

Integrated Geoheritage Framework: Linking Geology, Biodiversity, and Culture in Ranah Minang Silokek Geopark, Indonesia

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Abstract

The Ranah Minang Silokek Geopark (RMSG), West Sumatra, Indonesia, is a region with a concept of preserving the unique geological heritage, biodiversity, and culture of the Minangkabau people living in an area of 3,150 km². Designated a National Geopark in 2018 and holding the status of an aspiring UNESCO Global Geopark in 2026, RMSG was documented through integrated geological surveys, biodiversity inventories, and ethnographic research. Eighteen geological sites ranging in age from Permo-Carboniferous to Miocene were identified, along with high species richness and nine major cultural heritage sites. Five geo-bio-cultural linkages illustrate how lithology underlies ecological processes and cultural traditions, including honey production on sandstone cliffs, bat-mediated durian pollination, limestone flora as a geological indicator, tiger ecology codified in martial arts, and land-use zoning embedded in proverbs. These findings demonstrate RMSG as an archetype of integrated geological heritage, where geological processes form the abiotic foundation for biodiversity and cultural adaptation. This study highlights implications for geological conservation, geopark interpretation, and community-based sustainable development, and provides a Southeast Asian case study for global geopark science.

Keywords: Geoheritage; UNESCO Global Geopark; Geodiversity; Ethnoecology; Minangkabau; Silokek

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1. Introduction

The concept of geoparks as integrated management territories connecting geological heritage, biodiversity, and cultural diversity has gained substantial international traction since UNESCO formalised the Global Geoparks Network in 2004 and has become an official UNESCO program under the IGGP since 2015 (UNESCO 2016). Geoparks represent a practical mechanism for simultaneous geoconservation, nature education, and locally grounded sustainable development, with over 229 UNESCO Global Geoparks now operating across 50 countries. Yet the scientific foundation for geopark nomination and management remains unevenly developed, with integrated documentation of geo-bio-cultural linkages the substantive connections between geological features, ecosystem patterns, and cultural practices still relatively rare in the peer-reviewed literature (Gordon et al. 2021; Haryono et al. 2022).

Geodiversity, broadly defined as the natural range of geological, geomorphological, pedological, and hydrological features, processes, and systems, provides the abiotic foundation upon which biological diversity and cultural adaptation are built (Gray 2013; Brilha et al. 2018). The theoretical link between geodiversity and biodiversity is well established conceptually, though empirical demonstration at landscape scales remains insufficiently documented (Alahuhta et al. 2020). Geopark frameworks are particularly well suited to operationalise this integration by requiring documentation of how geological heritage supports ecological and cultural values, thereby producing empirical case studies of geo-bio-cultural interdependence (Swerkosz et al. 2017; Haryono et al. 2022). Figure 1 illustrates the conceptual framework adopted in this study, showing how geological diversity, biological diversity, and cultural diversity interact and overlap in the RMSG context.

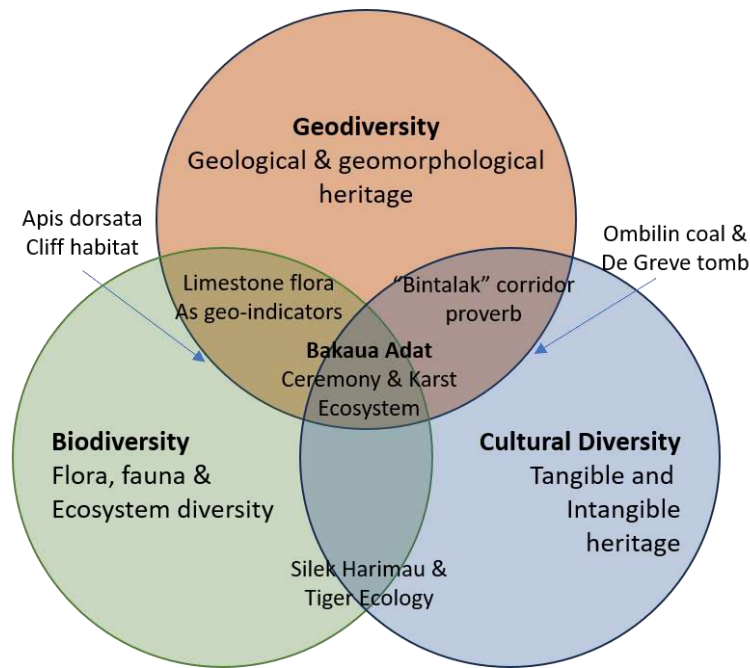


Fig. 1 Conceptual Venn diagram of the geo-bio-cultural framework. Overlapping circles represent geodiversity (orange), biodiversity (green), and cultural diversity (blue); the central intersection denotes fully integrated geo-bio-cultural linkages as documented in RMSG

Southeast Asia's geological complexity, arising from the Mesozoic amalgamation of continental blocks and ongoing active tectonics along the Sunda subduction zone, has created landscapes of exceptional geodiversity (Metcalf 2013; Barber et al. 2005). Sumatra, positioned along this active margin, exhibits particularly diverse geological features including Paleozoic continental basement, Triassic to Jurassic granitoid intrusions, Paleogene extensional basins, and Miocene marine sequences, all compressed within relatively small geographic areas. These geological foundations have profoundly shaped biodiversity patterns and human settlement strategies throughout Sumatran history.

Ranah Minang Silokek Geopark (RMSG), covering the entire 3,150.58 km² of Sijunjung Regency in West Sumatra Province, preserves geological evidence spanning from the Permo-Carboniferous Kuantan Formation to Neogene sedimentary sequences. The area supports four formally designated biodiversity conservation zones: Rimbo Larangan Paru community forest, Cagar Alam Batang Pangean I and II, and the Silokek riparian biosite, collectively harbouring numerous endemics and threatened species. Overlying both geological and biological foundations is the rich living Minangkabau cultural tradition, centred on the matrilineal adat system and expressed in traditional land management, ceremonies, martial arts, and oral knowledge.

Prior assessments of the 14-geosite RMSG inventory confirmed the geopark's moderate-to-high scientific value, identified the Silokek Karst Complex and Sijunjung Granite Complex as the highest-value sites, and proposed a tectono-stratigraphic narrative spanning nearly 300 million years as the geopark's principal international significance argument (Adrianda et al. 2025; Abdurrachman et al. 2026). The present study substantiates and extends that framing through 18 geosites and integrated bio-cultural evidence, linking geosite scores to the biological and cultural heritage dimensions those prior assessments did not pursue.

This study addresses three primary research questions: (1) What is the current geoheritage inventory of RMSG, and how does the 14 geosite assemblage represent the geological evolution of central Sumatra? (2) What is the geo-bio-cultural linkages operating within RMSG, demonstrating how geological features underpin biological patterns and cultural practices? (3) How can the integrated geo-bio-cultural framework developed here serve RMSG aspirations for UGGp recognition and contribute to broader geoconservation science? By answering these questions through systematic field documentation, we contribute an empirical case study from tropical Southeast Asia to the growing literature on integrated geopark science.

2. Study Area

RMSG is located in Sijunjung Regency, West Sumatra Province, Indonesia, approximately 100 km southeast of Padang city (Figure 2). The geopark encompasses 3,150.58 km² comprising 8 sub-districts, 62 nagari, and approximately 237,376 inhabitants. Terrain is rugged, forming part of the Barisan Mountain Range, with elevations ranging from below 100 m to 1,250 m above sea level.

The area experiences a Type B (Wet) tropical climate (Schmidt-Ferguson classification; Schmidt and Ferguson 1951), with mean annual rainfall of approximately 2,112 mm and a pronounced dry season from June to September, reflecting the rain shadow effect of the Barisan Range. Extreme events including flash floods affected multiple sub-districts in May and November 2024, causing damage to over 651 residential units and highlighting the hazard dimension of the karst and steep-valley landscape (BPBD Kabupaten Sijunjung 2024).

Major rivers including Batang Kuantan (86 km through the geopark), Batang Sumpu, and Batang Ombilin drain the region, creating deeply incised valleys that expose excellent geological cross-sections and serve as natural biodiversity corridors. Land use is dominated by forest (51.15%), followed by mixed gardens (38.44%), wet rice fields (3.93%), and plantations (1.64%).

The geological setting is explained in detail in Section 4.1. Briefly, RMSG occupies a tectonically significant position at the boundary between the West Sumatra Block and the Ombilin Basin, a Paleogene pull-apart structure developed along the Sumatran Fault System (Situmorang et al. 1991; Koning 1985). Four conservation zones provide formal biodiversity protection: Rimbo Larangan Paru (4,500 ha community forest governed since 2002 under Peraturan Nagari No. 1/2002), Cagar Alam Batang Pangean I (14,288 ha), Cagar Alam Batang Pangean II (33,580 ha), and the Silokek riparian biosite.

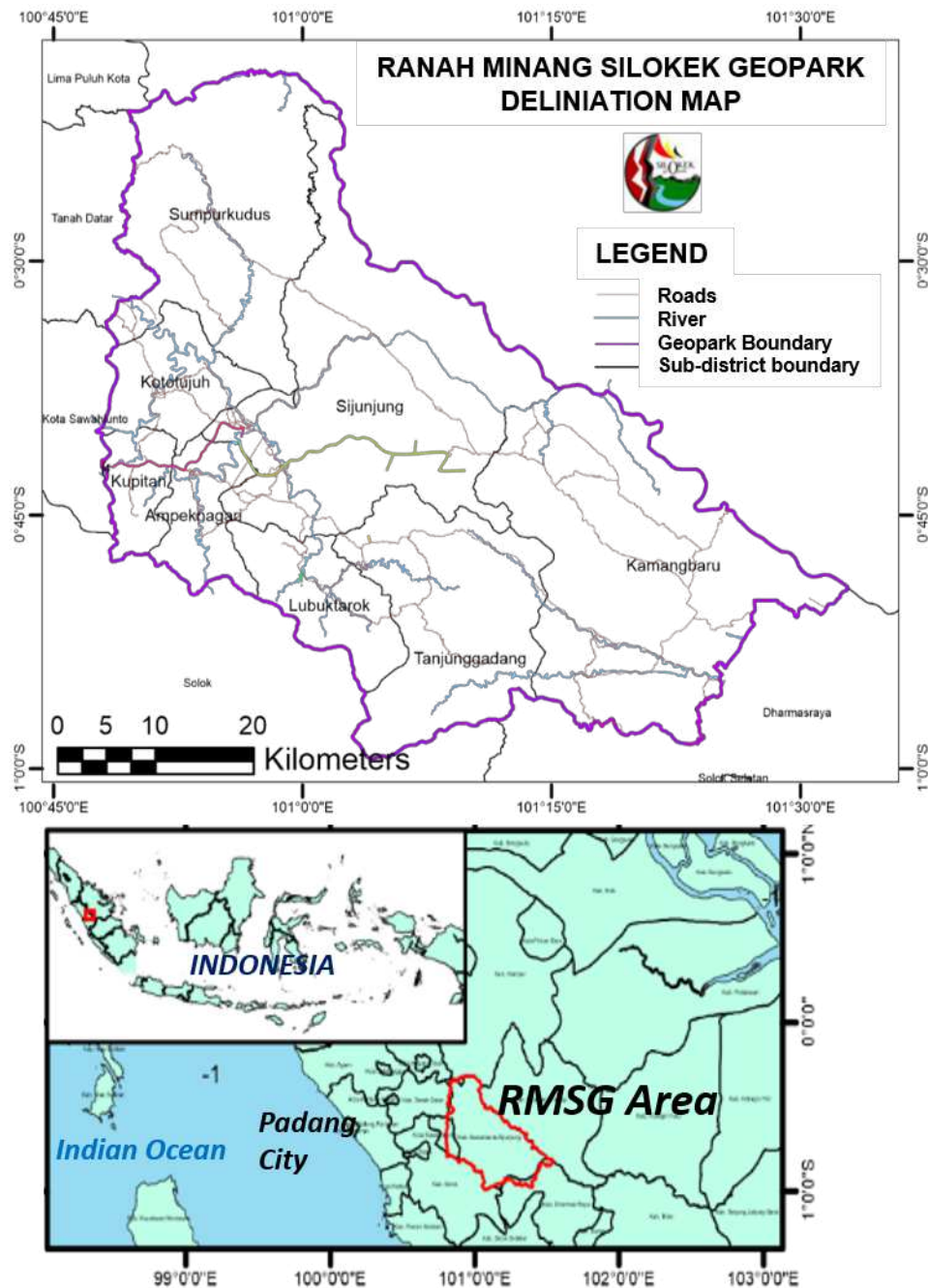


Fig. 2 Delineation map of Ranah Minang Silokek Geopark (RMSG) showing geopark boundaries, road network, and river systems, with a provincial inset map locating RMSG within West Sumatra, Indonesia

3. Materials and Methods

3.1 Geological Survey and Geosite Assessment

Geological field surveys were conducted during 2024 to 2025, involving lithological description, structural measurement, and geomorphological mapping at 1:50,000 scale using GPS, geological compass, and digital photography. Lithostratigraphic analysis combined megascopic hand-specimen description with petrographic examination of representative samples. A systematic review of the existing 14-geosite inventory was undertaken. Four additional significant exposures were identified in the field and four existing

geosite names were revised to better reflect their confirmed stratigraphic identity. Geosite assessment applied two complementary frameworks: (i) Kubalikova (2013) geomorphosite criteria addressing scientific, educational, aesthetic, and conservation values; and (ii) the Indonesian Geological Agency criteria (PSG 2017) incorporating representativeness, integrity, rarity, and scientific significance. Geosite significance was classified at international, national, and local levels following Brilha (2016).

3.2 Biodiversity Inventories

Flora was documented using line transect and opportunistic sampling methods (Rugayah et al. 2004), recording local names, scientific names, family, endemism, and conservation status for each species. Unidentified specimens were prepared as herbarium vouchers and identified against Whitten et al. (1997) and the Flora of Java and Flora Malesiana (Van Steenis 1950). Avifauna surveys used line transect methodology (Bibby et al. 1992) during morning (05:30 to 11:00) and afternoon (15:00 to 18:00) periods, recording local names, scientific names, family, endemism, and conservation status, with species identification aided by MacKinnon et al. (field guide to the birds of Sumatra, Java, Bali, and Kalimantan). Mammals were assessed through direct observation, indirect evidence (tracks, scats, vocalisations), and structured community interviews. Herpetofauna was surveyed using visual encounter methods during diurnal and nocturnal periods following Heyer et al. (1994). Lepidoptera were documented through direct encounter surveys at CA Batang Pangean II. Conservation status was determined using IUCN Red List categories, CITES appendices, and Indonesian PERMENLHK P.106/2018.

3.3 Cultural Heritage Documentation

Cultural heritage data were collected using qualitative methods: archival review of historical, archaeological, and ethnographic sources; field observation and photographic documentation at nine heritage sites; and semi-structured interviews with traditional leaders (penghulu), cultural practitioners, and community elders using purposive snowball sampling. Participatory observation of cultural events including the Bakaua Adat ceremony was undertaken. Cultural heritage was classified into tangible and intangible categories following UNESCO frameworks. Toponymic analysis, folkloristic interpretation, and visual analysis of cultural practices were applied to reveal geo-bio-cultural connections.

3.4 Integrated Geo-Bio-Cultural Analysis

Integration of geological, biological, and cultural data was achieved through GIS spatial overlay analysis examining relationships between geosite distribution, ecosystem boundaries, conservation zones, and settlement patterns (Fig. 3 provides the geological cross-section illustrating the spatial framework). Ethnogeological analysis explored community utilisation of geological resources. Geo-bio-cultural linkages were identified through three analytical lenses: (i) ecological analysis of how lithology and geomorphology determine habitat type and species distribution; (ii) folkloristic and ethnographic analysis of cultural narratives referencing geological features; and (iii) spatial correlation between geosite occurrence, biosite boundaries, and cultural site locations. Generative AI use in manuscript preparation is documented under Declarations.

4. Results

4.1 Geoheritage Diversity and Geological Setting

The geology of RMSG records four major periods of Earth history spanning nearly 300 million years, from Carboniferous–Permian carbonate platform deposition through Triassic magmatism to Cenozoic basin development (Abdurrachman et al. 2026), together explaining the present landscape structure (Fig. 3). The Kuantan Formation limestone karst, which initiated karstification from the Neogene following Takung Fault exhumation, is the geopark’s most distinctive geological asset and the foundation for interpreting all subsequent biodiversity and cultural patterns described in this paper. The geological map and cross-section are shown in Figure 3, and representative lithologies are illustrated in Figure 4.

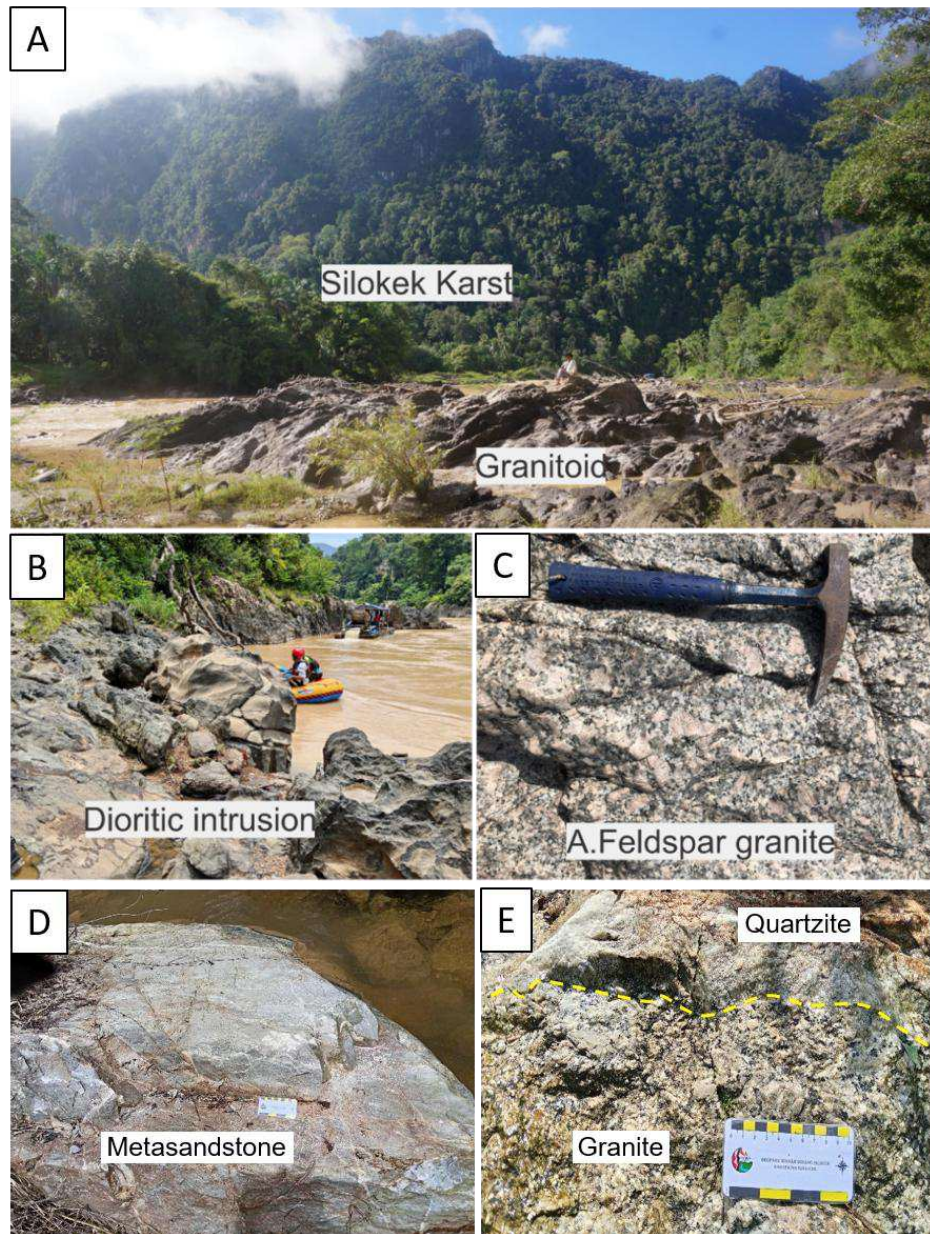


Fig. 4 Representative lithology of Ranah Minang Silokek Geopark. a Panoramic view of the Silokek Karst hills overlying granitoid basement rocks exposed along the riverbank; b dioritic intrusion outcrop along the Batang Kuantan River, observed during river rafting activity; c close-up of alkali feldspar granite showing coarse-grained texture with hammer for scale; d metasandstone boulder exhibiting metamorphic fabric; e contact relationship between quartzite (upper) and granite (lower), delineated by yellow dashed line, with scale bar for reference

The Permo-Carboniferous Kuantan Formation constitutes the oldest rocks of RMSG and forms the structural backbone of the geopark. It consists of three members: (1) the Lower Member (PCK1), comprising quartz-rich metasandstone, quartzite, phyllite, and schist; (2) the Limestone Member (PCKs), comprising crystalline limestone deposited in a carbonate platform margin sand shoal environment and now exposed as tower karst (Widiatama et al. 2023); and (3) the Phyllite and Shale Member (PCKs), comprising marine shelf metasediments. At Lubuk Pandakian, strong quartz interlocking in the metasandstone, gash fractures indicating normal faulting, and bedding preservation confirm the Anggota Batupasir classification. At Siaur, limestone has been contact-metamorphosed to marble and carries slickenside surfaces oriented N105 to 110

degrees E with dextral strike-slip kinematics, recording movement on the Takung Fault. At Muaro Takung, phyllite and metasandstone show hydrothermal alteration assemblages (chlorite, clay minerals, pyrite) associated with an andesitic intrusion to the northwest, indicating post-tectonic hydrothermal fluid circulation.

The Triassic Sijunjung Granite Complex (g) is the dominant igneous unit. Field observations at Silokek, Nagari Silukah, and the Silokek to Durian Gadang boundary document a multi-phase intrusion history. The main biotite granite hosts: alkali feldspar granite; pegmatitic granite with coarse feldspars and quartz; fine-grained biotite granite melt pockets; aplite dykes; and xenoliths of porphyritic diorite (at Silukah) and fine-grained microgranite (at Durian Gadang). An irregular intrusive contact approximately 10 m wide against Kuantan Formation metasandstone is exposed at Durian Gadang, with metasandstone enclaves within the granite body confirming the intrusive relationship. This multi-intrusion, magma-mixing signature, combined with A-type geochemical classification (high SiO₂, enriched REEs, ferroan composition), indicates formation during post-collisional crustal extension following West Sumatra Block amalgamation (Irzon et al. 2021).

The Jurassic Granite (Jgr) is a younger, more voluminous granitoid body forming much of the central Basement High visible in Figure 3. The detailed geological map and lithostratigraphic column are presented in Figure 4. Together with the Triassic granite, it produces dome-shaped hills and radial drainage patterns where deeply weathered granite saprolite supports lateritic soils.

Cenozoic sedimentary sequences record the formation of the Ombilin Basin to the west of the Basement High (Koesoemadinata and Matasak 1981). The Eocene to Oligocene Brani Formation (Tob) represents alluvial fan to fluvial deposits (conglomerate with sandstone interbeds) forming the syn-rift fill along basin-bounding faults. The Oligocene to Miocene Ombilin Formation (Tmol/Tmou) records the main lacustrine to fluvial phase with coal-bearing shale, quartz sandstone, and conglomerate horizons; the coal seams formed the economic basis for colonial-era mining. The Miocene Telisa Formation (Tmtl), exposed at Danau Biru in the east, records marine transgression with fossiliferous shale and sandstone intruded by a post-depositional igneous dyke visible in outcrop (USGS 1999).

Ministerial Decree No. 208.K/GL.01/MEM.G/2024 designated 14 geosites as formal geoheritage. Comprehensive field survey and re-assessment in this study identified four additional significant exposures and revised three geosite names, yielding 18 geosites that collectively document the full geological evolution described above (Table 1). Two sites merit international significance. This 18-geosite inventory expands the 14-site baseline of Adrianda et al. (2025), who placed all sites in the moderate-to-high value category. The four new geosites (hydrothermal alteration, xenolith-bearing magma mixing, dextral strike-slip deformation, and intrusive contacts) strengthen the tectonic narrative absent from that earlier assessment.

Table 1 Geosite inventory and significance levels in Ranah Minang Silokek Geopark. Asterisks (*) indicate new geosites identified or renamed in this study.

No	Geosite Name	Age	Lithology	Significance	Primary Value
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1	Karst Formasi Kuantan Silokek *	Permo-Carboniferous	Limestone, marble	International	Cathaysian Block; tropical karst system
2	Kompleks Granit Sijunjung Silokek	Triassic	Granite, meta-limestone	International	Post-collisional A-type magmatism
3	Hipostatotipe Formasi Telisa Danau Biru	Miocene	Sandstone, shale	National	Central Sumatra Basin stratigraphy
4	Granit Merah Timbulun Tujuh	Triassic	Alkali feldspar granite	National	A-type magmatism variant
5	Granodiorit Timbulun	Triassic	Granodiorite	National	Intermediate intrusive complex
6	Batugamping Ngalau Loguang	Permo-Carboniferous	Crystalline limestone	National	Active karst processes; cave habitat
7	Kompleks Batolit Granit Mambuik	Triassic	Biotite granite	National	Large plutonic batholith body
8	Batupasir Malihan Lubuk Pandakian *	Permo-Carboniferous	Quartzite, metasandstone	National	Basement metamorphism; Cathaysian terrane
9	Batupasir Sialang Lubuk Tarok	Miocene	Quartz sandstone	Local	Fluvial deposition; Apis dorsata cliff habitat
10	Diorit Aie Angek	Triassic	Diorite	Local	Intermediate intrusion
11	Bukit Kupitan Formasi Ombilin *	Miocene	Sandstone, conglomerate	Local	Cuesta structural landform
12	Gua Inyiak Umpuah	Miocene	Sandstone	Local	Cave formation; bat habitat
13	Batupasir Formasi Ombilin Sungai Rambutan	Miocene	Sandstone, coal	Local	Coal-bearing fluvial sequence
14	Konglomerat Brani Ngalau Bataui	Oligocene	Conglomerate	Local	Syn-rift alluvial fan deposits
15	Kontak Batupasir Malihan dan Granit Sijunjung *	Permo-Carb/Triassic	Contact zone	National	Intrusive contact; magmatic history
16	Xenolith Silukah *	Triassic	Granite with xenoliths	National	Magma mixing and differentiation
17	Filit dan Batupasir Malihan Muaro Takung *	Permo-Carboniferous	Phyllite, metasandstone	National	Hydrothermal alteration; structural geology
18	Marmer Siaur *	Permo-Carboniferous	Marble	National	Dextral strike-slip deformation record

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222 4.2 Biodiversity Patterns

Comprehensive surveys documented high species diversity across four biosites (Figure 5). Flora inventories recorded 145 species (46 families) at Silokek, 154 species (43 families) at Rimbo Larangan Paru, 159 species (49 families) at Cagar Alam Batang Pangean I, and 160 species (49 families) at Cagar Alam Batang Pangean II. A dedicated flowering plant inventory across the Silokek geopark area recorded 164 species within 121 genera and 55 families, confirming Moraceae (14 species) and Gesneriaceae (12 species) as the most species-rich families and identifying six species of elevated conservation concern including three Sumatran endemics: *Vanda sumatrana* (Orchidaceae), *Zingiber macradenium* (Zingiberaceae), and *Impatiens tribuana* (Balsaminaceae) (Nurainas et al. 2024). Moraceae is the keystone family with 16 species across all sites, providing year-round fruiting resources critical for frugivores. Gesneriaceae including *Paraboea capitata*, *Epithema strigosum*, *Monophyllaea horsfeldii*, *Begonia batuphila*, and *Impatiens tribuana* colonise limestone cliff faces and function as geoindicators of carbonate substrate (Kiew 2011). High-value timber species of conservation concern, including *Eusideroxylon zwageri* (IUCN VU) and *Dipterocarpus retusus* (CITES Appx. II), were recorded across all four sites. The occurrence of *Pandanus odorifer* inland on karst terrain at Silokek is anomalous for a species typically restricted to coastal environments and may represent a Quaternary relict population preserving palaeoenvironmental evidence of former marine conditions.

Avifauna surveys recorded 24 species at Silokek, 24 at Rimbo Larangan Paru, 30 at CA Batang Pangean I, and 34 at CA Batang Pangean II. Critically Endangered species include *Rhinoplax vigil* (CITES Appendix I). Other avifauna of significant conservation status include *Buceros rhinoceros* (IUCN VU; CITES Appx. II), *Rhyticeros undulatus* (IUCN VU; CITES Appx. II), and *Spilornis cheela* (CITES Appx. II), all recorded across multiple biosites. Mammalian diversity includes *Panthera tigris sumatrae* (IUCN CR), *Manis javanica* (IUCN CR), *Symphalangus syndactylus* (IUCN EN; CITES Appx. I), *Macaca nemestrina* (IUCN VU; CITES Appx. II), four subspecies of *Presbytis melalophos* (IUCN EN), and two subspecies of *Hylobates agilis* (IUCN EN), all Sumatran endemics. Total mammal species counts per site were 30 (Silokek), 31 (Rimbo Larangan Paru), 32 (CA Batang Pangean I), and 35 (CA Batang Pangean II), with 13 to 14 Sumatran endemic species per site. Herpetofauna surveys recorded 13 species; only *Broghammerus reticulatus* (CITES Appendix II) reached conservation priority status. Lepidoptera at CA Batang Pangean II include *Troides amphrysus euthydemus*, a male Sumatran endemic listed in CITES Appendix II.

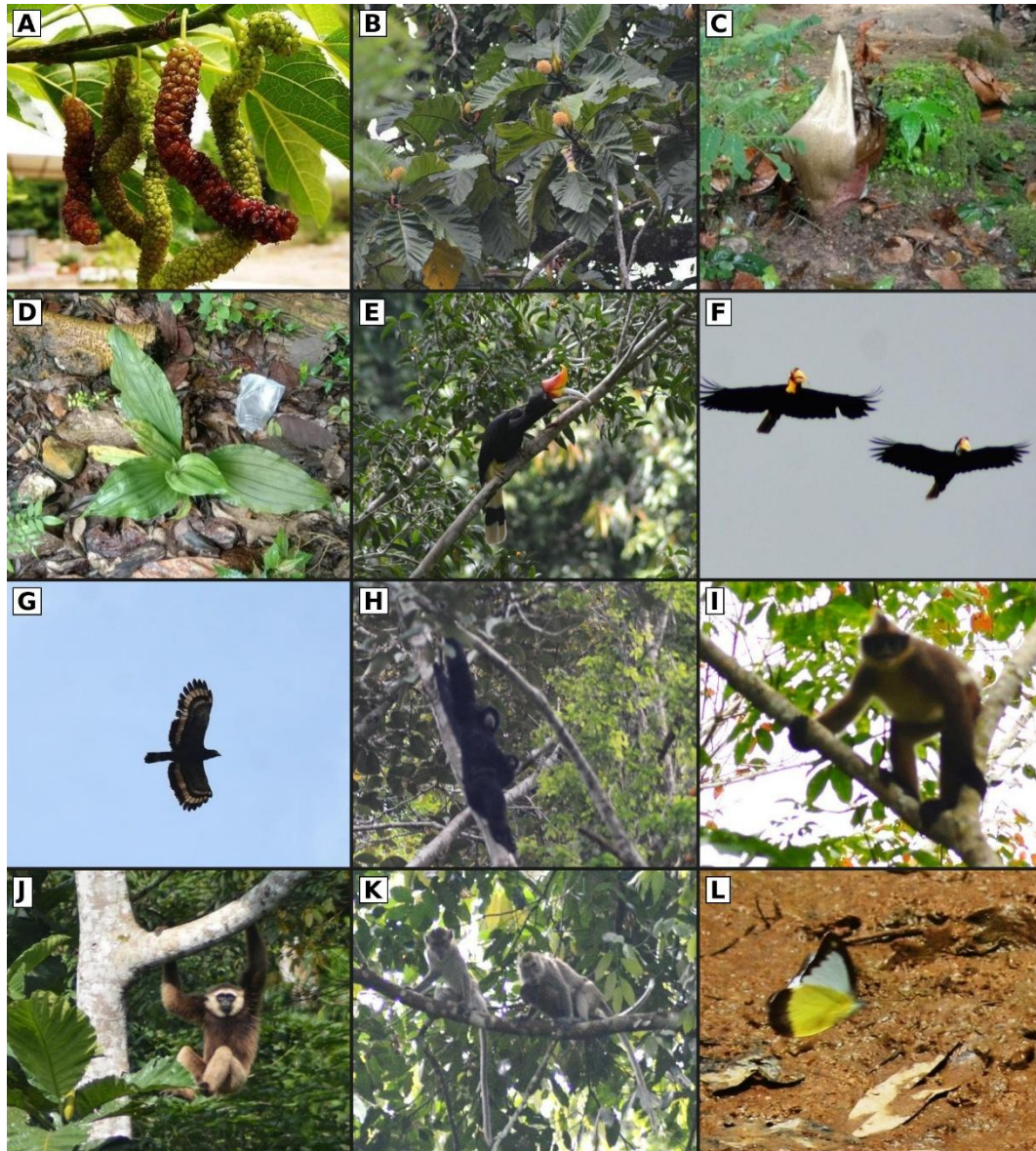


Fig. 5 Representative biodiversity of Geopark Ranah Minang Silokek with significant conservation and endemism status. Flora (a–d): a *Paraboea capitata* (karst flora; endemic Sumatra); b *Impatiens tribuana* (endemic West Sumatra); c *Eusideroxylon zwageri*; d *Dipterocarpus retusus* (endemic Sumatra). Fauna (e–l): e *Buceros rhinoceros*; f *Rhyticeros undulatus*; g *Spilornis cheela*; h *Symphalangus syndactylus*; i *Presbytis melalophos* (endemic Sumatra); j *Hylobates agilis ungko* (endemic Sumatra); k *Macaca nemestrina*; l *Troides amphrysus euthydemus*

4.3 Cultural Diversity

Nine major cultural heritage sites were documented (Table 2; Figure 6). Perkampungan Adat Nagari Sijunjung preserves 76 rumah gadang occupied by six clans, designated as National Cultural Heritage under Keputusan Mendikbud No. 106/M/2017. The settlement occupies an alluvial terrace between karst cliffs and two rivers (Batang Sokam and Batang Palangki), demonstrating ecological positioning that balances flood risk avoidance with permanent water access. Bakaua Adat was designated National Intangible Cultural Heritage (No. 3058/F4/KB.09.06/2022). Surau Simauang preserves 88 manuscript bundles (20,914 pages)

in Arabic and Jawi scripts (Fathurahman et al. 2015). Industrial heritage includes the Silukah Steam Locomotive and the grave of Willem Hendrik de Greve (1872), the Dutch geologist who discovered the Ombilin coalfields in 1867, directly linking the Miocene Ombilin Formation geology to colonial history.



Fig. 6 Representative cultural diversity of Geopark Ranah Minang Silokek. a–b Perkampungan Adat Nagari Sijunjung (traditional Minangkabau village); c Bakaua Adat ceremony site within Gua Nagari Solok Ambah; d Lokomotif Uap Silukah (colonial-era steam locomotive); e Makam Willem Hendrik de Greve; f Makam Rajo Ibadat, Sumpur Kudus; g Istano Kerajaan Jambu Lipo (royal palace); h Madu Sialang (wild honey harvesting tradition) of Kerajaan Jambu Lipo; i Surau Simauang

Table 2 Cultural heritage sites documented in RMSG.

Site	Type	Period	Primary Significance	Status
Perkampungan Adat Nagari Sijunjung	Settlement	Ongoing	Intact Minangkabau matrilineal architecture (76 rumah gadang)	National (2017)
Istano Kalambu Suto, Kerajaan Jambu Lipo	Royal palace	Pre-colonial	Kingdom centre; customary honey governance authority	Regional

Makam Sumpur Kudus	Rajo Ibadat,	Religious	Islamic period	Earliest Islamic authority in Minangkabau	Regional
Surau Simauang		Religious/Educational	Islamic period	88 manuscript bundles; Sattariyah tariqa knowledge hub	National
Makam Wahab	Syekh Abdul	Religious	Islamic period	Major pilgrimage site; 10,000 annual visitors (Rajab, Syaban)	National
Lokomotif Uap Silukah		Industrial	Colonial (1900s)	Coal railway artefact; geo-industrial heritage	National
Makam Greve	Willem H.D. de	Industrial	Colonial (1872)	Site of Ombilin coalfield geological discovery (1867)	Regional
Ngalau Adat)	Pakaulan (Bakaua	Ceremonial cave	Ongoing	National Intangible Cultural Heritage (2022); two-day cave ceremony	National ICH
Istano Kingdom	Jambu Lipo	Administrative	Pre-colonial	27-generation lineage; active royal Rajo Rantau ceremony	Regional

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278 5. Geo-Bio-Cultural Linkages

279 5.1 Spatial Patterns: How Geology Controls Heritage Distribution

280 Spatial analysis reveals that the geological cross-section in Figure 3 is also, in effect, a heritage
281 zonation map. Geosites follow the principal lithological units from west to east: Kuantan Formation
282 metamorphic basement exposed along the western margin; Triassic and Jurassic granitoid intrusions forming
283 the central Basement High; and Ombilin-Telisa Basin sedimentary sequences flanking both sides. Biosites
284 concentrate within hard-rock lithologies where rugged topography precludes agricultural conversion: Rimbo
285 Larangan Paru overlies phyllite and metasandstone; the Batang Pangean reserves are underlain by granitic
286 rocks. Culture sites cluster in alluvial valleys and river terrace positions, particularly along the Batang
287 Kuantan corridor, where karst and granitic uplands provide forest resources while flat lowland terrain permits
288 settlement and wet-rice cultivation. The Silokek area represents the most intense overlap of all three heritage
289 categories: karst limestone geosite, riparian karst biosite, and multiple cultural sites coexist within a 10-km
290 radius, making Silokek the thematic core of the geopark (Figure 7).

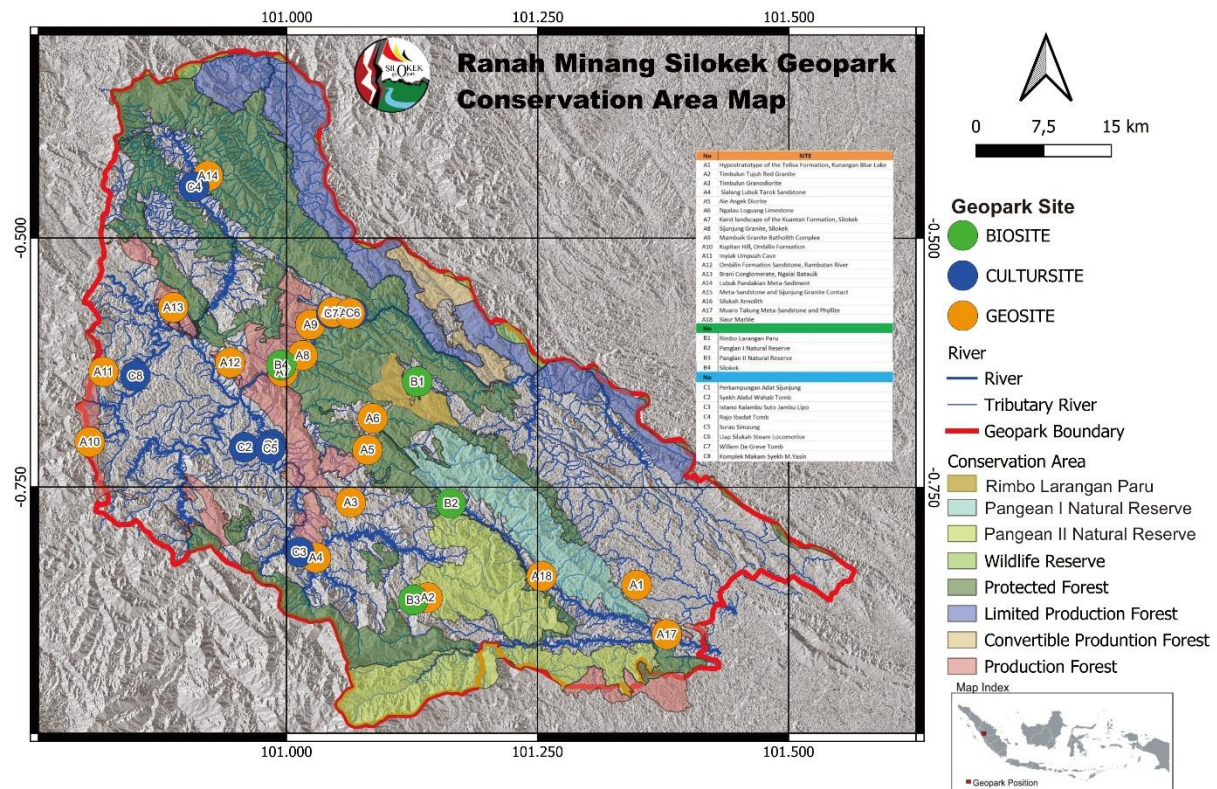


Fig. 7 Spatial distribution of Geosites, Biosites, and Cultural sites within Ranah Minang Silokek Geopark, illustrating the geographic overlap between geological, biological, and cultural heritage

5.2 Geological Landscape Formation and Land Use Implications

The cross-section in Figure 3 illustrates how each morphological unit of RMSG derives directly from its geological character. The Kuantan Formation limestone, exposed as tower karst in the western Basement High, produces vertical cliff faces 200 to 600 m in elevation with cave systems and karst springs. These springs emerge at the contact between impermeable granitic or metamorphic basement and overlying alluvium, providing dry-season water supply critical for wet-rice agriculture on adjacent plains. The granitic domes of Triassic and Jurassic age form radial dome-shaped hills resistant to erosion; their deeply weathered, acidic, nutrient-poor soils are unsuitable for annual crops but support diverse tropical forest. Brani Formation conglomerates produce sedimentary monadnocks projecting above the lower-relief Ombilin Formation lowlands, as visible in the morphology at Padang Laweh. Ombilin Formation alternating sandstone and mudstone produces cuesta ridges with dip-controlled asymmetric slopes, the best example being Bukit Kupitan. This systematic relationship between lithology, morphology, soil fertility, and water availability constitutes the geological determinism underlying all land-use decisions in RMSG, both historical and contemporary.

5.3 Linkage 1: *Apis dorsata* Honey Production at Sandstone Cliff Geosites

Batupasir Sialang Lubuk Tarok (Miocene quartz sandstone; Local significance) supports hundreds of *Apis dorsata* colonies nesting on vertical cliff faces (Figure 4H). The mechanical properties of the

sandstone determine habitat suitability: the rough, hard surface provides superior comb attachment compared to smooth rock, while the massive bedding and erosional cliff morphology create overhangs that protect colonies from rain and direct sun. Cliff orientation provides morning sun exposure with afternoon shade, and the river at the cliff base supplies colony water requirements. These geological properties collectively create the specific microhabitat that *Apis dorsata* selects preferentially for open-comb nesting (Oldroyd and Wongsiri 2006; Yang et al. 2018).

The ecological significance of these colonies extends beyond honey production. *Apis dorsata* is the primary pollinator of durian (*Durio zibethinus*), rambutan (*Nephelium lappaceum*), and numerous forest trees across the tropical forest matrix of RMSG. Colony decline would reduce pollination services across this forest-agriculture mosaic, cascading into reduced fruit yields and impaired forest regeneration (Gaucherel et al. 2018).

The Jambu Lipo Kingdom governs harvesting rights to these colonies under customary *hak ulayat alam* (natural commons law). Authorised *urang sialang* (bee guardians) follow strict adat protocols: only partial harvest to maintain colony viability, torch-calming rather than colony destruction, and ritual thanksgiving (*manangguang sialang*) before and after harvest. The economic value of *Madu Sialang Kerajaan Jambu Lipo*, premium honey sold under royal provenance, incentivises both conservation of the sandstone cliff habitat and maintenance of bee populations. This three-way linkage between sedimentary geosite, pollinator ecology, and customary governance exemplifies geosystem services (Fox et al. 2020) delivered through traditional institutions.

5.4 Linkage 2: Karst Cave Ecosystems and the Bakaua Adat Ceremony

Karst dissolution in the Kuantan Formation limestone (Figure 6C) has produced an extensive cave network including Ngalau Pakaulan, Ngalau Loguang, and Gua Inyiah Umpuah (Caesario et al. 2024). The dissolution chemistry controlling cave formation, carbonic acid weathering of calcium carbonate in the presence of CO₂-rich groundwater, also creates the cave microclimate conditions (stable temperature, high humidity, darkness) that support large bat colonies. These cave-roosting bats are the primary nocturnal pollinators and seed dispersers for durian and several other commercially important forest fruits in tropical Southeast Asia (Oldroyd and Wongsiri 2006).

The Bakaua Adat ceremony at Nagari Solok Ambah, designated National Intangible Cultural Heritage in 2022 (Figure 6C), is performed over two days inside Ngalau Pakaulan cave. The ceremony marks the end of the rice harvest cycle and the beginning of the next planting season, operating simultaneously as an agricultural calendar, community bonding ritual, and ecological management practice. A critical protocol requires all male participants to cover their heads using a cap (*peci*) or improvised leaf covering obtained near the cave entrance. Community elders explain this requirement as an expression of respect for the sacred cave space. The practical effect is to minimise physical disturbance to the bat colonies roosting overhead, directly reducing colony stress that could otherwise cause abandonment. Additionally, the ceremony timing is regulated in part by the availability of karst spring water for irrigation, connecting the hydrological

function of the karst aquifer (geological feature) to agricultural calendar management (cultural practice) through the biological necessity of bat-pollinated durian fruiting cycles.

5.5 Linkage 3: Karst-Specialist Flora as Geological Indicators

Inventories documented seven Gesneriaceae species restricted to limestone cliff faces and cave margins within RMSG: *Paraboea capitata*, *Paraboea treubii*, *Epithema strigosum*, *Epithema involucratum*, *Monophyllaea horsfeldii*, *Begonia batuphila*, and *Impatiens tribuana* (see Figure 8). These lithophytic specialists are restricted to alkaline calcareous substrates and specific microhabitats of humid shaded cliff faces (Kiew 2011; Geekiyanage et al. 2019; Nurainas et al. 2024). Notably, six of the seven species are confirmed karst area indicator plants, and three of them — *Impatiens tribuana*, *Paraboea treubii*, and *Monophyllaea horsfeldii* — have been specifically identified as diagnostic of karst limestone communities in this geopark (Nurainas et al. 2024). Their distribution faithfully maps the extent of Kuantan Formation limestone shown in Figure 3, providing a biological proxy that supplements geological mapping for geoheritage boundary delineation. Species occupying open porous cliff tops (*Paraboea capitata*, *Paraboea treubii*) are adapted to desiccation and root directly into rock; species of shaded cliff bases (*Epithema involucratum*, *Monophyllaea horsfeldii*) require continuous moisture from karst seeps. The two microhabitat guilds together reflect the full hydrological gradient of the karst cliff system, from seasonally dry exposed surfaces to permanently moist sheltered zones.

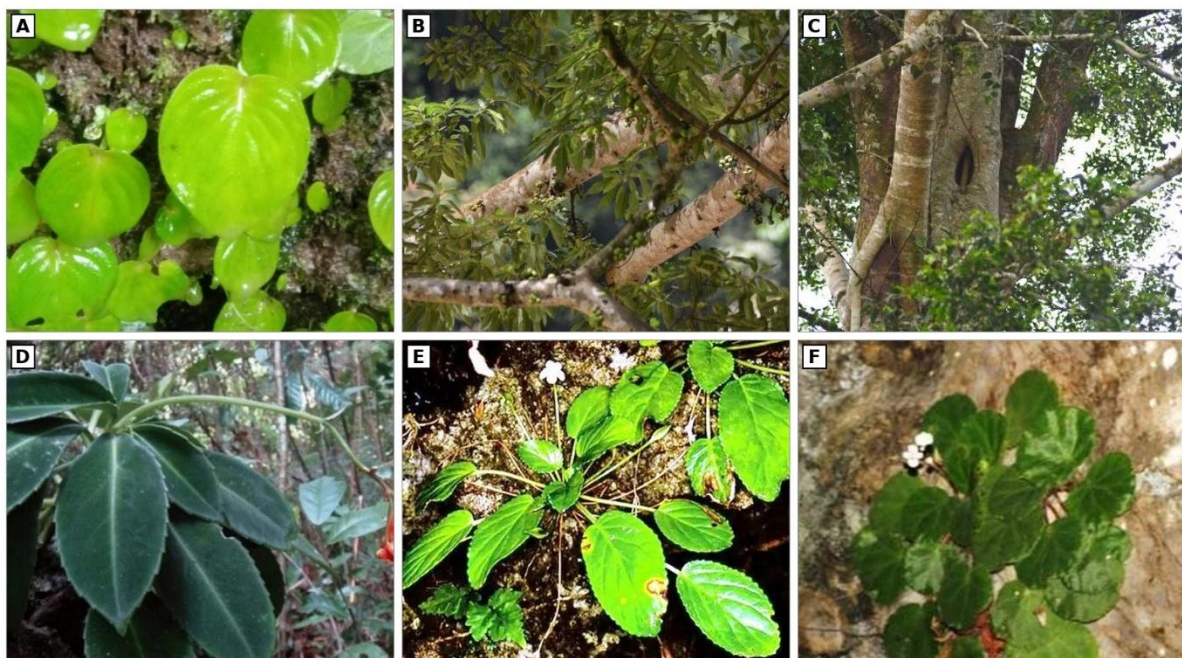


Fig. 8 Lithophytic Gesneriaceae of the Kuantan Formation limestone, Ranah Minang Silokek Geopark, representing two microhabitat guilds along the karst cliff hydrological gradient. a *Paraboea capitata* — open cliff top, rooted directly into porous rock surface; b *Paraboea treubii* — vertical limestone cliff face, desiccation-tolerant; c *Begonia batuphila* — seasonally dry limestone fissures; d *Epithema strigosum* / *Epithema involucratum* — shaded cliff base sustained by karst seep moisture; e *Monophyllaea horsfeldii* — cave margins and permanently humid sheltered zones; f *Impatiens tribuana* — permanently moist sheltered cliff base

5.6 Linkage 4: Sumatran Tiger and Silek Harimau Martial Art

The Sumatran tiger (*Panthera tigris sumatrae*, IUCN CR) persists in RMSG conservation areas, confirmed through camera trap records and community accounts. Island-wide wild populations are estimated at 400 to 600 individuals (Luskin et al. 2017), restricted primarily to large forest blocks of which the Barisan Mountains corridor is critical. Within RMSG, the Sumatran tiger occupies forest on granitic and karst substrates, precisely the terrain classified by the geological cross-section (Figure. 3) as Basement High. These substrates, being too rugged for cultivation, retain primary forest providing tiger habitat, while sedimentary lowlands have been converted to agriculture. Geological substrate thus directly determines the spatial extent of tiger range within the geopark.

Silek Harimau (*Tiger Silat*), a Minangkabau martial art practiced at Nagari Sijunjung, encodes this human-tiger coexistence in movement vocabulary: low postures, stalking, pouncing, and rolling movements that mimic tiger behaviour and reflect centuries of shared occupancy of the same forested landscape. Socio-culturally, *Inyik Balang* (literally "the one who is revered," a Minangkabau honorific for the tiger) occupies a guardian role in local cosmology, associated with forest margins and karst ridges. This spiritual framing reinforces behavioural norms of restraint in the forest, contributing indirectly to conservation. The training tradition of Silek Harimau is conducted outdoors in riverine environments, among boulders and tree roots, directly engaging the geological landscape as both physical training medium and philosophical reference. The term *inyik* also appears in the bintalak proverb (Section 5.7), where forest strips are explicitly designated as tiger pathways, embedding wildlife corridor management in cultural memory transmitted across generations.

5.7 Linkage 5: The “*Bintalak*” Proverb and Topographic Land-Use Encoding

The traditional *petatah-petitih* (proverbs and wisdom sayings) of Minangkabau society encode sophisticated geological and ecological knowledge. The most significant for geo-bio-cultural integration in RMSG is the *bintalak* proverb:

*"Ladang ba bidang di nan lereang, Sawah ba tumpak di nan data,
Sawah ba bateh nan jo pamatang, Ladang ba bateh jo bintalak,
Pamatangampaik nan urang lalu, Bintalak kaampaik inyik
malinteh."*

Translation: "Dry fields on sloping lands; rice fields on flat lands; rice fields bounded by dikes; dry fields bounded by *bintalak*; dikes as human pathways; *bintalak* as pathways for *inyik* (tiger)."

Interpreted through Figure 3, this proverb encodes the precise geological land-use gradient of RMSG (Figure 9). "Sloping lands" correspond to the Basement High margins, where Kuantan Formation metamorphic and granitic rocks produce steep, erosion-prone slopes used for dryland cultivation (*ladang*). "Flat lands" correspond to the Ombilin Formation lowlands and alluvial plains where deep, clay-rich soils support irrigated wet-rice (*sawah*). *Bintalak* (forest strips left uncleared between cultivation plots) correspond to the highest-standing Kuantan Formation ridges and granitic hills, which are agriculturally unsuitable but ecologically critical. These forested strips connect the larger conservation areas (Rimbo

Larangan Paru, CA Batang Pangean I and II) across the agricultural matrix, functioning as wildlife corridors for Sumatran tiger and primates exactly as modern landscape ecology recommends (Gray 2013; Turner et al. 2022).

Field mapping confirms that existing *bintalak* corridors align with Kuantan Formation metamorphic and granitic ridges visible in Figure 3. The proverb system thus constitutes de facto conservation zoning derived empirically from centuries of agricultural experience with the geological substrate, encoding lithological land-suitability knowledge in a culturally resilient verbal format transmitted without the need for formal geological education. The geomorphological boundary visible in the cross-section between the Basement High and the flanking basin lowlands is, in traditional Minangkabau cultural geography, the boundary between *inyiak* (tiger/spirit domain) and human cultivated space.

Fig. 9 The Bintalak traditional land-use zonation of RMSG. a Ground-level view of the three zones: Bintalak (dense forest on steep ridges, tiger corridor), Ladang (dryland cultivation on slopes), and Sawah (wet-rice on alluvial valley floor). b Aerial view of the forest–agriculture boundary, with karst cliff (Kuantan Fm.) on the right margin. c Aerial view of Danau Biru (flooded Ombilin coalfield), showing the contrast between the forested upland Bintalak (top) and intensive lowland human land use below, illustrating how the traditional proverb system encodes a geologically grounded land-use zonation

6. Discussion

6.1 Geological Heritage as Foundation for Integrated Conservation

Our findings demonstrate that geoheritage in RMSG provides more than scenic value or educational substrate. It forms the physical foundation determining ecosystem structure, resource distribution, and cultural adaptation patterns that have developed over centuries. This aligns with the paradigm conceptualising geodiversity as the abiotic foundation of biodiversity (Gray 2013; Brilha et al. 2018; Fox et al. 2020) and extends it by empirically documenting that cultural dimensions are similarly grounded in geological contexts. The strong spatial correlation between lithology and land use, with karst and granite areas conserved as forest while Ombilin and Telisa lowlands are cultivated, reflects rational adaptation to geological constraints operating across multiple centuries, comparable to patterns documented in Indonesian karst geoparks (Haryono et al. 2022) and in European geoparks where traditional farming systems align with geological unit boundaries (Swerkosz et al. 2017).

The 18-geosite assemblage demonstrates exceptional geological completeness, representing a continuous 300-million-year earth history narrative from Permo-Carboniferous continental margin sedimentation through Triassic magmatism, Paleogene rifting, and Miocene basin development. Two sites achieve international significance by documenting geological events of global relevance: the Cathaysian Block suture zone preserved in the Kuantan Formation karst, and post-collisional A-type magmatism recorded in the Sijunjung Granite complex (Metcalf 2013; Irzon et al. 2021). The four additional geosites identified in this study, particularly the hydrothermal alteration evidence at Muaro Takung and the dextral strike-slip deformation record at Siaur, significantly strengthen the structural geology narrative linking RMSG to the broader Sumatran Fault System, filling gaps in the three-cluster tectono-stratigraphic framework proposed by prior geodiversity inventories (Adrianda et al. 2025; Abdurrachman et al. 2026).

6.2 Geo-Bio-Cultural Linkages in Comparative Perspective

The five geo-bio-cultural linkages documented here exhibit a consistent tripartite structure: geological features provide habitat or resource substrate; biological communities respond to and depend on these features; and cultural practices manage the biological resources while simultaneously, if inadvertently, conserving the geological features. This tripartite structure parallels linkages documented in Sangkulirang-Mangkalihat Geopark candidature (Indonesia), where karst geodiversity underpins both biodiversity and Dayak rock art heritage (Haryono et al. 2022), and supports the geosystem services framework of Fox et al. (2020) in which abiotic features deliver benefits to ecosystems and human communities through coupled pathways.

The Bakaua Adat cave ceremony represents a particularly compelling case where traditional protocol functions as de facto ecological management without explicit conservation framing. The head-covering rule minimising bat disturbance illustrates how cultural practices can achieve conservation outcomes through embodied knowledge rather than codified regulation. Similar informal conservation mechanisms encoded in ritual have been documented in other traditional societies (Turner et al. 2022; Adade Williams et al. 2020). What is distinctive in the RMSG case is the full documented causal chain: karst limestone chemistry (geological) creates caves; caves provide bat roost habitat (biological); bats pollinate durian (biological-ecological service); durian harvest triggers Bakaua Adat ceremony (cultural); and ceremony protocols protect bat colonies (conservation outcome). This chain, operating from geology through biology to culture and back to conservation, constitutes what we term a closed geo-bio-cultural feedback loop, a phenomenon that to our knowledge has not previously been described with this degree of mechanistic completeness in the geoheritage literature.

6.3 The Bintalak System as Traditional Geoconservation

The bintalak proverb system merits broader recognition as an example of traditional geoconservation, knowledge-based land management that achieves conservation outcomes through cultural transmission of geomorphological understanding. The proverb encodes what geoscientists would call a lithological land-use capability classification: metamorphic and granitic ridges are recognised as erosion-prone and water-limited, therefore unsuitable for cultivation and suitable only for forest. This empirically derived classification, accumulated over centuries of farming on the RMSG landscape, reaches the same conclusions as modern soil science and geomorphological analysis (Klingebiel & Montgomery 1961). It is preserved and transmitted not through written geological surveys but through oral literature recited at adat gatherings, achieving conservation compliance through cultural authority rather than regulatory enforcement (Berkes 2008).

For geopark interpretation, this proverb system is an asset of exceptional communicative value. It translates complex scientific concepts, including lithological land suitability, soil geochemistry, slope stability, wildlife corridor ecology, and predator-prey dynamics, into culturally resonant vernacular accessible to non-specialist audiences. Incorporating the bintalak system into geotrail interpretation, visitor centre displays, and school educational materials would provide RMSG with a distinctive and authentic

interpretive identity rooted in local knowledge, precisely the kind of differentiation that distinguishes exceptional UGGp nominees from ordinary protected areas.

6.4 Implications for RMSG UNESCO Global Geopark Nomination

The integrated geo-bio-cultural documentation presented here directly addresses key requirements for UGGp designation. UGGp criteria require demonstration of geological heritage of international significance, active education and outreach programmes, and management approaches that deliver tangible socioeconomic benefits to local communities. Our findings establish international significance for two geosites, document community-based management systems (Jambu Lipo customary law; Rimbo Larangan communal forest) delivering both conservation and livelihood outcomes, and provide the geo-bio-cultural narrative essential for compelling visitor interpretation. The cross-section in Figure 3 and the conceptual Venn diagram in Figure 1 together provide the visual communication tools for conveying the integrated geopark concept to diverse audiences.

Adrianda et al. (2025) rated the Sijunjung Granite Complex as high degradation risk from flooding and flagged the Hypostratotype Formasi Telisa Danau Biru as threatened by mining; these risks extend to the biological and cultural values each geosite sustains, reinforcing the need for integrated hazard management as a nomination priority. Areas requiring further development for the nomination include: quantitative economic valuation of ecosystem services delivered by geoheritage features (honey production revenue, karst water supply value, forest carbon stocks); long-term biodiversity monitoring to establish baseline trends; and detailed hazard mapping integrating the 2024 flood events into a comprehensive disaster risk framework that links geological knowledge to community resilience.

7. Conclusions

Ranah Minang Silokek Geopark demonstrates that geodiversity is not merely a backdrop to biodiversity and cultural heritage but their generative foundation. This study addressed three primary research questions, yielding the following conclusions:

1. The 18-geosite inventory documents a complete 300-million-year geological narrative of central Sumatra, from Cathaysian continental margin sediments through Triassic to Jurassic magmatism to Paleogene-Miocene basin evolution, with two geosites of international significance. RMSG possesses a coherent geoheritage sequence recording the full tectonic history of the Sumatran continental margin, providing a robust foundation for scientific research and public geoeducation.
2. Biodiversity surveys recorded 618 plant species, 112 bird species, 128 mammal species, and 34 herpetofauna species including Critically Endangered Sumatran tiger, Helmeted Hornbill, and Sunda Pangolin. Species distributions follow geological substrate boundaries, confirming that geodiversity directly controls habitat structure and biodiversity pattern across the geopark.
3. Five geo-bio-cultural linkages demonstrate that geological features actively generate biological and cultural heritage. Sandstone cliffs sustain *Apis dorsata* colonies under customary governance; karst

caves house bat pollinators and host nationally designated intangible cultural ceremony; limestone boundaries are traced by lithophytic Gesneriaceae; tiger ecology is encoded in *Silek Harimau* martial art; and the *bintalak* proverb system translates geological land-use capability into a traditional geoconservation mechanism aligned with outcrop boundaries.

4. The *bintalak* system constitutes empirically derived geomorphological knowledge transmitted through cultural authority, creating wildlife corridors that correspond precisely with resistant geological substrates. It represents both a proven long-term conservation mechanism and an interpretive asset of exceptional value for the UGGp nomination.
5. The integrated geo-bio-cultural framework provides RMSG with a scientifically grounded basis for UNESCO Global Geopark designation and a replicable model for geoconservation in tropical regions with rich indigenous knowledge traditions, contributing an empirical Southeast Asian case study to the growing literature on integrated geopark science.

Declarations

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Competing interests

The authors declare no competing interests.

Author contributions

Rinaldi Ikhrum: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Visualization. **Katon Sena Ajie Nugraha:** Conceptualization, Data curation, Investigation. **Mega Fatimah Rosana:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Deden Nurjaman:** Methodology, Investigation. **Naufal Abdul Aziz:** Methodology, Investigation. **M. Irshal Erlangga:** Investigation. **Ridwan:** Investigation, Project administration. **Novizar Swantry:** Investigation, Resources. **Khamsiar:** Resources. **Afdar Yulius:** Funding acquisition, Resources. **Deswira Harneti:** Resources. **Raisha Marsheline:** Resources. **A.F. Afdi Muliawan:** Resources.

Data availability

The datasets (geological field descriptions, biodiversity inventory records, and cultural heritage documentation) generated and analysed during the current study are available from the corresponding author on reasonable request.

Generative AI use

During the preparation of this work the authors utilized Quillbot to support structural editing and improve language clarity. Following the use of these tools, the authors carefully reviewed and revised the material as necessary and assume full responsibility for the final published content.

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