The Phou Hin Poun Karst Landscape: Characteristics and Geoheritage Values

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Regional Setting

The Central Indochina Limestone is one of the largest karst regions in Southeast Asia. This region is also commonly referred to as the Khammouane Limestone, and forms a belt of karst 290 kilometers (km) long and 30 km to 120 km wide stretching across central Lao PDR and into Vietnam (Figure 1). In Lao PDR, the limestone is mainly an arcuate, NW to SE tending faulted anticlinorium, following the Thakhek fault at its southern boundary. The 500-1100 m thick main carbonate sequence is middle Carboniferous to early Permian, consisting of limestones, dolomitic limestones, and dolomites [8].

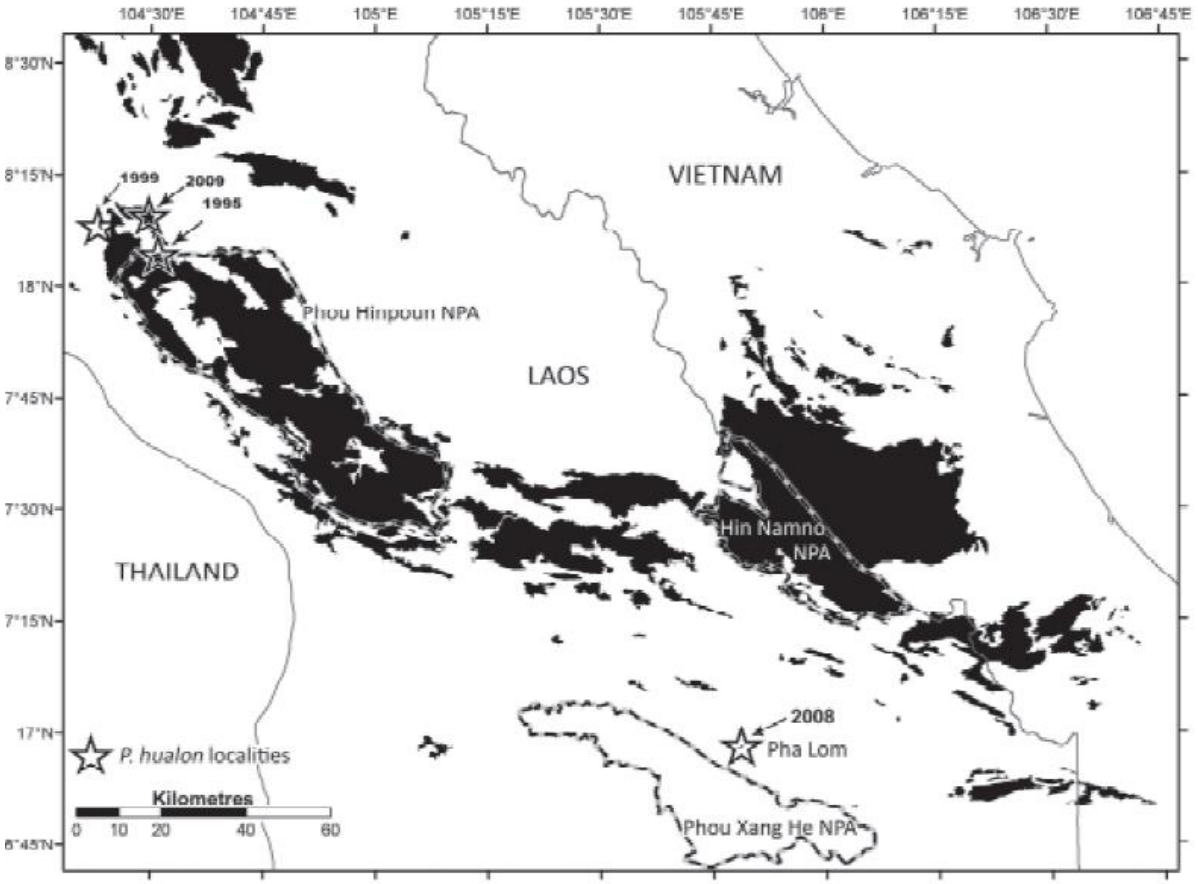

Figure 1. Map of the Central Indochina Limestone region with karst massifs shown in black.

The Phou Hin Poun National Protected Area (NPA) covers 2380 km^2 of mainly limestone landscape in the western part of the Khammouane karst (Figure 2). The Phou Hin Poun karst is characterized by fengcong karst massifs with pinnacles, closed depressions (called poljes by karst scientists and known locally as kouans), rivers and streams sinking underground, springs, and large caves. The karst uplands are mainly between 600 and 800 m, with some summits up to 1146 m. The northeastern and northern boundary of the limestone is against Mesozoic clastic rocks that form a higher plateau, mostly fringed by a sandstone escarpment that overlooks the karst [7,14]. This is shown on the Geological Map of Phou Hin Poun Protected Area, presented in the Appendix.

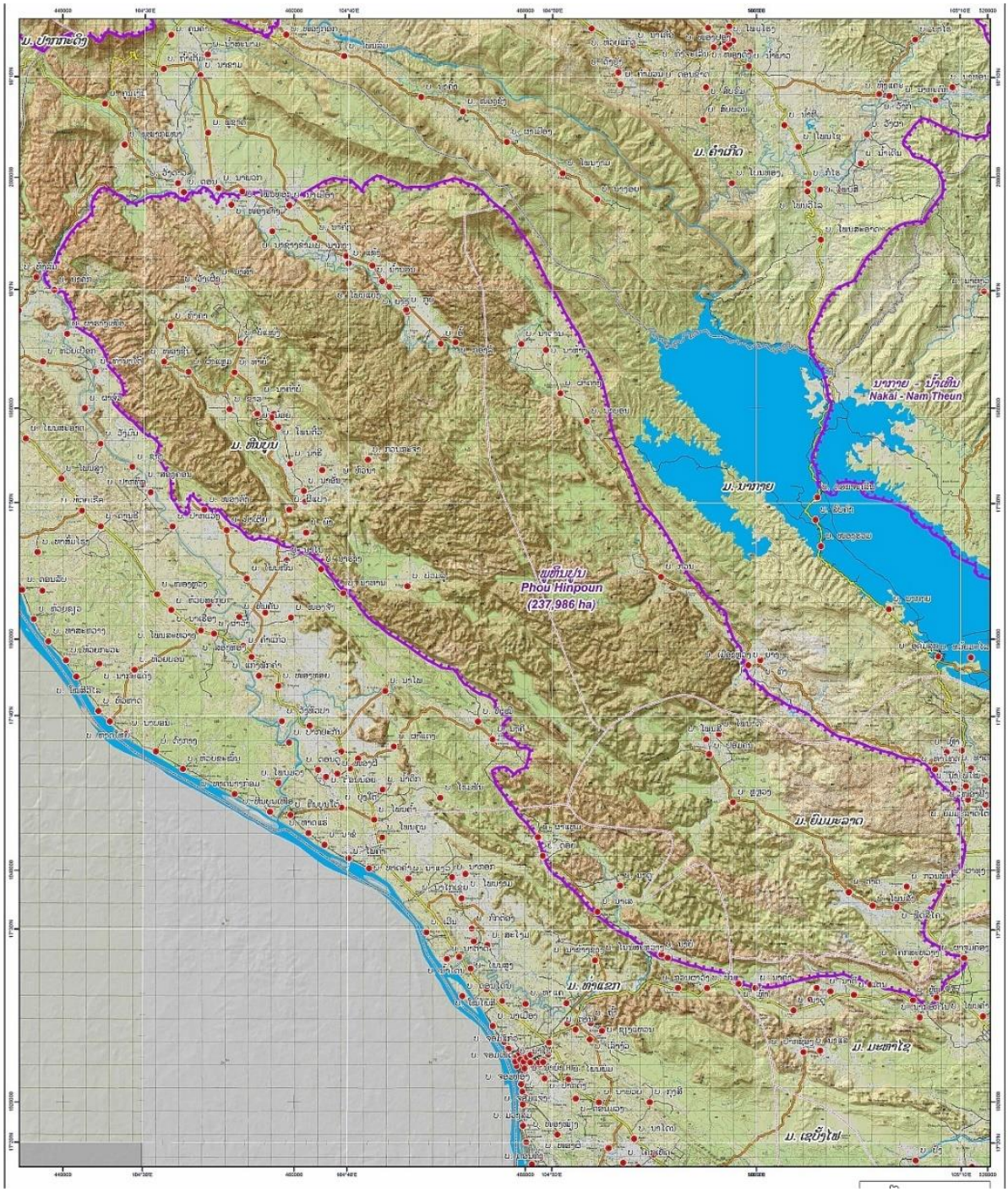

Figure 2. Map showing Phou Hin Poun NPA and nearby protected areas enclosed by purple lines.

The geosite study area is about 1000 km^2, comprised of the northeastern and northern part of Phou Hin Poun NPA and some adjacent areas (Figure 3).

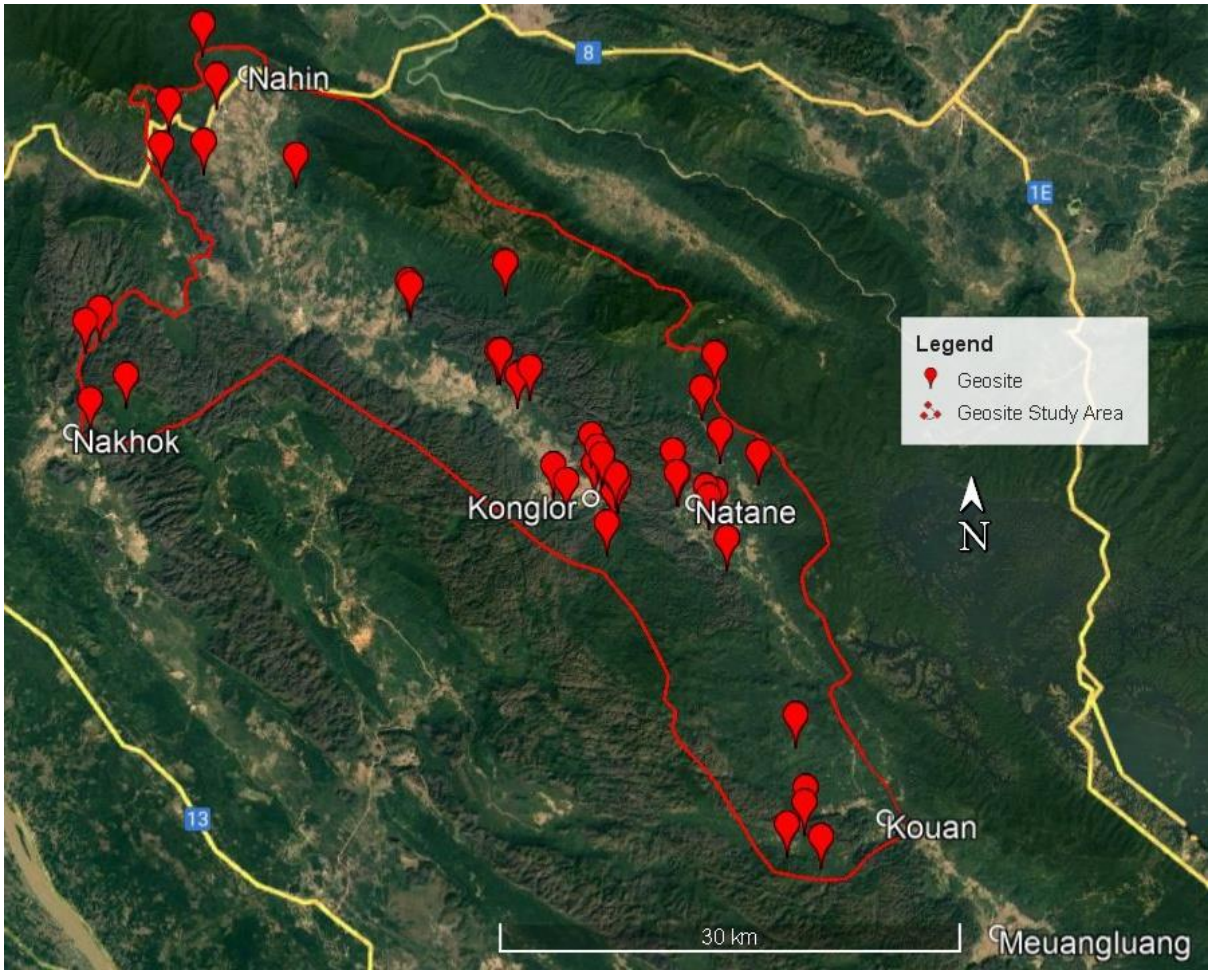

Figure 3. Map of the geosite study area and the geosites identified and assessed.

Geology of Phou Hin Poun

The modern karst topography of Phou Hin Poun has many variations in style. This arises because of internal variations in lithology, bedding thickness, joint spacing and faulting within the limestone sequence. Variations in the spacing of cross-cutting fissures (joints, faults, bedding planes) in the rock is particularly important. The folded rocks have dips to about 40 degrees and so the massif surfaces cut across these undulating beds expose different parts of the carbonate sequence to karst dissolutional processes. Subtle variations in lithology (e.g. more or less dolomitic horizons and more or less insoluble residues, such as chert) affect rock solubility and so are expressed in landform style. Thinner beds tend to be more intensely jointed, so some parts of the terrain are intensely fissured by cross-cutting corridors along closely spaced master joints and faults. Some limestone outcrops are almost devoid of higher plants, because there is so little insoluble residue to generate soil. Some enclosed depressions are deep and widely spaced because the rock is massive with low fissure frequency, and as the depressions incise their surrounding ridges are left as steep peaks. Yet in other places the limestone has been removed down to, or near to, the impermeable basement (Boualapha Fm), and so large flat-bottomed poljes expand near the level of the water-table [1,7,14].

Lithology and Stratigraphy

The karst of Phou Hin Poun is developed in Carboniferous-Permian limestones of the Khammouan Formation (Fm), about 320-270 million years old. These are thickly bedded, crystalline limestones and dolomitic limestones with cherty horizons becoming more evident lower in the sequence. They are 500-1100 m thick, with the difference in thickness partly being accounted for by variable erosion of the upper parts of the sequence. Compact, massive and pure carbonates of this kind provide the perfect host rock for karst development [1,8,13].

Beneath the limestones are sandstones and silty sandstones with occasional thin interbeds of coal. These rocks are 300-400 m thick and comprise the Boualapha Fm of early Carboniferous age. They provide the impermeable 'basement' underlying the karst and force underground streams to reappear around the edges of the limestone outcrop as springs [1,13].

Unconformably overlying the limestones are Jurassic (Ban Lao Fm and Nam Phouan Fm) and Cretaceous (Nam Xot Fm) sediments (200-65 million years old), mainly comprising gritstones, sandstones and marls. The accumulation of these Jurassic and Cretaceous terrigenous sediments resulted in the spreading of an impervious cover of about 2000 m thickness over the Triassic karst landscape. Erosion and downcutting during the Cenozoic resulted in the gradual removal of the clastic cover beds and re-exposure of the limestone terrain. Patches of Mesozoic cover beds still remain in a few places where the limestone meets the bordering cuestas of the sandstone plateaus [5,13].

Geologic Structure

The geological structure of Phou Hin Poun is dominated by the Truong Son fold belt, an anticlinorium extending NW-SE. It was formed during the late Devonian to early Carboniferous, and reactivated during the Cenozoic to the present. The fault systems in Phou Hin Poun comprise primary faults trending NW-SE, and NE-SW trending secondary faults [8,13].

Geologic and Geomorphic History

The Phou Hin Poun limestone had its origin as sediments deposited in the Paleo-Tethys Ocean from the middle Carboniferous to the early Permian period, about 320-270 million years ago (Ma). The limestone was deposited in a deep-water marine environment where the source of clastic grains (sand and clay) was remote, allowing thick layers of almost pure calcium carbonate to accumulate [4].

Morphogenetic evolution of the karst is the result of a complex tectonic history. The Indosinian orogeny occurred in the middle Triassic (247 Ma). This significant compression, uplift, and erosion episode affected much of Southeast Asia, bringing many carbonates into subaerial positions, and resulting in a prolonged karstification episode of about 20-35 million years in central Laos [5].

Tectonic movements of the Indosinian orogeny initiated a major period of erosion in the Triassic, when rivers from neighbouring mountains transported clastic sediments into the region where they were deposited across the karst in a lowland basin. The accumulation of these Jurassic and Cretaceous (200-65 Ma) terrigenous sediments resulted in the spreading of an impervious cover of about 2000 m thickness over the Triassic karst landscape, creating a paleokarst [5].

Then renewed tectonism associated with the Himalayan orogeny, between 70 and 50 Ma, led to further uplift and faulting and initiated a new phase of erosion. During the Cenozoic, rivers flowed across this surface and, after millions of years of erosion and downcutting, the gradual removal of the clastic cover eventually resulted in the superimposition of these rivers onto the carbonate rocks that lay beneath. As patches of the Triassic paleokarst terrain were exhumed, the surface drainage became karstified, being lost underground and re-organised [5].

In the Phou Hin Poun area, most of the Jurassic and Cretaceous cover beds have been stripped off, but traces of the old superimposed valleys are still evident as gentle southeast to northwest oriented troughs parallel to the tectonic grain of the country. Patches of Mesozoic cover beds are still eroding in a few places where the limestone meets the bordering cuestas of the sandstone plateaus, at the geosites: Phou Pha Marn, Pha Sakoup, Pha Bo, and the northeastern Natane Basin. These emerging limestone hills are exhumed remnants of the late Triassic karst landscape, and so constitute a paleokarst [5,13]. Sandstone fissure fills and karst breccias, with a reddish, sandstone matrix, are fairly widespread and have been dissected by later caves and cliffs. These paleokarst fills and breccias show that the karst massifs were once covered with Mesozoic sandstones. Paleokarst fills and breccias are represented at the geosites: Phou Pha Marn, Tham Lom, Tham Pha Kor, and Tham Phaban.

Tectonism through the Cenozoic has elevated the terrain well above sea level, and has rejuvenated and remodelled the ancient paleokarst topography. So, despite the long period of landscape evolution, most of the karst landforms are found well above local base level and varieties of polygonal karst, adjusted both to the prevailing tropical monsoonal environment and to bedrock conditions, now dominate the scene. This long-lasting uplift generated a relative deepening in base level, leading to extensive planation surfaces, large and deep poljes, and fengcong karst. Conditions for tower karst (fenglin) evolution are not met except locally around the edges of poljes or karst margin plains where the water table is near the surface [1,7].

Hydrology and Hydrogeology

In the Phou Hin Poun region there are two ways in which rainwater influences the karst hydrology. On the karst massifs, where the terrain is formed entirely in limestone, the rainfall is channeled directly underground. This is termed autogenic recharge. But, in the northeast of Phou Hin Poun, the headwater streams of the Nam Hinboun and Nam Pakan collect runoff from impervious non-karst rocks before flowing onto the karst. This is known as allogenic recharge, i.e. originating outside the karst. Autogenic and allogenic waters have different water qualities, because they are sourced from areas with different rock types and land uses. Allogenic water is generally more acidic and ‘dissolutionally aggressive’ compared to autogenic water in karst. But these waters mix underground and their combined flows emerge at karst springs.

At Phou Hin Poun, groundwater in the karst cannot penetrate deeper beneath the surface than the level of the underlying impervious Boualapha Fm sandstones and siltstones. So permanent and temporary springs are located around the edges of the karst massifs, generally near the foot of cliffs, which is close to the level at which Boualapha Fm rocks are encountered.

At the large scale, Phou Hin Poun, indeed the whole of the Khammouane karst, drains west to the Mekong River. The main rivers and streams have sections that flow west or southwest in the direction of the regional hydraulic gradient towards the Mekong, but also have long transverse portions which follow the axes of the karstic massifs or basins. This pattern results

from the influence of geological structures and landscape morphogenetic evolution on regional flows [7].

There are two river systems that drain the study area of Phou Hin Poun. The Nam Hinboun is a mainly allogenic river that drains the northern and central part of the study area (see Appendix). The headwaters of the Nam Hinboun are on the sandstones of the Nakai Plateau. Its headwaters flow off the sandstone escarpment and down the Moitok waterfall into the northeastern Natane Basin. It then flows along the edge of the karst to the southeast and then southwest before sinking underground and traversing the karst massif through the Konglor Cave. The Hinboun River resurges in the Hinboun Basin and flows to the northwest along the axis of the basin. The river turns to the west then to the southwest to flow through the Hinboun Gorge and onto the karst margin plain on the western side of the karst. It flows back to the southeast along the karst margin plain and to the Mekong River.

The Nam Hinboun has several major tributary streams. The Nam Thon is a mixed allogenic-autogenic stream which drains part of the northern Natane Basin. The Nam Non is an allogenic stream which flows off of the sandstone to the northeast, across the karst massif through Tham Nam Non and then across the Hinboun Basin to join the Nam Hinboun. The Nam Hai is an allogenic stream which drains the northeastern part of the Hinboun Basin and the surrounding sandstone plateaus. The Nam Mahoy is a mixed allogenic-autogenic stream which drains the northwestern part of the Hinboun Basin, flowing into the Nam Hinboun slightly upstream of the Hinboun Gorge. A number of springs drain the karst massifs of the northern Natane and Hinboun Basins and contribute autogenic water to the Nam Hinboun system.

The Nam Pakan is a mixed allogenic-autogenic surface and groundwater river system that drains the southern part of the study area (see Appendix). It originates from streams flowing off of the sandstones of the Nakai Plateau and from karst springs (e.g., Nong Meuang, Nong Khoun) in the Natane basin. The streams converge at Kouan Sam, a narrow 10 km long polje, then sink into Nam Pakan Cave and flow through the karst massifs to the polje of Ban Bouamlou. The Nam Pakan crosses the polje and sinks underground again in Tham Nathan to emerge on the western side of the karst. It flows to the southeast along the karst margin plain and turns west to join the Hinboun and Mekong Rivers.

The Khammouane Limestone exhibits little or no intracrystalline porosity. Thus, karst groundwater flows are guided by dissolutionally enlarged fractures, joints and bedding planes. The high degree of dissolved conduits in the Khammouane karst provides very efficient drainage, resulting in little storage and many karst springs and caves having very low or no flow during the dry season. For example, the Konglor Cave has a minimum flow estimated at 0.4 m^3/s, with a yearly mean flow of 11.2 m^3/s and a maximum flow greater than 100 m^3/s. Nam Non Cave, with a smaller but steeper catchment area, has an estimated minimum flow of 0.08 m^3/s, with a yearly mean flow of 2.6 m^3/s and a maximum flow greater than 200 m^3/s [2,6,9,10].

Flow Dynamics: During the wet season, there are typically 5 to 10 floods per year, with a short duration of less than a week. The delay to reach the peak does not exceed two days while the discharge generally decreases by a factor of three in less than five days [6].

Karst Landforms and Features (Geoheritage values of international significance)

The collection of fengcong karst massifs and pinnacles, poljes, and magnificent caves in Phou Hin Poun constitute a karst region that is of geomorphological significance in a worldwide context [7,14].

Fengcong Karst Massifs and Pinnacles

The characteristic landscape style of Phou Hin Poun is one of karst massifs that are almost completely bordered by bare limestone rock with very steep slopes or high cliffs rising up to 500m above intervening poljes and plains. The karst massifs have become dissected by karst processes into polygonal karst relief: a topography similar to an enormous egg-tray, where a multitude of deep depressions are surrounded by residual conical hills (fengcong). The upper surfaces of the steep fengcong hills are commonly eroded into sharp pinnacles interspersed with deep fissures, making them virtually inaccessible [8,14]. In the study area, the karst massifs bordering the Hinboun and Natane Basins are of international significance.

Spectacular, sharp-edged pinnacles are distinguishing features of the Phou Hin Poun karst landscape. The Phou Pha Marn pinnacle karst landscape is of international significance, however examples of well-developed pinnacles are widespread on the bare limestone rock. Pinnacle karst is a spectacular, small-area landform found mainly in the humid tropics and subtropics. The pinnacles are typically formed by the fracturing and weathering of hard, pure, massive limestone such as the Khammouane limestone of Phou Hin Poun [3,7].

Photo 1. Pinnacle karst and karst massifs at Phou Pha Marn. © Terry Bolger

Poljes

Enclosed within the Phou Hin Poun karst are numerous poljes, known locally as kouans, which by their size constitute one of the main karst forms. They result from erosion and planation at the wet season water table. Dissolutional planation has worked outwards, forming notches and cliff-foot caves that undercut the limestone walls, resulting in collapse and creating precipitous marginal cliffs. Poljes are relatively common in plateau karst either where alluviation has been dominant or where impermeable rocks such as sandstone or shale underlie the limestone. In Phou Hin Poun, the poljes are quite advanced in their degree of evolution, and some are developed on the breached cores of anticlines where the basement sandstone floors (Boualapha Formation) are exposed. Poljes are a 'climax' form, indicating well-developed karst [3,8,14].

Basins that have developed by erosion and planation, inwards from the edge of the karst, take the form of karst margin poljes. Two of the largest basins are the Natane Basin and the Hinboun Basin, which are alluviated karst plains. Excavations and exposures reveal that beneath the sediments the poljes are often cut across limestones, but in places can also be cut across sandstones and siltstones of the underlying Boualapha Formation. Isolated, still unconsumed parts of the karst are scattered across parts of the Natane and Hinboun basins, where island-like karst towers and hills produce attractive landscape features known as fenglin or tower karst. These two karst margin poljes are of international significance, together with the high fringing cliffs of the karst massifs which border them.

The Natane Basin gathers drainage partly from the sandstones of the Nakai Plateau to the northeast. Its western and southern margins are steep limestone walls. The Natane Basin is drained out through the Konglor Cave into the Hinboun Basin. The Hinboun Basin gathers more drainage from the sandstone plateaus along its northern and northeastern edges. It drains out to the southwest, through a gorge entrenched between limestone peaks that rise 300 to 500m above the Hinboun River.

Photo 2. The Natane Basin is a karst margin polje, with karst massifs to the west. © Terry Bolger

The polje of Ban Na Heup is completely enclosed by high karst cliffs and is hardly accessible except by going through the Tham Heup cave. The small village of Ban Na Heup and a temple, Wat Khiri Vongkot, said to be 600 years old are located in the polje, isolated from the outside world. Local people walk 1.2 km through Tham Heup to reach the temple and the village. An

eminent karst heritage expert has said that he knows of no other place where the main access to a settlement in a large enclosed depression, such as a polje, is achieved via a cave. Thus, the polje and cave are unique or at least very special for their cultural / spiritual aspects combined with their natural setting, and of international significance (Paul Williams, personal communication, 24 March 2022).

Other poljes within the study area are: Kouan Sam, an elongated polje with a narrow opening to the Natane Basin; Kouan Nai, a small kouan just to the southeast of Kouan Sam; and the polje to the south of Konglor village.

Large River Caves

The Central Indochina Limestone region, including Phou Hin Poun, is renowned for its very large and long river caves. Hang Son Doong cave, in Vietnam, is one of the world's largest caves by passage size. The Xe Bang Fai Cave in eastern Khammouane Province is perhaps the world's largest river cave. In Phou Hin Poun there two large river caves of international significance: the Konglor Cave and Nam Non Cave. These large caves have all been formed by allogenic water flowing off of sandstone catchment areas upstream of the karst [6,12,14].

The sandstone-limestone association is a powerful combination for karstification, and favorable to large cave formation. The sandstone catchment areas drain synclines at higher elevation, which provides large allogenic water flows, especially during floods. Where there are steep slopes (e.g. above Nam Non Cave) it provides a high velocity to the water. Water flowing from the sandstone is more acidic and also provides abrasive sand particles, pebbles and cobbles which may contribute significantly to cave erosion during flood episodes. The large allogenic rivers generate relatively linear cave passages, often with few tributaries [6,12].

The Hinboun River flows underground for 7.5 km through Konglor Cave, and the magnificent cave river is navigable by longtail boat throughout the year, making it a unique tourism experience. The river passage reaches up to 100m in width and up to 80m in height. The downstream 1 km of passage to the resurgence is smaller: about 25m wide and 15m. It is located downstream of the junction with a large relict passage leading to the outside, and is a younger phreatic tube. It may have formed as a leak from the main passage at the junction, possibly in response to lowering of the base level [6,14].

Photo 3. Large stream passage with cobbles in Nam Non Cave. © Dave Bunnell

Nam Non Cave has a main streamway that flows 6 km through the karst massif, with a water-filled siphon at the mid-point. It has a flowing river during the wet season and ceases flow early in the dry season. This passage is about 40m wide by 40m high. The streambed has abundant sandstone cobbles throughout, and sandstone boulders up to 30cm in diameter are frequent with the largest up to 60cm. They originate from the sandstone plateau upstream the cave and thus have crossed entirely through the karst. This indicates the occurrence of violent flash floods, which is corroborated by the steep slope of the watershed. Flood waters can rise about 10m in the wide entrance gallery. The cave also has a smaller flow diversion passage downstream of the siphon, and an extensive network of well-decorated relict passages to the northwest of the main stream passage [9]

Cultural links between man and karst

More than 14,000 people live a rural lifestyle in the Natane and Hinboun Basins, so their lives are intimately connected to the Phou Hin Poun karst landscape. The alluvial soils are used for growing crops such as rice, tobacco and cassava; and for raising livestock including water buffalo, cattle, goats, pigs, ducks and chickens. Water for domestic use and for irrigating tobacco and vegetable gardens is supplied by the rivers, streams, karst springs, and some shallow wells.

Forested areas in the basins and on the karst are utilized for harvesting timber and a variety of non-timber forest products. Rivers and streams are used for fishing and collecting other aquatic resources. The caves are used for collecting bats, swallows, and guano for use as fertilizer. More recently, the ecotourism potential of the karst and caves of Phou Hin Poun has gained recognition and is being developed progressively.

The caves are also used as transport routes through the rugged karst landscape. For example, by boat through the Konglor Cave to move between the Natane and Hinboun Basins, and on foot through Tham Heup to reach the village and temple in the closed polje of Kouan Ban Na.

The karst and caves of Phou Hin Poun are of spiritual significance also. Animist spirits (*Phii*) and Buddhist iconography are venerated, and often occur in association with caves, cliffs, poljes, and karst towers or outcrops. These are represented at the geosites: Pha Sieng Dung, Tham Phayavat Maengvanh, and Wat Khiri Vongkot in the Kouan Ban Na polje.

Photo 4. Buddhist stupa at Pha Sieng Dung. © Terry Bolger

There are also legends associated with some of the karst landscape features such as the sandstone-capped karst outcrop of Pha Sakoup, and Tham Heup cave.

Human hand stencils presumed to be from prehistoric times occur at Tham Pha Mue, the first known from Khammouane Province. The nodules and beds of chert commonly found in the Khammouane limestone were likely utilized by Stone Age humans to make stone tools, but evidence for this is lacking. Very little archaeological investigation has been done in Phou Hin Poun so far.

Photo 5. Hand stencils at Tham Pha Mue. © Terry Bolger

Comparative Analysis

The Phou Hin Poun karst has many landform features in common with the karst in Hin Nam No National Park in eastern Khammouane Province, and Phong Nha-Ke Bang National Park, just across the border in Vietnam. This is to be expected, as all three of these protected areas are located in the Central Indochina Limestone belt, with a similar geological and climatic history. Phong Nha-Ke Bang is a natural World Heritage site and World Heritage nomination for Hin Nam No is in progress. These two sites are located along the Annamite mountain chain and so have experienced more uplift and rejuvenation during the Cenozoic than Phou Hin Poun. Their karst plateaus are less incised and their poljes are smaller and less developed than the more mature karst massifs and poljes in Phou Hin Poun [1].

Non Nuoc Cao Bang Geopark is a karst site in northeast Vietnam. It has a similar age and purity of limestone and a similar tectonic history to Phou Hin Poun. It also has a number of landform features in common with Phou Hin Poun. However, the karst in Non Nuoc Cao Bang

has evolved further than that in Phou Hin Poun, to form mainly a tower karst landscape. The Non Nuoc Cao Bang karst has less bare rock and the pinnacles are smaller and less developed than at Phou Hin Poun. The poljes in Non Nuoc Cao Bang are surrounded by karst towers and are less spectacular than the high fringing cliffs which enclose or border the poljes in Phou Hin Poun. Furthermore, Non Nuoc Cao Bang has no large and long river caves, such as the world-class caves Konglor and Nam Non in Phou Hin Poun [11].

Photo 6. High fringing cliffs bordering the Hinboun Basin, a karst margin polje. © Terry Bolger

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Appendix

Geological Map of Phou Hin Poun Protected Area – provided separately as a digital file: (Geological Map-Phou Hin Poun.pdf)