

## Quantitative assessment of Permian limestone geosites in the Sai Yok District, Kanchanaburi Province, Western Thailand

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### ABSTRACT

Kanchanaburi Province in western Thailand is recognized as an exceptional natural tourist destination, offering many historical attractions and recreational activities. The Sai Yok District, located within Kanchanaburi Province, is characterized by distinctive geological and geomorphological features, hosting numerous remarkable geosites and geomorphosites, including waterfalls, caves, lapiés, and scenic karst topography. These features make it an exceptional location for geotourism. Inventory and quantitative assessments were conducted on seven Permian limestone geosites, namely Mueang Sing Historical Park, Tham Krasae, Tham Lawa, Tham Dao Wadung, Nam Tok Sai Yok Noi, Nam Tok Sai Yok Yai, and Hellfire Pass. The quantitative assessment process involved evaluating the scientific value and determining the level of deterioration of the geosites. Overall, these geosites were classified as having medium scientific value, with Mueang Sing Historical Park having the highest total score, while Tham Krasae had the lowest. Six of the seven geosites are classified as having a medium risk of deterioration, except Tham Dao Wadung, which has a low risk. The assessment of the total geosite value reveals that Mueang Sing Historical Park and Tham Dao Wadung possess a positive overall geosite value. At the same time, the other five have a negative value. It is important to note that because six of these seven geosites are classified as having a medium risk of deterioration, there is a need for increased attention and protection.

*Keywords:* Geosites, scientific values, degree of deterioration, inventory, assessment.

### 1. Introduction

For the past 30 years, there has been an increasing scientific interest in topics related to geotourism. In its simplest form, geotourism is a sustainable form of tourism that focuses on an area's geology and landscape, highlighting the geosites (locations with particular geological or geomorphological significance, regardless of their scale or size). Additionally, geotourism

encompasses ecotourism, which focuses on plants (flora) and animals (fauna) together with cultural characteristics of the region (Dowling and Newsome, 2006; Karadeniz et al., 2022), to generate benefits for conservation, education, and the local community economy (Duarte et al., 2020).

Understanding the character or identity of a region is necessary for the sustainable development of geotourism. It is also essential to include the components of form, process, and time of landforms and landscape when describing geotourism (Dowling, 2013). In

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summary, geotourism activities aim to determine the combination of geosites, biotic components of the environment, and cultural characteristics existing in an area. This knowledge is then shared with visitors to enhance the well-being of the local community in that area (Hose, 2008; Newsome and Dowling, 2010; Karadeniz et al., 2022). Consequently, this raises awareness among local residents about the importance of protecting their surroundings.

Every place has geotourism potential if the area is dissimilar from its surrounding and has its individual geological history (Dowling and Newsome, 2006). Tourist accessibility is an essential element of geotourism potential (Štrba, 2018). This includes transport accessibility, tourism development, tourist availability, information panels and popular science publications, education products, local products, and other crafts (Welc and Miśkiewicz, 2020).

Sai Yok is a district located in Kanchanaburi Province in western Thailand, which is a popular area known for its natural heritage and diverse biodiversity. The cultural heritage of Sai Yok District includes a rich history of temples, historical sites, and various civilizations that once inhabited the region. Additionally, the area has numerous tourist attractions, such as raft houses, bungalow accommodations, bamboo river rafting, boating, Mon Village, adventure park, camping facilities, crag, track and trail, and other recreational activities. Furthermore, the district hosts many interesting geosites and geomorphosites, especially karst topography, making it an excellent location for geotourism.

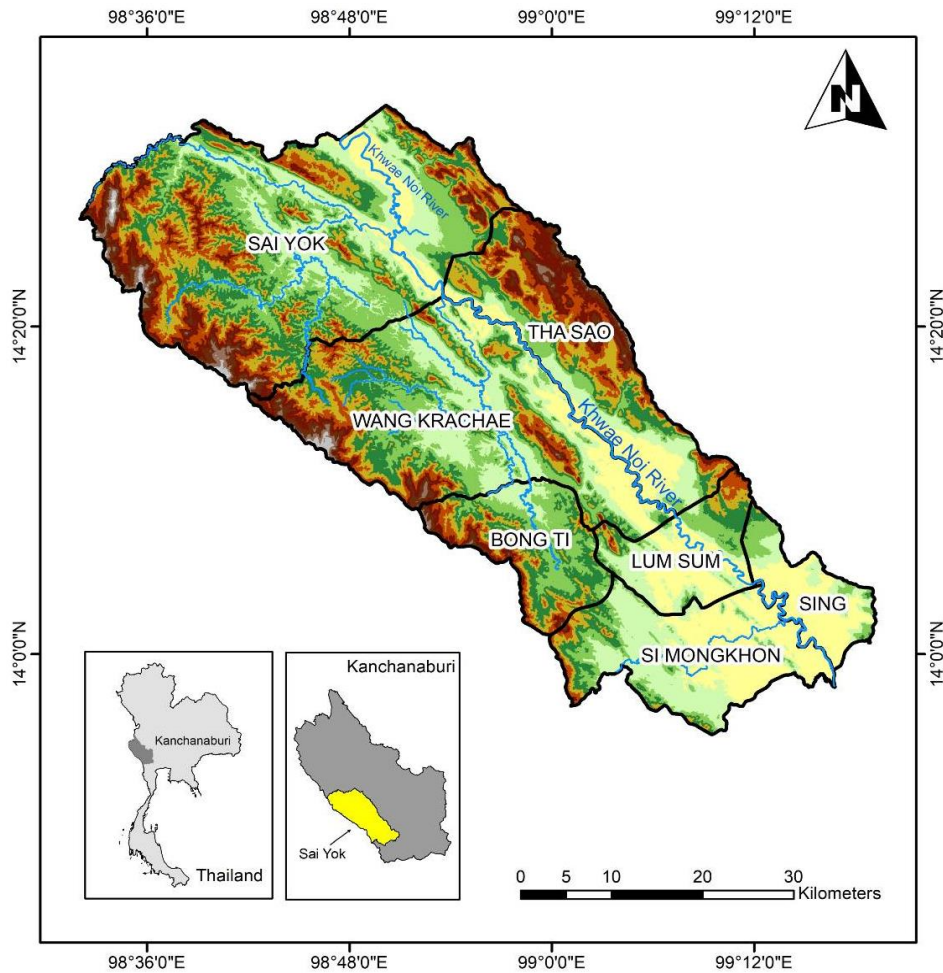
Recently, the study of geotourism in Thailand has garnered increasing attention, as evidenced by several notable publications (e.g., Singtuen and Won-In, 2018; Nazaruddin, 2019; Nazaruddin, 2020; Paungya et al., 2020; Singtuen et al., 2020). Most of them were focused in Thailand's

northern, northeastern, and southern regions, mainly contributing to clastic sedimentary rocks and igneous rocks geoheritages. However, there has been no comprehensive research dedicated to the geological heritage in the western region of Thailand, despite the presence of numerous valuable geosites there. In Thailand, karst covers approximately 18% of the land area, particularly in the western and southern regions, mainly of Ordovician and Permian limestone (Bolger and Ellis, 2015). Caves hold significance for various reasons, such as being habitats for endemic species, preserving archaeological and historical materials, and serving as temples or places for worship and rituals in Thailand (Smart, 2000). Thus, this present work aims to assess the scientific values and degree of deterioration of the Permian limestone geosite in the Sai Yok District, Kanchanaburi Province. Furthermore, this research contribute to creating an inventory of the main geosites in the region, presenting each one based on data from literature reviews and field observations.

## **2. Study area and geologic setting**

### **2.1. Study area**

Sai Yok District is situated in Kanchanaburi Province in western Thailand, approximately 50 km away from the city center. It is located between latitudes 13°55'N and 14°33'N and longitudes 98°32'E and 99°19'E (Fig. 1). The district covers an area of 2,583 km<sup>2</sup> and shares a border with Myanmar to the south. It is situated in the valley of the Khwae Noi River within the Tenasserim Hills region. The geography of Sai Yok District encompasses a range of terrain, from plains in the lowlands at an elevation of about 30-40 m above mean sea level (MSL) to high mountains. The average elevation of the district's mountain peaks ranges from 600 to 1,100 m above MSL. The highest point in the district reaches 1,112 m above MSL, located at the Thailand-Myanmar border.



**Legends**

	Subdistrict	<b>Elevation (m MSL)</b>		300.01 - 400.00		700.01 - 800.00	
	River		10.00 - 100.00		400.01 - 500.00		800.01 - 900.00
			100.01 - 200.00		500.01 - 600.00		900.01 - 1,000.00
			200.01 - 300.00		600.01 - 700.00		1,000.01 - 1,112.00

Figure 1. Location map of Sai Yok District, Kanchanaburi Province, Thailand

Sai Yok is part of the Kayah-Karen montane rain forests in the Western Forest Complex protected area, which makes it a hub of biological diversity. It is the main biodiversity conservation corridor (BCI) in the region. Sai Yok National Park covers an area of 953 km<sup>2</sup>, which consists of mostly dry evergreen broad-leaved forests, mixed

deciduous forests, and dry dipterocarp forests (Department of National Parks, Wildlife and Plant Conservation, 2014). It is home to various wildlife, including elephants, tigers, deer, wild boar, gibbons, and birds (Western Forest Complex, 2023). Some rare animals, such as the Regal crab (*Thaiphusa sirikit*) and Kitti's hog-nosed bat (*Craseonycteris*

*thonglongyai*), the world's smallest mammal weighing around two grams (Shrivastava and Shrivastava, 2020), are restricted to a single province and may be at risk of extinction (IUCN, 2009; Bates et al., 2019).

The climate of Sai Yok district is characterized by a predominant wet season, which is overcast and lasts from May to October, with September being the wettest month, with an average rainfall of 238.08 mm. The average annual precipitation in Sai Yok District from 1992 to 2021 ranges from 886.70 mm to 1,713.50 mm, with an average of 1,270.73 mm (Western Region Irrigation Hydrology Center, 2022). The dry season is hot and partly cloudy. The average temperature typically varies from 21.4°C to 33.6°C over the year. April is the hottest month, with an average maximum temperature of 37.5°C (data obtained from the Thong Pha Phum weather station, which is close to Sai Yok district) (Office of National Water Resource, 2020). Higher temperatures accompany lower precipitation amounts during the summer, showing a negative correlation.

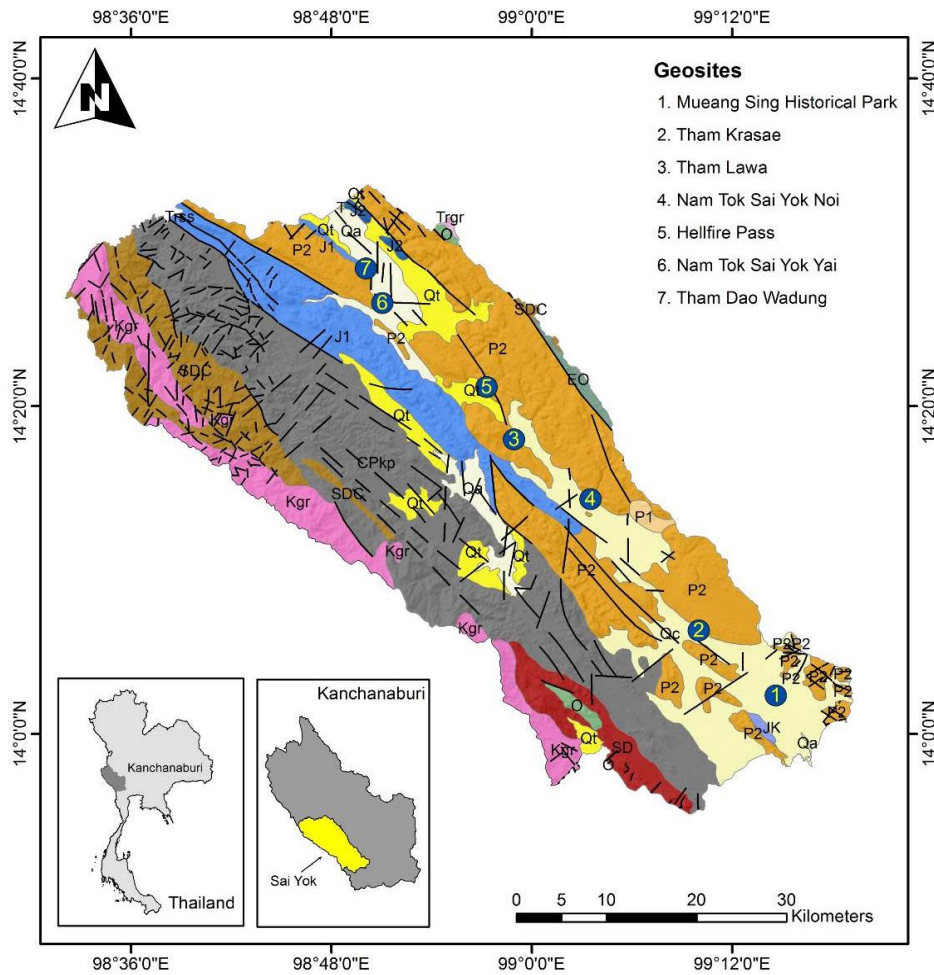
The Sai Yok district is famous for its stunning waterfalls, caves, historical sites, and raft houses along the Khwae Noi River. According to the 2022 Domestic Tourism Statistics, Kanchanaburi province welcomed approximately 11 million tourists yearly (Ministry of Tourism and Sports, 2023). During the same year, Sai Yok National Park attracted around 73,000 visitors, making it one of the most popular destinations in the western region of Thailand (Department of National Parks, Wildlife and Plant Conservation, 2023). Geologically, the Sai Yok district boasts abundant Permian limestone formations, primarily in the form of caves and waterfalls, which may attract geologists or those interested in geology to visit.

## **2.2. Geologic setting**

Geological data in the study area were

obtained from the Department of Mineral Resources (DMR) of Thailand, including a 1:250,000 scale geological map and geological reports of the region (Vimuktanandana, 1985a; Vimuktanandana, 1985b; DMR, 2007; DMR, 2008). The distribution and relationship of geosites with the geomorphology of the district were identified using the DMR database and implemented in GIS via ArcGIS software. Additionally, field observations were conducted to verify all information. The geosite locations were coordinated by the Global Navigation Satellite System (GNSS) and digitized in maps using ArcGIS software.

Geotectonically, Sai Yok district lies in the Sibumasu terrain, which includes the Shan States of Burma, Northwest Thailand, Peninsular Burma and Thailand, western Malaya, and Sumatra (Metcalf, 2013). According to Carboniferous-Permian tillites, Hall and Sevastjanova (2012) suggested that Sibumasu remained attached to Gondwana during the Late Paleozoic glaciation. The block separated from Gondwana as the large Tethyan Oceans opened and were assembled into one continent consisting of the East Malaya-Indochina, the Sukhothai Arc, and the Sibumasu (Hall and Sevastjanova, 2012; Metcalfe, 2013). Since the early Eocene, large-scale strike-slip faults can be recognized in SE Asia, including the NW-SE trending Three Pagodas Fault Zones, due to the influence of the collision between the Indian and Eurasian plates (Friederich et al., 2016; Morley and Arboit, 2019; Wang et al., 2022). The Sai Yok District is covered by Cambrian-Ordovician rocks to Quaternary sediments (Fig. 2). Table 1 shows the composition of geological units in the district, presented as area percentages. The supplementary information in the Appendix provides a detailed description of the geology of each rock unit.



**Legends**

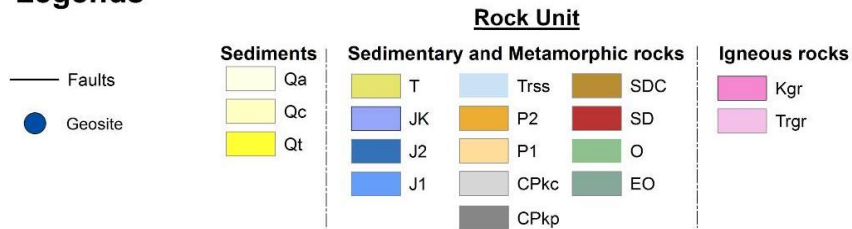


Figure 2. Geological sketch map of Sai Yok district, Kanchanaburi province, Thailand and identified Permian limestone geosites

Note: Quaternary alluvial deposits (Qa), Quaternary colluvial and residual deposits (Qc), Quaternary terrace deposits (Qt), Tertiary sediments (T), Jurassic to Cretaceous rocks (JK), Jurassic rocks unit 2 (J2), Jurassic rocks unit 1 (J1), Triassic sandstone and mudstone (Trss), Permian carbonate rocks unit 2 (P2), Permian carbonate rocks unit 1 (P1), Carboniferous-Permian Khao Chao Formation (CPkc), Carboniferous-Permian Khao Phra Formation (CPkp), Silurian-Carboniferous rocks (SDC), Silurian-Devonian rocks (SD), Ordovician rocks (O), Cambrian-Ordovician rocks (EO), Cretaceous granite (Kgr), Triassic granite (Trgr)

*Table 1.* Percentage area of geological units in Sai Yok District (according to DMR, 2007)

Geological units	Area (km <sup>2</sup> )	Percentage (%)
Qa	105.87	4.10
Qc	281.49	10.90
Qt	132.58	5.13
T	0.27	0.01
JK	3.90	0.15
J2	6.34	0.25
J1	209.99	8.13
Trss	0.39	0.02
P2	641.86	24.85
P1	9.18	0.36
CPkc	0.99	0.04
CPkp	692.38	26.81
SDC	193.52	7.49
SD	78.25	3.03
O	11.19	0.43
EO	12.18	0.47
Kgr	200.59	7.77
Trgr	1.64	0.06
<b>Total</b>	<b>2,582.61</b>	<b>100.00</b>

*Note:* Quaternary alluvial deposits (Qa), Quaternary colluvial and residual deposits (Qc), Quaternary terrace deposits (Qt), Tertiary sediments (T), Jurassic to Cretaceous rocks (JK), Jurassic rocks unit 2 (J2), Jurassic rocks unit 1 (J1), Triassic sandstone and mudstone (Trss), Permian carbonate rocks unit 2 (P2), Permian carbonate rocks unit 1 (P1), Carboniferous-Permian Khao Chao Formation (CPkc), Carboniferous-Permian Khao Phra Formation (CPkp), Silurian-Carboniferous rocks (SDC), Silurian-Devonian rocks (SD), Ordovician rocks (O), Cambrian-Ordovician rocks (EO), Cretaceous granite (Kgr), Triassic granite (Trgr). The supplementary information in the Appendix provides a detailed description of the geology of each rock unit

In the Sai Yok District area, the predominant rock formations are the Carboniferous-Permian (CP) rocks and the Permian (P) rocks. Shallow-marine facies primarily characterize these Carboniferous to Permian rocks in Thailand. Within the

Carboniferous sequence, siliciclastic rocks are the dominant lithology. The study area encompasses two formations of CP rocks, the Khao Phra Formation (CPkp) and the Khao Chao Formation (CPkc), arranged in ascending order. The Permian System is characterized by carbonate rocks, which give rise to distinct karst topography in the study area. Initially, Bunopas (1981) referred to the Permian rocks in the Kanchanaburi Province as the Sai Yok Group. Subsequently, several researchers (Bunopas, 1992; DMR, 1992; Raksaskulwong, 2002; Karapunar et al., 2022) introduced the term Ratburi Limestone Group to refer to this unit. In DMR's (2008) classification, the Permian rocks in this area were divided into two formations: P1 and P2. The P2 unit covers almost 25% of the Sai Yok District. It is characterized by gray bedded to massive limestone. Chert or siliceous nodules, dolomitic limestone, and minor sandstone and shale are also present within the P2 unit. The carbonate rocks in both P1 and P2 formations contain abundant fossil remains, such as fusulinids, radiolarians, brachiopods, corals, ammonoids, and crinoids (DMR, 2008; Sashida et al., 2022; Maneerat et al., 2022).

### 3. Methodology

The process of identifying and assessing Permian limestone geological sites in Sai Yok District involved several steps. Creating an inventory of geological and geodiversity sites represents the primary and essential stage in any conservation strategy, regardless of the scale of the area under consideration (Brilha, 2016). Several steps are involved in a

conservation strategy. This work focuses explicitly on the first two stages, which include inventory and quantitative assessment of geosites, addressing their scientific values and degree of deterioration.

Initially, this study conducted a comprehensive literature review to establish the study's theoretical foundation, incorporating various publications, reports, and relevant information. Then, the inventory of potential geosites was developed in alignment with the global framework for Geological World Heritage (Dingwall et al., 2005). This framework establishes a basis for evaluating the nominated World Heritage natural properties, particularly their exceptional universal value concerning science and conservation. In this work, the inventory was carried out by identifying, selecting, and listing all potential geosites of the Sai Yok

district primarily through literature reviews and geological surveys, specifically applied to the Permian limestone geosites, which was preliminarily assessed by the Department of Mineral Resources (DMR, 2008). Throughout the Sai Yok district, seven Permian limestone geosites were identified, namely Mueang Sing Historical Park, Tham Krasae, Tham Lawa, Tham Dao Wadung, Nam Tok Sai Yok Noi, Nam Tok Sai Yok Yai, and Hellfire Pass. These selections were made based on their occurrence, representativeness, documentation, substantial scientific value, and potential for tourism (Table 2). Besides their geological importance, selecting these geosites also considers their aesthetic, leisure, and cultural significance. Field observations were carried out to characterize and validate the suitability of these potential geosites and gather additional data.

Table 2. Selected geosite in the Sai Yok District

Sites	Location	Features
Tham Lawa	14.2995, 98.9822	Geomorphology (Cave)
Tham Dao Wadung	14.4733, 98.8346	Geomorphology (Cave)
Tham Krasae	14.1051, 99.1667	Geomorphology (Cave), History
Nam Tok Sai Yok Yai	14.4381, 98.8507	Geomorphology (Waterfall)
Nam Tok Sai Yok Noi	14.2387, 99.0586	Geomorphology (Waterfall), History
Hellfire Pass	14.3527, 98.9547	Geomorphology (Other karst systems), Viewpoint, History
Mueang Sing Historical Park	14.0389, 99.2434	Geomorphology (Other karst systems), History

Afterward, the quantitative assessment process involved assessing scientific value and determining the level of deterioration of the geosites (Baadi et al., 2020; 2021). This assessment applies to all types of geological sites, covering the scientific aspects and the determination of geosites influenced by human activity (Baadi et al., 2020). Additionally, this method lacks specific application modalities and can be employed

in all types of environments. Specific criteria and concrete statistics were employed to conduct the scientific value of each geosite, focusing on five criteria: representativeness, rarity, geological diversity, state of preservation, and documentation. Each criterion was assigned a score ranging from 3 to 1 (Table 3). Additionally, the degree of deterioration for each geosite was assessed using five

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criteria: vulnerability, fragility, both scientific values and the degree of accessibility, demography, and number of deterioration were assessed by multiplying visitors, with scores also ranging from 3 to them with the weighting coefficient 1 (Table 4). To calculate the final score, determined for each one (Tables 3 and 4).

Table 3. Criteria for the quantitative assessment of scientific value of geosite (according to Baadi et al., 2020; 2021)

Criteria	Description of the Pointing	Pointing (1-3)	Score of scientific value (Weighting x Pointing)	Weighting
Representativeness	<ol style="list-style-type: none"> <li>1. The site presents several known and previously known geological phenomena;</li> <li>2. The site has less known geological phenomena in the area. It testifies to the existence of a singular geological process;</li> <li>3. The site presents unusual geological phenomena in the area. It bears witness to unprecedented geological processes.</li> </ol>	-	-	24%
Rarity	<ol style="list-style-type: none"> <li>1. The site holds 5 or more similar cases in the area;</li> <li>2. The site holds less than 5 similar cases in the area;</li> <li>3. The site represents a unique reference in the area.</li> </ol>	-	-	18%
Geological diversity	<ol style="list-style-type: none"> <li>1. The site has only one geological particularity (mineralogical, paleontological, ...);</li> <li>2. The site holds 2 types of geological particularity;</li> <li>3. The site holds more than 2 types of geological particularity.</li> </ol>	-	-	20%
State of preservation	<ol style="list-style-type: none"> <li>1. The site is neither preserved nor protected by any law; it is not found in a geopark, reserve, natural park, etc.</li> <li>2. The site is neither well preserved nor protected by any law but is located in a geopark, reserve, natural park, etc.</li> <li>3. A legislative law well preserves the site; it is a geopark, reserve, natural park, etc.</li> </ol>	-	-	24%
Documentation	<ol style="list-style-type: none"> <li>1. The site is not listed in any published work;</li> <li>2. The site holds at least one article published in national and international journals, thesis or dissertations, etc.</li> <li>3. The site holds more than two articles published in national and international journals, dissertation work or, dissertations, etc.</li> </ol>	-	-	14%
Total		= $\Sigma$ pointing	>1; <3	100%



Table 4. Criteria for the degree of deterioration of geosite (according to Baadi et al., 2020; 2021)

Criteria	Description of the Pointing	Pointing (1-3)	Score of scientific value (Weighting x Pointing)	Weighting
Vulnerability	1. The site is not treated by human activity; 2. The site is threatened by a single type of anthropogenic action (construction, tourist activities, agriculture, harvesting samples, etc.); 3. Two or more human actions threaten the site.	-	-	19%
Fragility	1. The site is not exposed to any form of natural degradation (floods, tides, erosion, landslide, etc.); 2. The site is exposed to only one type of natural degradation; 3. The site is exposed to two or more types of natural degradation.	-	-	19%
Accessibility	1. The site is more than 1 km from an asphalt road; 2. The site is 500 m to 1 km from an asphalt road; 3. The site is less than 500 m from an asphalt road.	-	-	25%
Demography	1. The site is located in a low demography area where residents do not exceed 40,000 people; 2. The site is located in a medium-demographics area between 40,000-400,000 people; 3. The site is located in a high population exceeding 400,000 inhabitants.	-	-	20%
Number of visitors	1. The site is visited annually by less than 1,000 visitors; 2. The site is visited annually by 1,000 to 10,000 visitors; 3. The site is visited annually by more than 10,000 visitors.	-	-	17%
Total		= $\Sigma$ pointing	>1; <3	100%

Finally, the total geosite value is determined by calculating the final score, which is obtained by subtracting the score of the scientific value from the score of the degree of deterioration. This calculation follows the equation outlined in Baadi et al. (2021):

$$\text{Geosite value} = \text{scientific value} - \text{deterioration degree}$$

## 4. Results

### 4.1. Geosite Inventory of the Sai Yok District

Due to the presence of waterfalls, caverns, lapiés, karst topography, and scenic mountain landscapes, Sai Yok District has a strong potential of geotourism. In addition, there are various historical sites from World War II in this area, including Hellfire Pass and the Death Railway or Thai–Burma Railway,

which runs along the Sai Yok Noi River to Sai Yok Noi Waterfalls. Furthermore, Mueang Sing Historical Park is a Khmer-style temple dating back to the late 12<sup>th</sup> to the early 13<sup>th</sup> centuries (Pisnupong, 1999). It is the only building of Khmer architecture found in western Thailand (Surussawadee, 1987). Additionally, Sai Yok District boasts a diverse range of endemic and rare species, adding to its already high potential for tourism due to its scenic landscape, cultural richness, and numerous recreational activities.

In this study, the criteria used for identifying Permian limestone geosites were based on their occurrence, representativeness, documentation, substantial scientific value, and tourism potential. These criteria allowed for categorizing geosites and other elements within the study area into three groups based

on their similarities: caves, waterfalls, and other karst systems. The work delineated geological elements and incorporated geographical, historical, and archaeological elements to facilitate a comprehensive understanding of the natural composition and geoscientific significance. This contributes to the advancement of geotourism and serves as a valuable resource for further research endeavors.

4.1.1. Caves

Approximately 25% of Sai Yok District consists of Permian rocks which are predominated by carbonate rocks, mainly limestone. Caves generally develop in carbonate rocks due to their solubility in dilute acidic groundwater due to chemical interactions. They were slowly eroded for thousands of years and then built up again by speleothems as secondary deposits. There are various karst cave systems in the Sai Yok

District, mainly found in the P2 unit. Tham Lawa, Tham Dao Wadung, and Tham Krasae are more critical regarding size, structure, and speleothems (Tham means cave in Thai). There are several Buddha statues and shrines inside these caves for worship rituals. Caves have been part of Thai folklore for thousands of years, and some Thais respect caves as spiritual places. Additionally, many kinds of animals live in these caves, such as rats, cavefish, isopods, some cave salamanders, and insects.

Tham Lawa (Fig. 3) is 485 meters deep and is divided into five chambers with different characteristics. Inside a cave are many forms of spectacular speleothem, including stalactites, stalagmites, flowstones, pillars, bacon formations, rimstones, draperies, and helictites. It takes an average of 45 minutes to complete a route in a cave. The cave itself has lighting and is easy to access.

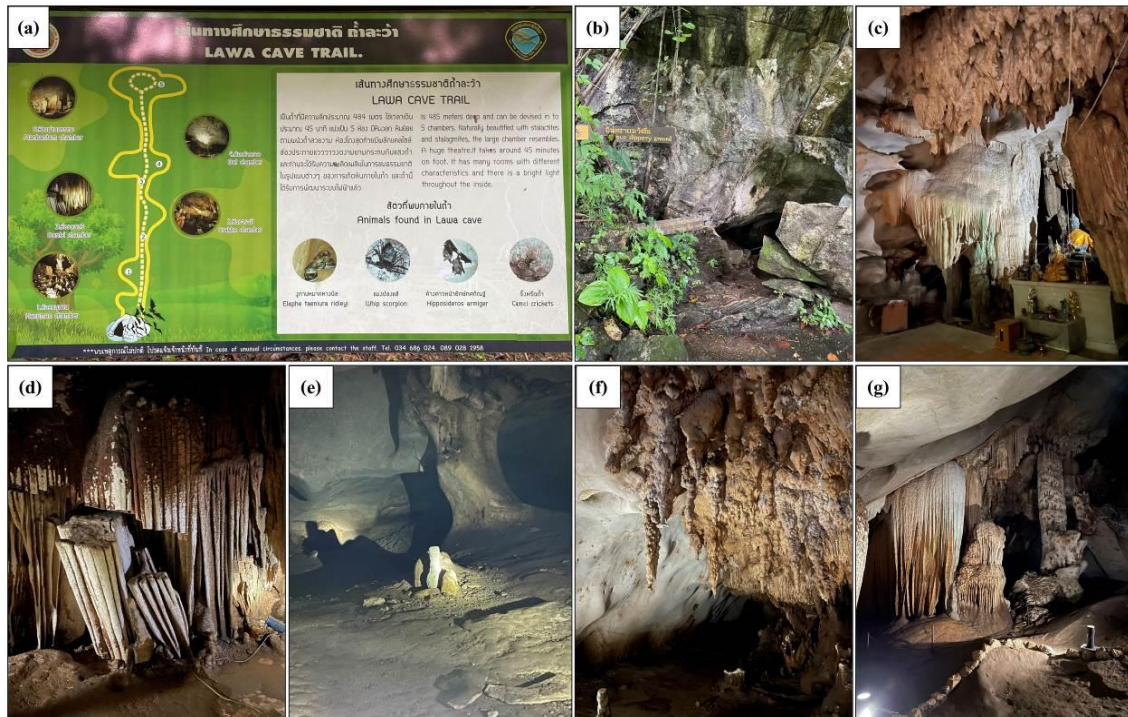


Figure 3. Tham Lawa (a) Tham Lawa notice board, (b) the entrance of a cave, (c) Buddha statues and shrines located near an entrance of the cave (d-g) various forms of speleothems

Tham Dao Wadung (Fig. 4) also features beautiful stalactite and stalagmite formations. Visitors must hike up a gentle trail approximately 500 meters long and surrounded by mixed deciduous forests to reach the cave. It is recommended that visitors wear suitable

footwear, bring water, and carry a flashlight. The cave consists of two main chambers and a 180-meter-long route. Many creatures can live in caves, including bats, cave-dwelling snakes, cave crickets, cave spiders, cave slugs, whip scorpions, and cave crabs.

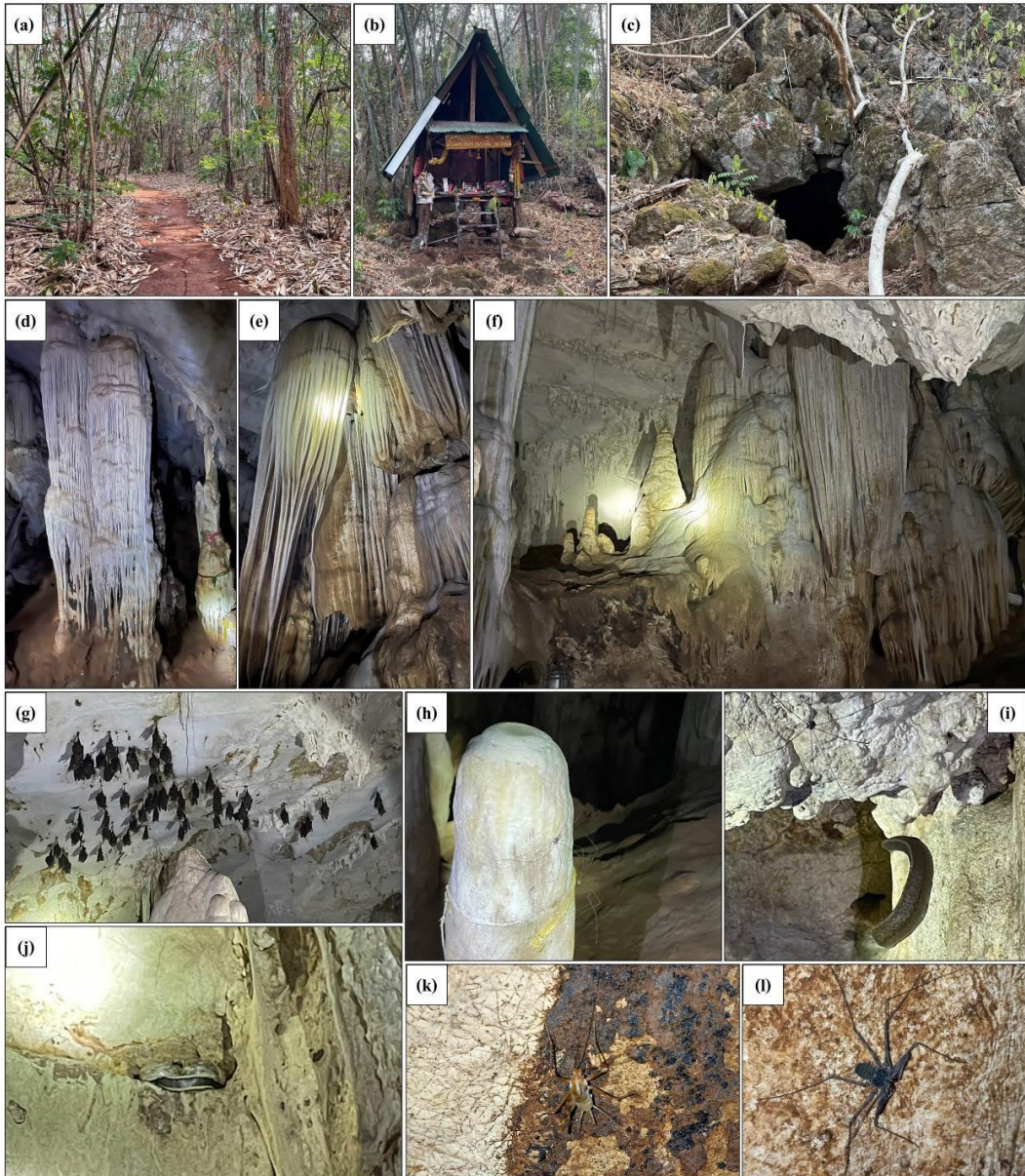


Figure 4. Tham Dao Wadung (a) trail to the cave entrance, (b) a shrine at the cave entrance, (c) the entrance of the cave, (d-f) various forms of speleothems, (g) leaf-nosed bats, (h) harvestmen, (i) slug and harvestmen, (j) cave dwelling snake, (k) cave cricket, (l) whip scorpion

Tham Krasae (Fig. 5) is adjacent to a part of the infamous Death Railway carved along a vertical limestone cliff above Khwae Noi River, giving it the most stunning view. Nowadays, trains traveling along the railway

stop at Tham Krasae, or visitors can visit the place by car. Strolling along the wooden bridge and getting some photos are the highlights here.

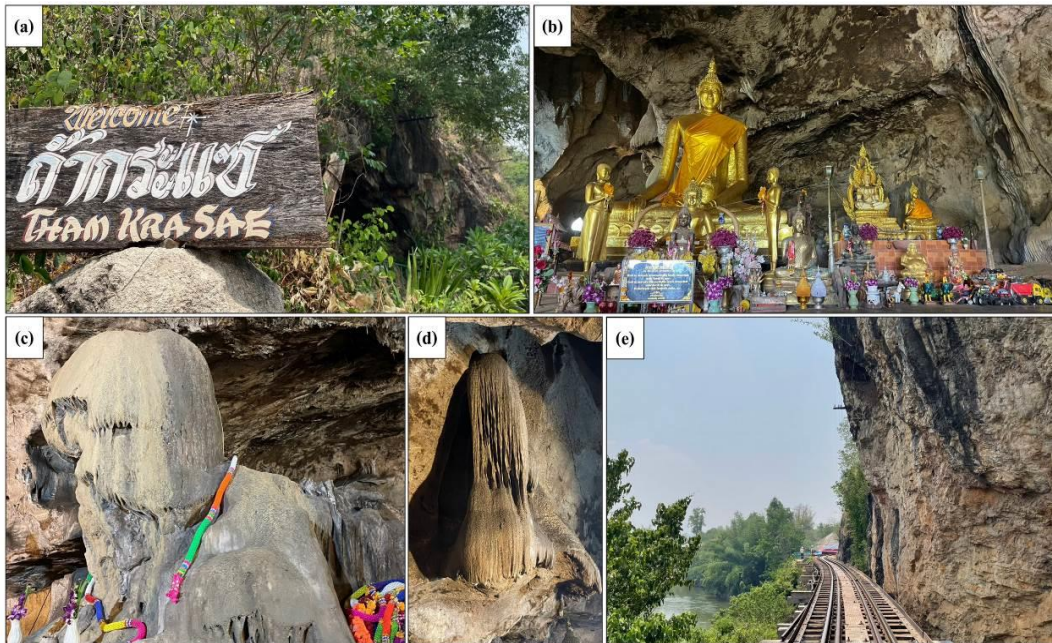


Figure 5. Tham Krasae (a) the entrance of the cave, (b) Buddha statues and shrines located near the entrance of the cave, (c) a stalagmite that resembles a lion or an old man, (d) drapery, (e) the Death Railway running along the cliff near Tham Krasae

#### 4.1.2. Waterfalls

A waterfall is generally defined as a point where flowing river water drops abruptly and is close to or directly vertical. In the Sai Yok area, there are two explicit waterfalls, namely Nam Tok Sai Yok Yai and Nam Tok Sai Yok Noi. Nam Tok means waterfall in Thai. Both were formed by the erosion of Permian limestone (P2 unit).

Nam Tok Sai Yok Yai (Fig. 6) is an 8-meter one-level limestone waterfall carved by a stream dropping directly into the Khwae Noi River. This place is easy to access by car. Visitors can walk onto a suspension bridge to

snap photos of the waterfall or take a boat to a lookout on the opposite shore.

Nam Tok Sai Tok Noi (Fig. 7), known by the residents as Nam Tok Khao Pung, is one of the most popular attractions of the Sai Yok National Park. This waterfall comprises crumbled or collapsing limestone cliffs that became the origin of the name Khao Pung. Water comes from the top of the mountain and flows along a limestone cliff about 15 meters high on many levels down to the foothills. This waterfall is easy to access by car or train, which stops at Nam Tok Sai Yok Noi Railway Station.

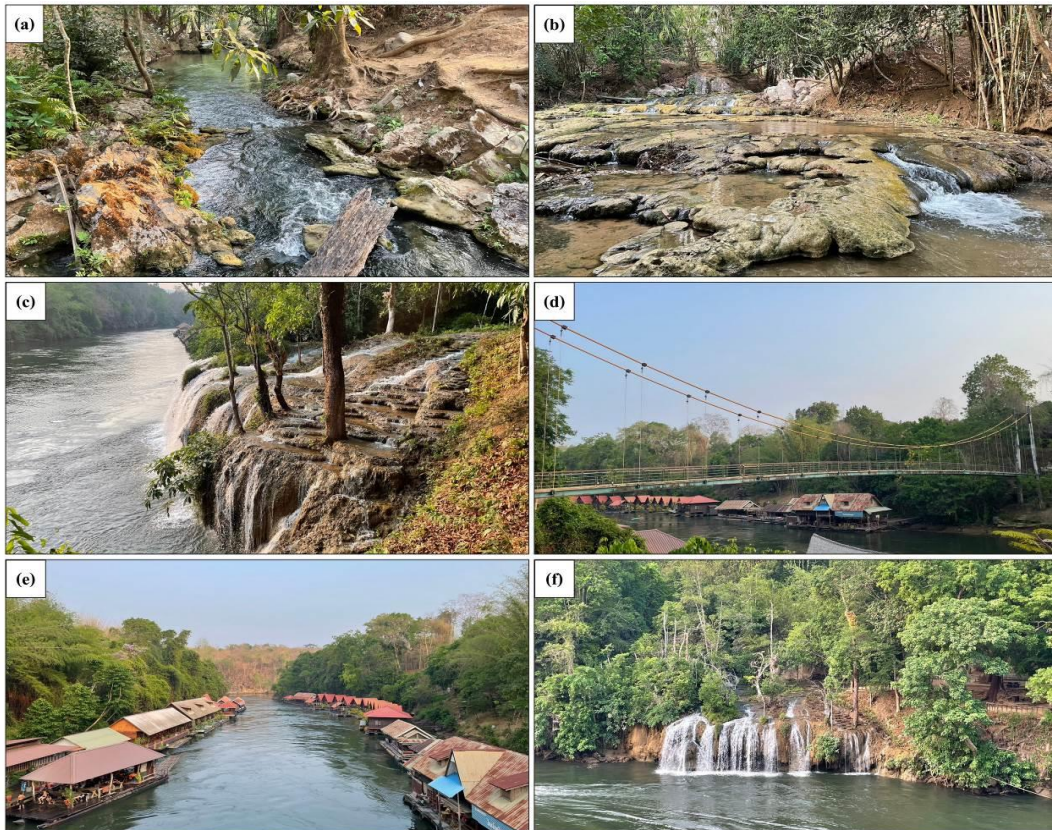


Figure 6. Nam Tok Sai Yok Yai (a-c) the waterfall, (d) a suspension bridge, (e) raft houses located along the Khwae Noi River, (f) a stream of Nam Tok Sai Yok Yai that drops directly into the Khwae Noi River



Figure 7. Nam Tok Sai Yok Noi (a-b) the waterfall, (c) rimstones, (d) an exhibition of a steam locomotive that was used in World War II to commemorate the construction of the Death Railway that runs by the falls to Myanmar

4.1.3. Other karst systems

Hellfire Pass (Fig. 8), also known as Chong Khao Khat, is a railway cutting on the former Burma Railway, or the Death Railway, to be the main transportation for supplies. It was built using forced labor by prisoners of war in World War II in harsh conditions with heavy loss of life suffered during construction. Hellfire Pass was named after prisoners who labored in the night with

torchlights shining, creating a scene resembling Hell. This pass lies above the limestone of the P2 unit, making it incredibly difficult to construct using only hammers and tap cuttings. However, the prisoners completed the cutting of the largest rock on the railway in about six weeks, but the railway was never built for lasting permanence. Nowadays, no trains are running off the line to the Hellfire Pass, and most of the tracks have been ripped up.

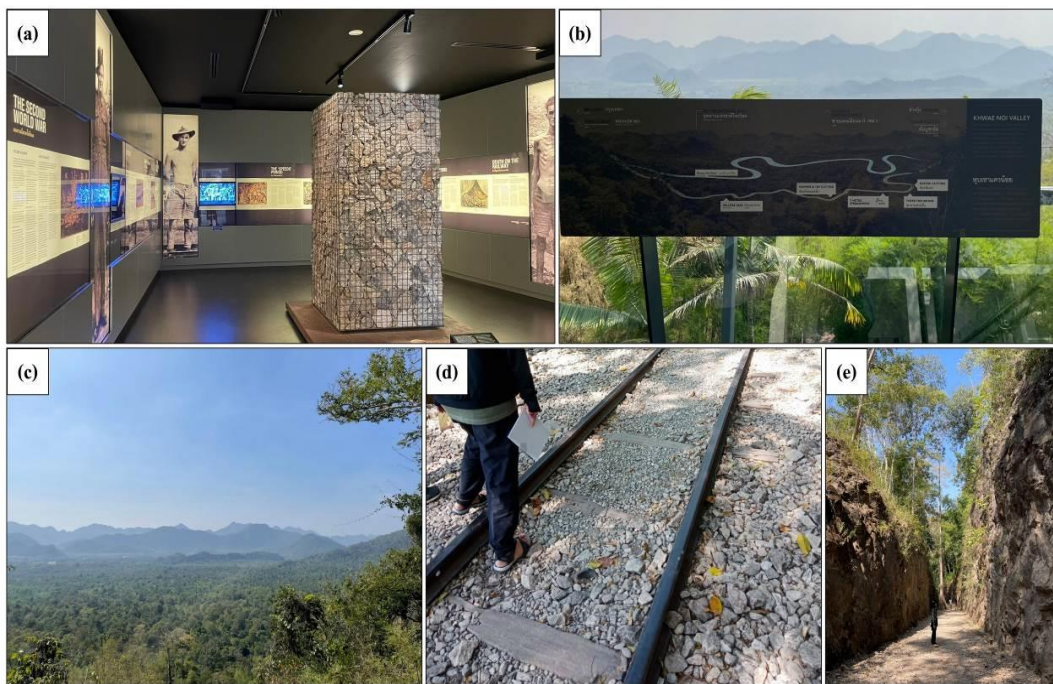


Figure 8. Hellfire Pass (a) the interpretive center of the Hellfire Pass, (b) a viewing terrace, (c) a view of the Khwae Noi valley, (d) a trace of railway sleepers, (e) a portion of Hellfire Pass

The Hellfire Pass Memorial Museum was established as a memorial dedicated to the Australian and allied prisoners of war. The museum has three sections: a display section, a section featuring movies, and a natural walking trail to the Hellfire Pass. The walking trail consists of two options: a short walk (40-50 minutes) and a long walk (more than 3 hours). The center staff provides an audio guide for a better understanding of the

construction of the railway pass. A viewing terrace was built near the museum to observe a scenic valley.

The Hellfire Pass serves as a location for studying the extensive limestone of the P2 unit and how prisoners constructed the railway using only hammers and hand tools. Additionally, it offers a viewpoint for observing the valley's landscape in the surrounding area.

Mueang Sing or Prasat Mueang Sing (Prasat means castle in Thai) (Fig. 9) is a historical park that preserves the well-maintained ancient ruins of two Khmer temples dating back to the late 12<sup>th</sup> to the early 13<sup>th</sup> centuries. It is the only building of Khmer architecture in the Bayon style found in western Thailand and marks the westernmost border outpost of the ancient Khmer Empire. It dates from about the same time as Angkor Wat in Cambodia and is similar in style to that

structure. The site is situated along the banks of the Khwae Noi River, and the walls, made from laterite, border the park on three sides along its river line from north to south. Entrance and exit gates are located on all four sides. There are six ponds and four archaeological sites (Numbered 1 to 4) with Buddhist structures. The main castle is located directly opposite the gates and represents the center of the universe, based on Hindu mythology.



Figure 9. Mueang Sing Historical Park (a) Archaeological Sites No. 1, (b) Archaeological Sites No. 2, (c) Archaeological Sites No. 3, (d) Archaeological Sites No. 4, (e) statue of Shiva, (f) carved relief of Prajnaparamita on laterite wall, (g) sculpture of Prajnaparamita, (h) edifice of Prajnaparamita

Additionally, the temple houses an enshrined Shiva Lingam for worship and served as a military stronghold. It is a symbol that stands for Lord Shiva in Hinduism. There is the edifice of the Goddess of Wisdom, "Prajnaparamita", which is the only remaining sculpture of human figures carved on the inner colonnade to the right of the central tower ruins (Fig. 9f). The temple was built mainly of laterite, dated at  $5.5 \pm 0.5$  ka within

the Holocene epoch of the Quaternary (Limsuwan et al., 2008; Limsuwan et al., 2011).

Within the historical park is an exhibition room showcasing various artifacts from the period long before the arrival of the Khmer (Fig. 10). These artifacts testify to the settlement in this area and the surrounding regions.



Figure 10. An exhibition room of the Mueang Sing Historical Park (a-b) exhibition room, (c-d) examples of artifacts found around the Mueang Sing

Additionally, prehistoric archaeological sites have been excavated outside the walls of Mueang Sing Historical Park. Significant evidence from the detailed excavation includes four prehistoric skeletal remains, which were assigned numbers from 1 to 4 according to their discovery order. These skeletal remains were discovered along with various funerary objects that demonstrate burial customs, rituals, and a belief in the afterlife. Currently, only two skeletons remain at the burial site (Fig. 11). Skeletons number 2

and 4 are female, with ages around 30 to 35 and 20 to 30 at the time of their death, respectively. Still, the age and gender of the other two cannot be determined.

In front of the entrance to Mueang Sing Historical Park, along a road on the eastern side of the park, there are outcrops of Permian weathered limestone and dolomite surface that show a lapiés landform (Fig. 12). Lapiés are typically found in karst topography, which is formed by the dissolution of soluble rock by water containing humic and carbonic acids.



This area consists of etched, pitted, and fluted limestone pinnacles separated by deep grooves. Chert nodules are found in some limestone beddings. Above these lapiés is a dark red lateritic layer formed by the weathering of rocks under strongly oxidizing and leaching conditions. Laterites usually

form in a humid climate in tropical and subtropical regions.

As for Mueang Sing Historical Park, this site is valuable for studying how ancient people excavated laterite to build the temple. Furthermore, it provides a representative example of lapiés in front of the park.



Figure 11. An archaeological site outside the Mueang Sing Historical Park (a) skeleton No. 2 (at the top of the figure), which was discovered at a depth of 2.15 meters from the assumed level or 1.5 meters from the soil level, while skeleton No. 4 (at the lower part of the figure) was discovered at a depth of 2.57 meters from the assumed level or 1.96 meters from the soil level, (b) funerary objects, such as bronze vessels, pottery vessels, metal tools, clay spindle whorls, and other decorative items, were found at the burial site

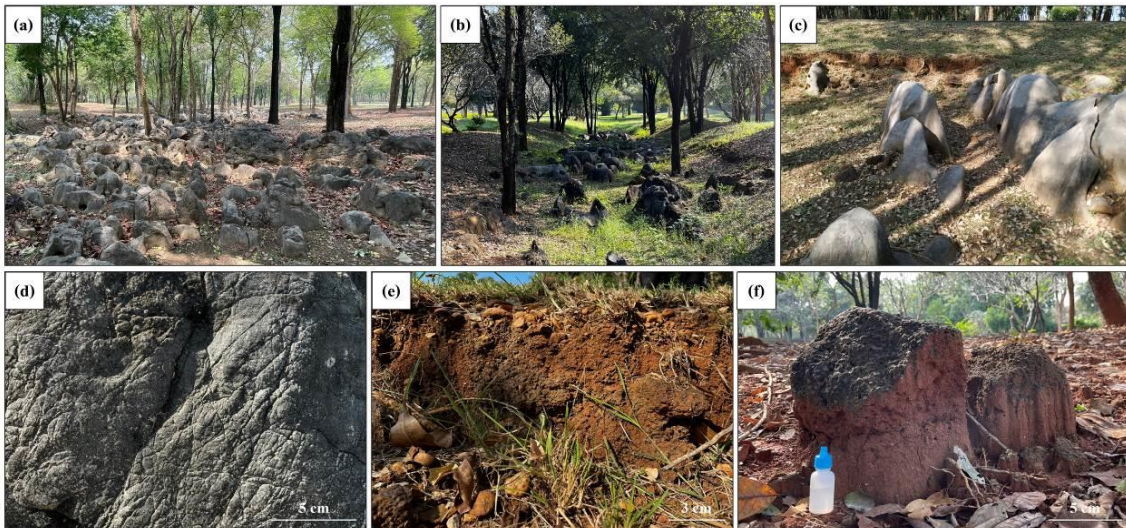


Figure 12. Lapiés near the entrance of Mueang Sing Historical Park (a-c) lapiés, (d) dolomite showing elephant skin weathering, (e-g) laterites covering surface of limestone

#### 4.2. Quantitative assessment of geosites

To establish a strategy for conserving and further developing geosites for tourism, it is necessary to evaluate the values of these geosites. The quantitative assessment of geosites, measuring their scientific value and

degree of deterioration, is a crucial tool for developing geoconservation strategies. The findings of this assessment are presented in Tables 5 and 6, showing the scientific value and degree of deterioration of the geosites, respectively.

Table 5. Quantitative assessment of the Sai Yok geosites

Criteria of quantitative assessment	Geosites						
	Tham Lawa	Tham Dao Wadung	Tham Krasae	Nam Tok Sai Yok Yai	Nam Tok Sai Yok Noi	Hellfire Pass	Mueang Sing Historical Park
Representativeness	2	2	2	1	1	1	2
Rarity	1	1	1	2	2	1	2
Geological diversity	1	1	1	1	1	1	2
State of preservation	3	2	1	3	3	3	3
Documentation	3	2	3	3	3	3	3
Total Pointing	10	8	8	10	10	9	12
Final scoring matrix							
Representativeness *24%	0.48	0.48	0.48	0.24	0.24	0.24	0.48
Rarity *18%	0.18	0.18	0.18	0.36	0.36	0.18	0.36
Geological diversity *20%	0.20	0.20	0.20	0.20	0.20	0.20	0.40
State of preservation *24%	0.72	0.48	0.24	0.72	0.72	0.72	0.72
Documentation *14%	0.42	0.28	0.42	0.42	0.42	0.42	0.42
Total quantitative assessment	2.00	1.62	1.52	1.94	1.94	1.76	2.38
Result	Medium	Medium	Medium	Medium	Medium	Medium	Medium

Remark: According to Baadi et al. (2021), geosites with a score below 1.5 are categorized as having a low scientific value, whereas those with a score above 1.5 have a medium scientific value. Geosites that score higher than 2.5 are classified as having a high scientific value

Table 6. Degree of deterioration of the Sai Yok geosites

Criteria of degree of deterioration	Geosites						
	Tham Lawa	Tham Dao Wadung	Tham Krasae	Nam Tok Sai Yok Yai	Nam Tok Sai Yok Noi	Hellfire Pass	Mueang Sing Historical Park
Vulnerability	2	2	3	3	3	2	2
Fragility	2	1	1	1	1	1	1
Accessibility	3	2	3	3	3	3	3
Demography	1	1	1	1	1	1	1
Number of visitors	2	1	3	3	3	3	3
Total Pointing	10	7	11	11	11	10	10
Final scoring matrix							
Vulnerability *19%	0.38	0.38	0.57	0.57	0.57	0.38	0.38
Fragility *19%	0.38	0.19	0.19	0.19	0.19	0.19	0.19
Accessibility *25%	0.75	0.50	0.75	0.75	0.75	0.75	0.75
Demography *20%	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Number of visitors *17%	0.34	0.17	0.51	0.51	0.51	0.51	0.51
Total degree of deterioration	2.05	1.44	2.22	2.22	2.22	2.03	2.03
Result	Medium	Low	Medium	Medium	Medium	Medium	Medium

Remark: According to Baadi et al. (2021), geosites scoring below 1.5 have a low degree of deterioration, while those scoring above 1.5 have a medium degree of deterioration. Geosites with a score exceeding 2.5 are categorized as having a high degree of deterioration

In Table 5, five criteria are assigned scores for conducting a quantitative assessment aimed at determining the scientific value of geosites. These criteria include representativeness, rarity, geological diversity, state of preservation, and documentation. Overall, these geosites were classified as having medium scientific value. Mueang Sing Historical Park had the highest total quantitative assessment score at 2.38, while Tham Krasae had the lowest total score at 1.52.

Representativeness is the geosite's ability to depict a geological phenomenon that contributes to understanding the area's history. The two waterfalls and the massive limestone formation at Hellfire Pass illustrate previously known geological phenomena, resulting in a score of 1. On the other hand, the caves and rocks within Mueang Sing Historical Park contribute more significantly to the understanding of the geological history in the area, thus earning a score of 2.

Most geosites in this study were deemed low to medium rarity because the study exclusively concentrated on one district. In Sai Yok, numerous caves were identified, leading to a score of 1 for geosites of the cave type. Conversely, waterfalls within the district and the lapies within Mueang Sing Historical Park had less than five occurrences. Consequently, these two geosites received a score of 2.

Most geosites were assessed as having low geodiversity due to the exclusive focus on Permian limestone geosites. The predominance of limestone primarily leads to the formation of caves and waterfalls, resulting in each geosite having only one geological characteristic. In contrast, Mueang Sing Historical Park represents a unique karst formation featuring lapies and is also valuable for examining laterites that contribute to the temple's formation. Consequently, the park receives a score of 2.

In terms of preservation, Tham Lawa, Tham Dao Wadung, Nam Tok Sai Yok Yai, and Nam Tok Sai Yok Noi are well-preserved due to legislative laws and their location within a natural park. Hellfire Pass is jointly maintained by the Royal Thai Armed Forces Development Command and the Australian government, while the Fine Arts Department of Thailand preserves Mueang Sing Historical Park. This results in a high level of preservation. Tham Krasae, managed by a local municipality and receiving many visitors each year, has a lower preservation score.

Most of the Permian geosites in Sai Yok are well-known tourist destinations that have attracted many researchers conducting various studies there. This has resulted in many published works, encompassing historical and geological studies, contributing to a high documentation score.

In Table 6, scores are assigned to five criteria to determine the degree of deterioration for geosites. These criteria include vulnerability, fragility, accessibility, demography, and the number of visitors. Overall, six of the seven geosites are classified as having a medium risk of deterioration, while one geosite has a low risk. Tham Krasae, Nam Tok Sai Yok Yai, and Nam Tok Sai Yok Noi had the highest total degree of deterioration at 2.22, whereas Tham Dao Wadung had the lowest total score at 1.44.

Regarding vulnerability, Tham Lawa, Tham Dao Wadung, Hellfire Pass, and Mueang Sing Historical Park are primarily threatened by tourist activities, resulting in a score of 2. Conversely, Tham Krasae and the two waterfalls face threats from construction and tourist activities, leading to a vulnerability score of 3.

Most Permian limestone geosites in the Sai Yok district are not exposed to any form of natural degradation, resulting in a fragility score of 1, except for Tham Lawa, which is

affected by landslides due to its site location. This results in a fragility score of 2.

Regarding accessibility, most geosites are located less than 500 m from an asphalt road, earning them a score of 3. However, in the case of Tham Dao Wadung, visitors must hike up a gentle trail of approximately 500 m to reach the cave, resulting in an accessibility score of 2.

Demographically, all geosites are situated in areas with low population numbers, where the resident population does not exceed 4,000 people. This results in a low demography score of 1 for each site.

Tham Krasae, Nam Tok Sai Yok Noi, Hellfire Pass, and Mueang Sing Historical Park are well-known tourist attractions, receiving more than 10,000 visitors per year. This results in several visitors score of 3 for these four geosites. In contrast, Tham Lawa is visited by 1,000-10,000 visitors annually, and Tham Dao Wadung receives fewer than 1,000

visitors. Therefore, the number of visitors scores for Tham Lawa and Tham Dao Wadung are 2 and 1, respectively.

The outcomes of this study indicate that the examined geosites possess varying levels of potential as tourist attractions. The primary geotouristic interest lies in Mueang Sing Historical Park, which holds geological significance and showcases historical and archaeological heritage. Two geosites, Mueang Sing Historical Park and Tham Dao Wadung, have a positive total geosite value (Table 7), indicating a higher scientific value than the deterioration degree. Therefore, these two geosites have great potential for geotourism. On the other hand, the remaining five geosites Nam Tok Sai Yok Yai, Nam Tok Sai Yok Noi, Hellfire Pass, Tham Lawa, and Tham Krasae have a negative total geosite value, indicating the need for enhanced protection and attention.

Table 7. The Sai Yok geosite values

Geosite	Tham Lawa	Tham Dao Wadung	Tham Krasae	Nam Tok Sai Yok Yai	Nam Tok Sai Yok Noi	Hellfire Pass	Mueang Sing Historical Park
Geosite value	-0.05	0.18	-0.70	-0.28	-0.28	-0.27	0.35

## 5. Discussions

Based on the geosite inventory and quantitative assessment, the Sai Yok district serves as a good example of Permian limestone geosites. While nearly all the geosites received high scores for accessibility, the majority also earned high scores for preservation. However, because each geosite is protected by different laws, it may result in varying levels of preservation. For instance, Tham Dao Wadung is protected by the Department of National Parks, Wildlife, and Plant Conservation. The staff of this department has numerous responsibilities within their area, which could lead to limited time for cave monitoring. On the other hand, the Mueang Sing Historical Park is under the protection of the Fine Arts Department,

ensuring its thorough preservation. In addition to the law, several suggestions should be presented to the local authority to protect all sites (Nazaruddin, 2020).

Since all geosites are located on land, and most of them are not situated near slopes, the fragility due to natural conditions is likely not to affect them, except Tham Lawa, which is situated at a higher elevation than the others. During the rainy season, there is a probability that landslides could occur in that area.

In general, most geosites in this study are located near asphalt roads, increasing the probability of visitor access to the sites. However, good accessibility also comes with the risk of increased damage and a higher number of visitors, which can result in a high degree of deterioration (Brilha, 2016; Nguyen-

Thuy et al., 2018). Additionally, well-known sites such as Tham Krasae, Nam Tok Sai Yok Noi, Hellfire Pass, and Mueang Sing Historical Park attract a high number of visitors, which could potentially lead to threats from human activity.

The application of this quantitative method, developed by Baadi et al. (2020, 2021), to the Permian limestone geosites in the Sai Yok area has proven to be effective. However, the medium rating assigned to the scientific value of all geosites may be attributed to the study's limited scope, which primarily concentrates on Permian limestone geosites. For future studies, the scope of the area should be broadened to gather more information and focused on more types of geosites.

While many tourist attractions in the area feature information boards, they frequently lack comprehensive geological information. This scenario resembles that of various geosites in Thailand, such as in Chaiyaphum Province (Singtuen and Won-In, 2018), Nakhon Sawan Province (Singtuen and Phajuy, 2020), Phetchabun Province (Paungya et al., 2020), and Yala Province (Nazaruddin et al., 2023). Therefore, it is recommended to establish geological information boards or panels that provide detailed insights into these sites' geologic settings and features. Collaborative efforts among relevant authorities, particularly the Department of Mineral Resources, are crucial in providing geological information to enhance the experience for local residents and tourists and foster sustainable geotourism in these locations. Furthermore, promoting local cultural education and economic activities that align with the biological and cultural heritage associated with these geosites is imperative.

In summary, out of the seven geosites, Mueang Sing Historical Park and Tham Lawa have the highest scientific value but also display significant levels of deterioration.

Therefore, they should be prioritized in implementing management strategies for these geosites. The deterioration is primarily caused by many visitors and human activities, mainly driven by tourism. Moreover, the accessibility of most geosites by car further exacerbates the risk of degradation.

The relevant authorities must develop and implement effective management strategies to ensure the preservation and sustainable development of these geosites. Additionally, promoting local cultural education and economic activities that align with the biological and cultural heritage associated with these geosites contribute to fostering sustainable geotourism in the area. By striking a balance between preservation and responsible tourism, the Sai Yok District can continue to captivate visitors while conserving its natural and cultural treasures for future generations.

## 6. Conclusions

The Sai Yok District is renowned not only for its rich natural heritage and diverse biodiversity but also for its significant potential in geotourism. The region boasts various captivating geosites and geological and geomorphological features spread across its expanse. This study specifically focused on the Permian limestone geosites in Sai Yok District. To assess their scientific interest and degree of deterioration, an inventory and characterization of seven geosites were conducted. These geosites were Mueang Sing Historical Park, Tham Krasae, Tham Lawa, Tham Dao Wadung, Nam Tok Sai Yok Noi, Nam Tok Sai Yok Yai, and Hellfire Pass. Based on specific criteria related to their scientific value and degree of deterioration, the assessment of geosite value revealed that Mueang Sing Historical Park and Tham Dao Wadung possess a positive total geosite value. However, the remaining five geosites have a negative value. Notably, six of the seven

geosites are classified as having a medium risk, necessitating the development and implementation of effective management strategies for these sites.

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## APPENDIX. GEOLOGY OF THE SAI YOK DISTRICT

### 1. Cambrian-Ordovician (EO)

The unit, which is located in a small area in the north of Sai Yok District, consists of greenish-gray bedded calc-silicate rock, laminated and thin-bedded marble with white and pale gray color, yellowish-brown fine-grained quartzite, yellowish-brown quartz schist, and fine-grained medium gray phyllite and mica schist (DMR, 2008). Upper Cambrian sequences are commonly dominated by coarse-grained clastic rocks of shallow marine origin (Agematsu and Oo, 2023). Bunopas (1981) introduced the name Chao Nen Group and divided the group into two formations: the Chao Nen Quartzite Formation overlain by the Tha Manao Limestone Formation.

### 2. Ordovician (O)

This unit, the Tha Manao Limestone Formation, is composed of limestone, argillaceous limestone, and sandy and silty limestone with gray, bluish-green, and pale gray colors. The lithology varies from shallow-marine clastic rocks to shallow-marine carbonate rocks (Agematsu and Oo, 2023). Previously, the unit was referred to as the Thung Song Limestone (Brown et al., 1951). Fossils of cephalopod *Sinoceras chinense* (Fang et al., 2021), the conodont *Baltoniodus cf. alobatus* (Bergström, 1971), *Scolopodus striatus* (Chen et al., 2022), and crinoid stems were identified within this unit. This indicates a range of deposition spanning from the latest Sandbian to Katian. Additionally, lead-zinc deposits are found in the Ordovician carbonate rock (Wang et al., 2023).

### 3. Silurian-Devonian (SD)

It consists of quartzose sandstone, fine- to coarse-grained lithic sandstone with brown, gray, and reddish-brown colors interbedded with shale and siltstone. Some have metamorphosed into quartzite, phyllite, and slate. Bedded chert with

fossils of tentaculite is reported (Maneerat et al., 2022), suggesting an age range from the lower to upper Devonian. The Silurian-Devonian sequences were named the Tanaosi Group by Javanaphet (1969), which was later subdivided into two formations: the Kanchanaburi Formation (ranging from lower Silurian to middle Devonian) and the Kaeng Krachan Formation (ranging from middle Devonian to lower Carboniferous). Subsequently, the rocks ranging in age from Silurian to Devonian were given the name Sukhothai Group (DMR, 1992).

### 4. Silurian-Carboniferous (SDC)

The unit consists mainly of yellowish-brown and greenish-gray shale and siltstone, gray flaser limestone with fossils of cephalopods and conodonts. Additionally, phyllitic shale, micaceous shale, micaceous sandstone, slate, and quartzite have also been reported. DMR (1992) introduced the name Thong Pha Phum Group for the rocks in Thailand ranging in age from the late Ordovician to early Carboniferous rocks.

### 5. Carboniferous-Permian (CP)

Most Carboniferous and Permian rocks in Thailand are of shallow-marine facies. The Carboniferous sequence is dominated by siliciclastic rock. Two formations of the Thong Pha Phum Group were assigned to rocks in the study area (in ascending order): the Khao Phra Formation (CPkp) and the Khao Chao Formation (CPkc). The Khao Phra Formation consists mainly of graywacke and shale with greenish gray to medium gray and white to light yellowish-brown arkosic sandstone. The Khao Chao Formation comprises white to light yellowish-brown arkosic sandstone and white to medium gray mudstone. Fossils of brachiopod, crinoid stem, and bryozoa have been reported (DMR, 2008).

## 6. Permian (P)

The Permian System is dominated by carbonate rocks, which form distinctive characteristics of karst topography in the study area. Previously, Bunopas (1981) introduced the term Sai Yok Group for Permian rocks in the Kanchanaburi Province. Later, many workers (Bunopas, 1992; DMR, 1992; Raksaskulwong, 2002; Karapunar et al., 2022) introduced the name of this unit as the Ratburi Limestone Group. DMR (2008) subdivided the Permian rocks in this area into two formations: P1 and P2. P1, composed of siliciclastic rock, comprises gray to greenish-gray shale and sandstone interbedded with dark gray to black sandy shale. Grey bedded to massive limestone is predominated in P2. The P2 unit also contains chert or siliceous nodules, dolomitic limestone, minor sandstone, and shale. There are numerous fossils found in these carbonate rocks, including fusulinids, radiolarians, brachiopods, corals, ammonoids, and crinoids (DMR, 2008; Sashida et al., 2022; Maneerat et al., 2022).

## 7. Triassic (Tr)

The unit, which covers only 0.02% of the northwestern part of the Sai Yok District, comprises mainly sandstone and mudstone (Trss) with a dark gray to brown color. Fossils of bivalves (*Halobia* sp. and *Daonella* sp.) and brachiopods have been reported. At the lower part of the unit, there are brownish-gray limestone conglomerates. This unit accumulated unconformably on Permian rocks and tends to be strongly folded (Chonglakmani, 2011).

## 8. Jurassic (J)

The Jurassic rocks in this area are subdivided into two units: J1 and J2. J1 mainly consists of light brownish-gray to gray dolomitic limestone with local concretion and sandstone fragments. Unit J2 comprises a limestone conglomerate with rounded to subrounded clasts of limestone, sandstone, quartzite, shale, and some conglomerate. The Jurassic rocks and their faunas

indicate shallow marine facies (DMR, 2008; Meesook and Saengsrichan, 2011).

## 9. Jurassic-Cretaceous (JK)

Jurassic to Cretaceous rocks mainly consist of reddish-brown arkosic sandstone interbedded with white to light gray mudstone, sandstone conglomerate, and limestone conglomerate.

## 10. Tertiary (T)

Tertiary sediments of the Neogene epoch cover only 0.01% of the northern part of a study area. They consist of semi-consolidated light gray to greenish-gray cross-bedded sandstone, siltstone, and mudstone. The upper part of the unit contains freshwater conglomerate limestone, marly limestone, and gravel beds.

## 11. Quaternary (Q)

The Quaternary sediments crop out an area covering approximately 20.13% of Sai Yok District. The classification of the Quaternary unit depends on the relationship between landforms and the chronological evidence (Choowong, 2011). The unit is subdivided into three sub-units: terrace deposits (Qt), colluvial and residual deposits (Qc), and alluvial deposits (Qa). Qt consists mainly of gravel and sand, reflecting the topography of the terrace along the river channel. Qc comprises rock fragments of quartzite, sandstone, siltstone, and granite. Sand and silt, lateritic soil, and terra rosa soil are found in this sub-unit. Alluvial deposits (Qa), containing thin layers of gravel, sand, silt, and clay, are found in the lower floodplain and along the channel.

## 12. Igneous Rocks

Igneous rocks in the Sai Yok District comprise intrusive felsic igneous rocks of two ages: Triassic granite (Trgr) and Cretaceous granite (Kgr). Trgr is found in the northern part of the study area, covering an area of about 0.06%. The unit contains a coarse-grained porphyritic texture of biotite granite, pegmatite, and quartz veins (DMR, 2008). Kanjanapayont et al. (2020) suggested that the

magmatic evolution of granites of the Sibumasu terrane results from the Sibumasu and Indochina collision during the Triassic. The events of collision can be distinguished at approximately  $241.8 \pm 8.2$  to  $235 \pm 12$  Ma and  $230.6 \pm 3.4$  to  $213.4 \pm 3.0$  Ma.

Cretaceous granite mainly comprises medium-to-coarse-grained biotite granite, muscovite-biotite, aplite granite, and diorite, occurring locally as dikes (Oo et al., 2023), and borders the region

between Thailand and Myanmar. Kgr belongs to Thailand's Western Province of granitic belts (Nachtergaele et al., 2019). Radiometric dating of the U-Pb zircon method yielded ages of approximately 78.97 to 79.59 Ma, which corresponds to the timing of the Indian Ocean subduction and collision between the west Myanmar Terrane and the Sibumasu Terrane (Oo et al., 2023). This unit of granite rocks hosts one of the large deposits of tin-tungsten in the world.