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The Sagaing Fault, deadly earthquake and volcanoes in Myanmar: Geodynamic perspectives

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ABSTRACT

The Sagaing Fault is a prominent, right-lateral strike-slip fault that extends approximately 1,400 km through central Myanmar. The Fault is one of the most seismically active fault systems in the world, with a history of producing large and devastating earthquakes including a recent Mw 7.7 earthquake on March 28, 2025, at approximately 12:50 pm that struck near Mandalay. Although the primary cause of the earthquake is regarded as being the result of a rupture that occurred along the Sagaing Fault due to the horizontal sliding between the Myanmar plate and Sunda plate, we here discuss the other geodynamic factors on the deadly nature of the earthquake. Preparedness, in advance, is the key to staying safe and reducing the damage caused by natural hazards. Ongoing scientific research and regular monitoring are also crucial for spotting early warning signs of natural hazards like earthquakes, landslides, and volcanic eruptions. Given the easy accessibility along the Sagaing Fault and volcano area such as the Mt. Popa region, further integrated research combining seismic, volcanological, petrological and tectonic studies is strongly encouraged and highly warranted.

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Research Highlights

- The recent Myanmar earthquake occurred along the active Sagaing Fault.
- Indentation tectonics, Sunda subduction and Andaman Sea opening causes seismicity.
- The Sagaing Fault and Mt. Popa region has high potential for multidisciplinary seismic, volcanic, and tectonic investigations.

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1 Introduction

On March 28, 2025, at approximately 12:50 p.m. local time, a powerful magnitude Mw 7.7 earthquake struck near Mandalay, Myanmar's second-largest city. The earthquake originated along Sagaing Fault at a shallow depth of approximately 10 km, causing intense shaking across central Myanmar resulting in widespread destruction. The earthquake has resulted in ∼3,400 deaths, 4,508 people injured, and 220 missing, together with huge damage to infrastructure such as schools, hospitals, bridges, roads and buildings.

The Sagaing Fault is a significant geological feature in Myanmar, representing a major right-lateral (dextral), strike-slip, transform fault that demarcates the boundary between the West Myanmar Terrane (Myanmar Plate) and the Sibumasu Terrane (Sunda Plate) (Fig. 1). The Sagaing Fault extends over 1,400 km, beginning in the northern part of Kachin State near the Indawgyi region and extends southward through major cities such as Mandalay, Yamethin, Pyinmana, the capital Naypyidaw, Toungoo, Bago and Yangon, ultimately reaching the Gulf of Martaban (e.g., Swe, 1972, 1981). This major right-lateral strike-slip fault accommodates significant relative motion between the Indian Plate and the Sunda Plate. GPS measurements and geodetic studies have estimated the slip rate along the fault to be approximately 18–20 mm/year (Vigny et al., 2003; Socquet et al., 2006; Steckler et al., 2016). The Sagaing Fault is widely recognized as one of the most seismically active fault systems in Southeast Asia, with a history of hosting large and damaging earthquakes, such as those in 1931, 1946, 1956, 1990 (e.g., Wang et al., 2014; Tun and Watkinson, 2017), and the recent 28 March 2025. Its proximity to densely populated urban centres significantly increases the seismic risk in central Myanmar.

Although the primary cause of the earthquake is attributed to a rupture along the Sagaing Fault, resulting from the horizontal strike-slip motion between the Myanmar plate and Sunda plate, Myanmar's complex geology situated at the convergence of three plates, including an east-dipping mega subduction zone, should not be ignored. This conjunction of crustal plates frequently experiences seismic activity, as in the most recent earthquake that propagated shockwaves across the nation and into neighbouring countries such as Thailand and Yunnan.

In recently published discussions and commentaries in the academic and social media on the earthquake in Myanmar, attention has largely centred on the destructive impacts of the Sagaing Fault, with blame often assigned to it in isolation, without considering the broader geological and tectonic framework. In reality, the devastating earthquake along the Sagaing Fault is a manifestation of Myanmar's long and complex tectonic evolution, dating back to the Phanerozoic Eon—over 600 million years ago—and particularly shaped during the Cenozoic Era (the past 66 million years).

2 Tectonic framework

Myanmar is situated within a highly complex and active tectonic regime shaped by the ongoing collision between the Indian and Eurasian plates (Zaw, 2017). The central tectonic feature is the Sagaing Fault, accommodating northward movement of the Indian Plate relative to the Sunda Plate. The tectonic setting of Myanmar is dominated by the interplay of multiple geodynamic processes: (1) indentation tectonics resulting from the Indian Plate's northeastward push, (2) active subduction along the Sunda (Sumatra–Rakhine) Subduction Zone, where the Indian Plate is descending beneath the Myanmar Plate, (3) the Shan Scarp Fault, a less studied but significant normal fault east of the Sagaing Fault. Additionally, (4) seismic imaging has revealed a hidden or blind subduction zone beneath central Myanmar, further complicating crustal dynamics. (5) The back-arc opening of the Andaman Sea since the Miocene has also influenced regional stress fields, and (6) Quaternary volcanism along the Mt. Popa–Monywa–Twinywa axis suggests an underlying magmatic system linked to these tectonic processes. Together, these factors contribute to high seismic hazard potential across Myanmar, with frequent earthquakes and the possibility of reactivation of dormant volcanic systems.

2.1 Indentation Tectonics

The "Indentation Tectonics", "Escape Tectonics," or "Extrusion Tectonics" concept was first introduced by Paul Tapponnier and group (Tapponnier et al., 1982). According to this model, the Indian Plate has been colliding northward into the Eurasian Plate for the past 60 million years, resulting in the uplift of the Himalaya—one of the highest mountain ranges on Earth (Fig. 1). Within this dynamic setting, the Sagaing Fault has borne a significant portion of the immense tectonic strain generated by this collision, acting as a crucial accommodation zone for crustal deformation across Myanmar.

2.2 Sunda subduction zone

To the west of Myanmar lies a massive east-dipping megathrust subduction zone, where the Indian Plate pushes beneath the Myanmar Plate. This tectonic boundary is a part of the broader Sunda subduction zone and is responsible for generating some of the most powerful earthquakes and tsunamis in the region (Steckler et al., 2016). One of the most devastating events associated with this zone was the magnitude Mw 9.2 earthquake on December 26, 2004, which triggered a catastrophic tsunami across the Indian Ocean (Fig. 1). The tsunami claimed of over 230,000 lives in 14 countries, including Myanmar,

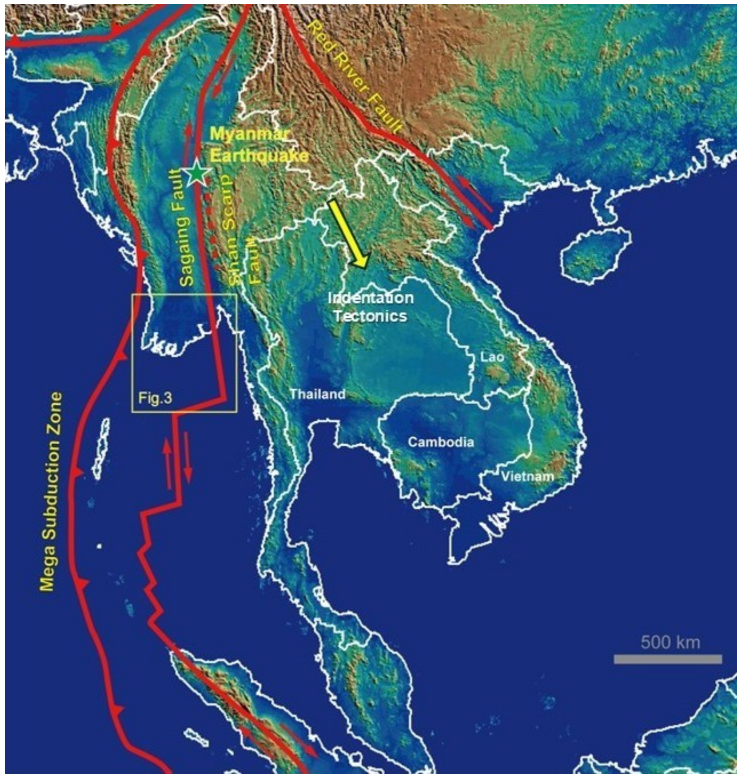

Fig. 1. Tectonic framework of the India–Myanmar region, showing the Sagaing Fault, surrounding plates, and the Andaman Sea alongside the escape tectonics model illustrating crustal indentation (extrusion) of Southeast Asia due to the northward collision of the Indian Plate with Eurasia and associated stress on the Sagaing Fault (adapted after Tapponnier et al., 1982). The yellow arrow denotes direction of extrusion.

Indonesia, Sri Lanka, India, and Thailand, making it one of the deadliest natural disasters in the recorded history. This subduction system remains highly active and poses a continuing seismic and tsunami threat to the region with stress transfer and interaction contributing to increased activity and strain along the Sagaing Fault.

2.3 Shan boundary (Shan Scarp) Fault

Previous studies (e.g., Chhibber, 1934; Thein, 1973) believed that the Central Lowlands was a subsiding graben bounded by major fault zones on both sides suggesting the presence of a N-S trending, normal fault at the boundary of the Central Lowlands (back-arc basin) and the western margin of the Shan Plateau (Sino-Myanmar Ranges). This Boundary Fault, being located strictly at the foot of the Shan Scarp is topographically very distinct and is spatially related with the Sagaing Fault to the west which lies in the alluvial plains (Figs. 1, 2). Although their temporal relations are still uncertain, these two tectonically significant, N-S trending, faults (Shan Scarp and Sagaing Faults) presumably belong to the same system.

The prominent normal fault along the Shan Scarp, recognized for decades (e.g., Thein, 1973), and the ongoing displacement along the Sagaing Fault may be further intensified and amplified by interactions creating a compound effect on regional tectonic stress. The complex kinematic relationship and interplay between these fault systems contributes to the region's dynamic tectonics and may significantly influence both the intensity, magnitude and spatial distribution of seismic activity in Myanmar.

2.4 Hidden subduction zone

Many recent seismic studies in Myanmar have identified evidence for a previously unrecognized, or "hidden," subduction zone beneath the Sagaing Fault region providing a double subduction zone (e.g., Figs. 2, 4, Yang et al., 2022). The presence of a recent easting subduction zone of 7 Ma has been accepted by previous workers (e.g., Chhibber, 1934; Stephenson and Marshall, 1984; Belousov et al., 2018). However, the existence of the additional older suture of $\sim$51 Ma was only speculated based on geological, geochemical, and geochronological data (e.g., Zaw, 2017), and hence these new findings provide critical support for the presence of an additional suture zone. The reactivation or rejuvenation of movement along this hidden subduction zone can have a significant impact in compounding the

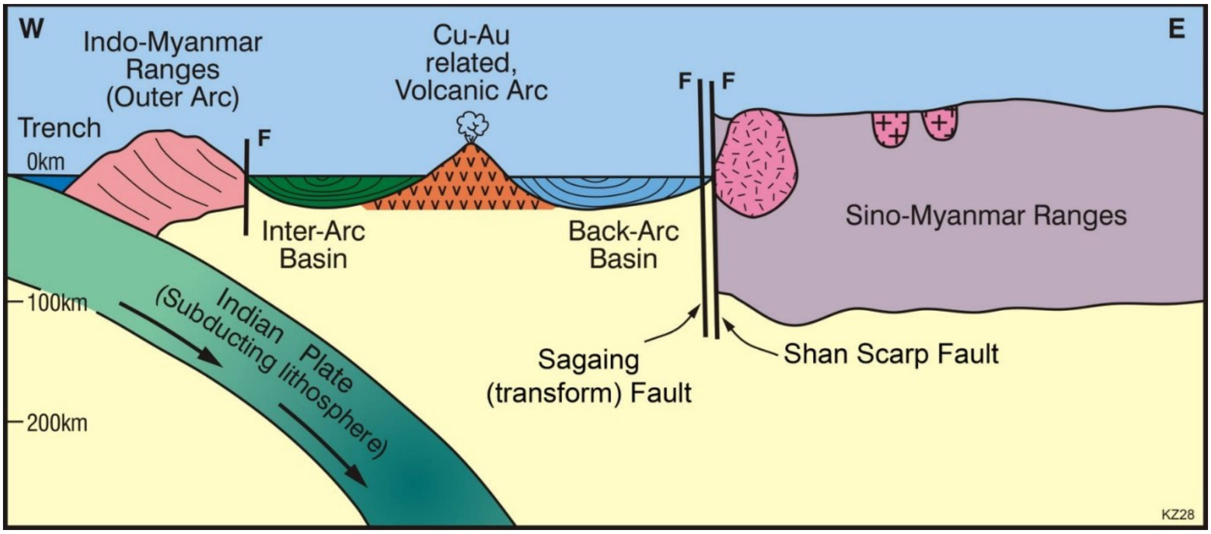

Fig. 2. Schematic cross-section showing tectonic setting of Myanmar: Indo-Myanmar Ranges, inter-arc and back-arc basins and Sino-Myanmar Ranges as well as the relation of two major faults (Sagaing Fault and Shan Scarp Fault).

tectonic stress and potential destructiveness associated with the Sagaing Fault, further increasing seismic hazard in the region.

2.5 Opening of Andaman Sea

The recent tectonic movement and deadly destruction along the Sagaing Fault should not underscore the relationships and interaction of the fault with the Andaman Spreading Centre (ASC) in the south (Figs. 1, 3). Curray (2005) has long documented the formation of the Sagaing Fault due to back-arc spreading in the Andaman Sea during Miocene and Pliocene. Curray (2005) estimated the rate to be 2.5–3.8 cm/year, based on magnetic anomaly interpretations and seafloor morphology.

The Sagaing Fault and the ASC are integral components of the complex tectonic framework in Myanmar and the surrounding regions. The ASC's seafloor spreading contributes to the tectonic regime that influences stress accumulation along the Sagaing Fault. Understanding the relationship between the Sagaing Fault and the ASC is essential for assessing seismic hazards in the region. The recent earthquake underscores the need for comprehensive studies that integrate offshore tectonic processes with onshore seismic risk assessments. Such integrated analyses are vital for developing effective mitigation strategies and improving preparedness for future seismic events in Myanmar and its neighbouring countries.

2.6 Mt. Popa-Monywa-Twinywa Volcanism

Central Myanmar is characterized by a magmatic-volcanic belt that runs parallel to the Sagaing Fault and this volcanic belt is represented by the dormant Mount Popa volcano and the volcanism in the Monywa-Twinywa area (Belousov et al., 2018). The Mt. Popa volcano is the most prominent and geographically distinct landmark in central Myanmar and is located close to the highly acclaimed but congested tourist region of Bagan, an 11th-century civilization site. The volcano did not produce eruptions in the recorded history and is considered extinct. However, it has been investigated that the age and timing of the youngest lava flows and pyroclasts of Mt. Popa are 8000 yr old or even younger (Belousov et al., 2018).

The main volcano is known as Taung-Ma-Gyi, and a volcanic plug (neck) occurs at the southwest of the Taung-Ma-Gyi which rises 660 meters above sea level, and it is known as the Taung Kalat. The main Mt Popa volcano has its crater blown open on the north side. The volcanic crater itself is about 1.6 km in diameter.

The volcano is built on Pliocene sandstones of the Ayerwaddy Formation. Its complex volcanic edifice is composed of lava flows and domes; the composition ranges from basalt to dacite of calc-alkaline affinities. Sano et al. (2022) recently reported adakitic affinities of the Mt Popa volcanics based on geochemistry (e.g., Sr/Y vs Y) and Sr–Nd isotopic studies. Several age dating techniques were applied to determine the ages of eruption at Mt Popa (Maury et al., 2004; Lee et al., 2016; Belousov et al., 2018; Sano et al., 2022). They recorded older volcanics are yielded 10.7 to 19.7 Ma (Miocene), whereas the beginning of the Taung-Ma-Gyi stratovolcano eruption is $\sim$0.33 Ma and the Taung Kalat (volcanic plug) was formed at 0.82 ± 0.07 Ma to 0.68 ± 0.04 Ma.

A local folklore reported that Mt. Popa could have had an eruption at 442 BCE (Chhibber, 1934; Belousov et al., 2018). The timing and type of the most recent eruptions of

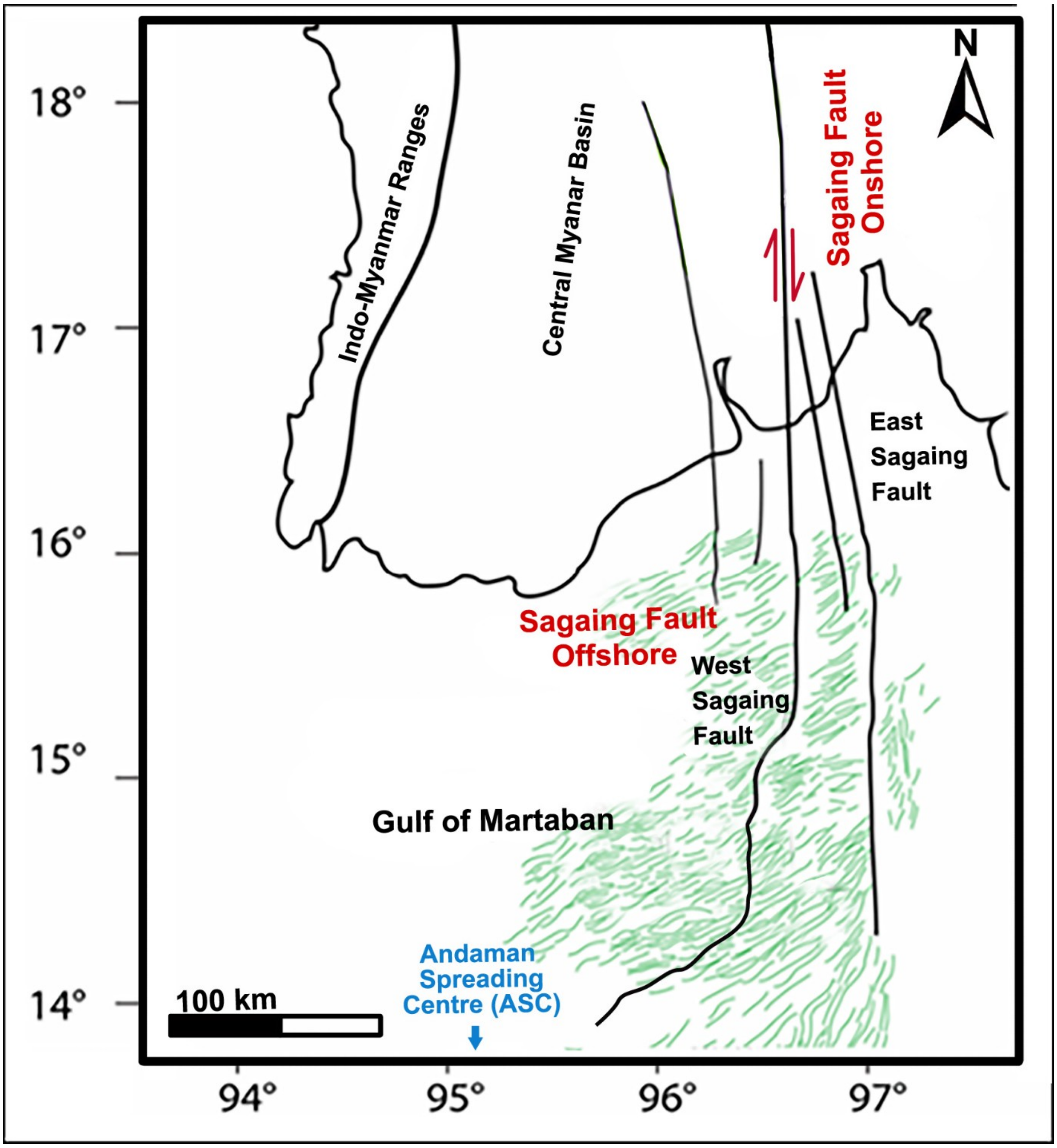

Fig. 3. Map showing linkage between Sagaing Fault and Andaman Spreading Centre (APC) modified after Sloan et al. (2017). The green lines are normal fault array.

the volcano as well as the origin and age of relatively recent volcanoclastic fan coming out from the crater breach are previously described as lahar or debris flow by Stephenson and Marshall (1984). It included several mild explosive eruptions probably of Vulcanian Type ∼12700-8500 BP, followed by large-scale edifice collapse ∼8000 BP, then followed (probably immediately) by strong magmatic eruption with deposition of the pyroclastic flow (Belousov et al., 2018). Probably the edifice of Mount Popa was destabilized by the intrusion of magma and the collapse triggered explosive eruption. Further research work is required to understand the crater wall collapses, and crust-mantle interaction in the area due to the potential for future eruptions and geohazards. A recent landslide was also reported in October 2017 in Mt Popa area. The heavy monsoonal rains caused the problems as the volcano is composed of soft and loose volcanic sandstones, ash, and lahar as well as deforestation making the soil erodible and more susceptible to landslides.

Holocene eruptions of Mt. Popa, Myanmar are volcanological evidence of the ongoing subduction of the Indian Plate along the Arakan Trench. The proximity of the Mount Popa volcanic edifice to the Sagaing Fault suggests that tectonic activity could destabilize the magma chamber, potentially leading to magma intrusion and triggering a collapse-induced explosive eruption. A strong

Fig. 4. Map showing the location of Mt Popa volcano, Myanmar, and volcanoes in Sumatra and Java in West Myanmar Terrane. The devastating earthquake of Mv 9.1 and the tsunami in Sumatra in 2004, the deadliest tsunami in history, killed more than 230,000 people across 14 countries. Note the historical deadliest volcanic eruptions at Toba (74,000 yr), Krakatoa (1883 yr), and Mt Popa (<8000 yr) ago. Map modified after CODES unpublished data.

earthquake may initiate vesiculation of magma within the chamber, which can, after a time delay, lead to the eruption of a dormant volcano.

3 Discussion and conclusions

The destructive and damaging effect of the Sagaing Fault is not a one-stop event due to lateral sliding of Myanmar Plate and Sunda Plate. It is due to a lengthy and protracted history of geological and plate tectonic movement over at least past 60 million years. The Sagaing Fault has long borne the brunt of immense tectonic forces, accommodating vast amounts of strain due to ‘Escape Tectonics’ while held together the plate fabric of this volatile region. When the accumulated strains exceed the holding capacity of constituent rocks, major powerful earthquakes occur.

The gigantic east-dipping Sunda mega subduction system at the west of Myanmar remains highly active and contributes to strain build up to the occurrence of earthquakes. The Shan Boundary or Shan Scarp Fault, documented by Myanmar geologists since the 1970s, runs parallel to the Sagaing Fault and marks a major geographic boundary. Its interaction with the Sagaing Fault may intensify regional stress and influence the scale and extent of seismic activity in Myanmar. These major fault lines are not as a single line as seen on the map, they are an array of fault lines and should be considered appropriately while preparing for earthquake resilience.

Central Myanmar features a magmatic-volcanic belt, running parallel to the Sagaing Fault, marked by the dormant Mount Popa near the Sagaing Fault. Studies suggest Mt. Popa’s youngest lava flows and pyroclasts are $\sim$8000 years old or as young as recent (Belousov et al., 2018), while local legends mention eruptions around 442 BCE (Chhibber, 1934; Belousov et al., 2018). The possible volcanic eruption along the belt should not be overlooked.

Preparedness is essential for minimizing the risks and impacts of geohazards such as earthquakes, landslides, and volcanic eruptions. In tectonically active regions like Myanmar, understanding potential hazards and implementing early warning systems can save lives and reduce economic loss. Community education, evacuation planning, and resilient infrastructure are key components of disaster preparedness (e.g., Bryant, 2005; UNDRR, 2015). Scientific research and continuous monitoring also play a vital role in identifying early signs of geohazards. By integrating technology, policy, and public awareness, societies can strengthen their ability to respond effectively and recover swiftly from future geological disasters in Myanmar.

The combined approach has the potential to offer valuable insights into the interplay between tectonic and geological processes, as well as the assessment of seismic risks, including earthquakes, landslides, and mitigation of geohazards in Mt Popa and Bagan area, central Myanmar. It is interesting to note that a double subduction system and slab remnants were recorded based on seismic tomography and related to the occurrence of earthquakes in Myanmar (Yang et al., 2022). Further research work integrating seismic and volcanological/petrological studies in the Mt Popa area is highly warranted, given the exceptional accessibility of the area.

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Credit authorship contribution statement

Khin Zaw: Conceptualization, Validation, Writing—original draft, Writing—review & editing.

Jung-Woo Park: Conceptualization, Writing—original draft, Writing—review & editing

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.

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