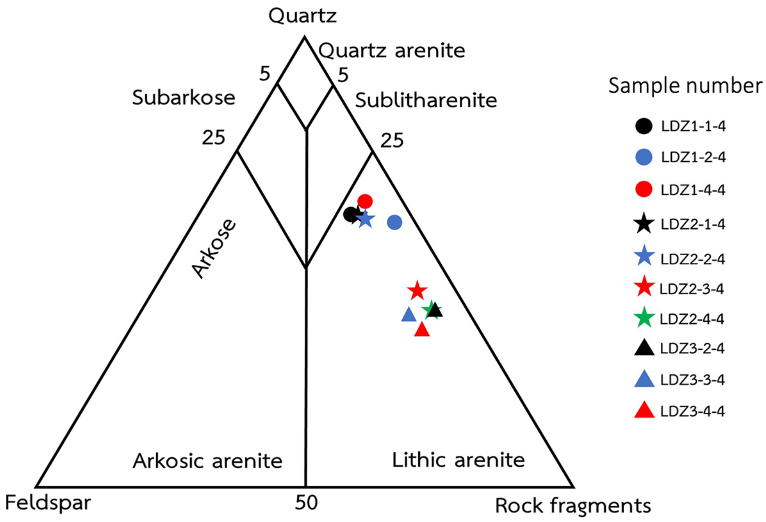


**Fig. 3.** Sandstone classification of rocks studiem at Loei Dun, presenting lithic arenite plotting (ternary diagram modified from Dott, 1964; Pettijohn, 1975).

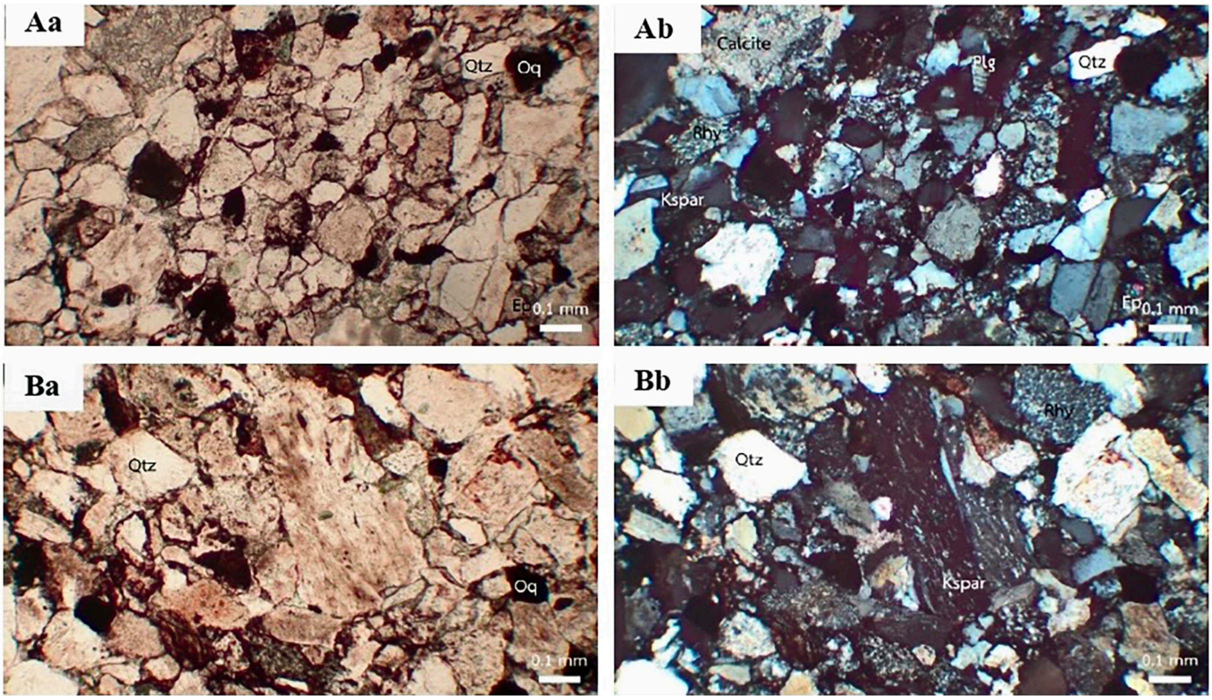


**Fig. 4.** Photomicrograph of lithic arenites (**A**) sample LDZ1-4-4 (from zone 1) and (**B**) sample LDZ3-3-4 (from zone 2) with a myrmekitic character, presented in plane-polarised light (**a**) and cross-polarised light (**b**). Qtz – quartz, Plg – plagioclase, Kspar – orthoclase, Rhy – rhyolite, Ep – epidote, Oq – opaque minerals.

## 4.2. Engineering geology

Results obtained from geotechnical testing of zones 1, 2 and 3 are listed in Table 1 and show rock strength, water absorption, porosity, specific gravity according to the ASTM C127-15 (2015) standard and slake durability index, following the ASTM D4644-16 (2016) standard.

Results of the Schmidt hammer testing of the three areas demonstrated that zone 1 had a large number of potholes, with a lower mean of compressive strength than zone 2, which had a lesser num-

**Table 1.** Rock strength, water absorption, porosity, specific gravity and slake durability index values of the sandstone bedrock in the Loei Dun geoheritage site.

| Geo-engineering test | Zone 1 | Zone 2 | Zone 3 |
|---|---|---|---|
| Rock strength (MPa) | 54.12 | 59.86 | 57.25 |
| Water absorption (%) | 2.15 | 1.62 | 2.14 |
| Porosity (%) | 5.44 | 4.17 | 5.42 |
| Specific gravity | 2.59 | 2.62 | 2.59 |
| Slake durability index I (%) | 99.05 | 99.38 | 99.23 |
| Slake durability index II (%) | 98.46 | 98.98 | 98.73 |

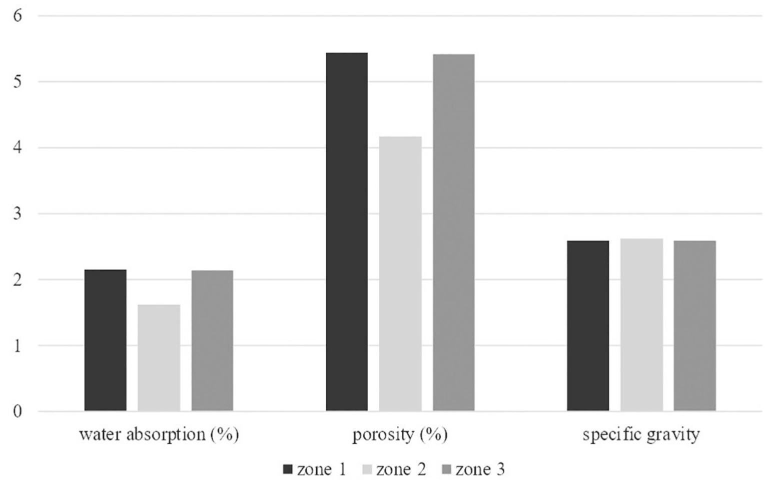


**Fig. 5.** Diagram of water absorption, porosity and specific gravity of sandstones studiem in the three areas of the Loei Dun geoheritage site.

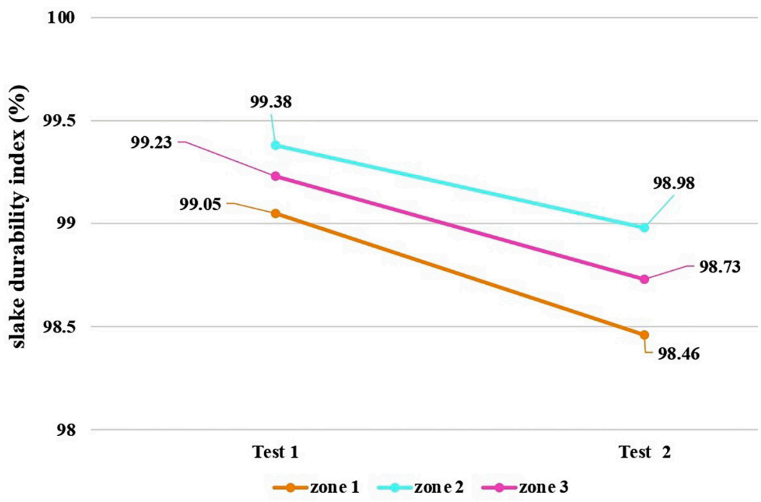


**Fig. 6.** Diagram presenting different slake durability indexes of rocks studied in the three areas of the Loei Dun geoheritage site.

ber of potholes, while zone 3 has no potholes at all. The minimum strength of rock in zone 1 supports the large number of potholes (Table 1).

Rocks in All three zones had a very similar specific gravity (Fig. 5), indicating that this is not a factor in pothole formation. Water absorption and porosity in zones 1 and 3 were similar, but slightly lower in zone 2, as shown in Figure 4. This suggests a good correlation, as low water absorption and lower porosity produces a large number of potholes in the study area. Values for zone 3 are close to those for zone 1, but the lack of potholes may be linked to the fact that it occurs on the bank of the river and has not connected with the dynamic river axis.

Slake durability index values for all areas are identical. However, zone 1 represents the least resistance, followed by zone 3, whereas zone 2 has the highest slake durability index values (Fig. 6). There are numerous potholes in zone 1, most likely because the rock is less resistant than in the zone 2. Similarly, zone 3 is also less resistant to corrosion than zone 2, but it lacks potholes which may be because the area is not exposed to water flow. It may be assumed that the slake durability index corresponds to the occurrence of potholes.

### 4.3. Pothole classification

Potholes in the Loei Dun geoheritage site are classified following Maxson & Campbell (1935), Zen & Prestegaard (1994), Richardson & Carling (2005) and illustrate varying sizes, from 10 to 200 cm. In zone 1 there are five types: simple potholes, potholes with external furrows, compound potholes, breached potholes and lateral potholes. Zone 2 displays only simple potholes.

– Simple potholes show an uncomplicated nature and lack a second recurrence within potholes. The upper part, where the water enters, is squarer than the outflow area. This is the commonest trait in the Lori Dun area, and is found in circular, ovoid, spirally furrowed and incipiently shaped potholes (Fig. 7A–D).
– Potholes with external furrows form through different corrosion rates in each direction of the opening where water flows before encountering a hole. These are composed of furrows at the entry and exit of the pothole (Fig. 7E–F).


**Fig. 7.** Simple potholes in the Loei Dun geoheritage site. **A** – Circular pothole; **B –** Ovoid pothole; **C –** Spirally furrowed pothole; **D –** Incipient pothole; **E –** Pothole with entry furrow; **F –** Pothole with exit furrow; **G –** Pothole with internal short furrows; **H –** Pothole with internal short furrows; **I –** Coalesced potholes; **J, K –** Natural arches; **L –** Lateral pothole; **M –** Closed lateral pothole; **N –** Closed lateral pothole and open lateral pothole; **O –** Open lateral pothole. The geological hammer measures 25 cm in length.

- Compound potholes are formed as small secondary potholes or occur together with primary potholes. In the study area, these consist only of short-curved furrows or potholes with short internal furrows (Fig. 7G–H).
- The breached pothole type is the group of perfect potholes that have completely damaged floors or walls as a result of corrosion and abrasion. Wall collapse may create a connection between two or more of these. The study area presents subgroups of this type as coalesced potholes and natural arches (Fig. 7I–K).
- Lateral potholes form pits on the river banks and show evidence of both vertical and horizontal erosion. Some parts of this area are classified as closed lateral and open lateral potholes (Fig. 7L–O).

The surface in this area encompasses various types of pothole, including complex ones. Coalesced potholes may be formed by interlocking, while walls and edges are corroded with some parts still in the same condition, resulting in rocks resembling Swiss cheese. Highly evolved potholes show that most are rounded, indicating that the ground, although separated, is connected by the ridge and apex that has split into the wall from the original potholes. The upstream side of the potholes shows smooth and curved ridges with eroded undercut, while the downstream one comprises a hook-like pothole (Fig. 7).

Natural arches and pillars can be found in the breach and coalesced types, which corrode the bottom of the pit; the wall does not collapse when a small portion of the damaged wall remains intact. The bottom area of potholes where the water can flow is called arches or pillars, depending on the orientation of the remaining walls.

## 5. Discussion on pothole origin and geotourism development

Petrographical studies of rock samples from all three areas suggest that they were of the same type of "lithic arenite", with calcite as cementing matrix. Sandstones studied are composed mainly of rock fragments (rhyolite), quartz and opaque minerals. Owing to the fact that the calcite cement is easily soluble, the sandstone corrodes easily.

Our geo-engineering tests and analyses indicate that rock strength, water absorption, porosity and slake durability index affect the formation of potholes. Zone 1 has many potholes with low strength and slakes durability index, meaning that this zone is more easily eroded than zones 2 and 3 by flowing water. Furthermore, zone 1 had high absorption and porosity, which caused rocks to absorb much water during the rainy season, while in the dry season, water in the rocks evaporates dissolving some matrix, hence secondary porosity is created which results in enhanced erosion (Udomsak et al., 2021). Bedrocks of zone 2 have greater strength and a higher slake durability index with lower water absorption and porosity, while zone 3 is on the river bank and lacks potholes, although it has a low strength and slake durability index with high water absorption and porosity.

Joints are an essential factor in pothole formation (Alexander, 1932; Sane et al., 2020), but it is insignificant in the study area. The direction of the current flow and bedrock slope can result in erosion, while

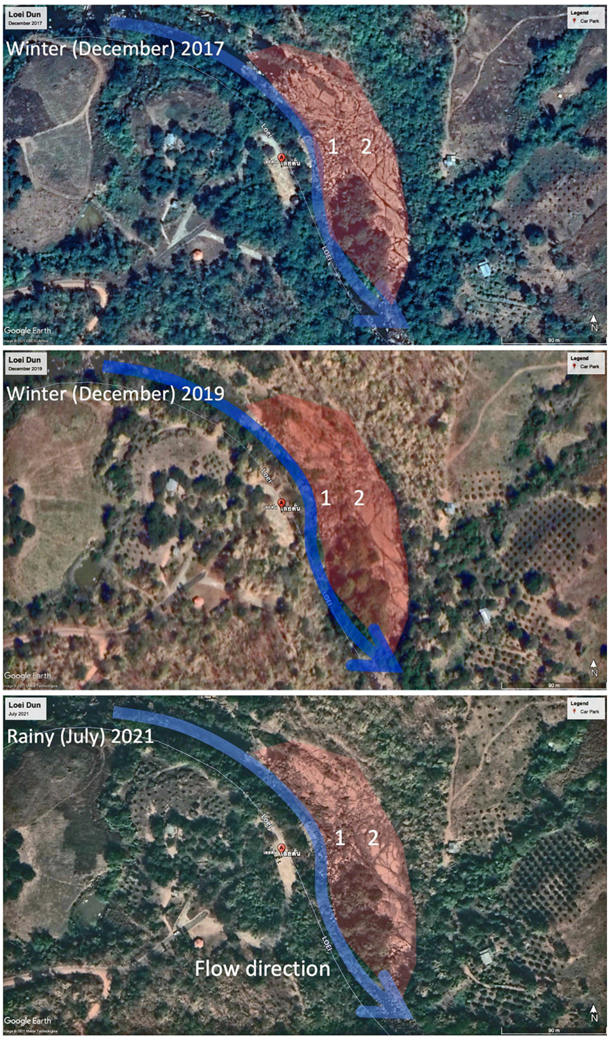


**Fig. 8.** Satellite image of pothole distribution, local forest and structural geology of the study area over the years (data analysed by Google Earth Pro). The blue line displays the flow direction of the River Loei; the red symbol is the Loei Dun geoheritage site.

the bedrock has a steep slope that can make the currents move more rapidly, increasing the severity of erosion (Das, 2018; Sane et al., 2020). In addition, the fluvial conditions (water velocity, erosional power of river currents, average monthly discharge, water depth, suspended load, etc.) can also affect the potholes. Water depth in all three zones is different, with zone 1 showing the greatest (1.6–2 m) and zone 3 the shallowest (10–30 cm). Thus, the difference in water depth explains varying rates of velocity and power of current as well as fluvial processes (corrasion, eversion etc.) that mainly affect the process of formation of potholes in zone 1. Furthermore, the erratic rainfall pattern, large temperature difference (data from Thai Meteorological Department) and ever-increasing vegetation in the Loei Dun area during the last decade may have enhanced bedrock erosion (Fig. 8).

Based on field data, we created a pothole occurrence model in the Loei Dun area; this comprises three main stages of evolution (Fig. 9). Initially, the River Loei flows along joints and cracks in zone 1, forming a large channel mainly by horizontal erosion. During the secondo stage vertical erosion is dominant in zone 1, then in zone 2, while zone 3 becomes elevated land as a riverbank and is not affected by the stream. The calcareous cementing matrix in zone 1 boosts erosion by dissolving it in sandstone bedrock. Finally, pothole evolution is assumed to be have gone about in a quite complex manner, starting with normal potholes with merely superficial vertical erosion, followed by potholes with external furrows, compound potholes, breached potholes and lateral potholes, respectively.

According to Brilha (2016), geoheritage should be recognised for its scientific value with four criteria: representativeness, integrity, rarity and scientific knowledge. The educational value comprises didactic potential, geological diversity and accessibility, while touristic value centers around scenery, interpretative potential and accessibility. The Loei Dun site meets all criteria of scientific, educational and touristic values and thus ranks among the prime geoheritage sites to provide knowledge of sedimentary rocks, structural geology, river processes, landforms and factors governing pothole formation and occurrence. The Phetchabun Geopark has installed informative geological panels to educate tourists

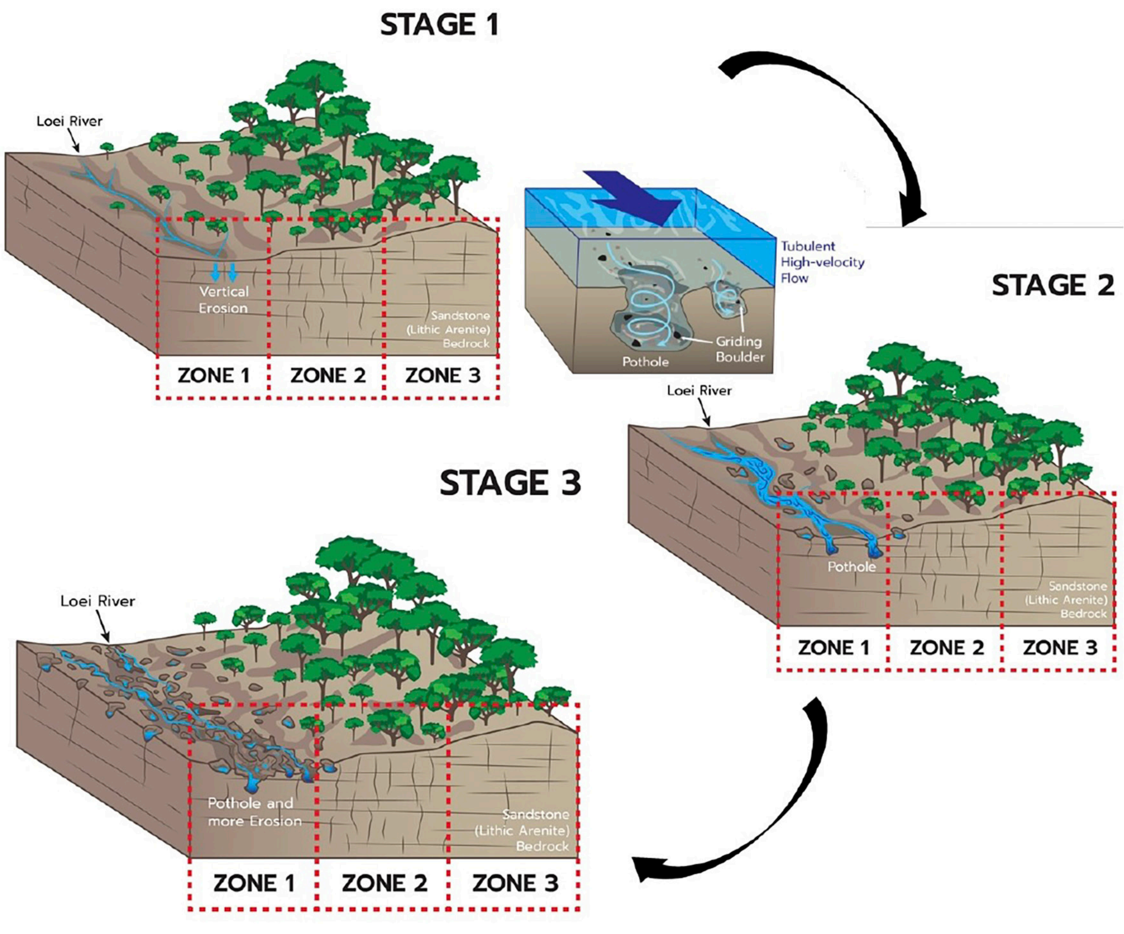


**Fig. 9.** Pothole Occurrence Model in three stages of the Loei Dun geoheritage site (Phetchabun Geopark, Thailand)

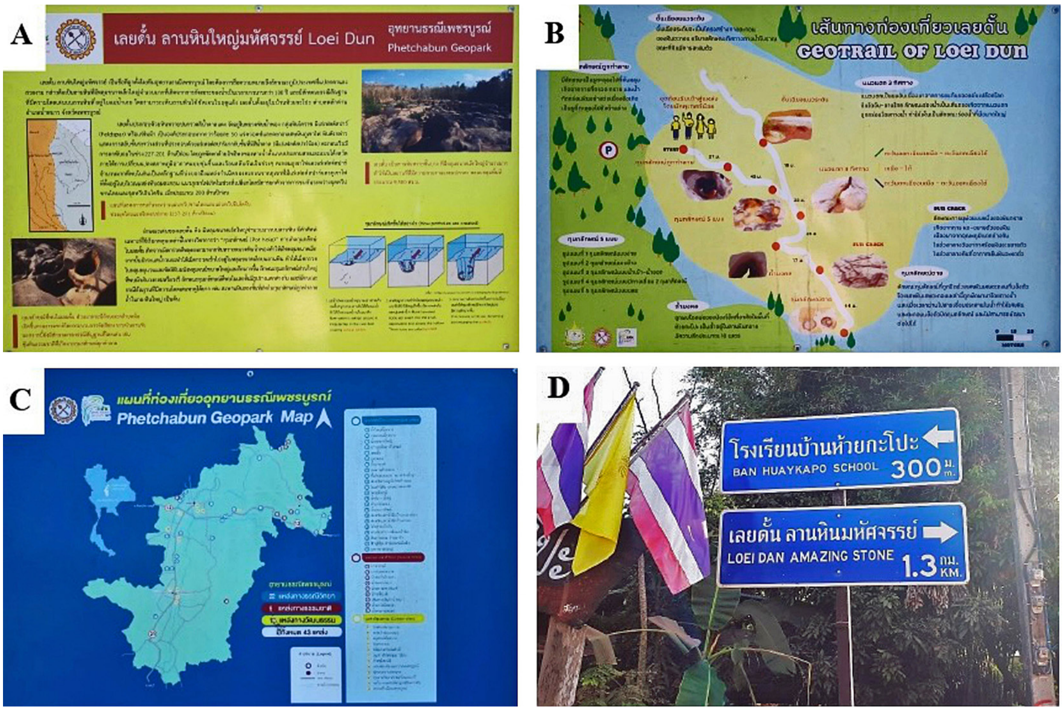


**Fig. 10.** Informative panels in the Loei Dun geoheritage site (Phetchabun Geopark). **A –** Geological information on rocks and process of pothole formation; **B –** Travel-route at the Loei Dun geoheritage site; **C –** Geotour-route map in Phetchabun Geopark; **D –** Accessibility information.

and communities (Fig. 10). The natural values in the Loei Dun area are characterised by bedrock terraces along the River Loei, as well as mountains and forests surrounding the site and a range of plant and animal species. Accessibility is an important property of geoheritage sites. Mikhailenko et al. (2021) described that the cultural and aesthetic values of sites include recreation at the site; tourist facilities and road accessibility, while Kirillova et al. (2014) suggested that the beauty of a tourist destination was uniquely judged, admired and appreciated, and assessment of beauty went beyond the visual aspects and engaged all senses on the part of both nature-based and urban tourists. In view of the fact that the present site is located along the river, suitable recreation and panoramic views with spectacular landforms are guaranteed. In addition, there are many good gazebos for sitting, as well as car parks and concrete roads. However, many toilets are quite inaccessible, making them less valuable to tourists. All in all, the number of tourists and internet promotion of the Loei Dun site presented positive trends in 2021, as based on statistic information of Facebook sharing and interviews with people. Phetchabun Geopark has collaborated with the local community and school to train students as geo-guides for tourists. Moreover, geoconservation could be promoted through geo-education and geotourism (Henriques et al., 2019) in order to make people realise the importance of their georesources, especially the Loei Dun pothole area, which is a rare, yet representative landform in the Phetchabun Geopark.

## 6. Conclusions

Loei Dun is a geoheritage site that presents innumerable potholes along the Loei River (Phetchabun national geopark), occurring in the Khorat Group reddish-brown lithic arenite and pebbly sandstone of Nam Phong Formation (Mesozoic). Based on field data and laboratory analysis, factors affecting potholes at Loei Dun are low rock strength and a low slake durability index with high absorption and high porosity. In addition, there are other factors such as joints, speed rate and turbulence of stream currents. Petrographical analysis identified the rocks studied as lithic arenite and calcite cement, which makes the rocks more vulnerable to erosion. Loei Dun has five types of pothole, as follows: simple potholes, potholes with external furrows, compound potholes, breached potholes and lateral potholes. Loei Dun is suited to be developed through geo-education and geotourism. Phetchabun geopark can be managed very well as geoheritage resources co-operate with the local community and school, having many informative geological and tourism panels and junior geo-guides (local students) serving the tourists. In addition, this site consists of facilities and constructions and accessibility is good enough for the development of geotourism.

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