EXPLORING THE DISTRIBUTION AND OCCURRENCE OF CENOZOIC VOLCANIC GEOHERITAGES IN THE KHORAT PLATEAU, THAILAND

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Abstract: The Cenozoic basalts of the Khorat Plateau are prevalent in Thailand's lower northeastern region. Despite their abundance, detailed studies on the composition and morphology of these basalts are scarce. This research examines the relationship between volcanic morphology and geochemistry in northeastern Thailand, focussing on basalts from Buriram, Surin and Sisaket Provinces. Using polarised microscopes and X-ray fluorescence (XRF) analysis, this study investigates the petrography and geochemistry of these basalts. Field observations reveal eruptions from both shield volcanoes and fissures, with notable shield volcanoes including Khao Phanom Sawai, Khao Phra Angkhan, Khao Phanom Rung, Khao Kradong, Khao Plai Bat and Phu Fai. Petrographic analysis identifies these basalts as olivine basalt with porphyritic textures and occasional trachytic textures. Geochemical classification includes trachybasalt, basalt, basaltic andesite, basaltic trachyandesite and andesite, with SiO_2 contents ranging from 51.07% to 61.46%. Trace element analysis categorises them as alkaline basalt. Although shield volcanoes show higher SiO_2 concentrations compared to lava flows, morphological differences do not consistently align with SiO_2 trends, suggesting that magma viscosity and eruption patterns are influenced by additional geochemical factors. This study also highlights the importance of engaging local communities to enhance understanding of volcanism's historical and cultural impacts.

Keywords: volcano, geochemistry, petrography, Cenozoic volcanic rocks, Khorat plateau, geoheritage

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Introduction

The Cenozoic basalt formations in Thailand stem from volcanic activity triggered by tectonic shifts and the opening of the South China Sea, coupled with the emergence of the Hainan magma bulb due to the collision between the Indian and the Eurasian lithospheric plates (Yang et al., 2015; Yan et al. 2018). This geological event resulted in volcanic eruptions during the late Cenozoic era (approximately 0.43–3.3 million years ago) throughout East Asia, particularly in the southeastern region i.e. Thailand, Laos, Cambodia and Vietnam. Cenozoic basalt is extensively distributed across various provinces in Thailand, including Lampang, Phrae, Phetchabun, Ubon Ratchathani, Chanthaburi, Trat, Rayong, Kanchanaburi, Nakhon Ratchasima, Buriram and Sisaket (Barr, Macdonald 1981, Charusiri 1989, Barr, James 1990, Intasopa 1993, Sutthirat et al. 1994, Intasopa et al. 1995, Charusiri et al., 2004; Boonsoong et al. 2011; Yang et al., 2015).

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In addition, these volcanic rock formations are predominantly concentrated in the southern part of northeastern Thailand, particularly in areas such as Khao Kradong, Khao Phanom Rung and Khao Angkhan in Buriram Province; Khao Phanom Sawai in Surin Province and the southern region of Sisaket Province (Fig. 1). These sites exhibit prominent features of extensive, columnar-jointed lava flow fields, indicative of large-scale volcanic activity (Singtuen, Phajan 2021, Singtuen, Anumart 2022). These formations display characteristics resembling trachybasalt and basaltic trachyandesite, similar in appearance to hot spot volcanism associated with lithospheric thinning, and possibly analogous to ocean island basalts or OIB (Yan et al. 2018, Singtuen, Phajan 2021, Singtuen, Anumart 2022). Notably, the basalt in this region shows xenoliths and xenocrysts from the upper mantle and crust, reflecting rapid ascent of the melt without significant stalling en route, thereby preventing crustal contamination, and is believed to have formed through the partial melting of garnet pyroxenite (Yan et al. 2018). The magma source is suggested to be a blend of depleted mid-ocean ridge basalt mantle (DMM) and enriched mantle (EMII), resembling the composition found in the Hainan magma chamber (Yan et al. 2018). Radiometric dating using the K-Ar method indicates that the basalts in these areas have ages ranging from approximately 0.9 to 3.3 million years (Yan et al. 2018). Additionally, samples from Khao Kradong in Buriram Province were conducted for radiometric dating using the Ar-40/Ar-39 method, yielding an approximate age of 0.43 million years (Barr, Macdonald 1981).

Previous studies on the petrography and geochemistry of these basalts typically involved collecting 1–2 samples from each province, allowing for regional comparisons of age or occurrence. However, while some provincial-level investigations, such as those in Buriram and Sisaket Provinces, have been conducted, Surin Province has received relatively less attention (Fig. 1). Furthermore, existing research has primarily focussed on inventories, lithogenesis, rock determination and magma-type characterisation, with limited integration of volcanic morphology with basalt geochemistry. Consequently, there exists a research gap regarding the chemical geology, volcanology and magma-tectonic characterisation of basalt petrology in Surin Province. This study aims to address this gap by conducting detailed petrological analyses, situating the findings within the broader context of existing research, and elucidating the interplay between volcanic morphology and the geochemical signatures of Cenozoic basalt in northeastern Thailand. Additionally, it seeks to identify the

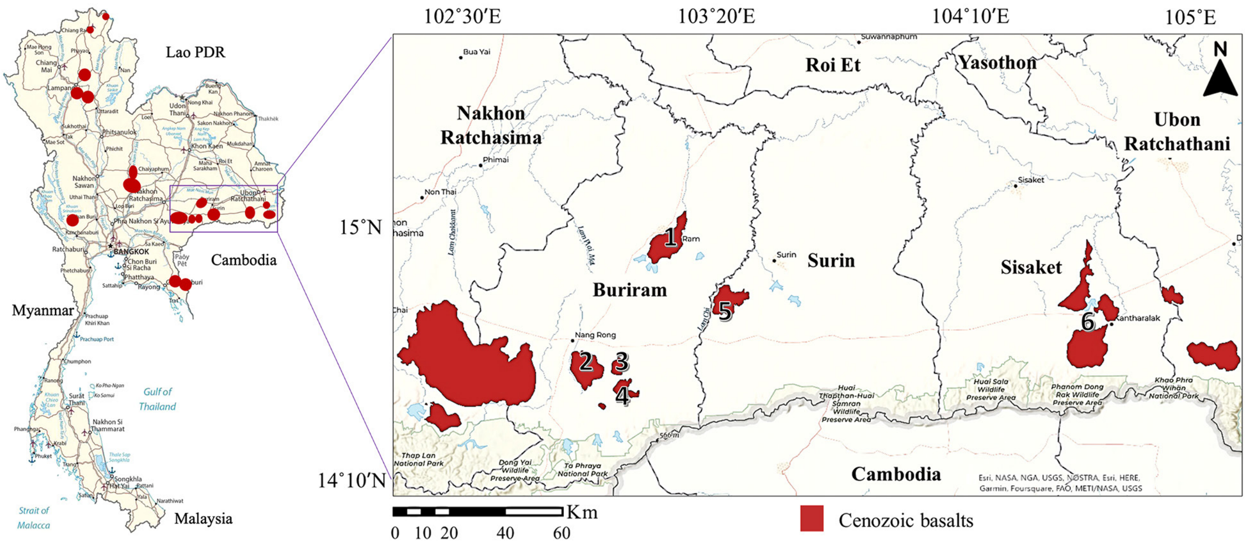

Fig. 1. Map of Cenozoic basalt distribution in Thailand (Geological data from Department of Mineral Resources, 2013), includes several key volcanoes indicated by numbered symbols: 1 = Khao Kradong, 2 = Khao Phra Angkhan, 3 = Khao Phanom Rung, 4 = Khao Plai Bat, 5 = Khao Phanom Sawai and 6 = Phu Fai. Basemap data sources: Esri, National Aeronautics and Space Administration (NASA), National Geospatial-Intelligence Agency (NGA), United States Geological Survey (USGS), NOSTRA (Thailand), HERE Technologies, Garmin, Foursquare, Food and Agriculture Organization (FAO), and meteorological data from NASA (MET/NASA).

value of these volcanoes to the local community. The objective is to enhance understanding of the geological history of the area, particularly the origin of its volcanoes, thereby contributing to the development of sustainable territories.

Volcanic geoheritage can be defined as the ensemble of volcanic landforms, materials, processes and cultural associations that possess significant scientific, educational, cultural or aesthetic value, contributing to the understanding and appreciation of volcanism within Earth's geological history (Németh et al. 2017a). Recent advancements have significantly strengthened geotourism, geoeducation and geoconservation initiatives within newly established geoparks, many of which include volcanic geoheritage sites recognised as UNESCO Global Geoparks – such as the Bakony-Balaton Geopark in Hungary (Csillag et al. 2004, Szepesi et al. 2017). Similarly, inactive volcanic regions like the Eifel in western Germany, known as type localities for unique volcanic phenomena, provide exceptional educational opportunities to enhance public understanding of volcanic processes (Bitschene, Schueller 2011, Bitschene 2015). These areas may serve as comparable models to the volcanic geoheritage highlighted in this study.

The Cenozoic basalts that erupted in northeastern Thailand are found in provinces such as Nakhon Ratchasima, Buriram, Surin, Sisaket and Ubon Ratchathani, which are all part of the Khorat Plateau (DMR 2013). The geological distribution encompasses five lithological groups, including the Phra Wihan Group (JKpw), the Sa Kaeo Group (Ksk), the Phu Phan Group (Kpp), the Khok Kruat Group (Kkk) and the Maha Sarakham Group (KTms) as shown in Figure 2. The majority of the northern region is covered by unconsolidated sediments from the Quaternary period, including floodplain deposits (Qa) and alluvial fan deposits (Qt). These sediments originate from the erosion and accumulation of alluvium from the upstream areas in Nakhon Ratchasima, flowing through Buriram, Surin and Sisaket, until it merges with the Chi River in Ubon Ratchathani. This river flows in a predominantly west-east direction, suggesting it follows a fault line. Additionally, occurrences of basalt rocks are evident along the southern edges, marked by red symbols (bs) in geological maps (DMR 2013).

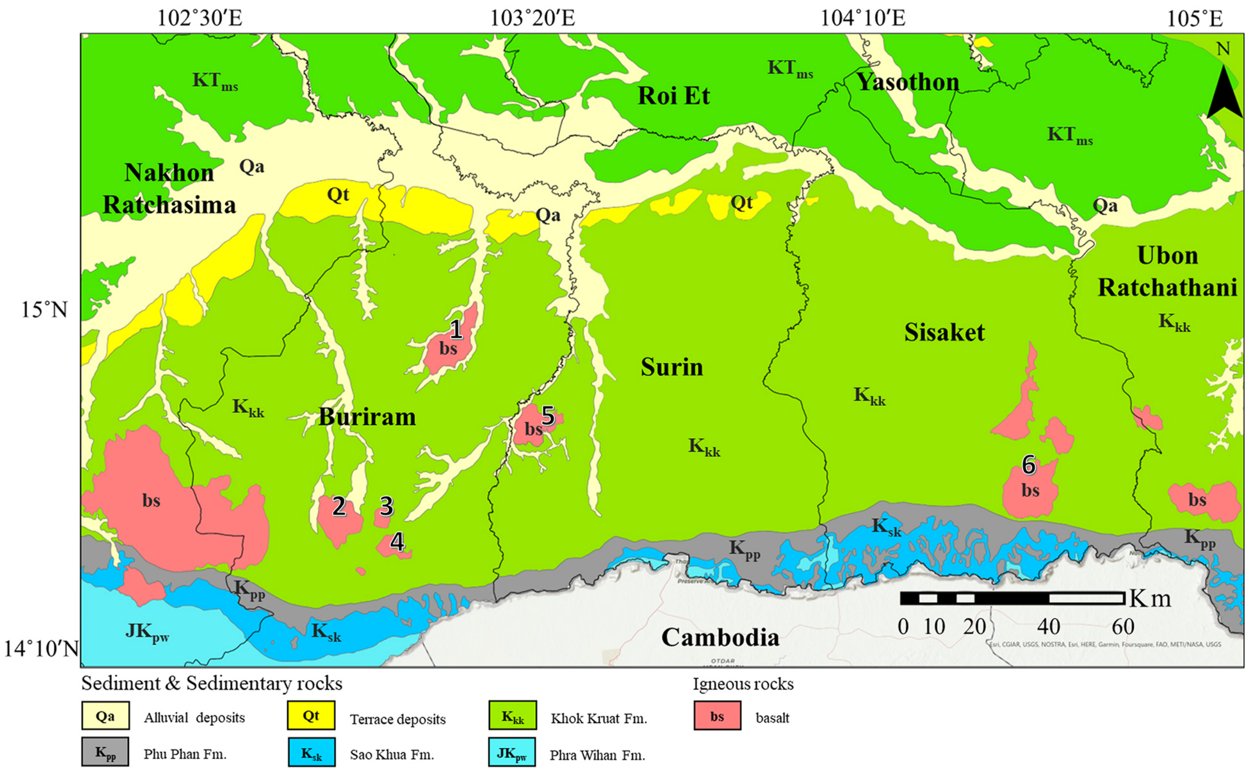

Fig. 2. Geologic map of the southern Khorat Plateau of Thailand (Geological data from the Department of Mineral Resources 2013), includes several key volcanoes indicated by numbered symbols: 1 = Khao Kradong, 2 = Khao Phra Angkhan, 3 = Khao Phanom Rung, 4 = Khao Plai Bat, 5 = Khao Phanom Sawai and 6 = Phu Fai.

The basaltic rocks, characterised by blackish-grey colours overlaying sandstone formations of the Khok Kruat Group, extend from the east to the western edge of the southern Khorat Plateau.

Methodology

The study commenced with a literature review to explore volcanic occurrences in the southern part of the Khorat Plateau, followed by field surveys to determine coordinates, describe features, collect rock samples and capture photographs. Basalt samples were systematically collected from Buriram, Surin and Sisaket provinces for lithological description and geochemical analysis. Petrographic studies were conducted under a polarising microscope, and geochemical analyses were performed using X-ray fluorescence (XRF) spectrometry to analyse major oxides and trace elements. The geochemical data of Cenozoic basalt in the study area were then compared with those of Cenozoic era basalt in other provinces of northeastern Thailand from relevant previous research. This comparison aimed to analyse the relationship between volcanic morphology and geochemical characteristics of basalt in the northeastern region of Thailand.

In addition, societal, social geology and cultural heritage data – including historical, lifestyle, cultural and tourism development information related to volcanoes – were collected to understand the broader context and impact of volcanic occurrences on society. This multidisciplinary approach enhances the comprehensive understanding of volcanic geoheritages, revealing their significance beyond geological aspects. Moreover, a transdisciplinary approach was adopted by collecting and integrating societal, social geology and cultural heritage data – including historical narratives, lifestyle practices, cultural traditions and tourism development related to volcanoes – to explore their interconnections and reciprocal influences. For instance, the spatial association of sacred sites with volcanic landforms highlights deep-rooted cultural and spiritual values, while indigenous knowledge of volcanic hazards contributes to local risk mitigation and resilience. Geotourism initiatives centred on volcanic features further demonstrate how geological heritage can support both economic development and cultural preservation. By combining social data with geological and environmental analyses, this approach offers a comprehensive understanding of the dynamic interactions between natural processes and human societies – an essential foundation for formulating sustainable management and conservation strategies that safeguard volcanic geoheritage while promoting regional socio-economic growth.

Results

Field observation and lithology

Following an extensive review of literature and field surveys, six principal volcanic heritage sites have been delineated on the Khorat Plateau, spanning across three provinces: Buriram, Surin and Sisaket. These sites include Khao Kradong, Khao Phanom Rung, Khao Phra Angkhan, Khao Plai Bat, Khao Phanom Sawai and Phu Fai (Fig. 3).

Khao Kradong, a small shield volcano located in the central part of Buriram Province, is distinguished by its gently sloping flanks and a well-defined summit crater measuring approximately 300 m in diameter (Fig. 3A). The volcanic edifice displays characteristic morphological and lithological features of basaltic shield volcanoes, indicative of low-viscosity lava flows and prolonged effusive eruptive activity. Representative volcanic deposits include basalts, vesicular basalt, scoria, volcanic bombs and basaltic tuff. This heritage site is administered as a forest reserve, overseen by the Department of National Parks, Wildlife and Plant Conservation, which operates under the auspices of the Ministry of Natural Resources and Environment.

Khao Phanom Rung, situated in the southern region of Buriram, is classified as a shield volcano, distinguished by its gentle slope (Fig. 3B). At its summit lies a notable crater, now occupied by the Phanom Rung Historical Park. Consequently, this area is under the management and conservation regulations of the Historical Park authorities. Geologically, the site comprises basalts, vesicular basalt, scoria, volcanic bombs and basaltic tuff.

Khao Phra Angkhan, a relatively large shield volcano located in the southwestern part of Buriram Province, features a broad summit depression – interpreted as a caldera approximately

1.2 km in diameter (Fig. 3B) – along with prominent columnar basalt outcrops. The caldera interpretation is supported by its subcircular shape, inward-dipping crater walls and surrounding lava flows indicative of collapse structures typical of basaltic shield volcanoes. However, its morphology also resembles that of large pit craters found in Hawaiian-type shield volcanoes. It warrants further detailed stratigraphic and structural investigations to determine whether it represents a true collapse caldera sensu stricto or a non-collapse erosional or pit crater feature. A central vent appears to have formed during a subsequent eruptive phase. The enclosing crater rim, which connects to Khao Phra Angkhan, likely resulted from structural collapse following caldera formation. Volcanic ash deposits accumulated within the depression, forming fertile soils that support local agriculture, particularly the cultivation of rice, field crops and various fruits such as banana and melon. According to public data from the Ministry of Agriculture and Cooperatives (www.moac.go.th), these nutrient-rich volcanic soils contribute to significantly high crop yields in the region. The caldera rim is defined by a continuous ridge (Fig. 3C), and beyond the volcano's margins, large volcanic pillars are scattered, interpreted as remnants of varied lava flows emitted from the central vent.

Khao Plai Bat, located in the southern region of Buriram, is a diminutive shield volcano characterised by a crater that has been ravaged by rock quarrying activities and human settlements. The geological makeup of this area includes basalts, vesicular basalt, scoria, volcanic bombs and basaltic tuff, all linked with basaltic flows

Fig. 3. Field observation of Cenozoic volcanoes in the southern Khorat Plateau: A – the crater of Khao Kradong (14°56'19.3"N 103°05'36.8"E), B – the gentle slope of Khao Phanom Rung (14°31'53.6"N 102°56'21.8"E), C – the depositional section of a caldera rim of Khao Phra Angkhan (14°31'54.6"N 102°49'48.2"E), D – sandstone xenoliths in Cenozoic basalts (14°40'01.7"N 104°30'05.5"E), E – Pahoehoe and Aa at the top of Khao Phanom Sawai (14°45'32.6"N 103°21'56.4"E), F – columnar and platy basalts near Khao Phanom Sawai (14°45'35.0"N 103°23'40.7"E), G – *in situ* float rocks of diabase at the Phu Fai (14°38'21.3"N 104°29'36.5"E), and H – columnar and platy basalts near Phu Fai (14°38'31.0"N 104°29'51.4"E).

that manifest as columnar basalt formations. The majority of basaltic flows commonly exhibit xenoliths (crustal rocks of crystalline basement), which are sandstones uplifted during the rising of magma (Fig. 3D).

Khao Phanom Sawai, another shield volcano situated in Surin Province, showcases a substantial summit crater along with columnar and platy basalts at its base. Governed as a forest reserve, this area falls under the jurisdiction of the Department of National Parks, Wildlife and Plant Conservation, functioning under the authority of the Ministry of Natural Resources and Environment. Geologically, the site encompasses basalts, vesicular basalt, scoria, volcanic bombs and basaltic tuff, as well as other formations such as Pahoehoe and Aa (Fig. 3E). Outside the volcano's perimeter or mining areas (rock quarry for construction), there are scattered volcanic pillars of various sizes (Fig. 3F), created by the different lava flows originating from the volcano's vent.

Phu Fai, interpreted as a small shield volcano located in Sisaket Province, is characterised by a low-relief structure approximately 1.5 km in basal diameter and less than 100 m in elevation. It is surrounded by an extensive basaltic lava field, suggesting emplacement through effusive eruptions of low-viscosity magma. The volcanic edifice bears a resemblance to a shallow intrusion of basaltic magma – commonly classified as diabase or dolerite – indicating a possible transition between intrusive and extrusive processes during its formation (Fig. 3G). In the vicinity of Phu Fai, well-preserved exposures of columnar and platy basalt are observed (Fig. 3H), further supporting its basaltic origin and providing key insights into the cooling history and emplacement mechanisms of the lava flows.

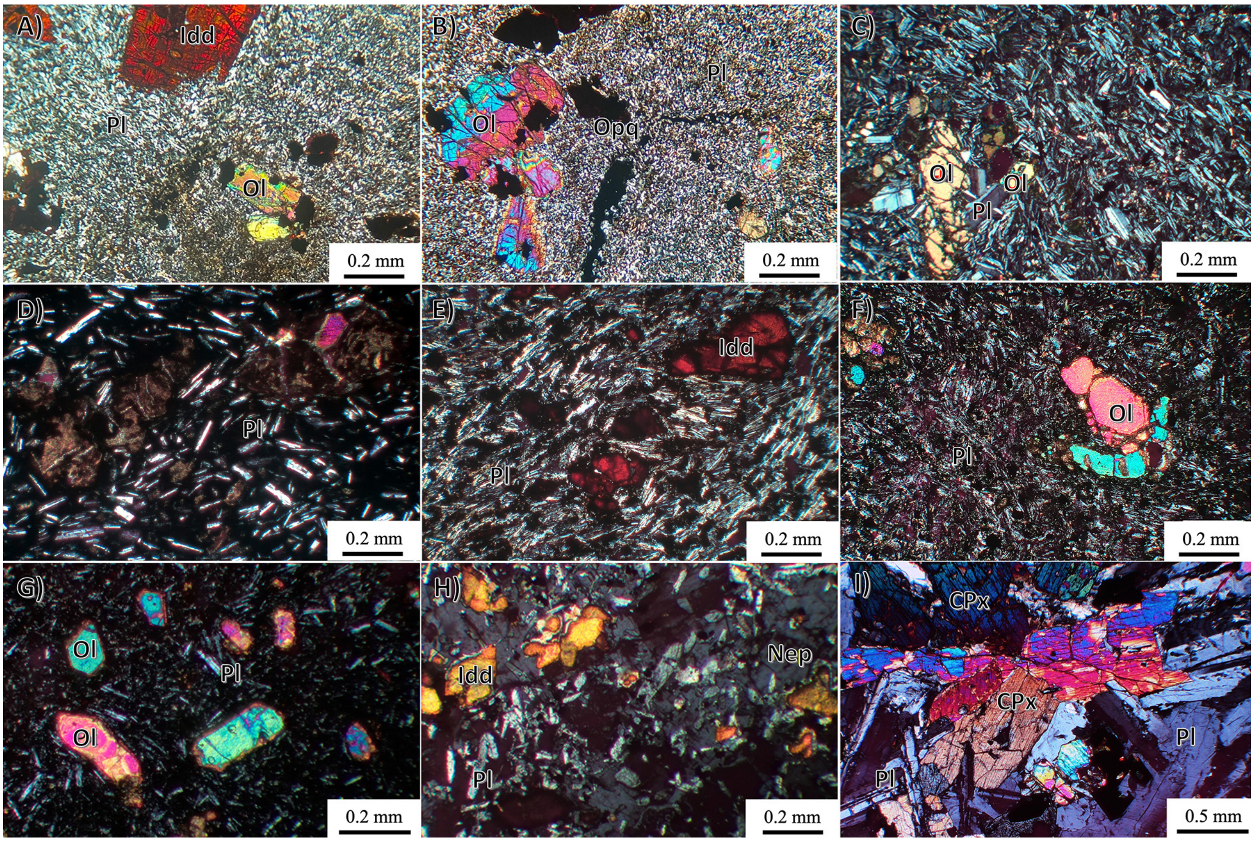

Fig. 4. Photomicrographs of Cenozoic basalts in the southern Khorat Plateau. Buriram Province: A – altered phenocryst as iddingsite in olivine basalt porphyry, B – olivine basalt porphyry, C – olivine and plagioclase phenocryst present trachytic texture of olivine basalt. Surin Province: D – mafic volcanic glasses in the groundmass of olivine basalt, E – altered phenocryst as iddingsite in olivine basalt porphyry and F – olivine basalt porphyry present a trachytic texture. Sisaket Province: G – very fine-grained olivine basalt porphyry, H – nepheline in the groundmass of alkaline basalt and I – the intergrowth of plagioclase and clinopyroxene as ophitic/subophitic texture of diabase at Phu Fai. Cpx – clinopyroxene, Idd – iddingsite, Nep – nepheline, Ol – olivine, Opq – opaque minerals, Pl – plagioclase.

Petrography

The rocks studied in the Buriram area have been identified as olivine basalt based on their mineral composition, featuring a porphyritic texture with olivine microphenocrysts (Fig. 4A–C). The groundmass of these olivine basalts mainly consists of plagioclase, along with smaller amounts of olivine, clinopyroxene and opaque minerals. The olivine microphenocrysts are slightly altered to iddingsite, an amorphous alteration product of mafic microphenocrysts. The groundmass plagioclase shows a trachytic texture, indicating that this basalt erupted from a lava flow.

Similarly, the basalts from the Surin area are classified as olivine basalt, showing both porphyritic and trachytic textures (Fig. 4D–F), similar to those in Buriram. Some samples illustrate mafic volcanic glasses in the groundmass. Additionally, basaltic rocks from the Sisaket area display porphyritic, vesicular and diabase textures. Under a polarised light microscope, these rocks are classified as olivine basalts with olivine microphenocrysts similar to those in Buriram and Surin (Fig. 4G) and as alkaline basalts (some flood basalts) containing nepheline in the groundmass (Fig. 4H). Some olivine basalts also exhibit a diabase texture with diameters ranging from 0.1 mm to 0.475 mm, or more specifically, subophitic/ophitic textures (Fig. 4I), found only in samples from the Phu Fai shallow intrusion.

Geochemistry

An examination of the petrography and geochemistry of Cenozoic era basalt in the southern northeastern region reveals distinct characteristics across delineated areas, the west-to-east edge of the Khorat Plateau. Based on petrographic and geochemical data, the rocks in the Korat Plateau can be classified into two groups. Group A, located in the central Khorat Plateau and encompassing areas such as Khao Phra Angkhan, Khao Plai But, Khao Phanom Rung, Khao Kradong and Khao Phanom Sawai, includes basalt, basaltic trachyandesite, basaltic andesite and andesite (Fig. 5A). This group is characterised by a higher silicon dioxide content, ranging from 51.07% to 61.46% by weight. Group B, situated in the eastern part of the Khorat Plateau, particularly in the Phu Fai area of Sisaket, consists of basanite, trachybasalt, basalt and basaltic trachyandesite, with silicon dioxide content between 43.81% and 50.87% by weight. Furthermore, these basaltic

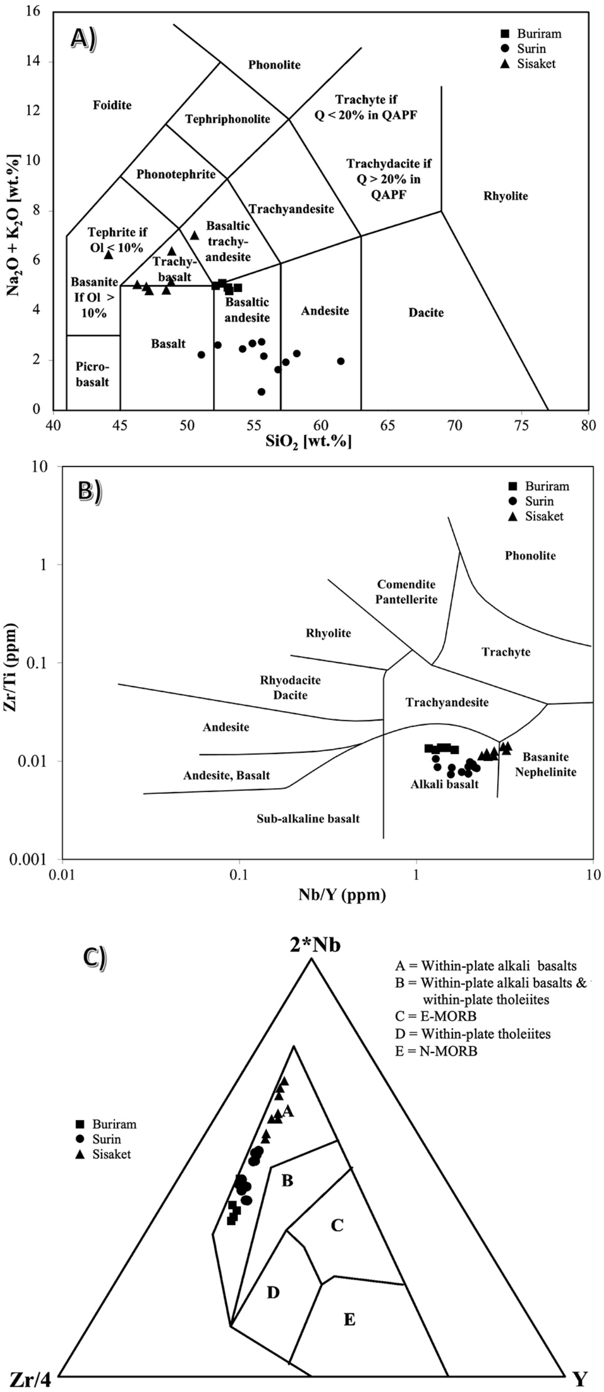

Fig. 5. Geochemical classification of Cenozoic basalts in the southern Khorat Plateau: A – Total Alkali-Silica (TAS) diagram presents the ratio of SiO_2 vs. Total alkalines ($Na_2O + K_2O$), diagram modified from Le Bas et al. (1986). B – plotted of Nb/Y vs. Zr/Ti for name classification of volcanic rocks (diagram modified from Winchester and Floyd (1997)) and C – Nb–Zr–Y tectonic discrimination diagram (diagram modified from Pearce and Cann (1973)).

rocks are classified as alkaline basalt and basanite based on trace element analysis (Nb/Y vs. Zr/Ti) as illustrated in Figure 5B. All volcanic rocks resulting from fissure eruptions in Sisaket exhibit high alkalinity and low silica dioxide content. According to the Nb–Zr–Y ratios shown in Figure 5C, the basaltic rocks of the Korat Plateau originated from an alkaline magma series within a within-plate tectonic setting.

By focussing specifically on samples collected from distinct volcanic landforms, rather than widespread flood basalt flows, we aim to better resolve the geochemical signatures of individual volcanic centres, enabling more accurate interpretations of their magmatic evolution and morphological comparisons. Khao Kradong's composition includes 48.23% silicon dioxide (SiO_2) by weight, 2.02% potassium oxide (K_2O) and 3.89% sodium oxide (Na_2O). The geological formations are identified as trachybasalt, alkali basalt and basalt, which are classified as intraplate basalts via hotspots beneath the continental crust. These rock types are predominantly alkaline, with some samples showing tholeiite characteristics. Similarly, Khao Phanom Rung, Khao Phra Angkhan, Khao Plai Bat, Khao Phanom Sawai and Phu Fai are shield volcanoes with silicon dioxide content ranging from 48.52% to 55.96% by weight. These formations also exhibit intraplate basalt characteristics and belong to the alkaline series.

Geomorphology

The investigation identified several volcanoes dispersed across the northeaster region, namely Khao Phanom Sawai, Khao Kradong, Khao Phanom Rung, Khao Plai Bud, Phu Fai and Khao Phra Angkhan (Fig. 6). These volcanic formations primarily consist of basalt, alkaline basalt, trachy basalt, basaltic trachy andesite and basaltic-andesite, all characterised as shield volcanoes, see Table 1. Using the Google Earth Pro application, slope angles were calculated from elevation data extracted from its digital elevation model (DEM) by measuring the gradient between systematically sampled adjacent points across the volcano's flanks to provide a representative average slope. The average elevation of Khao Phanom Sawai was calculated by sampling multiple elevation points evenly distributed across the volcanic edifice, yielding an average height of 200.33 m, with the highest elevation reaching 216.67 m above the surrounding plateau. The average slope of 4.54% was derived from digital elevation data by calculating the inclination between adjacent sampled points. Khao Phra Angkhan, situated on a plateau with an average elevation of approximately 200 m above sea level, has an average volcanic edifice height of 97.00 m, reaching a summit elevation of 127.00 m above the plateau surface. This corresponds to an average elevation of 297.00 m

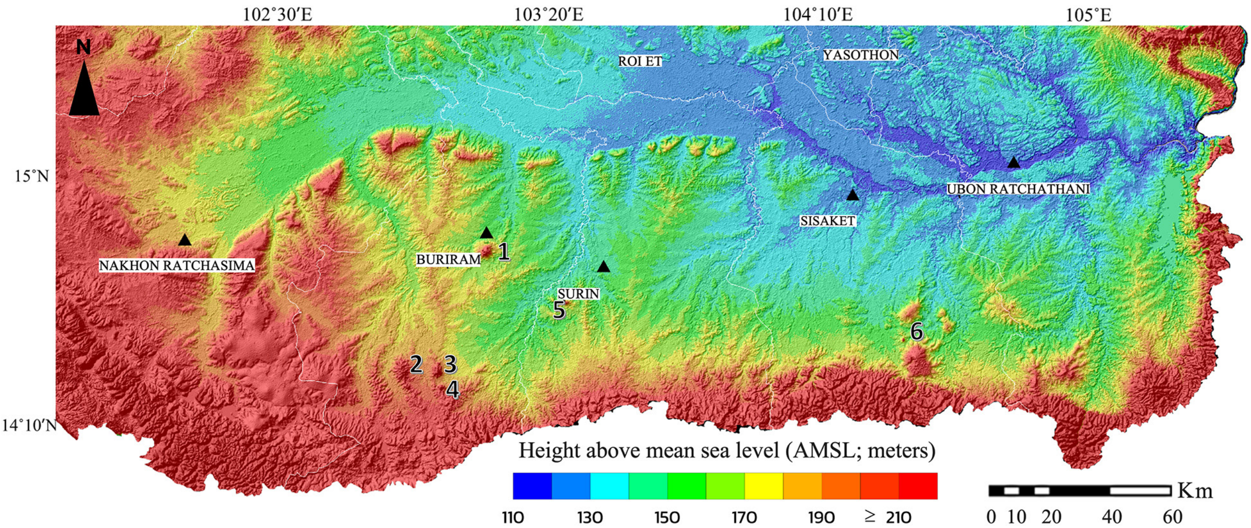

Fig. 6. Geomorphological map of the southern Khorat Plateau, combined with GIS techniques, includes several key volcanoes indicated by numbered symbols: 1 = Khao Kradong, 2 = Khao Phra Angkhan, 3 = Khao Phanom Rung, 4 = Khao Plai Bat, 5 = Khao Phanom Sawai and 6 = Phu Fai. A digital elevation model (DEM) and 20-meter interval contour lines (source: www.asterweb.jpl.nasa.gov) were analyzed using geographic information system (GIS) software (ArcGIS, developed by Esri, Redlands, CA, USA).

Table 1. Geomorphological and geochemical data of volcanoes in the southern part of the Khorat Plateau.

Group	Volcano name	Average slope	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	LOI*
		[%]	[wt.%]					
1	Khao Phanom Sawai	4.52	51.07	14.57	14.60	2.69	8.62	1.25
	Khao Kradong	6.10	48.55	14.36	10.81	6.00	9.28	1.25
2	Khao Plai Bat	7.95	52.04	14.91	10.93	5.50	6.98	0.34
	Khao Phanom Rung	9.87	52.56	15.22	9.82	3.46	6.27	1.54
3	Khao Phra Angkhan	15.00	55.96	19.55	12.05	1.30	4.63	0.78
	Phu Fai	17.15	50.36	19.68	6.27	5.56	7.12	1.76

* LOI – loss on ignition.

above sea level and a summit height of 327.00 m above sea level, with an average slope of 15.00% (Fig. 6). Using the plateau as the base reference provides a more accurate measure of the volcano's relative relief and morphology. Phu Fai registers an average altitude of 238.50 m, with its pinnacle rising to 278.50 m above the plateau, and displaying an average slope of 17.15%. Khao Kradong maintains an average height of 223.00 m, with its highest point reaching 270.00 m above the plateau, and showcasing an average slope of 6.10%. Khao Phanom Rung stands at an average elevation of 282.00 m, with its summit towering at 380.00 m above the plateau, and presenting an average slope of 9.87%. Lastly, Khao Plai Bud registers an average altitude of 248.33 m, with its highest point reaching 283.00 m above the plateau, and featuring an average slope of 7.95%, as illustrated in Figure 7.

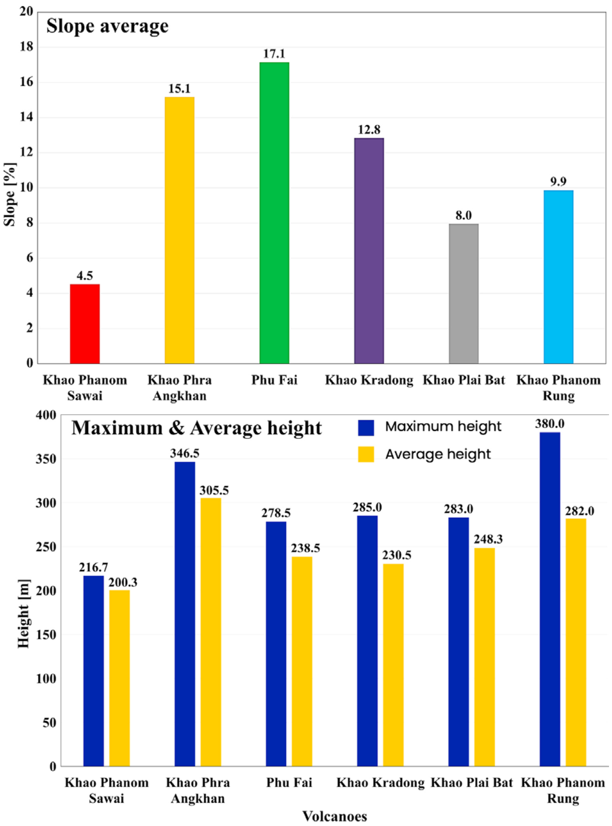

Fig. 7. Geomorphological characteristics of Cenozoic volcanoes in the southern Khorat Plateau.

Geochemical analysis and morphological comparison of volcanoes in northeastern Thailand reveal that these volcanoes can be categorised into three groups based on their average slope. Group 1 consists of low-slope volcanoes, including Khao Kradong and Khao Phanom Sawai, with an average slope of 4.52–6.10%. Group 2 includes medium-slope volcanoes, such as Khao Phanom Rung and Khao Plai Bat, with an average slope of 7.95–9.87%. Group 3 comprises high-slope volcanoes, such as Phu Fai and Khao Phra Angkhan, with an average slope of 15.00–17.15%, as shown in Table 1. The low-slope volcanoes have lower silicon dioxide (SiO_2) content, ranging from 48.55% to 51.07% by weight, which increases in the medium- and high-slope volcanoes to 52.04–52.56% and 50.36–52.77% by weight, respectively. Notably, Phu Fai, despite being a high-slope volcano, has a SiO_2 content of 50.36% by weight, lower than that of the medium-slope volcanoes, but it has the highest aluminium oxide (Al_2O_3) content at 19.68% by weight. This observation suggests that the morphology of volcanoes is influenced not only by the SiO_2 content but also by the Al_2O_3 content. The study of magma evolution indicates that highly evolved magma tends to have higher SiO_2 and Al_2O_3 contents, leading to greater viscosity and steeper volcanic morphology. In contrast, the contents of iron (III) oxide (Fe_2O_3), magnesium oxide (MgO), calcium oxide (CaO) and volatile substances do not show clear trends in relation to volcanic morphology. However, these volatile substances are related to the explosiveness of volcanic eruptions.

Discussion

Implications of volcanic and tectonic evolution

The integrated results from field surveys, petrographic observations and geochemical analyses suggest that the study area experienced significant geological evolution beginning with the deposition of gravel, sand and soil. These sediments comprise part of the extensive Khorat Group, a predominantly continental sedimentary sequence characterised mainly by sandstones, siltstones and conglomerates, with subordinate mudstones and rare limestones. The Khorat Group developed across northeastern Thailand during the Mesozoic era, from the Late Triassic to the Late Cretaceous, approximately 66.5 million years ago (Fig. 8). Tectonic uplift of the Khorat Plateau induced tilting and faulting of these strata, shaping the present-day landscape. In the southern margin, where sedimentary sequences are thicker, this process led to the formation of the Phanom Dong Rak mountain range, while central areas experienced greater erosion, allowing volcanic activity to intrude through weakened sedimentary units.

Volcanic eruptions produced a variety of basaltic rocks, indicating a complex magmatic history. The region shows evidence of both early stage basanite or highly alkaline rocks and later-stage tholeiitic basalts, suggesting evolving magma sources influenced by tectonic rifting episodes (Fig. 8). The volcanic architecture, particularly the shield volcanoes with summit craters such as Khao Phra Angkhan and Khao Kraduk, demonstrates classic patterns of caldera formation and dome resurgence (Fig. 9), which subsequently influenced the geomorphology and soil fertility of the surrounding plains.

These findings align with broader patterns of Mesozoic tectono-volcanic activity across Thailand i.e. Lampang, Kanchanaburi, Chanthaburi and Phetchabun. The magmatic evolution in this region reflects geodynamic forces such as the rifting associated with the South China Sea and Andaman Sea openings and the subsequent continental collision between the Indian and the Eurasian plates (Barr, Macdonald 1981, Yan et al. 2018). Such insights deepen our understanding of Thailand's paleogeographic

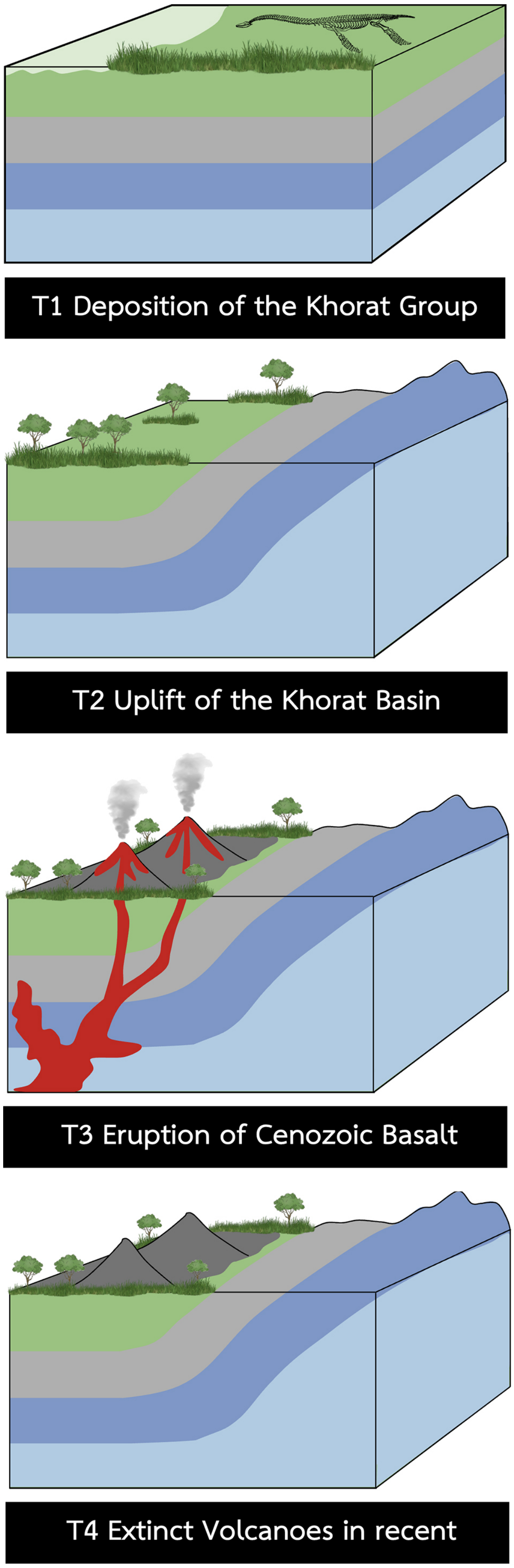

Fig. 8. Simplified model of historical geological events of the southern Khorat Plateau.

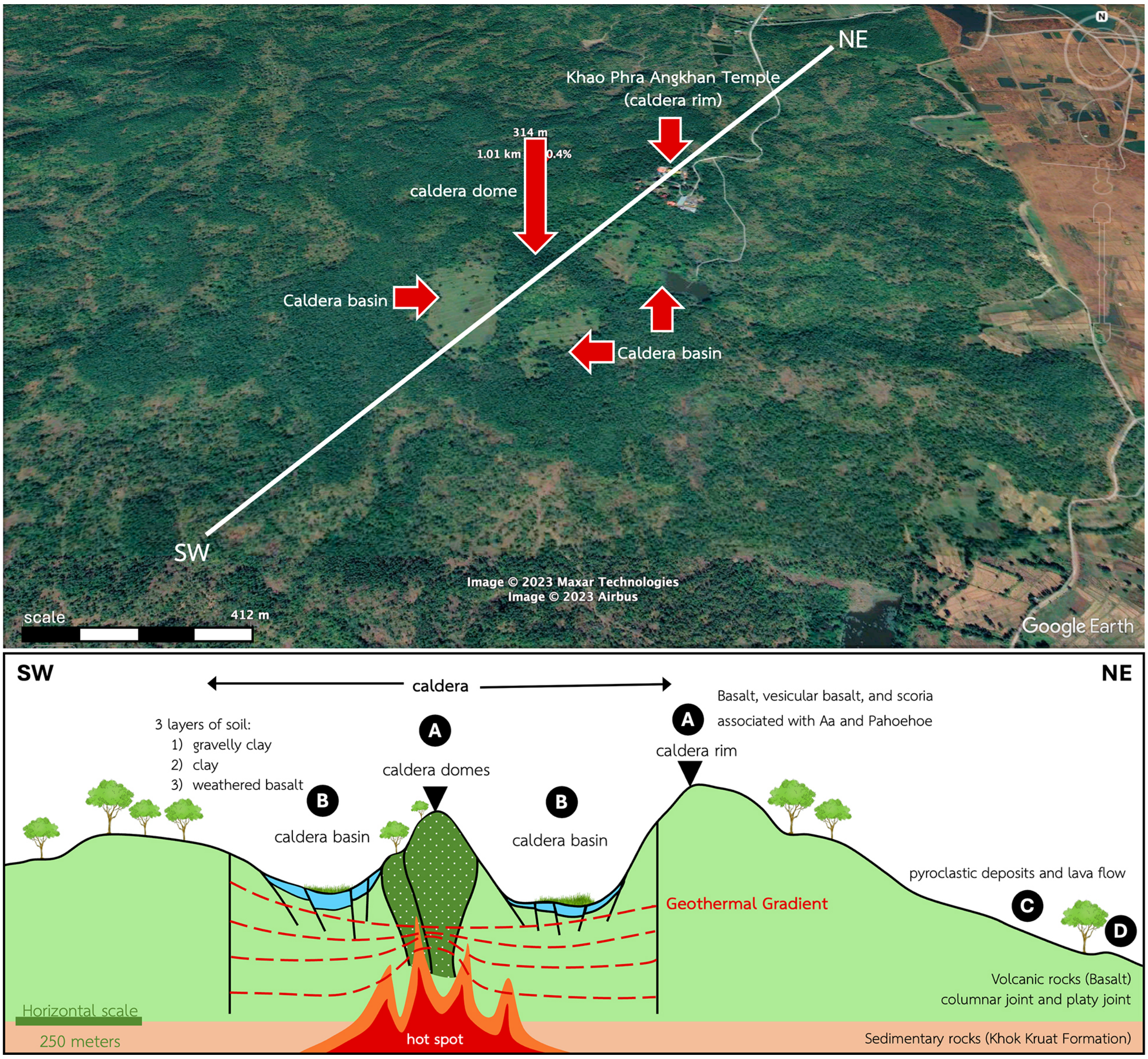

Fig. 9. Simplified Structural Model of Cenozoic volcanoes in the Southern Khorat Plateau: Notable Khao Phra Angkhan in Buriram Province. The satellite image was generated by Google Earth Pro®.

evolution and the tectonic underpinnings that have shaped its plateau and volcanic landforms.

In the wider Asian context, the volcanic history of the Khorat Plateau shares common tectonic drivers with basaltic provinces across Southeast Asia, including Laos's Bolaven Plateau, Vietnam's Pleiku Plateau and southern China's Leiqiong Peninsula (Fig. 10). These areas also experienced intra-plate volcanism due to back-arc extension and mantle plume activities during the Cenozoic. Thus, the volcanic successions of northeastern Thailand contribute to the regional geodynamic model of post-collisional magmatism in mainland Southeast Asia.

From a broader tropical perspective, the post-volcanic landscapes in this region follow a pattern common to tropical basaltic terrains: rapid weathering of volcanic materials into nutrient-rich soils, resulting in agriculturally productive landscapes. Similar patterns are observed in tropical volcanic areas such as Java (Indonesia), the Western Ghats (India) and parts of Central America. The geomorphological transformation from active volcanism to fertile caldera basins exemplifies how tropical volcanic landscapes evolve into socioeconomically vital zones.

Geoheritage potential and comparative assessment

The dormant volcanic features in the study area – such as shield volcanoes, calderas, lava

Fig. 10. Satellite image showing the locations of the studied volcanic geoheritage sites in Thailand, along with other significant volcanic heritage sites in Southeast Asia exhibiting similar geological features. The image was generated using Google Earth Pro®.

domes and basaltic flows – offer substantial geoheritage value. These features not only narrate a dynamic geologic past but also continue to shape cultural and religious identities. The adaptation of summit craters as sacred sites for Khmer monasteries and Buddhist temples highlights the integration of geodiversity with cultural heritage.

Comparatively, the geoheritage value of this region stands on par with other recognised volcanic heritage sites in tropical zones, such as Mount Bromo in Indonesia (Abidin et al. 2004) or the Arxan–Chaihe Volcanic Field, Inner Mongolia, China (Németh et al. 2017b). However, unlike many of these heavily touristed sites, the Khorat Plateau volcanoes remain underrepresented in global geotourism frameworks. Their potential for educational, scientific and community-based tourism is significant, particularly when viewed through the lens of sustainable development and conservation. According to tourism statistics from the Tourism Authority of Thailand and the Ministry of Tourism and Sports, Buriram, Surin and Sisaket provinces collectively recorded approximately 1–3 million visitors in 2024 (www.tat.or.th/th, www.mots.go.th/). While these figures indicate robust regional tourism, the data do not disaggregate visits by specific attractions. Interviews with local residents suggest that the majority of tourists are primarily drawn to religious sites, cafés and shopping centres. Visitors to volcanic sites often arrive incidentally while touring nearby temples or ancient Khmer sanctuaries, rather than with explicit interest in the volcanic heritage itself. This indicates a missed opportunity to highlight these unique geosites as focal points for geotourism development.

Promoting the volcanic landscape of Buriram, Surin and Sisaket as part of a regional geopark network – perhaps linked with the Khorat UNESCO Global Geopark or Khon Kaen Geopark – could enhance awareness and preservation efforts while supporting local economies. Integration with UNESCO Global Geopark initiatives may provide international recognition, funding and management models that align geoconservation with cultural heritage preservation.

Local development

Recently, women's weaving groups have adapted ancestral wisdom by using volcanic soil from Angkhan, believed to be sacred, in the dyeing process. This practice is thought to bring good fortune to the wearers. Fabrics dyed with this soil, known as Phu Akani cloth (Akani means fire in the Thai language), exhibit light brown and reddish-brown hues, with a soft, lightweight and cool texture. This tradition links geological heritage with local craftsmanship.

Additionally, soils formed from the weathering of volcanic rocks are highly fertile and valuable to local farmers, significantly enhancing agricultural productivity. These nutrient-rich soils support the cultivation of key crops such as rice, durian, banana and melon. This fertile soil has led to the registration of geographical indications (GI) for local products, such as the renowned volcanic durian from Sisaket (Singtuen et al. 2021).

Furthermore, all studied volcanoes are legally protected from mining industries. For instance, Khao Phanom Sawai and Khao Kradong are protected as forest parks, while Khao Phanom Rung is a historical park nominated for UNESCO World Heritage status. The nomination is based on three criteria (www.whc.unesco.org/en/tentativelists/6401): (i) its unique integration of sacred Angkorian architecture across volcanic craters and plains, showcasing exceptional stone carving and cultural symbolism; (ii) its outstanding example of ancient engineering, architecture and landscape design related to water management; and (iii) its demonstration of human adaptation to volcanic landscapes through innovative use of crater-based water systems that supported sustainable communities. Other volcanoes like Khao Phra Angkhan, Khao Plai Bat and Phu Fai, which host Buddhist temples, are preserved by local communities through their inherent cultural and spiritual significance.

By incorporating social data into the study, researchers can assess the cultural, historical and economic value of volcanic landscapes, contributing to the promotion of geotourism and heritage preservation initiatives (García-Cortés et al., 2018, Brilha 2018, Pérez-Umaña et al. 2020, Tefogoum et al. 2020, Quesada-Román et al. 2022, Quesada-Valverde, Quesada-Román 2023). Additionally, understanding the societal perceptions and attitudes towards volcanoes is crucial for effective risk communication and disaster preparedness efforts. Therefore, the inclusion of social data enriches the scientific understanding of volcanic landscapes and enhances the relevance of research findings for both academic and practical applications.

This multidisciplinary approach aligns with the principles of integrated landscape management and sustainable development, emphasising the interconnectedness of natural and human systems.

By considering social, economic and environmental factors, researchers can develop holistic strategies for the conservation and sustainable utilisation of volcanic geoheritages, contributing to the long-term well-being of both ecosystems and communities (Quesada-Román et al. 2020, Quesada-Román, Pérez-Umaña 2020, Mejía-Agüero, Quesada-Román 2024, Quesada-Valverde, Quesada-Román 2025). Notably, volcanic geoheritage is recognised as a key thematic category within the IUGS Geological Heritage Site programme (i.e. IGCP 731: *IUGS Geological Heritage Sites*), which identifies and promotes globally significant geological sites to foster international collaboration, education and geoconservation initiatives (www.iugs-geoheritage.org).

This approach is supported by various studies emphasising the importance of integrating social sciences into geological research for a comprehensive understanding of volcanic landscapes and their sociocultural significance. For example, research by Fearnley et al. (2012, 2017, 2018) underscores the value of integrating social data into volcanic hazard assessments to better understand community vulnerabilities and enhance disaster risk reduction strategies. Similarly, interdisciplinary studies by Carr et al. (2016) and Cronin et al. (2014) highlight the importance of combining geoscience with social science for effective volcanic risk communication and meaningful community engagement. These approaches are further advanced by international initiatives such as IGCP Project 692: *Geoheritage for Geohazard Resilience* (www.geopoderes.com), which promotes the use of geoheritage and geoeducation to build resilient societies in the face of natural hazards. In line with this, Németh and Moufti (2024) emphasise the role of geoheritage as a driver for the development of resilient volcanic hazard programmes, positioning geoeducation as a critical tool for long-term risk reduction and sustainable development. Overall, the inclusion of social data in geological research enhances the relevance and applicability of findings, contributing to more informed decision-making processes and sustainable management practices for volcanic heritages.

Conclusion

The Cenozoic volcanoes in Buriram, Surin and Sisaket, located along the southern edges of the Khorat Plateau, are characterised by basaltic rocks overlaying sandstone formations. These basaltic rocks, identified from shield volcanoes (Khao Phanom Sawai, Khao Phra Angkhan, Khao Phanom Rung, Khao Kradong, Khao Plai Bat and Phu Fai) and fissure eruptions, exhibit features such as columnar basalts and are predominantly olivine basalt with porphyritic and trachytic textures. Some basalts in Sisaket are classified as alkaline basalts with nepheline in the groundmass. Geochemical analysis classifies these rocks as trachybasalt, basalt, basaltic andesite, basaltic trachyandesite and andesite, with SiO_2 contents ranging from 51.07% to 61.46% by weight, and trace elements identifying them as alkaline basalts. The eruptions, occurring between 0.43 and 3.3 million years ago, show that magma viscosity and eruption patterns are influenced by a range of geochemical factors beyond SiO_2 content alone. Despite their dormancy, these volcanoes continue to benefit local communities through cultural and agricultural practices. The legacy of these volcanoes is preserved in the construction of Khmer monasteries and Buddhist temples, as well as in the use of volcanic soils for handicraft weaving and agriculture. Legally protected as forest parks and historical sites, as well as these volcanoes are conserved by both official regulations and local communities.

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Authors' contribution

VS: conceptualization, investigation, methodology, formal analysis, resources, visualization, writing – original draft, writing – review & editing. SS: conceptualization, investigation, methodology, formal analysis, resources, writing – original draft in Thai.

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