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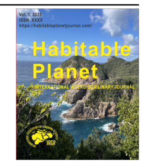

Mount Popa in the Central Dry Zone of Myanmar: From legacy of a volcano to a habitable refugium

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ABSTRACT

The Mount Popa is regarded as one of the most significant volcanoes in Myanmar, revered not only for its geological prominence but also as a sacred site deeply embedded in local traditions and spiritual beliefs. Conservation efforts have led to widespread forest cover across the Mt. Popa region, which benefits from significantly higher rainfall compared to neighboring towns in the central dry zone. The volcanic activity of Mt. Popa has shaped distinctive geological formations and enriched the area with fertile soils, making it a vital biodiversity refuge amid the otherwise arid central landscape. Furthermore, the area has sustained successive human populations, whose long-standing presence is closely tied to the site's enduring religious and cultural importance. Recent seismic activity along the Sagaing Fault has prompted concerns regarding the nearby dormant, most likely active status of Mt. Popa and underscores the necessity for comprehensive scientific investigation. Given that geopark initiatives, integrate research, conservation, and socioeconomic development, robust support from both local and international stakeholders is essential to sustain Mt. Popa as a viable ecological and cultural refugium.

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Research highlights

- The 2025 Sagaing Fault rupture, marked by supershear rupture and widespread aftershocks, underscores ongoing seismic hazards and regional geodynamic impacts.
- Near the Sagaing Fault, Mount Popa offers a unique site for research in geodynamics, seismic activity, ecology, and cultural studies.
- Multidisciplinary research is required for tectonic and seismic interactions, paleoecology, anthropology, biodiversity conservation, and geotourism.

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1 Introduction

Myanmar is the largest country in mainland Southeast Asia, and holds a strategically and tectonically important position as a key link in the India–Eurasia convergence system. It connects the active continental collision between the northward-moving Indian Plate and the Eurasian Plate to the Sumatra–Andaman oceanic subduction zone in the south (Yin and Harrison, 2000).

The country's tectonic setting is shaped by a complex interplay of geodynamic processes: (1) indentation tectonics driven by the northeastward displacement of the Indian Plate, (2) ongoing subduction at the Sunda Subduction Zone, (3) activity along the Shan Scarp Fault, (4) a concealed or blind subduction zone beneath central Myanmar, (5) back-arc extension in the Andaman Sea, and (6) Quaternary volcanic activity along the Mt. Popa–Monywa–Twinywa line, reflecting magmatic systems tied to these tectonic dynamics (Fig. 1) (Zaw and Park, 2025). Combined, these elements generate substantial seismic hazard throughout Myanmar.

Research on tectonics, geodynamics, seismology, and geomorphology has expanded rapidly in Myanmar in recent decades. However, comprehensive and interdisciplinary studies remain limited. This study aims to underscore the need for multidisciplinary collaboration to disentangle the potential impacts of tectonics and earthquakes, focusing on Mount Popa, a geologically significant volcano in Myanmar's central dry zone.

2 Tectonic context and seismicity

Myanmar is tectonically active region with a high risk of powerful earthquakes. Myanmar region consists of major tectonic elements of Myanmar: Sunda subduction, the Indo–Myanmar Range (IMR), the Central Myanmar Basin (CMB), Volcanic arc with Mt Popa, Sagaing Fault and Shan Plateau (SP) (Fig. 1).

The IMR constitutes Mesozoic to Cenozoic rocks extending along the western margin of Myanmar to India and Bangladesh. In contrast, the CMB represents a narrow, elongated sedimentary basin, with its eastern boundary delineated by the Sagaing Fault (SF) (Mitchell et al., 2012; Najman et al., 2020; Zaw and Park, 2025).

Contemporary tectonic activity in Myanmar is principally governed by the northeastward subduction of the Indian Plate, which has given rise to north–south trending active faults, most notably the SF and the Kabaw Fault (KBF) (Yang et al., 2024). To the west of Myanmar, a major east-dipping megathrust subduction zone accommodates the underthrusting of the Indian Plate beneath the Myanmar Plate. This tectonic interface forms part of the broader Sunda subduction system and is instrumental in generating some of the most significant earthquakes and tsunamis recorded in the region (Fig. 2) (Steckler et al., 2016; Yang et al., 2024).

Among the most catastrophic events associated with this subduction zone was the Mw 9.2 earthquake that occurred on 26 December 2004, which generated a devastating tsunami that propagated across the Indian Ocean. The subduction system remains highly seismically active, presenting an ongoing threat of both large-magnitude earthquakes and tsunamis to the region. Stress transfer and tectonic interactions within this system are also recognized to contribute to increased seismic activity and strain accumulation along the SF (Zaw and Park, 2025).

3 Sagaing Fault and Mt. Popa Volcano

The occurrence of devastating earthquakes along the Sagaing Fault (SF) reflects Myanmar's extensive and intricate tectonic evolution, which extends to the Phanerozoic Eon—spanning over 600 million years—and has been notably influenced during the Cenozoic Era ($\sim$66 million years ago) (Zaw and Park, 2025).

The Sagaing Fault extends about 1,400 km and delineates the boundary between the CMB and the SP (Fig. 1). The SF, Myanmar's most seismically active one, played as the principal structure accommodating the strike-slip component of the oblique convergence between India and Sunda Plates (Tun and Watkinson, 2017; Tin et al., 2022; Yang et al., 2024). Notably, earthquakes having 7.7 and 6.4 magnitudes occurring on March, 2025 along the SF resulted in at least 4,000 fatalities, about 6.3 million people identified with urgent needs, and widespread destruction of infrastructure in Myanmar (UNOCHA, 2025). Since then, more than 300 aftershocks with $\geq$3 magnitude happened across the country (EMSC, 2025).

Mount Popa, positioned between 20° 53′ 27″ N and 95° 15′ 02″ E, is situated in Kyaukpadaung Township, Nyaung Oo District, Mandalay Region (Fig. 2a; 3). The principal volcanic structure at Mt. Popa is known as Taung-Ma-Gyi (Fig. 2b); to its southwest, a prominent volcanic plug, termed Taung-Kalat (Fig. 2c), is present. The volcanic crater associated with Taung-Ma-Gyi measures approximately 1.6 km in diameter. Mt. Popa volcanic area consists of volcanic rocks and edifice is constructed atop Pliocene sandstones of the Ayerwaddy Formation and comprises a complex of lava flows and domes, with compositions ranging from basalt to dacite of calc-alkaline affinity (Fig. 3). Studies documented the ages and volcanic activities spanning from the Miocene to the Pleistocene. Older volcanic deposits have been dated to between 10.7 and 19.7 Ma (Miocene), while the initiation of stratovolcano activity at Taung-Ma-Gyi occurred at approximately 0.33 Ma, and the Taung-Kalat volcanic plug was emplaced between 0.82 $\pm$ 0.07 Ma and 0.68 $\pm$ 0.04 Ma (Maury et al., 2004; Lee et al., 2016; Belousov et al., 2018; Sano et al., 2022).

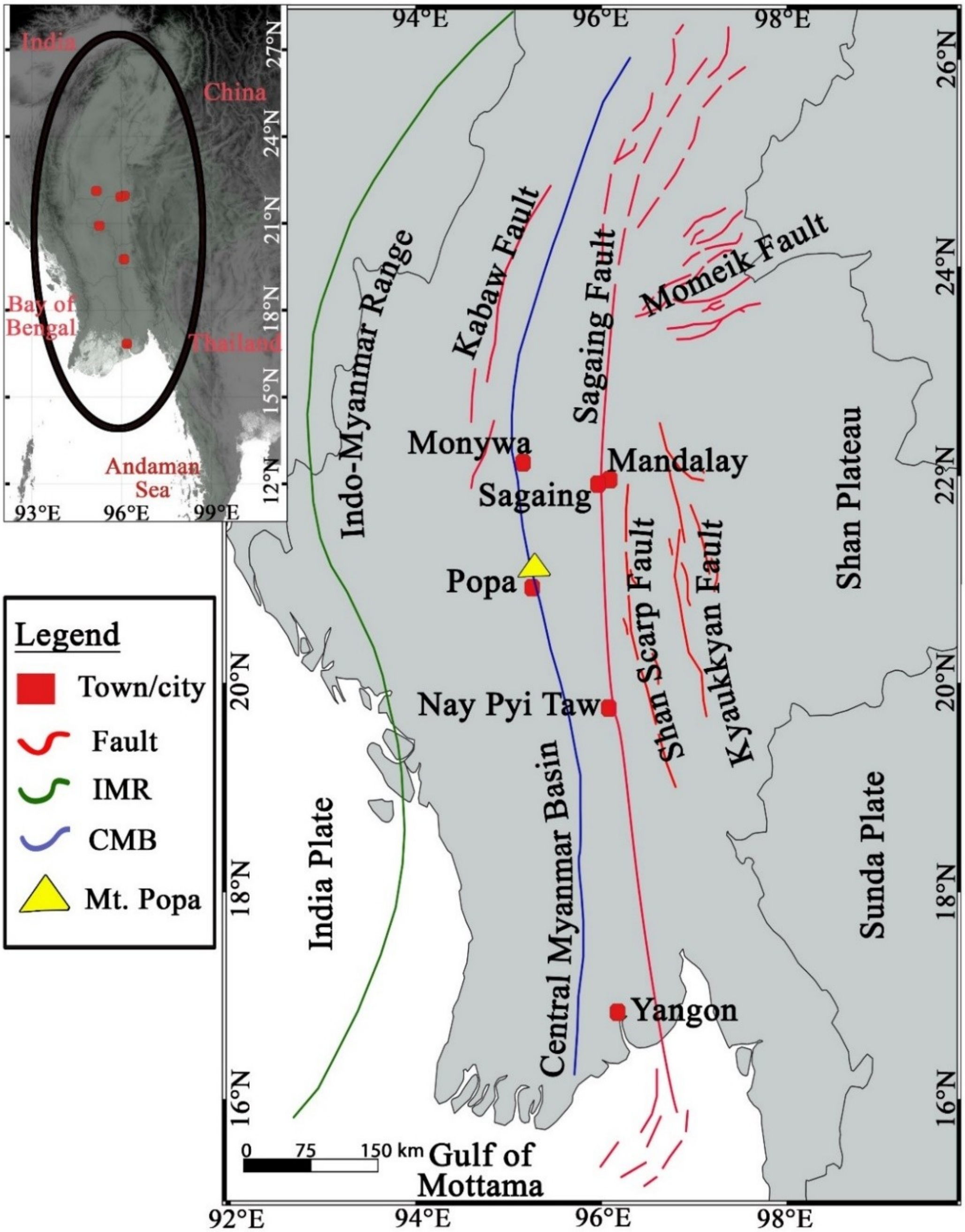

Fig. 1. Schematic map of tectonic elements and faults in Myanmar (simplified after Stephenson and Marshall, 1984; Tun and Watkinson, 2017; Khin et al., 2023). Abbreviations: CMB, Central Myanmar Basin; IMR, Indo–Myanmar Range.

The edifice of Mt. Popa is hypothesized to have been destabilized by the intrusion of magma, with subsequent collapse potentially triggering explosive eruptions (Belousov et al., 2015; Belousov et al., 2018). The eruptive history of Mt. Popa includes several relatively mild explosions, occurring between approximately 12,700 and 8,500 BP, followed by a large-scale edifice collapse around 8,000 BP (Belousov et al., 2018). This collapse was subsequently succeeded by a strong magmatic eruption, resulting in the deposition of pyroclastic flows (Belousov et al., 2018; Sano et al., 2022).

The region experiences heavy monsoonal rainfall, and ongoing deforestation increases soil erodibility and susceptibility to landslides. The volcanic edifice is composed of soft and loosely consolidated volcanic sandstones, ash, and lahar deposits, further exacerbating landslide risk. Additionally, the proximity of Mt. Popa to the SF suggests that tectonic activity may destabilize the magma chamber,

Fig. 2. Location map of Mount Popa volcano (Fig. 2a). Fig. 2b illustrates Taung-Ma-Gyi, and Fig. 2c illustrates Taung-Kalat of Myanmar (modified after Zaw and Park, 2025).

potentially facilitating magma intrusion and collapse-induced explosive eruptions. A significant seismic event could induce vesiculation of magma within the chamber, which may result in the eruption of a previously dormant volcano (Zaw and Park, 2025).

4 Environment and biodiversity

The Mount Popa area was initially designated as the Popa Reserved Forest in 1902, and as the Popa Extension Reserved Forest in 1912. Subsequently, Popa Mountain Park (PMP) was established in 1989. PMP encompasses 128.5 km^2, of which about 82% is covered by forest (MONREC, 2025). The primary objectives of PMP are to conservation of dry zone ecosystem, protection of Kyet-mauk-taung dam watershed area and securing water sources availability, conservation of medicinal plants, preservation of religious sites, cultures and traditions, geosite such as ancient fossilized wood and promote ecotourism. Climatic data indicate monthly mean maximum and minimum temperatures of 25.8 °C and 15.6 °C, respectively, and a mean annual rainfall of 1,170 mm (GAD, 2025).

Popa Mountain Park (PMP) contains 113 natural springs that provide essential drinking and irrigation water to residents. PMP supports a rich biodiversity, including 26 mammal species, 185 bird species, 23 reptile species, 7 amphibian species, and 112 butterfly species, as well as over 300 plant species. Vegetation within PMP is characterized by dry hill forest, mixed deciduous forest, grassland, and plantation stands of *Pinus kesiya*. Dominant vegetation species at PMP vary with elevation. Above 1,000 m, the forest is characterized by *Neonauclea excelsa*, *Quercus spinosa*, and *Schima wallichii*. Below 1,000 m, *Adina cordifolia*, *Chukrasia tabularisaris*, *Tectona grandis*, and *Xylia xylocarpa* are prominent. Dipterocarpus forests are found between 400 and 700 m, while *Tectona hamiltoniana*, *Terminalia chebula*, *Terminalia oliveri*, and *Senegalia catechu* dominate below 450 m. Plantations of *Eucalyptus camaldulensis*, *Santalum album*, and *Xylia xylocarpa* are established below 900 m. The park's wildlife includes Eld's deer (*Rucervus eldii thamin*), dhole (*Cuon alpinus*), muntjac (*Muntiacus muntjak*), wild boar (*Sus scrofa*), Assam macaque (*Macaca assamensis*), rhesus macaque (*Macaca mulatta*), Shortridgei's langur (*Trachypithecus shortridgei*), and Popa langur (*Trachypithecus popa*) (MONREC, 2025).

The Mount Popa volcano is the most prominent and geographically distinctive landmark in central Myanmar.

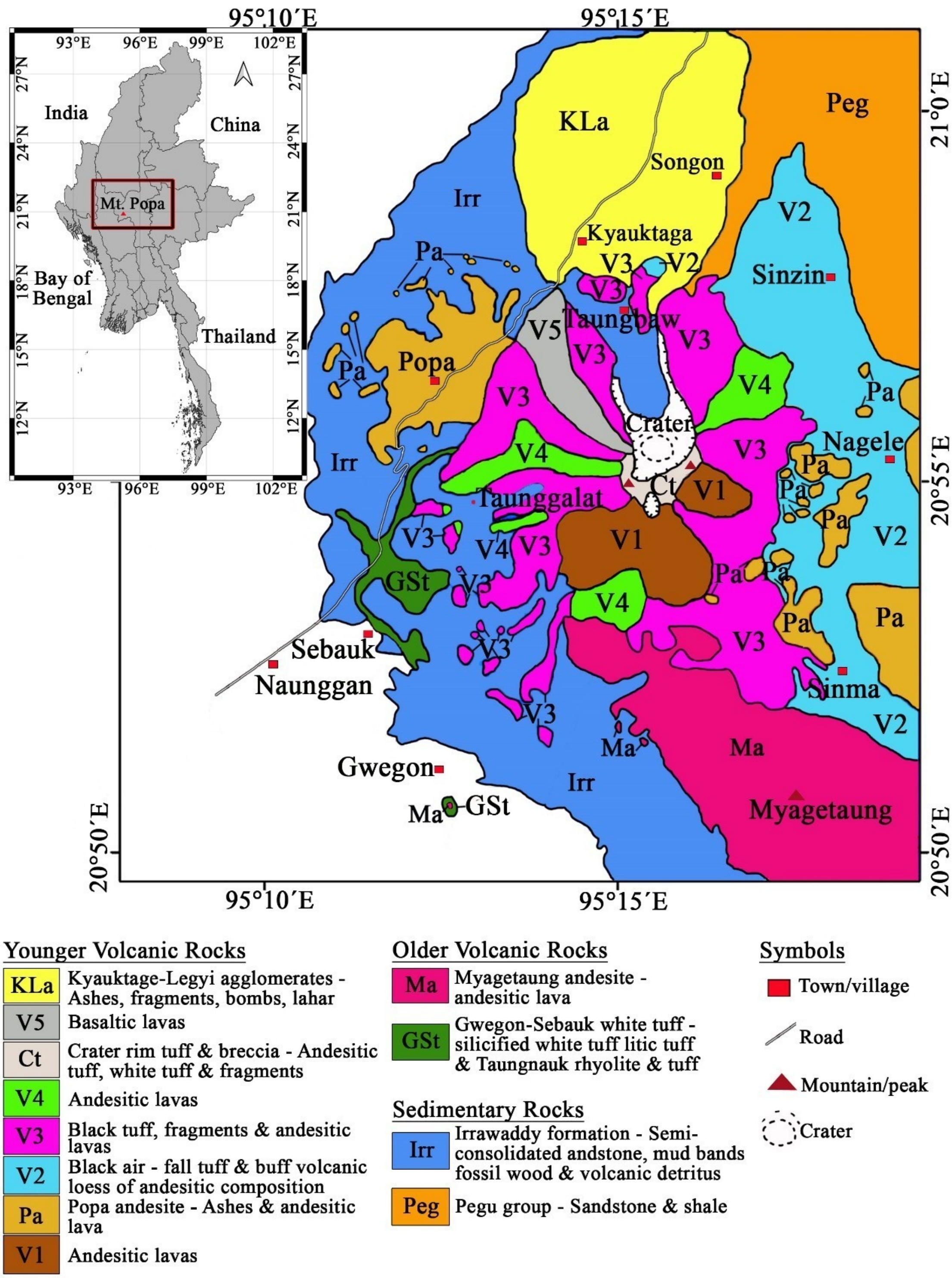

Fig. 3. Geological map of the Mount Popa region, Kyaukpadaung Township, Myanmar (modified after Moe, 1980; Khin et al., 2023).

Situated in close proximity to the densely visited tourist region of Bagan—an 11th-Century civilization and UNESCO World Heritage Site—the Popa area attracts significant visitor numbers. Annual visitation is estimated at approximately 800,000 locals and 25,000 internationals (GAD, 2025). Economic assessments indicate that domestic visitors spend an average of USD 20–24 per trip or USD 16.1–19.6 million in annual contribution (Zin et al., 2019).

The PMP also offers significant opportunities for nature-based recreation, and hiking along forest trails to the volcanic summits. PMP's prominent peaks—Taung-Ma-Gyi (1,518 m) and Taung-Kalat (657 m)—provide exceptional panoramic views of the surrounding plains, enhancing the aesthetic value of the area. In addition to its ecological and scenic attributes, PMP holds cultural, religious, and historical significance for Myanmar. Taung-Kalat serves as an important pilgrimage site, featuring numerous Nat (spirit or deity) temples and relic sites atop the mountain, and offers a venue for the study of Myanmar's ancient animist traditions.

5 Livelihoods

The PMP is situated within a densely populated region, with an estimated population of 300,000 individuals distributed across 44 villages (GAD, 2025). The predominant livelihood in the area is agriculture, and only few individuals took part in ecotourism and forest management activities. Main agricultural activities include the cultivation of dragon fruits, guava, bananas, melons, rice paddies, palm-sugar production, and seasonal farming. Harvesting of fuelwood, collection of forest and non-timber forest products, and livestock grazing are widespread practices that contribute to deforestation and forest degradation within and around PMP (MONREC, 2025). Given current levels of funding, human resources, accessibility, and infrastructure, it is not feasible to comprehensively manage the park. The adoption of alternative energy sources for local communities is therefore essential for effective conservation in the PMP. According to Htun et al. (2013), the distribution of fuel-efficient stoves, development of fuelwood plantations, adoption of solar energy, use of fuelwood alternatives, promotion of agroforestry, and improved electricity access can significantly reduce the depletion of forest resources.

6 Geopark

A geopark is defined as a territory recognized for its unique and internationally significant geological and biological diversity, which serves as a site for research, education, conservation, and sustainable development through comprehensive management. In addition to the protection and preservation of geological heritage, geoparks are utilized for sustainable development via systematic resource use, education initiatives, networking, and knowledge exchange. Recently, the number of geoparks has increased substantially; as of 2025, 229 areas have been designated as UNESCO Global Geoparks across 50 countries (UNESCO, 2025). Despite the ongoing expansion in the number of national and UNESCO Global Geoparks worldwide, public interest in geoparks and their impact on regional economic development remains relatively limited. Certain geopark management organizations have sought to enhance public engagement by developing distinctive geopark identities characterized by approachability and accessibility, and by promoting the use of geoparks for educational and tourism purposes. However, the effectiveness of these initiatives is often constrained by insufficient funding and planning, expertise, storytelling capacity, and management infrastructure (Ha et al., 2021).

In Myanmar, since 2016, the Ministry of Natural Resources and Environmental Conservation (MONREC) and Myanmar Geosciences Society has undertaken initiatives to identify significant geological features and establish geoparks across the country. Among numerous potential geopark sites, the most promising locations were selected for further development. As a result, on December 6, 2023, in recognition of its profound geological, biodiversity, social, and cultural significance, Mount Popa National Geopark—encompassing an area of 52,317.85 Ac (21,172.28 ha) and including 15 geosites—was officially designated as Myanmar's first national geopark (Table 1, Fig. 4). Representative photos of some of the Geosites are shown in Fig. 5. Ongoing efforts are focused on increasing the number of geosites and pursuing future recognition as a UNESCO-accredited geopark (MONREC, 2025).

7 Discussion and conclusion

The term 'refugium' is broadly defined as a geographical area where species survive during harsh environmental periods. The Mt. Popa region has a rich history of not only geological dynamics but also social, cultural, and environmental developments, and it now serves as a habitable refugium for both humans and biodiversity amid global changes.

Radiocarbon dating indicated that the Mt. Popa volcano experienced multiple eruptions at the onset of the Holocene. No significant explosive eruptions have occurred at Mt. Popa since ~8,000 BP (Maury et al., 2004; Mitchell et al., 2012; Belousov et al., 2018).

The subduction process in this region is distinguished by a high degree of obliquity and a slow convergence rate of approximately 13 mm/year, resulting in the sparse distribution of volcanoes and a low magma production rate. Such tectonic settings are typically associated with infrequent volcanic eruptions (Mitchell et al., 2012; Belousov et al., 2018). Consequently, the current repose period of ~8,000 years since the last eruption of Mt. Popa does not justify the conclusion that this volcano is being extinct. It is generally recognized that a volcano may be classified as active if it has erupted within the last 10,000 years (Szakács, 1994). Notably, certain volcanoes within the Sunda arc have exhibited even longer periods of dormancy. For instance, Gede volcano in Java resumed its activity

No.	Geosites	Significant features	Core value		
			Geological	Cultural	Biological
1	Summit of Mount Popa	Biodiversity; Pagoda; Summit of the volcano; View point	*	*	*
2	Alternated layers of volcanic ash and Irrawaddy sandstone	Sedimentary rock; Volcanic eruption; Volcanic rock	*		
3	Thone Htat Kway pyroclastic rocks	View point; Volcanic rock	*		
4	Irrawaddy formation	Fossil; Petrified wood; Sedimentary rock; Structure	*		*
5	Taung Ni Taung chalcedony and altered clay minerals	Clay alteration; Mineralization; Silica cap	*		
6	Medicinal plantation and science gallery	Biodiversity; Ecosystem	*		*
7	Sandal wood forest and Myanmar's golden deer farm	Biodiversity; Ecosystem			*
8	Birds' nest cliff	Biodiversity; Ecosystem; Petrified wood	*		*
9	Lava plateau view point	Geomorphology; View point	*		
10	Basaltic lava flow	Basalt, Lapilli tuff; Lava flow; Pozzolan	*		
11	Taungpaw Taung village's scenic view	Center of crater; Endangered Popa langur; Geomorphology; View point	*		*
12	Popa Taungkalat fossil wood	Culture & life style; Fossil wood; Geomorphology; Monkey	*	*	*
13	Taungnar Taung View Point	Morphology; Petrified wood; Plant; View point;	*		*
14	Crater of Mount Popa	Ecosystem; Geomorphology; Horse shoe-shaped crater; View point;	*	*	*
15	Gae Moe Aing	Landscape; Volcanic Tuff	*		

* - denote the core values offered by each geosite.

Table 1. Geosites of the Mount Popa National Geopark, Myanmar.

following a repose interval exceeding 30,000 years (Belousov et al., 2015). The most recent phase of volcanic activity at Mt. Popa occurred at the onset of the Holocene and included a series of mild, Vulcanian-type explosive eruptions between 12,700 and 8,500 BP. Local legendary remark postulated that Mount Popa may have erupted around 442 BCE (Chhibber, 1934; Belousov et al., 2018). Therefore, Mt. Popa can also be regarded as an active volcano (Belousov et al., 2018).

Studies demonstrated a strong correlation between fault activity and volcanic eruptions (Lin et al., 2018; Sahara et al., 2021; Fountoulakis and Evangelidis, 2025). In tectonically dynamic regions like Myanmar, the identification of potential hazards and the deployment of early warning systems are critical for minimizing loss of life and economic impact. Effective disaster preparedness relies on community education, evacuation planning, and the development of resilient infrastructure. Scientific investigation and ongoing monitoring are also essential for early detection of geohazards. Through the integration of technological solutions, policy initiatives, and public awareness campaigns, societies can enhance their capacity to respond efficiently and recover rapidly from future geological disasters in Myanmar.

Myanmar, situated within the Indo–Myanmar Biodiversity Hotspot, confronts substantial challenges posed by environmental destruction, rapid development, persistent environmental degradation, and the effects of climate change (Myers et al., 2000; Thang et al., 2020; Neugarten et al., 2024). Due to past volcanic eruptions, the Mt. Popa region supports a habitable and socioeconomically viable environment in the semi-arid Central Dry Zone of Myanmar. Despite the extraction of natural resources and land use changes are major drivers to deforestation and forest degradation in PMP area, grant-oriented programs could achieve the goals of conserving biological diversity, restoring ecosystems, and climate change mitigation, when effectively managed (MONREC, 2025; Thang and Yu, 2022). Investing in tourism and conservation in Mt. Popa area which has integrated values of biodiversity, cultural and geology could provide substantial economic benefits and support the green economy initiatives (Zin et al., 2019). Consequently, comprehensive documentation and the implementation of effective conservation strategies are essential

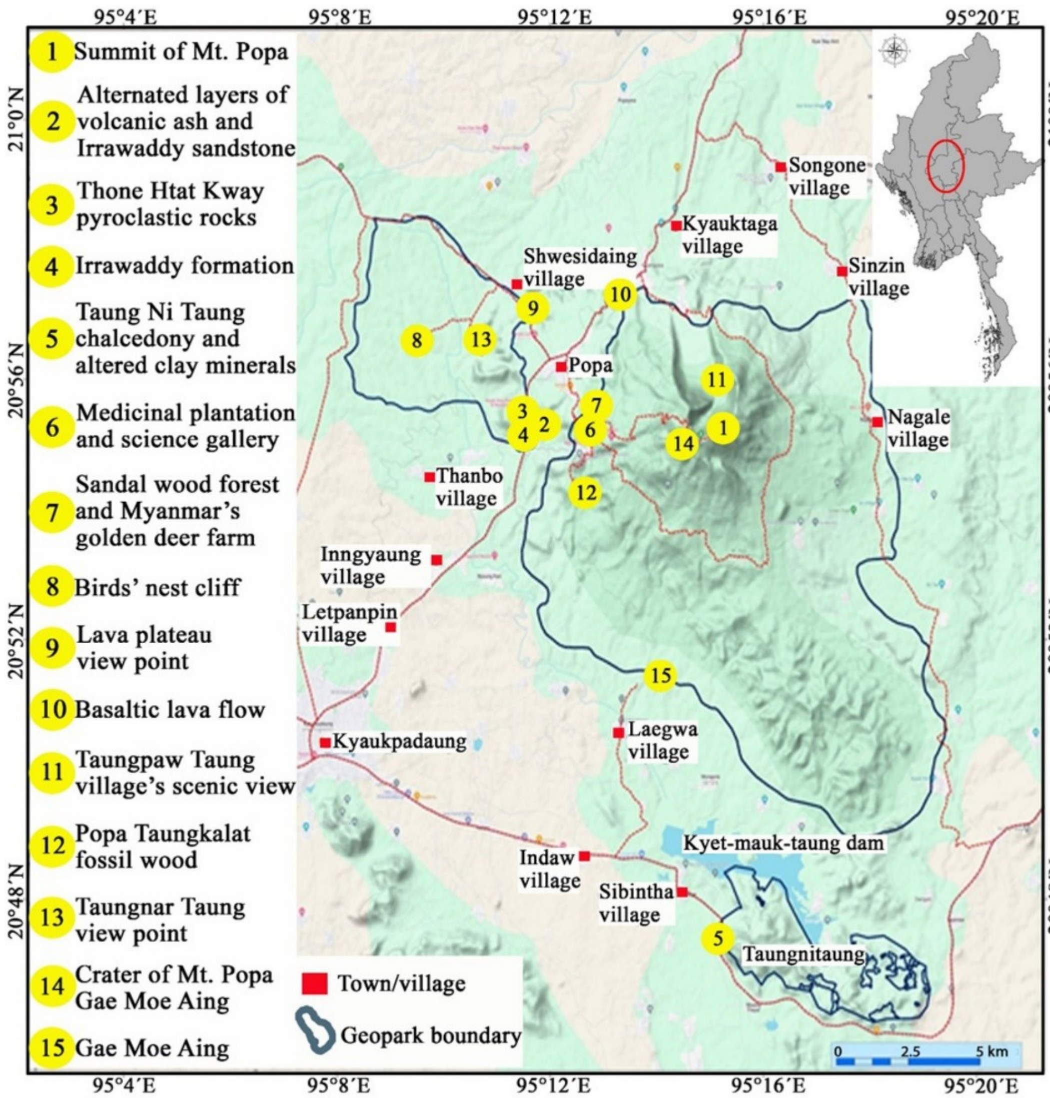

Fig. 4. Map showing locations of the geosites in the Mount Popa National Geopark, Myanmar.

to safeguard biodiversity and geodiversity. These efforts may also serve to reinforce the availability of refugia and habitable environments against both natural disasters and anthropogenic pressures, as cascading hazards can occur following one after another, which are destructive to infrastructures as well as human lives (Yanites et al., 2025).

An integrated approach holds significant potential for elucidating the complex interactions between tectonic and geological processes, as well as for evaluating seismic risks—including earthquakes, landslides, and other geohazards—in the Mt. Popa region of central Myanmar. Notably, seismic tomography has revealed the presence of a double subduction system and slab remnants, which are closely associated with earthquake occurrences in Myanmar (Yang et al., 2022). Therefore, the potential for volcanic eruptions along this belt should not be underestimated, and preparedness remains essential to minimize the risks and impacts of geohazards such as earthquakes, landslides, and volcanic eruptions. Additional investigations are needed to understand crater wall collapses and crust-mantle interactions, particularly in light of the possibility of future eruptive activity and geohazards (Zaw and Park, 2025). The Mount Popa National Geopark initiative, with potential for inclusion in the UNESCO Global Geopark network, represents one of Myanmar's first interdisciplinary collaborations. It involves scholars, experts, local stakeholders, universities, and government agencies from disciplines including geology, environmental science, seismology, archaeology, agriculture, tourism, and foreign affairs. This integrated conservation effort aims to enhance the recognition of geological, social, cultural, and biological diversity while promoting knowledge dissemination to

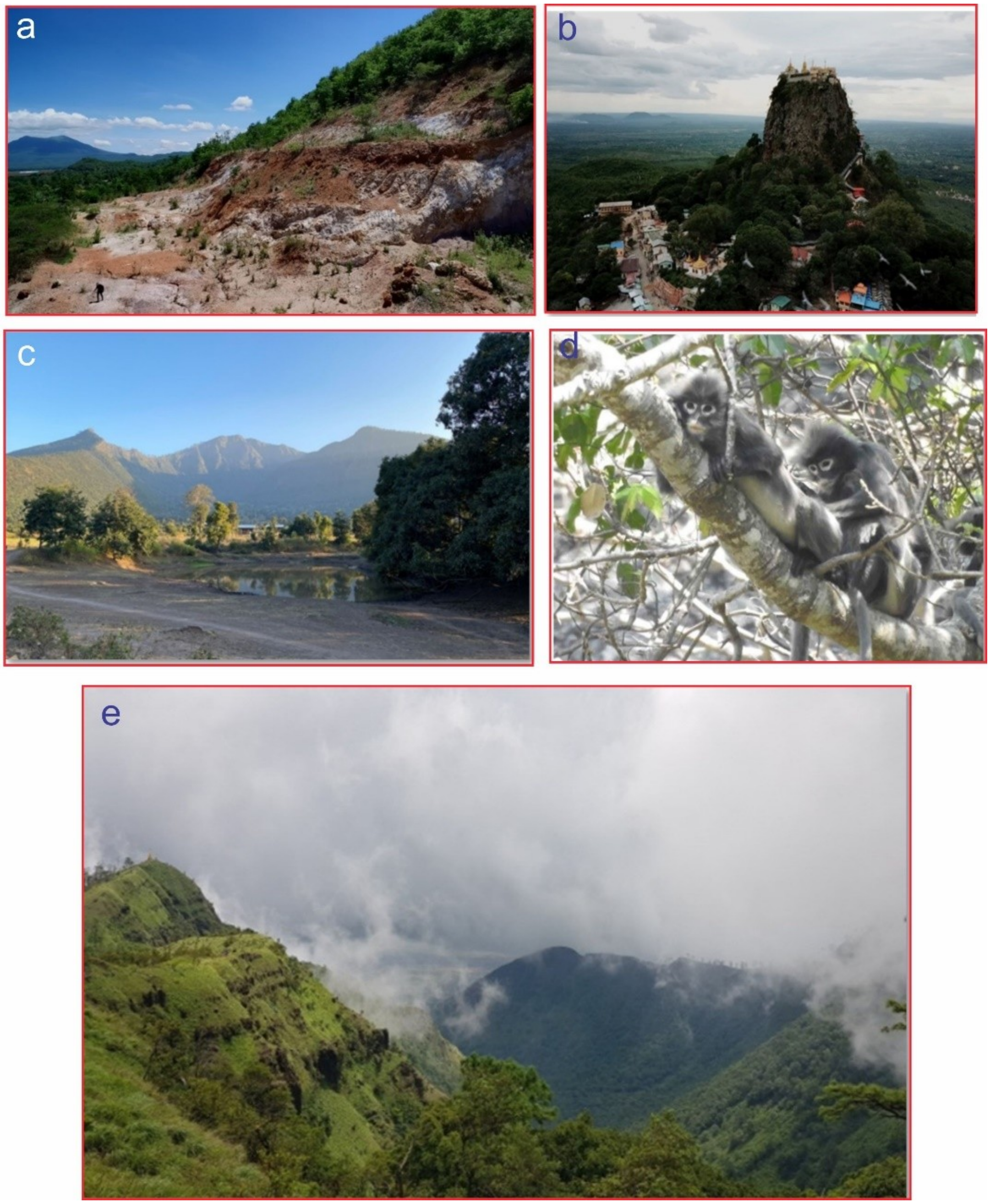

Fig. 5. Photographs of some the geosites in the in the Mount Popa National Geopark, Myanmar. (a) Geosite 5: Taung Ni Taung chalcedony and altered clay minerals. (b) Geosite 12: Popa Taungkalat fossil wood geosite. (c) and (d) Geosite 11: Taungpaw Taung village's scenic view geosite. (e) Geosite No. 14: Crater of Mount Popa.

local communities and tourists for a comprehensive understanding of Mount Popa National Park's critical role. In light of such endeavors, owing to the convenient access to the SF and volcanic features such as Mt. Popa, comprehensive and multidisciplinary research that integrate seismic, volcanological, petrological, tectonic and palaeoecological methodologies are strongly recommended. Future research could promote the sustainable economic and ecological integrity of the Mt. Popa region while enhancing geohazard preparedness, risk mitigation, and biodiversity conservation in this tectonically active area.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit author statement

Tluang Hmung Thang: Conceptualization; Data curation; Validation; Writing—original draft; Writing—review & editing.

Esther Tun Lin: Conceptualization; Writing—original draft; Writing—review & editing.

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