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Shake and Bake: Structural or Subduction Control on Sumatran Volcanism? A Statistical Approach

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Abstract

The extent to which Sumatran volcanism is controlled by subduction processes or by the dextral Sumatran Fault (SF) remains debated. We address this question using a statistical approach that integrates morphometric, structural, and geodynamic parameters from 19 active or potentially active volcanoes in Sumatra, Indonesia. Principal Component Analysis (PCA) and a variance-weighted influence matrix were used to derive a Fault Affinity Index (FAI) that quantifies the similarity of each edifice to a benchmark structural signature defined by independently recognised SF-controlled volcanoes (Lubukraya, Sibualbuali and Talang). Our results confirm the Sumatran Fault affinity of volcanoes previously proposed in the literature (Talang, Lubukraya, Sibualbuali, Kaba, Daun Bukit) and identify four potential additional centres (Dempo, Sorikmarapi, Seulawah Agam, and Malintang), as newly emerging candidates for structural control by the SF. Conversely, volcanoes with negative FAI values (e.g. Rajabasa, Peuet Sague, Telong Bur ni) exhibit morphometric patterns inconsistent with SF influence. Complementary mantle melting calculations and along-arc trace-element systematics reveal only minor variations in melt flux and melt fraction from North to South Sumatra, consistent with relatively uniform slab depths and subdued primary magmatic forcing. This indicates that magmatic variability alone cannot explain the observed volcanic morphologies, reinforcing the structural influence of the Sumatran Fault on at least some centres. Supported by these geochemical constraints, our statistical approach provides a reproducible basis for distinguishing structurally controlled volcanoes from those shaped primarily by magmatic processes, applicable to other analogue regions.

Introduction

Holocene volcanism on Earth predominantly occurs along plate boundaries, with approximately 70% associated with convergent margins (e.g. subduction zones), characterized by compressional regimes, 18% linked to divergent margins (e.g. rift zones) where extensional mechanisms prevail, and approximately 12% is attributed to intraplate settings (Global Volcanism Program and Venzke 2025). Because subduction zones host the majority of Holocene volcanoes, and that populations living near volcanoes are projected to reach ~473 million by 2030 (Meredith et al. 2026), understanding the underlying processes at these settings is particularly important. Many subduction zones exhibit diverse tectonic regimes, where extensional, compressional and strike-slip processes coexist and interactively shape local volcanism and crustal deformation (Acocella and Funiciello 2010). A classic example is in Sumatra, Indonesia, with the slightly oblique subduction (~29° dip angle; Acocella et al. 2018) of the Indo-Australian Plate beneath the Sunda Plate that has been proposed as the primary driver of the dextral strike-slip Sumatran Fault (SF) (McCaffrey et al. 2000) (Fig. 1). Most volcanoes in Sumatra are located within 25 km of the SF, yet the precise role of the fault in controlling volcanic emplacement remains debated. Sieh and Natawidjaja (2000) conducted a detailed mapping study of the SF and argued that the proximity of volcanoes with the SF is a simple coincidence. Acocella et al. (2018) reached a similar conclusion inferring that most volcanoes in Sumatra do not have a direct relationship with the SF, however, the same authors report a list of volcanoes that are “likely”, “probably” and “possibly” related to the SF (Table 1), indicating that the relationship may vary along the arc. Lai et al. (2021) carried out a study on the Sunda arc volcanism, including west Sumatra, and attributes the primary origin of volcanism to regional subduction processes, with spatial volcano distribution and migration influenced by local structural systems.

In this study, we develop a physically informed multivariate framework to analyse several Holocene and selected Pleistocene volcanoes in Sumatra that are active or potentially active, assessing the extent to which their morphometric, structural, and seismological characteristics resemble those of volcanic centres independently proposed to be influenced by the Sumatran Fault. Rather than assigning a unique causal origin to each edifice, the analysis aims to identify integrated signatures that are more or less consistent with a structural imprint of the SF. Our approach combines Principal Component Analysis (PCA) with a weighted influence matrix, integrating key geodynamic and volcano-morphometric parameters to derive a Fault Affinity Index (FAI) for each volcano. Additionally, we incorporate mantle melting calculations together with along-arc geochemical insights derived from existing compiled datasets to assess whether variations in melt production or source

characteristics may contribute to differences in volcanism along the arc. Owing to the limited availability of geochemical data in Sumatra, this component could not be incorporated into the statistical analysis.

Determining whether Sumatran volcanism is primarily controlled by fault-related processes, subduction dynamics, or other factors, is essential for reconstructing long-term tectono-magmatic evolution and for improving short-term eruption forecasting, particularly in contexts where seismic activity may trigger volcanic unrest (Seropian et al. 2021), or vice versa (Lippiello et al. 2026). By clarifying the structural controls on magma emplacement and storage, this study provides the basis for understanding the tectonic–volcanic interplay in Sumatra, also offering key elements for assessing the potential for earthquake-induced eruptions in this and other hybrid tectonic settings that could complement global statistical analyses (Jenkins et al. 2024).

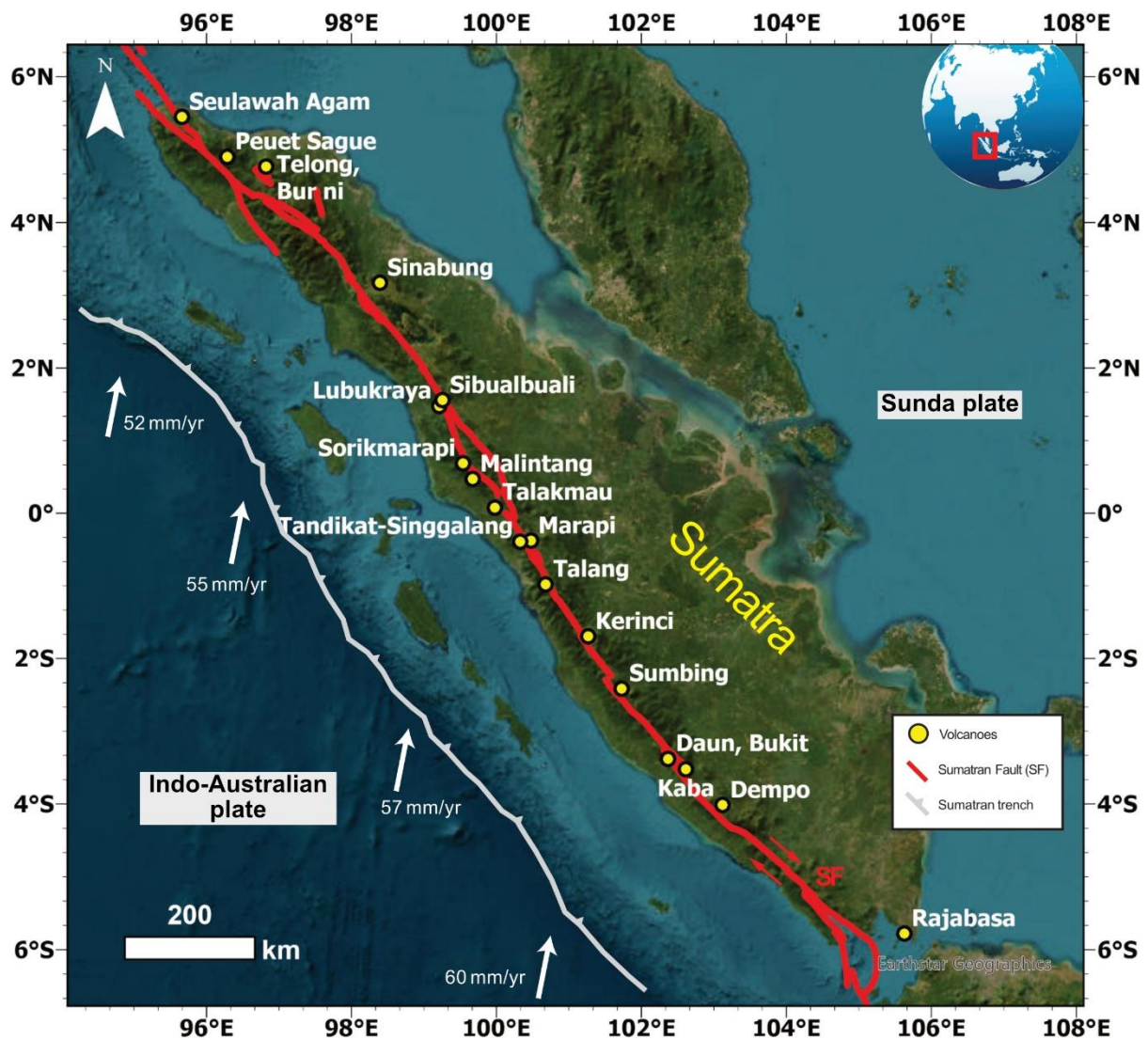


Fig. 1 Map of the study area. The convergence rate values are from Acocella et al. (2018)

Methods

Volcano selection criteria

We chose volcanoes in Sumatra based on several criteria. We selected volcanoes from the Smithsonian Global Volcanism Program that last erupted in the Holocene, and we also included volcanoes classified as Pleistocene or Holocene whose last recent eruption age is uncertain (Global Volcanism Program and Venzke 2025). This choice reflects the fact that many Sumatran volcanoes have poorly constrained eruptive histories and may be younger than currently inferred, making them highly relevant for hazard assessments (Forni et al. 2025). From this initial dataset, we excluded calderas because most morphometric parameters are not representative of the processes governing volcanism in such systems. For example, erupted volumes are often incomplete and difficult to estimate, mean edifice slopes are strongly influenced by caldera infill and geometry, and evidence of former vents may be erased by caldera-forming events. We also excluded volcanoes that are highly dissected and lack a clearly preserved edifice morphology (e.g. Patah, Hululais), as this also would compromise the morphometric analysis and potentially bias our statistical analysis. After applying these criteria, 19 volcanoes were selected for analysis (Table 1).

Table 1 List of selected volcanoes

Volcano	Epoch	Latitude	Longitude	Distance from SF ¹	Link to SF ¹
Dempo	Holocene	-4.016	103.121	14.00	
Kaba	Holocene	-3.522	102.615	1.00	Possible
Kerinci	Holocene	-1.697	101.264	9.00	
Malintang	Holocene	0.47	99.67	12.00	
Marapi	Holocene	-0.38	100.474	7.00	Possible
Peuet Sague	Holocene	4.903	96.289	22.00	
Sinabung	Holocene	3.17	98.392	31.00	
Sorikmarapi	Holocene	0.686	99.539	3.00	
Sumbing	Holocene	-2.414	101.728	9.00	
Talang	Holocene	-0.979	100.681	1.00	Very likely
Tandikat	Holocene	-0.39	100.331	6.00	
Telong Bur ni	Holocene	4.769	96.821	45.00	
Daun Bukit	Pleistocene	-3.38	102.37	1.00	Probable
Lubukraya	Pleistocene	1.478	99.209	3.00	Very likely
Rajabasa	Pleistocene	-5.78	105.625	94.00	
Seulawah Agam	Pleistocene	5.448	95.658	4.00	
Sibualbuali	Pleistocene	1.556	99.255	3.00	Very likely
Singgalang	Pleistocene	-0.39	100.331	6.00	
Talakmau	Pleistocene	0.079	99.98	19.00	

¹Acocella et al. (2018)

Data sources and parameters

To conduct a PCA grounded in physical criteria rather than purely data-driven selection, we compiled morphometric and geodynamic parameters of Sumatran volcanoes from multiple sources. The morphometric parameters were derived from the MATLAB version of MORVOLC (O'Hara et al. 2024), originally developed by (Grosse et al. 2009), and applied to terrestrial (Grosse and Kervyn 2018) and extra-terrestrial volcanoes (Leone et al. 2026). As GIS-based inputs we used the Indonesian high-resolution (10 m) Digital Elevation Model DEMNAS (Geospatial Information Agency 2018), and the volcano basal outline, derived in Esri® ArcMap™, following the framework proposed by Van Wees et al. (2024). The list of parameters (Table 2) includes *total edifice volume*, *edifice mean slope*, *summit orientation*, *summit width*, *edifice height*, and *basal width*. Additional tectonic and geodynamic parameters were retrieved and incorporated from Acocella et al. (2018), such as the *trench distance*, *slab depth*, *distance to the Sumatran fault*, *number of vents*, and *vent alignment*. We also included the β -value estimated using the *b-more-positive* method (Lippiello and Petrillo 2024; Godano et al. 2025; Lippiello et al. 2026), with β representing the exponential slope of the Gutenberg–Richter frequency–magnitude distribution, defined as

$$\beta = b \ln(10) \quad (1)$$

where b is the classical Gutenberg–Richter b -value. The β was computed independently from the regional seismic catalogue of the Indonesian Agency for Meteorology, Climatology and Geophysics (see Data availability for access to the catalogue) seismic catalogue, as a proxy for the stress state of the crust in each volcano. The β -value variations have been widely interpreted as indicators of changes in differential stress and fault strength (Wyss 1973; Amitrano 2003; Gulia and Wiemer 2010; Scholz 2015). In particular, we used $\Delta\beta$ (Convertito et al. 2025), defined as the difference between the β -value estimated beneath each volcano, computed from events within a 60-km diameter window, and that of the average of the whole volcanic region. While a 60-km window is relatively wide and may cause overlap between the areas enclosing nearby volcanoes (e.g. Tandikat and Singgalang), this choice represents a trade-off between spatial resolution and statistical robustness: for smaller radii, the number of events becomes insufficient to ensure a reliable and statistically meaningful estimate of β . Together, these variables (Table 2) offer a comprehensive description of volcano morphometry and tectonic setting, providing insight into the mechanisms that may control volcanism in Sumatra (see the section “Parameters selection criteria” for the rationale behind this choice).

141 **Table 2** Tectonic and morphometric parameters used for the statistical analysis conducted in this
142 study

Parameter	Description	Notes	Source
Trench distance (D_{tre})	Distance from volcano summit to Sumatran subduction trench		Acocella et al. (2018)
Slab Depth (Z_{slb})	Depth of slab beneath the volcano		Acocella et al. (2018)
Fault Distance (D_{fit})	Distance from volcano summit to Sumatran Fault	Modified from Acocella et al. (2018), converting all distances in positive values	Acocella et al. (2018)
Vent alignment (Al_{ven})	Orientation of main vent alignment on the volcano	Modified from Acocella et al. (2018), converting values into 0-180° format from -90° to +90°	Acocella et al. (2018)
Edifice Volume tot (V_{tot})	Total measured volume of the edifice, also accounting for minimum eroded volume*		*This study
Edifice mean slope (Θ_{ed})	Mean slope of the entire edifice		*This study
Summit orientation (O_s)	Orientation in degrees (0-180) of the summit area of the volcanic edifice	We only utilised the orientation of the summit area because considered more reliable than the basal orientation (defined by the MORVOLC algorithm and not by manual delineation)	*This study
Summit Width/Basal Width (W_s/W_b)	Ratio between the width at the summit and at the base of the edifice		*This study
Height/Basal Width (H/W_b)	Ratio between the edifice height and the width at the base of the edifice		*This study
Number of vents ($\#_{vents}$)	Number of mapped vents of the edifice	Counted from analysis of high-resolution (10 m) DEMs	**This study
Delta Beta ($\Delta\beta$)	Measure of the state of stress of the crust	Here we report the difference between the volcano beta (within 60 km from the volcano considered) and the background beta (regional average for all volcanoes considered)	***This study

*MORVOLC (O'Hara et al., 2024)

**GIS-based analysis

***See methods

Principal component analysis and influence matrix

We applied principal component analysis (PCA) to a suite of parameters (Table 2) for the Sumatran volcanoes considered. Because the parameters are expressed in different units and scales (e.g. kilometres, degrees, dimensionless ratios), we conducted a standardisation, with each parameter normalized to zero mean and unit variance prior to analysis. Standardisation ensures that no single parameter dominates the multivariate analysis due to its numerical range, allowing each variable to contribute equally to the variance structure. It is important to note that the PCA is employed to decompose the covariance structure of the dataset and to generate variance-weighted multivariate profiles for each volcano. These profiles are then combined in an influence matrix reconstructed as the sum of all PC scores multiplied by their respective variance weights. This transformation adds information beyond directly weighting the standardised parameters, because it integrates the dominant modes of co-variability among variables rather than treating each parameter independently. In this sense, the approach merges multivariate statistical decomposition with geological knowledge to identify patterns potentially consistent with tectonic influence. The principal components therefore do not represent physical processes per se, but instead capture the dominant modes of covariance among the selected parameters. Physical interpretation is therefore not assigned to individual components, but rather emerges from the combined behaviour of parameters across the multivariate space. The PCA produced orthogonal components ranked by the proportion of variance, and the cumulative variance distribution was used to assess how much of the dataset's structure was captured.

Then we reconstructed a combined influence matrix that incorporated all principal components, each weighted by its variance. This ensured that the dominant modes of variability contributed most strongly, while higher-order components added proportionally less but still retained potentially meaningful structure. The resulting volcano-parameter influence matrix was subsequently adjusted using geologically informed weights, whereby distance to fault, $\Delta\beta$, number of vents, ratio summit width over basal width, and ratio height over basal width were emphasized (weight = 1.5) relative to the other parameters (weight = 1.0). We applied this weighting scheme based on geological knowledge, prioritising parameters that are thought more diagnostic of fault control (Dhont et al. 1998; Toprak 1998; Magee et al. 2016; Nieto-Torres and Martin Del Pozzo 2019; Lippiello et al. 2025). Before proceeding with the analysis, we also explored alternative weighting configurations, including uniform weights and stronger emphasis on the same subset of parameters, and found that the qualitative structure of the results remained stable, supporting the robustness of our chosen scheme (Appendix A). From this weighted matrix, we derived a Fault Affinity Index (FAI) by comparing each volcano's influence profile to a benchmark signature defined by

volcanoes previously interpreted as having a relatively strong structural association with the SF (Lubukraya, Sibualbuali and Talang; Acocella et al., 2018). Affinity values were used to rank volcanoes and reorder the matrix, while hierarchical clustering (average linkage, Euclidean distance) of parameters improved interpretability of the heatmap visualization. This approach integrates statistical dimensionality reduction with domain knowledge to highlight morphometric patterns diagnostic of tectonic control.

Details on the calculation of the FAI, test results on the utilisation of different parameters weighting schemes and an assessment of its robustness are provided in the Appendix A.

Parameters selection criteria

Parameters for the statistical analysis were chosen on the basis of geological knowledge and used to derive the FAI, providing a statistically supported and physically motivated assessment of the potential influence of the SF on volcanism in Sumatra, but also capturing controls and local-scale structural influences. From a geological perspective, volcanoes developing in oblique-subduction settings with a strong lateral component (e.g. the Sumatran Fault system) may exhibit systematic morphometric differences compared to volcanoes formed in classic, trench-perpendicular subduction environments (e.g. Java). These differences may be subtle and not readily captured in conventional two-dimensional plots, as seen in Acocella et al. (2018). Therefore, we adopted a statistical approach based on multi-parameter and multi-volcano assessment. A brief rationale for the parameters is provided below. These descriptions are general rather than specific to the Sumatra case, and they serve only to justify the choice of parameters, independently of the results. The results themselves are reported and discussed in later sections.

Trench distance, slab depth and total edifice volume: Trench distance and slab depth generally show a positive correlation, but how do they relate to the magma production, hence the resulting total edifice volume? Gazel et al. (2021) found that for central America volcanoes, the more voluminous edifices are located at a slab depth of around 100 km, with volcanoes sitting atop deeper slab segments being less voluminous. Similarly, Wu et al. (2024) used a thermo-mechanical model to argue that shallower slabs (<300 km) produce larger volumes of melt compared to deeper slabs (>300 km). Also the slab dehydration is an important process, and this is generally more efficient in locations relatively closer to the trench. In these regards, Ribeiro (2022) argues that subducting plates dehydrate more efficiently within 80 km from the trench. Higher slab dehydration may promote greater melt production and magma supply; we therefore test whether variations in these parameters are associated with differences in cumulative edifice volume along the Sumatran arc. However, there are plenty of other process involved in the formation of large volcanoes that should not

be ignored, for example the convergence rate, slab geometry, slab temperature, slab angle, mantle heterogeneity, among others, not accounted for in our statistical analysis (Karlstrom et al. 2014; Lai et al. 2021). Furthermore, there are additional complexities for Sumatra given the oblique subduction.

- Fault distance, $\Delta\beta$, vent alignment, summit orientation, number of vents, summit width/basal width: Volcanic morphology and vent distribution are strongly modulated by the interplay between crustal structures and stress regimes (Nakamura 1977). Proximity to major crustal faults often facilitates magma ascent by reducing lithostatic resistance through fracturing, which in turn may promote higher vent densities, and distributed and aligned eruptive centres (Van Wyk De Vries and Van Wyk De Vries 2018). In contrast, volcanoes situated far (>15 km) from fault zones are generally less likely to have their shallow magma pathways directly influenced by its principal damage zone (Acocella et al. 2018). This distance is also consistent with the width of the fault damage zone and the spatial extent of associated seismicity around major strike-slip fault cores, which, for example in the case of the San Andreas Fault in California, USA, reach ~10 km (Powers and Jordan 2010). One parameter that captures the state of stress of the crust is $\Delta\beta$, defined as the deviation between the β -value estimated beneath each volcano and the regional background β -value. The β -value is known to decrease with increasing differential stress and to increase in fluid-rich or highly damaged crustal volumes (Amitrano 2003; Scholz 2015). Therefore, large $\Delta\beta$ values may indicate anomalous stress, damage, or fluid conditions; we test whether such anomalies are preferentially associated with volcanoes located close to, or structurally influenced by, the SF (Godano et al. 2024). Conversely, values of $\Delta\beta$ close to the regional average indicate that the local earthquake-size distribution does not differ strongly from the regional background. This does not exclude structural control, but provides less evidence for an anomalous local seismological signature (Convertito et al. 2025). From a physical perspective, variations in β can be interpreted as reflecting changes in stress heterogeneity and damage within the crust. Highly fractured or faulted regions tend to exhibit increased stress variability and enhanced fluid circulation, both of which promote the activation of numerous small seismic sources, leading to higher β -values. In contrast, more homogeneous and mechanically coherent regions are associated with lower β -values, reflecting more localized stress release. In this sense, $\Delta\beta$ provides an indirect proxy for the degree of crustal damage, fluid pressure influence, and stress complexity, all of which are expected to be enhanced in fault-controlled environments; hence, our hypothesis here is that regions closer to the Sumatran Fault zone will have higher $\Delta\beta$. Vent alignments and high vent density may provide a direct manifestation of these stress conditions (Guffanti and Weaver 1988). Summit morphology may also encode tectonic influence, with preferentially

elongated summits aligning with regional stress orientations or fault systems, underscoring structural control. Such patterns can arise from the preferential propagation of dykes along orientations dictated by the regional stress field or by pre-existing crustal weaknesses; if vent localisation occurs along these intrusions, vents will tend to develop a consistent directional alignment (Mantiloni et al. 2024). The summit-width/basal-width ratio provides an additional indicator of structural control, as broader, elongated, and directionally oriented summit areas may reflect magma migration along inherited fracture zones. However, this ratio can also be influenced by edifice stability, depending on deposit type, repose angle, and the preferential directions in which the cone is more susceptible to collapse. Such collapse directions may themselves be weakly guided by pre-existing structural weaknesses generated by faulting, which has implications for volcanic hazard assessment and the potential localisation of future flank failures.

- Edifice mean slope and height/basal width ratio: these two parameters are positively related, with large slope angles corresponding to large height/basal width ratios. The geological meaning behind these parameters lies in the type of volcanic deposits making up the edifice. Steeper slopes and larger height/basal width ratios are typically associated with viscous, explosively generated and mechanically strong edifices, while gentler slopes and smaller height/basal width ratios may reflect effusive, low-viscosity lavas or repeated flank collapses. Erosion also affects these parameters, and it may depend on different short-term and long-term factors, such as local precipitation rates and volcano age. Importantly, small height-to-basal-width ratios may also characterise edifices that lack a single, punctual central source, instead reflecting an edifice evolution in which magma migration leads to broad basal footprints relative to edifice height (Magee et al. 2013; Castruccio et al. 2017; Verolino et al. 2019, 2022; O'Hara et al. 2024; Leone et al. 2026).

It is important to note that the selected parameters represent geologically motivated hypotheses about characteristics that may be sensitive to structural influence. The FAI therefore evaluates the relative expression of this integrated structural signature across the volcanoes, rather than providing independent evidence of fault control. Rather, their inclusion represents a priori, geologically motivated hypotheses regarding characteristics that may be sensitive to structural influence. Their value lies in the fact that each captures a different physical aspect of edifice growth, stress orientation, magma transport, or structural inheritance. When considered together in a multivariate statistical framework, these parameters provide a more robust basis for identifying patterns that are consistent with structural influence. In this sense, our approach does not rely on any single morphological indicator, but on the integrated signature that emerges from the combined behaviour of all variables.

Mantle flux calculations: testing the role of convergence rate

So far, we have focused on volcanic-tectonic interactions in Sumatra, however, to gain a more holistic perspective on Sumatran volcanism it is also important to consider the role of melt production in the mantle and subsequent processing in the lower crust (Till et al. 2019). To independently complement the top-down tectonic perspective of our principal component analysis and influence matrix, we have also adopted a bottom-up approach by calculating mantle-derived magma fluxes using the recent mathematical melting model of Goltz et al. (2026). Along the Sumatran arc, oblique convergence rates vary from approximately 60 mm/yr in the South to 52 mm/yr in the North with slab depth beneath the recorded Holocene/Pleistocene volcanoes ranging from 110 to 180 km with an average of 130 ± 20 km (Acocella et al. 2018). We therefore used the model of Goltz et al. (2026) to test how varying convergence rate could impact mantle magma flux. As the model uses orthogonal convergence rates, we calculated orthogonal-equivalent convergence rates along the arc, which ranged from 44 to 52 mm/yr and were calculated assuming a 32° angle between the true convergence vector and the vector orientated perpendicular to the trench. The model adopts a Monte Carlo approach in which to test the sensitivity of the parameters of interest and to assess uncertainties (Goltz et al. 2026). For each convergence rate (44, 46, 48, 50 and 52 mm/yr), we ran 10,000 realisations. Fractions of wet and dry melts were both fixed at $7 \pm 0.5\%$. Mantle density was varied between 3200 and 3300 kg/m³, whilst melt density was varied between 2190 and 3030 kg/m³. Mantle grain size and viscosity were set to 10^{-1} and 10^{-3} m and $1 - 10$ P s, respectively. Slab dip ($23.3 - 32^\circ$) and lithosphere-asthenosphere boundary (LAB, 80 – 150 km) depths were allowed to vary between values recorded for all oceanic arcs. The radius of the melting region perpendicular to the arc and the arc length were maintained at 28 km and 500 km, respectively. The melt channel radius was varied from 1.5 – 5 km. For each convergence rate along the Sumatran arc, the model calculates a distribution of magma fluxes, which we then compare with along-arc geochemical data and our calculated physical and morphometric parameters. It is important to note that the Monte Carlo analysis quantifies uncertainty within the mantle-melting model only and does not assess the statistical robustness of the PCA/FAI framework, which is evaluated independently.

Results

Morphometric and structural characteristics

Before conducting the PCA using the parameters listed in Table 2, we first assessed whether individual parameters exhibited systematic spatial–temporal variations across the volcanoes investigated. To do so, we divided the volcanoes into two temporal groups, Holocene and

presumably Early Pleistocene (for the reasons explained in the introduction) and compared their distributions. Figure 2 summarises these results.

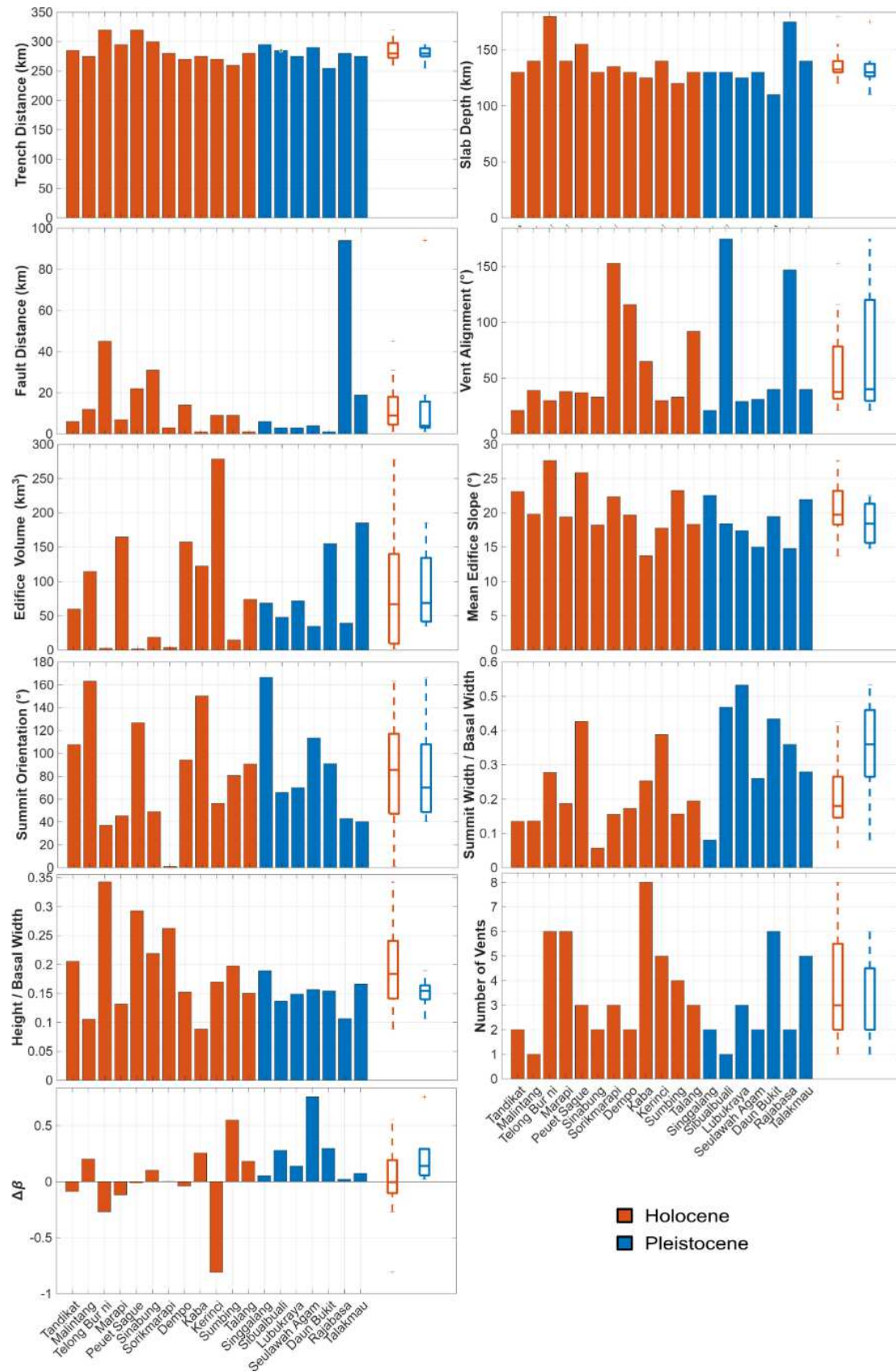


Fig. 2 Bar plots of individual parameters used for the PCA

Trench distances remain relatively consistent across all centres, ranging from 250 to 310 km, with Holocene volcanoes positioned slightly closer to the trench (mean: 275 ± 23 km) than their Pleistocene counterparts (mean: 285 ± 18 km). Slab depths are broadly comparable between the two groups, with most Holocene centres underlain by slabs at ~ 120 – 145 km and most Pleistocene centres at ~ 115 – 135 km, although Holocene Telong Bur ni and Pleistocene Rajabasa occur above substantially deeper slab segments (~ 180 and ~ 175 km, respectively), though box plot distributions indicate substantial overlap between the two populations. Fault distance values reveal that most centres are located within 25 km of the SF, with the notable exception of one Pleistocene centre, Rajabasa, positioned approximately 95 km from the SF, and two Holocene volcanoes as well (Telong Bur ni at 45 km and Sinabung at 31 km from the SF). Edifice volumes also have comparable median values for Holocene (67 km^3) and Pleistocene (69 km^3) volcanoes, but both are highly variable across all volcanoes. Mean edifice slopes are broadly similar between groups (Holocene: $19.5 \pm 3.2^\circ$; Pleistocene: $18.8 \pm 2.8^\circ$), indicating comparable overall cone geometries despite volumetric differences; however, Pleistocene volcanoes have slightly gentler mean slopes. Summit-width-to-basal-width ratios show higher median values in Pleistocene (0.36) than in Holocene (0.18) centres, indicating that Pleistocene edifices possess proportionally wider summit regions. Height-to-basal-width-ratios tend to be slightly larger in Holocene centres (0.18) than Pleistocene edifices (0.15), but with much less variability across Pleistocene volcanoes. The number of vents varies considerably, with Holocene centres displaying 1–8 vents (median: 3) compared to 1–6 vents for Pleistocene centres (median: 2). The $\Delta\beta$ values show contrasting distributions between the two age groups. Holocene volcanoes display large variability, with both positive and negative values, two clear outliers (Kerinci, $\Delta\beta = -0.81$; and Sumbing, $\Delta\beta = 0.56$), and an overall median close to 0.0. In contrast, Pleistocene centres have a higher median (0.14) and predominantly positive values, including a positive outlier at Seulawah Agam ($\Delta\beta = 0.76$). Vent alignment orientations (bearings 000° to 180°) also show considerable variability ($\sim 020^\circ$ – 180°) across both temporal groups. However, both Holocene and Pleistocene centres show comparable median values ($\sim 040^\circ$). Also, summit orientation appears highly variable across individual volcanoes, for both age groups, but with relatively similar medians of 086° and 070° for Holocene and Pleistocene volcanoes, respectively. The directional distributions of vent alignment and summit orientation are shown more clearly in the rose diagrams in figure 3.

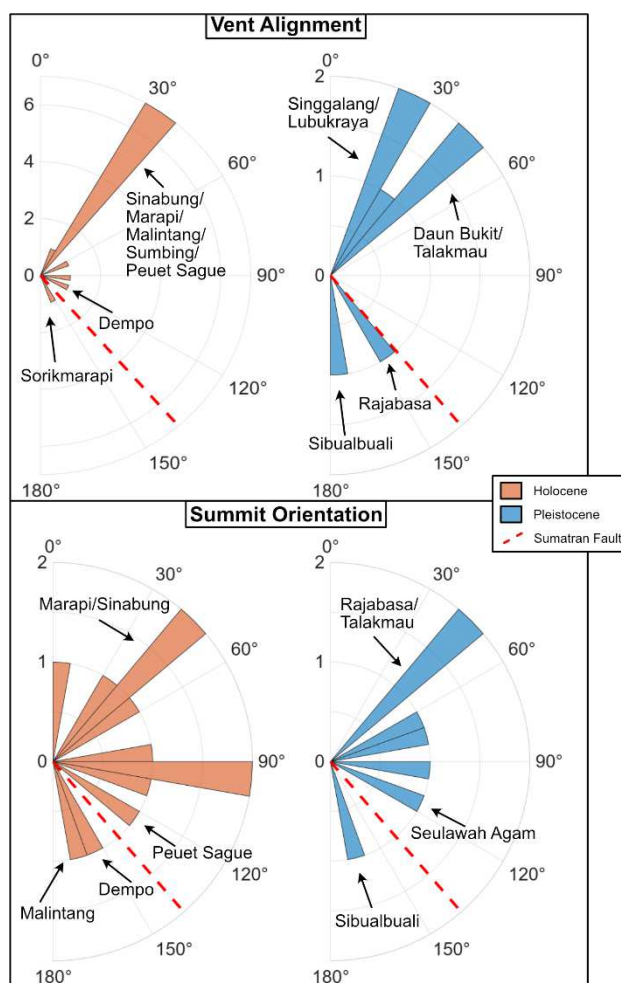


Fig. 3 Rose diagrams showing the bearings of vent alignments (top panels) and summit orientations (bottom panels) for each volcano, separated into Holocene (orange) and Pleistocene (blue) groups. The bearing of the Sumatran Fault is also shown for reference (red dotted line). Some volcanoes are labelled where their orientations lie approximately parallel or perpendicular to the Sumatran Fault

Statistical analysis

Principal component analysis (PCA)

The PCA of 11 morphometric parameters across the studied Sumatran volcanoes reveals that the first three principal components collectively explain 67.7% of total variance (PC1: 31.5%; PC2: 19.1%; PC3: 17.1%; Fig. 4). All remaining components individually account for less than 10% of variance.

Along PC1 (Fig. 4a), trench distance (D_{tre}), slab depth (Z_{slb}), fault distance (D_{fit}), mean edifice slope (Θ_{ed}), height-to-basal width ratio (H/W_b), and number of vents ($\#_{vents}$), load positively on this axis, while vent alignment (Al_{ven}), total edifice volume (V_{tot}), summit-to-basal width ratio (W_s/W_b), summit orientation (O_{sum}), and delta beta ($\Delta\beta$) load negatively. Telong Bur ni and Peuet Sague are pronounced positive outliers along PC1, plotting in strong isolation from all other edifices. Their position reflects a combination of greater trench distance, deeper slab, and relatively steep edifices. In contrast, the majority of edifices,

including Kaba, Dempo, Talang, Malintang, Lubukraya, Sorikmarapi, Sibualbuali, and Seulawah Agam, form a coherent negative PC1 group. For PC2, positive loadings are dominated by the delta beta ($\Delta\beta$), summit orientation (O_{sum}), mean edifice slope (Θ_{ed}), H/W_b , and D_{tre} , while volumetric and structural parameters (V_{tot} , $\#_{\text{vents}}$, Al_{ven} , D_{flt} , Z_{slb} , W_s/W_b) load negatively. Among the volcanoes occupying the positive quadrants of the PC2, Peuet Sague is still an outlier, while other volcanoes form a relatively coherent group either associated with the $\Delta\beta$ and O_{sum} (Talang, Malintang, Seulawah Agam, Sumbing) or characterised by Θ_{ed} , H/W_b , and D_{tre} (Sinabung, Peuet Sague), with the twin volcanoes Singgalang and Tandikat being between these two groups. For the PC2 negative quadrants, Kerinci and Rajabasa stand out as outliers, because of a strong association with the D_{flt} (Rajabasa) and stronger contribution from V_{tot} , Al_{ven} and W_s/W_b (Kerinci). Sorikmarapi appears to plot in the direction of the V_{tot} and Al_{ven} , while Talakmau and Marapi are more characterised by W_s/W_b and $\#_{\text{vents}}$. Other volcanoes in the negative PC1 and PC2 quadrant seem to not show strong association with any particular parameter, and these include Sibualbuali, Dempo, Lubukraya, Kaba, and Daun Bukit. The absence of a clear separation between Holocene and Pleistocene edifices along PC1 and PC2 suggests that the broadly defined age groups do not explain the dominant variation in first-order edifice morphology or tectonic position within this dataset.

In the PC3–PC1 biplot (Fig. 4b), the same parameters that load positively on PC1 in the PC1–PC2 plot also point toward the right side, with Telong Bur Ni and Peuet Sague remaining outliers in that direction, mainly associated with trench distance (D_{tre}), slab depth (Z_{slb}), and distance from the Sumatran Fault (D_{flt}). In the opposite direction, parameters such as $\Delta\beta$, vent alignments (Al_{ven}), summit orientation (O_{sum}), and, to a lesser extent, summit width-to-basal width ratio (W_s/W_b) tend to characterise a group of volcanoes that includes Dempo, Talang, Sorikmarapi, Malintang, Seulawah Agam, and Sibualbuali. Lubukraya and Sumbing appear more influenced by the total edifice volume (V_{tot}), whereas Marapi and Talakmau plot in the direction of the number of vents ($\#_{\text{vents}}$) vector. Daun Bukit and Kerinci represent extreme cases of the contribution from V_{tot} and $\#_{\text{vents}}$, respectively. Kaba also stands out, but on the left-hand side of the plot, where no particular parameter vector points. Also, in this case, no particular volcano age pattern can be clearly identified.

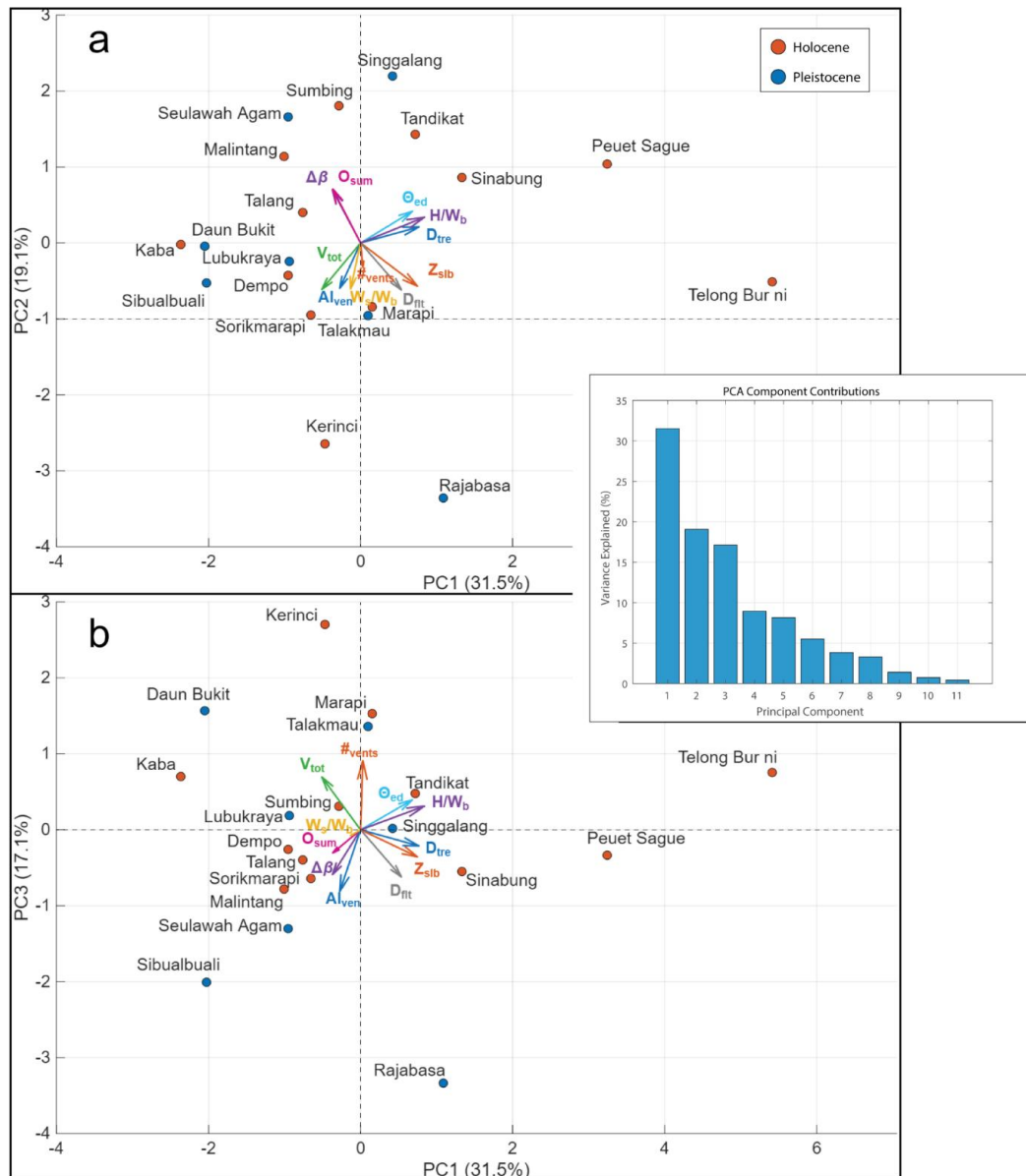


Fig. 4 Principal component analysis for the volcanoes investigated in this study. The parameters symbols are the same as in Table 2

The heatmap in figure 5a shows the weighted influence (weighted across all Principal Components) of each parameter per volcano. While most volcanoes have a moderate and consistent influence across all parameters (e.g. Dempo, Talang, Sorikmerapi, Talakmau, Sinabung, Tandikat), other volcanoes show a strong influence from specific parameters. For example, Telong Bur ni shows high weighted contributions from slab depth (Z_{slb}), trench distance (D_{tre}), and edifice slope angle (Θ_{ed}), with relatively low contributions from $\Delta\beta$, fault distance (D_{fit}), and the height-to-basal-width ratio (H/W_b). A similar pattern is observed for Peuet Sague, although with slightly lower intensity. Kerinci shows a relatively strong contribution from the number of vents ($\#_{vents}$) and total edifice volume (V_{tot}), while displaying very low association with $\Delta\beta$. Rajabasa shows a high contribution from slab depth (Z_{slb}) and

a very low association with fault distance (D_{fit}). Sibualbuali and Kaba are characterised by the height-to-basal-width ratio (H/W_b). Overall, this matrix highlights the same outliers identified in the PCA plots in figure 4, while also providing quantitative information on the contribution of individual parameters at each volcano.

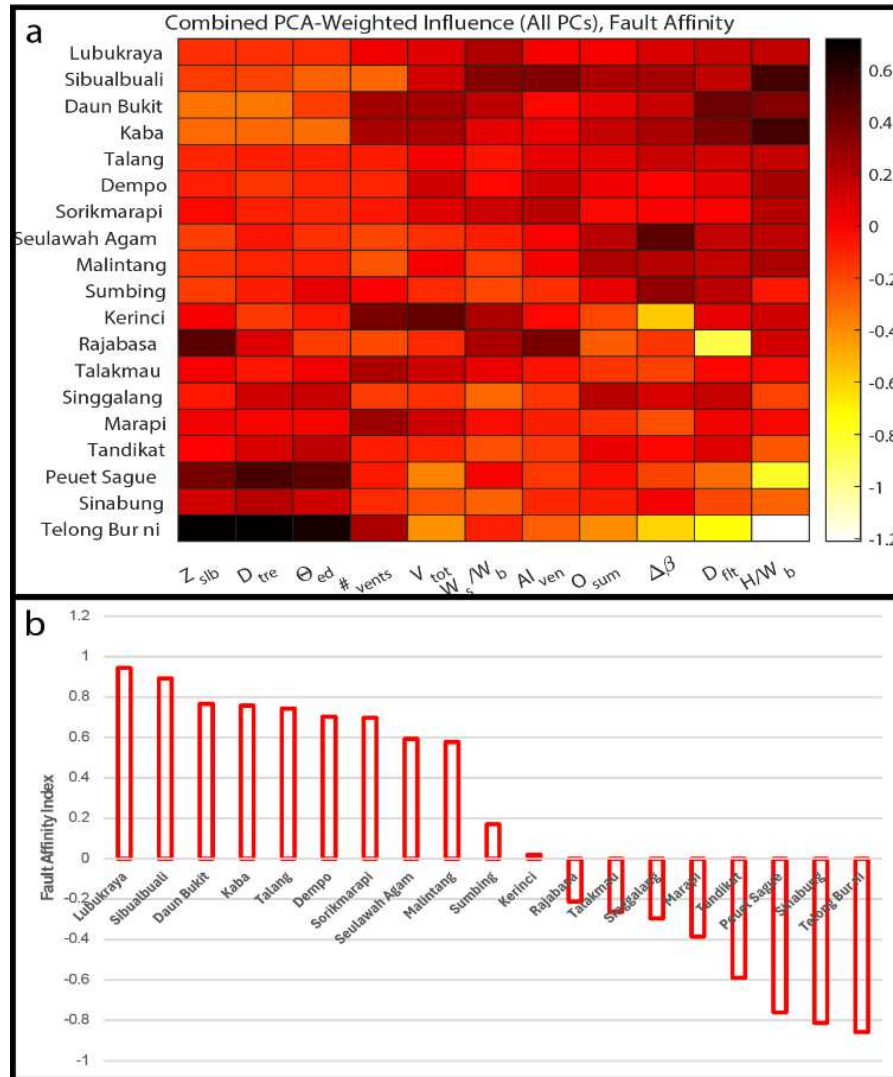


Fig. 5 Statistical analysis results. a) Weighted influence matrix highlighting the contribution of each parameter for each volcano considered (the parameters symbols are the same as in Table 2). The colours represent the influence weighting of each parameter (higher influence for darker colours), and the volcanoes are ordered by FAI (highest to lowest). b) FAI bar plots (see methods and Appendix for details on how the FAI was obtained)

Fault Affinity Index (FAI)

The PCA-weighted results translate into a wide range of FAI values (Fig. 5b). Lubukraya and Sibualbuali, two of the volcanoes used to define the benchmark signature, exhibit the highest positive index (0.89–0.94), reflecting consistently strong positive contributions from multiple parameters. In contrast, Telong Bur ni shows the lowest negative index (−0.86), indicating that its multivariate parameter profile is strongly dissimilar to the fault-affinity signature.

Other highly positive volcanoes include Daun Bukit, Kaba, Talang, Dempo, and Sorikmarapi, with values between 0.70 and 0.77. Seulawah Agam and Malintang follow with slightly lower FAI (0.58–0.59). Sumbing and Kerinci, although still positive, represent the lowest end of the positive range (0.02–0.17). Among the volcanoes with negative FAI are Rajabasa, Peuet Sague, and Telong Bur ni, which also stand out as outliers in the PCA.

Overall, the results suggest that fault affinity reflects the integrated contribution of multiple parameters rather than any single parameter, with each volcano characterised by a distinct multivariate signature.

Variations in mantle magma flux along Sumatra

Our mantle melting modelling indicates a weak positive relationship between mantle derived magma flux rates and orthogonal convergence rates (Fig. 6a). In southern Sumatra, a convergence rate of 62 mm/yr, corresponding to an orthogonal component of 50 mm/yr, produces a median magma flux approximately 62 km³/Myr. Meanwhile, the slower convergence rates in the northern Sumatra (52 mm/yr converted to 44 mm/yr) produce lower magma flux rates with median values of 55 km³/Myr. Given the large parameter space explored by the model, the uncertainties on the outputs overlap. However, because convergence rate is the only parameter we systematically varied, our results suggest a minor relative increase in magma flux from North to South, consistent with the increase in convergence rate.

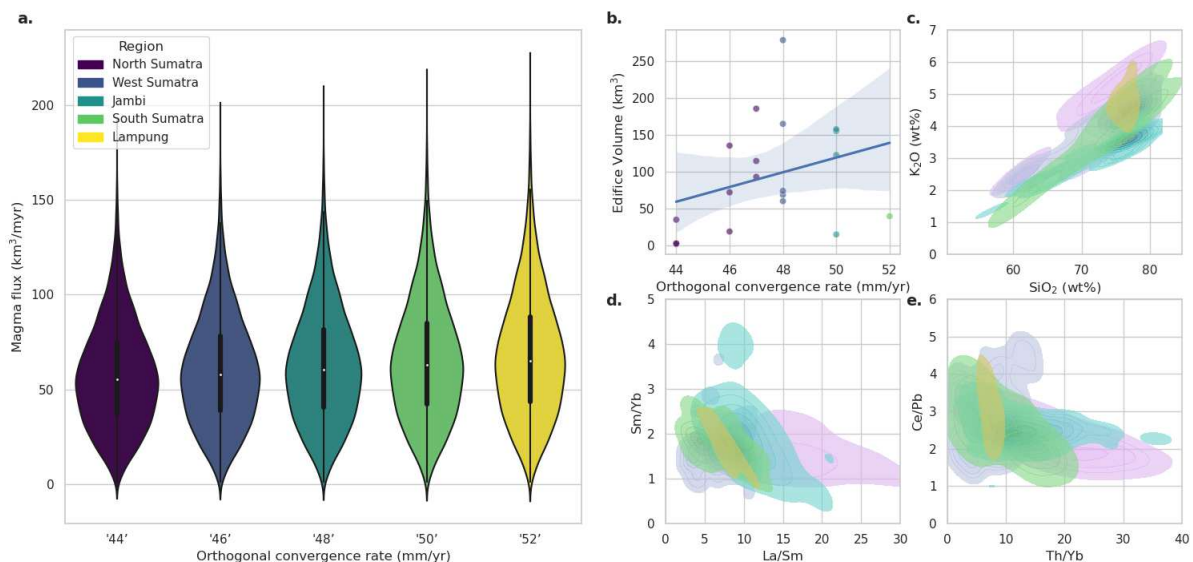


Fig. 6 Linking convergence rates, geochemical proxies and volcano morphology. (a) shows estimated mantle magma fluxes calculated using different orthogonal convergence rates along Sumatra. Violins have been colour-coded for the corresponding regions of Sumatra as shown by the legend. (b) Relationship between convergence rate and volcano edifice volume. (c) Major element variation in

Sumatran volcanism across different regions (adapted from Forni et al. 2025 and Phua et al. 2025).
(d-e) Trace element systematics (La/Sm versus Sm/Yb; Th/Yb versus Ce/Pb) for Sumatran volcanics

Discussion

Sumatran volcanoes and their PCA signature

A notable outcome of our PCA analysis is that all volcanoes with positive FAI cluster systematically on the negative side of PC1 in both the PC1–PC2 and PC1–PC3 biplots (Fig. 4). Although the FAI is derived from the PCA influence matrix, the PCA itself was computed beforehand and without reference to the affinity calculation. The resulting coherence therefore reflects intrinsic multivariate patterns rather than any imposed similarity to the benchmark signature. This spatial coherence indicates that the attributes typical of volcanoes influenced by the Sumatran Fault—including shorter distance to the SF, medium-high $\Delta\beta$, aligned vents along an oriented edifice, relatively large edifice volume, high summit-to-basal width ratio, and low height-to-width ratio—form a consistent multivariate pattern that the PCA identifies as the dominant axis of variation in the dataset. The negative side of PC1 therefore corresponds to a region where these parameters co-vary in a manner characteristic of structurally controlled edifices, and volcanoes plotting in this region naturally exhibit high FAI.

Conversely, volcanoes plotting on the positive side of PC1 display structural-morphometric combinations that diverge from this structurally-controlled pattern, including larger distances from the SF, weaker vent alignment, small edifice volume, low summit-to-basal width ratio and high height-to-width ratio. Their position in the PCA space is consistent with their lower FAI values and suggests a lower likelihood of genetic association with the SF. The convergence between our PCA results and the independently derived FAI, therefore, reinforces the interpretation that the negative PC1 domain represents the morphometric-structural expression of the SF influence, whereas the positive PC1 domain corresponds to volcanoes whose development is not (or less) affected by the SF. It is relevant to note, however, that a low fault affinity does not necessarily imply a stronger subduction-control on those volcanoes, rather, it may indicate that other tectono-magmatic processes exert a greater influence on the development of those volcanoes (e.g. Rajabasa, see discussion below).

Sumatran volcanoes and their Fault Affinity Index

Whether Sumatran volcanism is mostly influenced by subduction processes or by the strike-slip regime of the Sumatra Fault, or by both, has been debated for decades (e.g. Sieh and Natawidjaja 2000; Acocella et al. 2018). Richards (2003) appears to be in agreement with the hypothesis proposed by Acocella et al. (2018), in which volcanism is favoured at the

edge of pull-apart basins. In Sumatra, this is the case of Sibualbuali, Lubukraya and Talang. Acocella et al. (2018) argued that Sumatran volcanoes located more than 20 km from the Sumatran Fault (SF) are highly unlikely to be directly related to the fault. Following this criterion, 15 volcanoes among those analysed here fall within this distance. Among these 15 volcanoes, our statistical analysis shows that 9 exhibit a strong positive FAI (>0.5), 2 display weak positive or near-neutral values (Kerinci and Sumbing; $0.02\text{--}0.17$), and 4 show negative values (Talakmau, Tandikat, Singgalang, and Marapi; < -0.21) (Fig. 5). The FAI is not intended to identify in absolute terms which volcanoes are exclusively controlled by the SF. Instead, it provides a relative measure of how similar each edifice is to the morphometric/structural signature of volcanoes previously interpreted as having a likely structural relationship with the SF. This implies that multiple processes, acting in different proportions, may contribute to the development of these edifices. Conversely, low FAI values identify volcanoes whose multivariate characteristics show relatively weak similarity to the selected SF-related reference signature.

The volcanoes analysed here have relatively consistent distance from the trench, slab depth underneath them, and distance from the SF (most volcanoes are within 20 km from the SF) (Figs. 1-2). There are exceptions to this pattern, with one of the most obvious represented by Rajabasa volcano, located at 94 km from the SF, and a slab depth of 175 km, despite a trench distance of 280 km, approximately in line with most of the other volcanoes in Sumatra. Rajabasa has been interpreted in different ways in the literature. Nishimura et al. (1986), have interpreted it to be part of a N-S volcanic lineament, of which also Krakatau is part of, in turn associated with a fracture zone in the Sunda Strait. More recently, Rajabasa has been associated with back-arc volcanism (Zulkarnain 2011) and with a slab tear underneath it (Yu et al. 2025). These interpretations, together with its large distance from SF, suggest that Rajabasa is unlikely to have a direct structural relationship with the Sumatran Fault. This is also supported by its distinct position in PCA space (Fig. 4, Fig. 5a) and its negative FAI (Fig. 5b). Similarly, Telong Bur ni has a relatively deep slab, large fault distance (>40 km), steep edifice slope angle, and a high height-to-basal-width ratio, resulting in an outlier in the PCA and the lowest FAI, which makes it confidently unrelated to the SF. Following this principle, and the previously-discussed relationship between the PCA results and FAI, and considering that Rajabasa and Telong Bur ni represent the two end members of negative fault affinity values, then we may argue that the volcanoes with a FAI between those of Rajabasa and Telong Bur ni are also unlikely related to the SF. For example, Singgalang and Tandikat form a nested volcanic pair, with Tandikat (to the southwest) being younger than Singgalang (to the northeast). Despite being located <10 km from the SF, their FAI is negative (<-0.59). From a geological–structural perspective, the Singgalang–Tandikat

twin-volcano complex has a broad NNE–SSW orientation, forming an angle of ~60–70° with respect to the SF. In general, volcanic systems influenced by strike-slip fault systems tend to align parallel to the main fault or along fractures normal to the local least principal stress (σ_3) (Tibaldi et al. 2009). This expected pattern is not observed in the Singgalang–Tandikat complex: neither the edifice orientations, nor the vent alignments reflect the geometry of the SF. Notably, Tandikat hosts a collapse feature also parallel to the Singgalang–Tandikat alignment rather than the SF. Similarly, Marapi volcano, located ~15 km from the Singgalang–Tandikat complex and ~7 km east of the SF, also has a negative FAI. Its vents, together with a 1.5 km-wide collapse structure on its eastern flank, are aligned roughly perpendicular to the SF. Marapi is furthermore interpreted here to be young toward the S–SW, as suggested by its erosion pattern (Fig. 7). Differently, the nearby Maninjau caldera complex (not investigated in this study because a caldera, but discussed for context), located just ~15 km SE of the Singgalang–Tandikat complex, has an orientation N–S, with the south portion inferred to be younger (Hadiwidjono et al. 1979). This orientation, which is closer to that of the SF and differs from the Singgalang–Tandikat trend, may indicate a structural link between the SF and the formation of the Maninjau caldera, as also suggested by Wiwik Dyah Hastuti (2017), and as inferred for most caldera systems in Sumatra (Bellier and Sébrier 1994). Talakmau, located ~65 km northwest of the Singgalang–Tandikat complex, also has a negative FAI. Although its distance from the SF is greater (~19 km), its vent alignment is similar to that of Singgalang–Tandikat and Marapi, being oriented roughly perpendicular to the SF (Mount and Suppe 1992), hence unlikely related to it. Sinabung, after Telong Bur ni, is the volcano with the lowest FAI (-0.81), which is probably because of its large distance (31 km) from the SF, and this alone should indicate a non-influence of the SF in its formation. Additionally, Sinabung is cut by a fault oriented roughly perpendicular to the SF (Haerani et al. 2012), further supporting its structural dissociation from the SF.

Regarding the volcanoes with a positive FAI, we know that Lubukraya, Sibualbuali and Talang are previously interpreted as likely related to the SF (Bellier and Sébrier 1994; Acocella et al. 2018), and were used here as a benchmark for the FAI calculation. Despite of this, Talang ranked fifth in the fault affinity indexing, after Lubukraya, Sibualbuali, Daun Bukit and Kaba, but with similar values to the latter two (probably because Talang’s weighted-influence vector does not match the benchmark median as closely as Sibualbuali and Lubukraya, with some parameters slightly deviating from the main tendency of the benchmark group, resulting in a slightly lower, but still strongly positive FAI). Both Daun Bukit and Kaba were considered by Acocella et al. (2018) as *probably* and *possibly* linked to the SF, given their position adjacent (Daun Bukit) and in between (Kaba) two segments of the SF (Fig. 7). Additionally, Daun Bukit and Kaba, are among the closest volcanoes to the SF (≤ 1 km), have the higher number of mapped vents (8 and 6 respectively), and this may

reflect local structural influence, with fractured crust providing preferential pathways for magma ascent; their relatively high $\Delta\beta$ values, are also consistent with anomalous stress, damage and/or fluid conditions beneath these volcanoes; factors that point in the direction of a likely link to the SF. Regarding Talang volcano, besides its location at the intersection of two segments of the SF, and being identified by Acocella et al. (2018) as likely linked to the SF, it was also mapped and surveyed by Posavec et al. (1973). Posavec and colleagues, besides assessing the highly faulted nature of the area around Talang, also found a magnetic anomaly underneath it oriented along the two segments of the SF, from aerial surveys. Dempo and Sorikmarapi are among the “new” potential candidates for possible structural influence from the SF, given their relatively high FAI (~0.70); yet both have been broadly interpreted in the literature as typical subduction-related stratovolcanoes rather than SF-related systems (Sieh and Natawidjaja 2000; Acocella et al. 2018; Hinz et al. 2021; Liu et al. 2021). However, despite Sorikmarapi lying much closer to the SF (3 km) than Dempo (14 km), both volcanoes exhibit summit vents younging toward the NW (Global Volcanism Program and Venzke 2025), roughly parallel to the SF. Seulawah Agam, also not previously listed as potentially related to the SF (Acocella et al. 2018), has a relatively high FAI (0.59). Despite being classified as a Pleistocene volcano, the timing of Seulawah Agam’s most recent eruption remains debated, and the edifice is currently monitored due to unrest recorded in 2013 (Global Volcanism Program and Venzke 2025). Seulawah Agam is located ~4 km north of the SF, in a structurally complex region characterized by multiple major and minor fault systems. Among these, the Seulimeum Fault, a northern segment of the SF, is inferred to exert a significant structural influence on the volcano and its hydrothermal system (Dharma et al. 2026). The highly fractured/faulted nature of this area underneath Seulawah Agam is also confirmed by its high $\Delta\beta$, the highest across all volcanoes analysed here. All this together makes Seulawah Agam a likely candidate of volcanoes in Sumatra potentially influenced by the SF. Malintang volcano, which has a slightly lower FAI (0.58) than the other positively-indexed volcanoes, is nevertheless notable because fault-related seismicity has been detected beneath it (Weller et al. 2012), despite being 12 km away from the mapped SF. Moreover, Malintang has a summit orientation sub-parallel to the SF, and a relatively high $\Delta\beta$. These combined observations support the hypothesis that the SF may exert some influence on the formation or structural evolution of Malintang. Finally, Sumbing has a modest but positive FAI (0.17), and displays the second-highest $\Delta\beta$ value after Seulawah Agam. It is also situated above a secondary segment of the SF in proximity to normal faults whose strike is parallel to the SF (not mapped in Fig. 1), features that have been interpreted as transform-parallel normal faults, that may influence the location of Sumbing and other nearby volcanoes not included in this study (Hulunilo and Masurai Pleistocene volcanoes) (Bellier and Sébrier 1994).

Kerinci volcano falls between the positive and negative regimes of the FAI, with a value close to zero (0.02). Its distance from the SF (9 km) does not preclude a possible structural influence; however, its vents are aligned along a NE–SW direction, sub-perpendicular to the

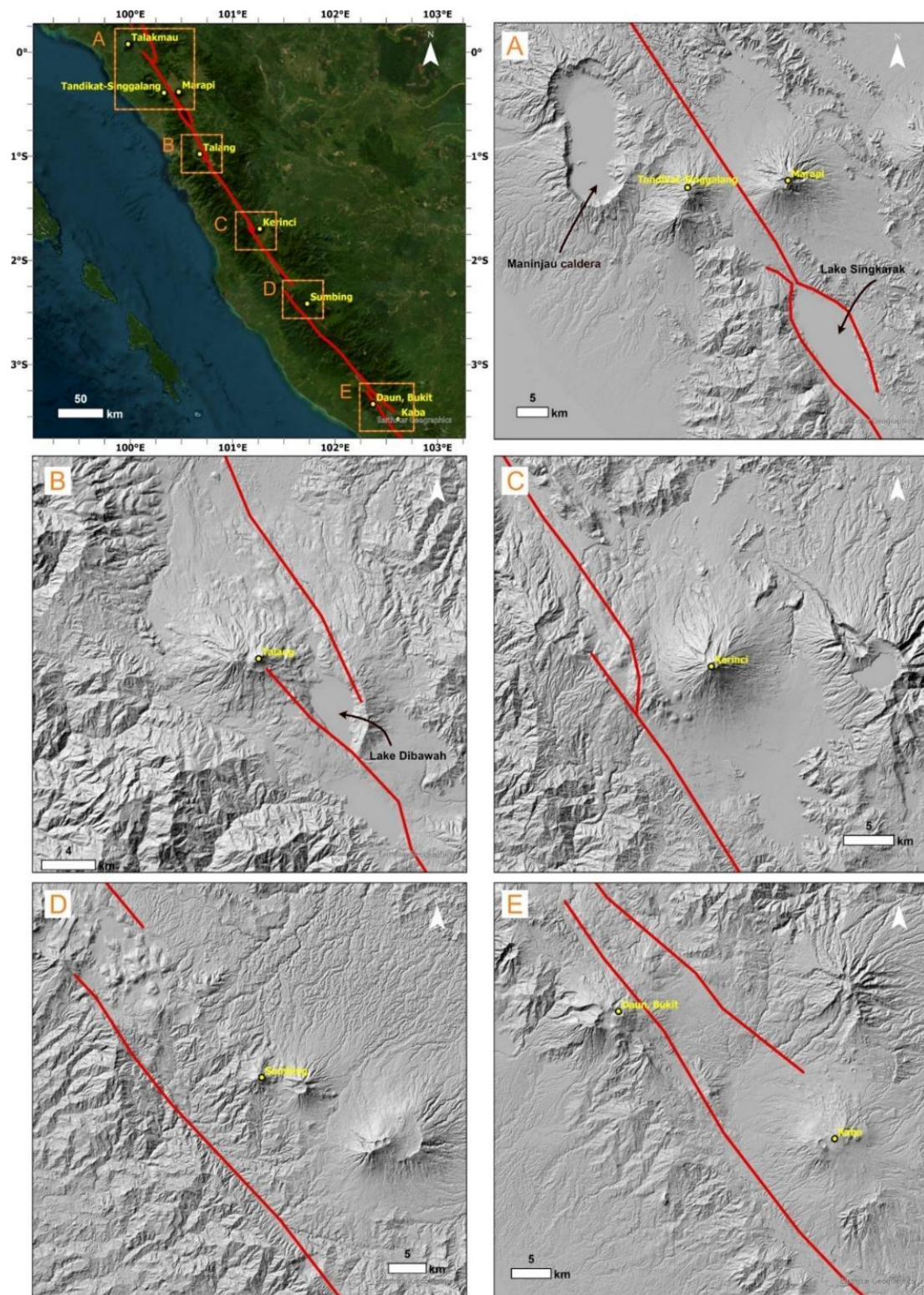


Fig. 7 Illustration of some of the key volcanoes investigated in this study. The basemap of the volcanoes in panels A-E is the hillshade created from the Indonesian DEMNAS Digital Elevation Model (10m resolution). The red lines represent segments of the Sumatran Fault (Acocella et al. 2018)

SF, and the PCA results indicate only a weak contribution from $\Delta\beta$. This suggests that Kerinci shows limited similarity to the seismological component of the SF-affinity signature. Kerinci is also one of the most active volcanoes in Sumatra (Global Volcanism Program and Venzke 2025), and its predominantly basaltic-andesitic composition implies relatively short magma-residence times and efficient transfer through the crust. Although the Holocene edifice sits within the dilatational Kerinci–Siulak pull-apart basin, where fault-related extension may facilitate vertical magma ascent via a shallow reservoir at ~4 km depth connected to a deeper dike-like source (Zhan et al. 2017), this structural setting appears to exert limited influence on the morphology of the present volcano. Taken together, these characteristics support the interpretation that Kerinci’s persistent activity reflects an efficient but largely self-contained shallow plumbing system, with only minor influence from the Sumatran Fault or its subsidiary structures.

Implications for short-term earthquake-volcano coupling and seismic triggering

So far, we have examined the potential genetic links between the SF and several active or potentially active volcanoes of Sumatra, primarily from the perspective of long-term structural controls on edifice formation. Where such links exist, however, they may also influence short-term volcanic behaviour. In this section, we discuss this aspect, reporting key examples from the Sunda region.

The relationship between large earthquakes and subsequent anomalous volcanic activity has been widely documented (e.g. Manga and Brodsky 2006; Walter and Amelung 2007; Bebbington and Marzocchi 2011). Sumatra and the broader Sunda arc provide several notable examples. Following the 2004 Great Sumatra earthquake (M_w 9.2) and the subsequent 2005 Nias–Simeulue aftershock (M_w 8.6), unusual volcanic activity was reported at Talang volcano and Barren Island (Walter and Amelung 2007). Thirty days after the 2004 rupture, a sequence of $M > 5$ seismic swarms beneath seamounts in the Andaman Sea, offshore north of Sumatra, was reported and subsequently interpreted as possible submarine volcanic activity (Špičák and Vaněk 2016). More recently, the 2013 eruption of Sinabung began only two days after the M_w 6.1 Bireun earthquake, which occurred on a fault oriented perpendicular to the SF (Haerani et al. 2012; Kriswati et al. 2019). These cases illustrate that megathrust earthquakes can perturb magmatic systems across a wide region, both in the near and far field.

Importantly, megathrust earthquakes in the Sunda region may also influence the SF itself. Several studies have inferred that large megathrust ruptures can transfer stress to the SF, potentially promoting slip (Qiu and Chan 2019; Salman et al. 2020; Rafie et al. 2023). Lupi and Miller (2014) showed that multiple $M > 5$ strike-slip earthquakes along the SF between 2006 and 2009 were likely triggered by stress changes associated with the 2005 megathrust

events. They further argue that such SF ruptures, whether seismic or aseismic, can eventually enhance future magma mobilisation by shearing or perturbing magmatic reservoirs located near the fault. Taken together, these observations suggest a dual hazard pathway for volcanoes structurally connected to the SF. Like most volcanoes, SF-related volcanoes may respond directly to megathrust-induced static or dynamic stress changes; however, they may also experience an additional layer of triggering susceptibility arising from fault-controlled stress redistribution along the SF itself. In other words, megathrust earthquakes can load the SF, and subsequent SF slips can further perturb the magmatic systems of SF-related volcanoes.

According to the USGS seismic catalogue (accessed April 23, 2026), on 6 March 2007 two strike-slip earthquakes of M 6.4 and M 6.3 occurred along the SF at depths of 11 km and 19 km, respectively, and 2-hours apart. Their epicentres were located ~5 km north of Lake Singkarak (a pull-apart basin along the SF), ~58 km N–NW of Talang, and only ~12 km south of Marapi. Thirteen days later, on 19 March 2007, Talang produced a VEI 2 eruption. A similar event occurred later that year: on 18 November 2007, a M 5.0 earthquake struck ~11 km north of Talang, and nine days afterwards Talang erupted again (Global Volcanism Program and Venzke 2025). Although these earthquakes were investigated (Salman et al. 2020), their possible relationship with the subsequent Talang eruptions has not, to our knowledge, been specifically evaluated. Their temporal and spatial proximity raises the possibility of earthquake-volcano interaction, although a causal relationship cannot be established from timing alone, as earthquake-triggered volcanic responses depend on both the imposed seismic perturbation and the state of the volcanic system (Manga and Brodsky, 2006). Notably, the 6 March 2007 earthquakes were not followed by an eruption at Marapi, despite its much shorter epicentral distance. This contrast may indicate differences in the pre-existing state of the two volcanic systems, as volcanic responses to earthquakes are strongly dependent on the condition of the magmatic–hydrothermal system at the time of perturbation (Hill et al. 2002; Manga and Brodsky 2006).

Such a hypothesis is broadly consistent with our statistical parameter-based assessment, in which Talang shows substantially greater affinity with the SF-related structural signature than Marapi. This raises the possibility that longer-term structural relationships with the SF may also influence the sensitivity of individual volcanic systems to short-term seismic perturbations.

Therefore, because triggering processes remain complex and volcano-specific, including static and dynamic stress changes, and because subsurface structures vary significantly between systems (e.g. Manga and Brodsky 2006), identifying which volcanoes are structurally associated with the SF becomes important. Such volcanoes may increase their susceptibility to stress perturbations associated with megathrust earthquakes or SF

reactivation. This structural configuration therefore represents a distinct and potentially under-recognised element of volcanic hazard in Sumatra, and integrating earthquake hazard forecasts for the SF with volcano monitoring networks could ultimately contribute to improve short-term assessment of eruption likelihood at volcanoes with strong structural affinity to the SF.

Volcano age and Fault Affinity Index

A comparison between volcanoes whose last known eruption occurred in the Holocene and those whose last activity dates to the Pleistocene (even if here was uncertain) shows no systematic relationship between eruptive age and FAI. Both groups span the full range of FAI values, and volcanoes with high or low affinity occur in each category. This suggests that FAI is not systematically related to the timing of the most recent known eruption, at least within the Holocene–Pleistocene resolution available for Sumatra.

The main differences observed between the two groups are geomorphological, reflecting the longer time available for degradation of Pleistocene edifices rather than differences in structural control. Pleistocene volcanoes generally exhibit higher summit-to-basal width ratios, lower mean edifice slopes, and smaller height-to-basal-width ratios compared to Holocene centres, patterns expected for older edifices that have undergone more extensive erosion, flank widening, and summit modification over time. Because the ages of several Pleistocene-classified volcanoes are poorly constrained, this comparison should be regarded as first-order rather than chronologically precise.

Geochemical variation along Sumatra

To gain a comprehensive understanding of the relationship between volcanism and tectonics throughout Sumatra, it is important to consider magma geochemistry and how this may vary along the arc and in relation to the Sumatran fault. Magma major, trace and isotopic compositions are sensitive to magma source composition in the mantle, as well as the processing that magma undergoes as it transits through transcrustal magmatic systems (Cashman et al. 2017). These processes include mantle melting (Plank and Langmuir 1988), magma storage (Hildreth and Moorbath 1988; Annen et al. 2006), magma mixing (Huppert and Sparks 1981), crustal assimilation (DePaolo 1981), fractional crystallisation (Grove et al. 2003; Davidson et al. 2007), reactive porous flow (Jackson et al. 2018), degassing (Caricchi et al. 2018) and magma transport. Large scale tectonics, such as crustal thickness and subduction parameters, can exert fundamental controls on mantle melting behaviour (Plank and Langmuir 1988; Syracuse and Abers 2006; Turner et al. 2016) and via slab tears (Ward et al. 2024), whilst crustal stress state may influence crustal processing by providing pre-

existing weaknesses that may inhibit magma stalling and promote preferential ascent (Rivalta and Chamberlain 2025).

Assessing geochemical variability along the Sunda arc has been hindered by the limited number of geochemical datasets published across Sumatra, as highlighted by the fact that only filtered data from Marapi were incorporated into the geochemical compilation of Ward et al. (2024). A recent study by Forni et al. (2025) published a comprehensive geochemical dataset of Sumatran caldera-forming systems that erupted during the Quaternary. They found distinct K_2O versus SiO_2 trends for the Sumatran caldera systems from different regions, with North Sumatra and South Sumatra having much higher K_2O contents for a given SiO_2 than West Sumatra and Jambi respectively (Fig. 6c). They suggest that these variations may stem from differences in crustal processing (e.g. fractional crystallisation, storage conditions or crustal contamination) and/or mantle source heterogeneity. We explore trace element systematics of Sumatra by supplementing the data of Forni et al. (2025) with additional proximal data from West Sumatra (Phua et al. 2025), and then combining it with our mantle melting modelling to see whether variations in convergence rate may contribute to systematic changes in volcanism alongside tectonic influences. However, because these compositions are dominantly intermediate to silicic rather than basaltic, they should not be viewed as direct samples of mantle melts. Instead, they likely integrate mantle, slab, and crustal processes to varying degrees. Our compilation excludes Toba caldera, which has anomalous geochemical characteristics that have been linked to the Investigator Fracture Zone and a potential slab tear (Fauzi et al. 1996; Koulakov et al. 2016; Ward et al. 2024).

To compare the geochemical data to the mantle flux calculations, we assigned an orthogonal convergence rate to each volcanic region of Sumatra using linear interpolation along the arc. Northern Sumatra was assigned convergence rates of 44 – 47 mm/yr, West Sumatra was assigned 47 – 48 mm/yr, Jambi was assigned 48 mm/yr, and Southern Sumatra and Lampung 50 – 52 mm/yr. Calculated magma fluxes for these convergence rates are shown in Fig. 6a. The estimated fluxes increase from 55 km³/Myr in the North to 62 km³/Myr in the South, although these overlap in uncertainty. La/Sm versus Sm/Yb cross-plots for each region (Fig. 6d) can provide constraints on the degree and depth of mantle melting (Plank and Langmuir 1988). Sm/Yb, which is sensitive to the depth of melting via garnet and/or amphibole fractionation (Hawkesworth et al. 1993; Davidson et al. 2007), shows limited variation across the dataset (1-3) and may indicate relatively stable depths of melting or a consistent role for amphibole fractionation in the crust. If primarily inherited from mantle melting, this pattern would be consistent with the relatively uniform slab depths across much of Sumatra. Conversely, La/Sm shows slightly more variation, with South Sumatra and West Sumatra reaching the lowest values that overlap into higher values from Lampung and

Jambi. North Sumatra has the highest La/Sm, which, if primarily inherited from the mantle source and melting process, could indicate lower melt fractions. This would also support apparent enrichments of K₂O in these rocks, which can also be generated by low melt fractions (Forni et al. 2025). The possible variations in melt fraction may be consistent with the along-arc changes in convergence rate explored by our mantle flux modelling, whereby the lower modelled mantle melt flux in North Sumatra could be associated with lower degrees of partial melting and greater enrichments in incompatible trace elements. However, because these are not basaltic compositions, the trace element ratios could also reflect overprinting by fractionation and crustal processing in addition to any primary melting signal.

Changes in convergence rate and mantle melting flux provide one possible contribution to the observed along arc geochemical variation, but regional source heterogeneity and crustal processing may also exert important controls (Lai et al. 2024; Forni et al. 2025). Firstly, much of the geochemical data we use is based on intermediate and silicic volcanics that have undergone variable degrees of crystal fractionation. La/Sm is prone to be modified by apatite and monazite fractionation, whilst Sm/Yb can be influenced by amphibole and garnet (Davidson et al. 2007). Across our compiled dataset, there is no apparent correlation between P and La/Sm, suggesting that apatite fractionation is unlikely to be the dominant control on the observed variation. Meanwhile, monazite has only been reported in the Maninjau eruptions from West Sumatra. Most of the units have observed amphiboles, which may influence the variance on Sm/Yb. Forni et al. (2025) argue that most of the silicic systems in Sumatra had similar storage conditions, and that regional variations in major element compositions, notably incompatible K₂O, are also preserved in more primitive dacites and andesites that could act as parental melts. This means that some of the trace element systematics may reflect source compositional variability or variations in mantle melting. Secondly, when assessing other trace element ratios (Fig. 8), it becomes apparent that source heterogeneity may also be important. This interpretation is consistent with zircon Hf isotopic data from Sumatra, which indicate a broadly juvenile mantle-wedge source but also substantial regional isotopic variability and anomalously evolved signatures around Toba, interpreted to reflect additional crustal and/or subducted-sediment contributions (Lai et al. 2024). For example, samples from Lampung have elevated Ba/Th indicating greater fluid contribution (Patino et al. 2000), whilst samples from North Sumatra are enriched in Nb/Y. To better distinguish these possibilities, Ce/Pb versus Th/Yb (Fig. 6e) may help distinguish mantle-dominated compositions from those more strongly influenced by slab- or sediment-derived components because Pb and Th are particularly sensitive to slab-derived components, whereas Ce and Yb are comparatively less affected by those additions and

therefore provide a useful contrast. Ce/Pb, however, should also be interpreted cautiously because the dataset is dominated by evolved compositions rather than primary basalts, so it is likely recording mixed mantle, slab, and crustal processes rather than a direct mantle-endmember signal. Andikagumi et al. (2021) suggest an alternative mechanism in which K₂O and trace element enrichments may be driven by active fracture zones in the downgoing slab that drives fluid release from the dehydration of K-rich phases. More comprehensive geochemical datasets that represent the primitive endmembers of the Holocene volcanics will be needed to gain greater clarity on differentiating geochemical variability and the connection to tectonics.

Do mantle melt fluxes correlate with volcano edifice volumes?

If variation in mantle melt fluxes play a significant role along Sumatra, one would expect them to be expressed in erupted and edifice volumes as well as magma geochemistry if extrusive to intrusive ratios remain constant. To test this concept, we compared along-arc convergence rates to our calculated edifice volumes of the Holocene and Pleistocene volcanoes used in our statistical assessment (Fig. 6b). We observe a very weak positive relationship between

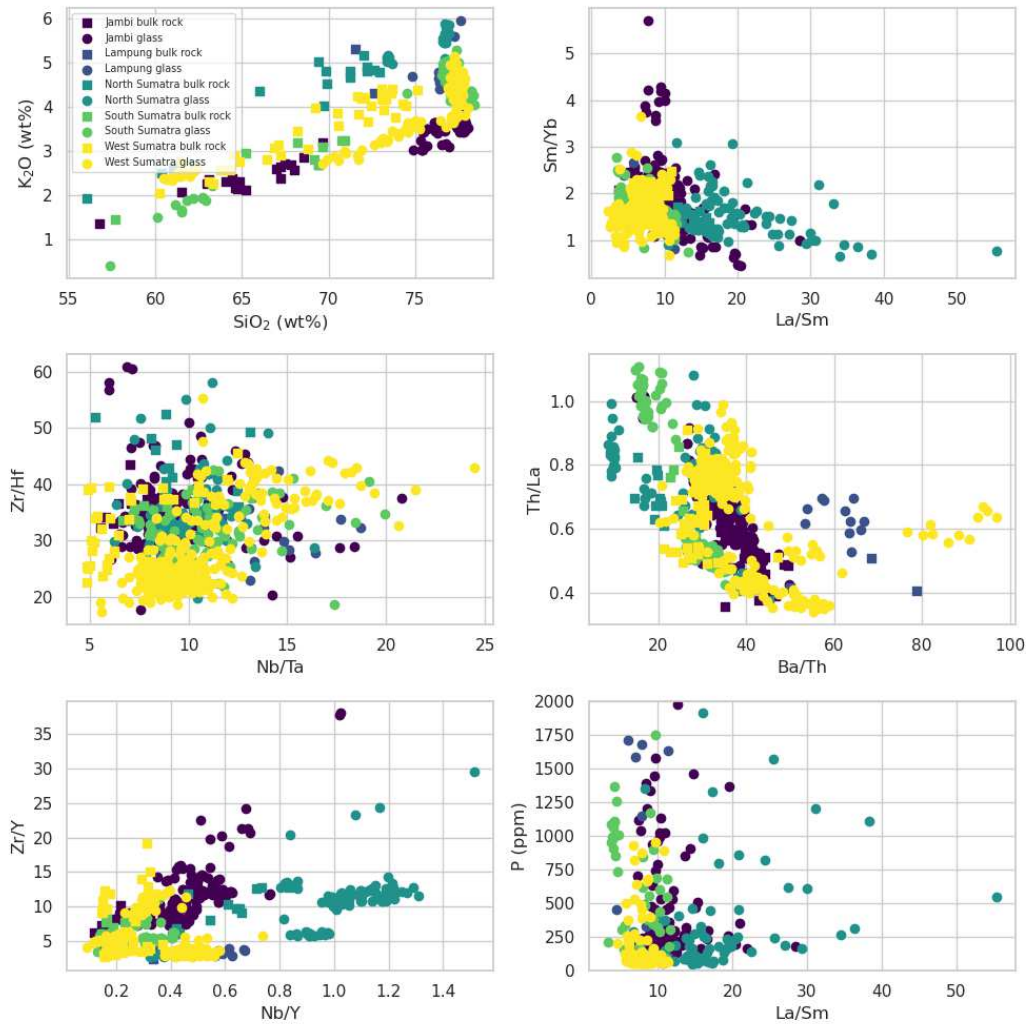


Fig. 8 Geochemical characteristics of Sumatran volcanics adapted from the compilation of Forni et al. (2025) and Phua et al. (2025). Whole rock data are shown as squares, and glass data are shown as circles. Points have been colour-coded based on region

convergence rates and edifice volumes, whereby Northern Sumatra has smaller edifices which increase towards the South. This trend is consistent with the smaller modelled mantle fluxes in the North relative to the South. The high variability in edifice volumes may partly reflect differences in structural setting and regional tectonics, which can enhance magma ascent to the surface and alter intrusive-extrusive ratios (Ingebritsen et al. 2026). Alternatively, uncertainties associated with erupted volume estimates, due to manual selection of topographic baselines, non-conical edifice morphologies (e.g. induced by sector collapse) and accounting for the effects of erosion and age, could also act to obfuscate primary magmatic influences.

Limitations and future directions

Although this study provides a statistical method for assessing the structural influence of the SF on selected volcanic systems in Sumatra, several limitations exist and must be

acknowledged. First, our analysis relies primarily on morphometric, structural, and geodynamic parameters derived from remote sensing, DEM-based measurements, and regional seismicity. These variables capture first-order edifice geometry and tectonic context, but they cannot resolve the magmatic, petrological, or temporal evolution of individual volcanoes. In particular, the absence of systematic, volcano-specific geochemical datasets limits our ability to determine whether volcanoes with high fault affinity also share common magma sources, differentiation histories, or crustal assimilation pathways.

A second limitation concerns the resolution at which deeper geodynamic and magmatic processes can be evaluated. Although we incorporated regional mantle melting calculations and along-arc geochemical compilations to assess broad variations in melt production and source characteristics, these datasets are spatially sparse and dominated by evolved compositions from large caldera-forming systems that were not included in our statistical analysis. As a result, they cannot be integrated directly into the PCA framework nor used to constrain magmatic conditions at the scale of the individual Holocene and Pleistocene volcanoes considered here. Consequently, processes such as mantle heat flux, slab dehydration efficiency, volatile release, or melt productivity can only be explored from a relative regional perspective rather than tested explicitly for each volcano. These deeper controls likely play a significant role in shaping Sumatran volcanism, but they remain only partially resolved within the scope of the present analysis.

Third, DEM-derived morphometric parameters may be affected by some level of uncertainty, due for example to erosion, incomplete edifice preservation, or uncertainties in basal outline delineation. These factors can introduce noise into the PCA and influence matrix, particularly for older or more degraded edifices. Targeted field studies, even if challenging due to dense vegetation/erosion, including structural mapping, vent alignment surveys, and detailed stratigraphic logging, would help validate the morphometric interpretations and refine the relationships between edifice geometry and underlying tectonic processes. Improved constraints on vent locations, eruptive histories, and edifice volumes would further reduce uncertainties in key parameters.

The statistical analysis presented here is exploratory and based on a relatively small dataset. Consequently, the PCA loadings, transformed multivariate profiles, and FAI rankings may be sensitive to individual volcanoes, measurement uncertainty, parameter selection, and weighting choices. The FAI should therefore be interpreted as a relative measure of similarity to a selected reference signature rather than as a probability or definitive classification of causal control. Because the approach is inherently comparative, low affinity values do not imply subduction-dominated origins; they simply indicate that a volcano's morphometric, structural, or seismological characteristics differ from the benchmark SF-related signature and may instead reflect local structures, crustal heterogeneities, or magmatic processes not captured by the

selected parameters. work integrating geophysical imaging (e.g. targeted seismic tomography), petrological modelling, and time-dependent deformation data would provide a more comprehensive understanding of the interplay between faulting, magma transport, and volcanic construction in Sumatra.

Despite these limitations, the approach developed and proposed here offers a reproducible, and quantitative framework for evaluating tectonic controls on volcanism. By integrating multivariate morphometric analysis with geodynamic context, this study provides a valuable foundation that can be expanded with future geochemical, geochronological, and field-based datasets, ultimately enabling a more complete understanding of the processes shaping Sumatran volcanism.

Conclusions

This study provides a quantitative reassessment of the long-debated relationship between the Sumatran Fault and volcanism in Sumatra. By integrating morphometric, structural, and geodynamic information into a multivariate framework, we identify a coherent morphometric–structural signature associated with stronger affinity to the Sumatran Fault rather than any single diagnostic parameter. The resulting Fault Affinity Index highlights a consistent group of volcanoes whose characteristics resemble those of centres previously interpreted as having a likely structural relationship with the SF. Our analysis consistent with previously proposed candidates (Talang, Lubukraya, Sibualbuali, Kaba, Daun Bukit) and identifies at least four additional volcanoes, Dempo, Sorikmarapi, Seulawah Agam, and Malintang, as new systems with a possible SF influence. In contrast, several volcanoes display consistently negative affinity values, indicating lower relative similarity to the selected SF-related structural signature.

To complement this structural assessment, we incorporated regional mantle melting calculations and available along-arc geochemical datasets, to evaluate broad variations in melt production and source characteristics. These analyses suggest only modest along-arc differences in melt fraction and melt flux, indicating that regional variations in mantle melt flux alone are unlikely to account for the observed morphometric variations at the volcanoes investigated in this study.

Overall, our findings demonstrate that the structural relationship between the Sumatran Fault and volcanism can be evaluated quantitatively using a reproducible and physically informed statistical framework. The approach developed here provides a foundation for future studies that incorporate geochemical, geophysical, geochronological, and field-based observations, and it offers a new pathway for understanding tectono-magmatic interactions in hybrid plate-

boundary settings. By identifying volcanoes with stronger structural affinity to major crustal structures, this work provides a basis for improving interpretation of volcanic unrest in relation to regional fault activity for short-term regional volcanic hazard assessments and for evaluating how crustal structure may influence magma transport and eruptive behaviour in Sumatra and comparable volcanic arcs worldwide.

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Author contribution

AV and EM idealised the work; AV drafted the original version of the manuscript; GP assisted with the $\Delta\beta$ estimates; EM and AM assisted with the mantle flux calculations; CW assisted with relevant discussions on the short-term earthquake-triggered Sumatran volcanism; all authors edited and reviewed the manuscript.

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Availability of data and materials

Data for reproducibility (MORVOLT results and vents shapefiles) are available in the public Nanyang Technological University public repository DR-NTU (<https://researchdata.ntu.edu.sg/privateurl.xhtml?token=350d3861-e889-44ad-8ed7-7a381575d0b4>). All other reproducibility data are available in this and other published manuscripts. The regional catalogue of the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG), used to determine the $\Delta\beta$, can be downloaded at <https://repogempa.bmkg.go.id/>.

Appendix A

Calculating the Fault Affinity Index

The Fault Affinity Index (FAI) quantifies how closely each volcano resembles the structural–morphometric pattern of systems known to be structurally influenced by the Sumatran Fault (SF). All morphometric parameters were first standardised (Eq. (1)):

$$X_{std} = \frac{X - \mu_X}{\sigma_X} \quad (1)$$

where X is the raw parameter value, μ_X its mean, and σ_X its standard deviation. A principal component analysis (PCA) was then applied to the standardized dataset. For each principal component, in Eq. (2), S_i denotes the vector of volcano scores, C_i the vector of parameter loadings, and f_i the fraction of variance explained by that component. Hence, a PCA-weighted influence matrix was reconstructed as:

$$I = \sum_{i=1}^k f_i S_i C_i^T \quad (2)$$

which yields, for each volcano, a multivariate morphometric signature integrating the full PCA structure. In Eq. (3), parameter-specific weights w_k were then applied to emphasise variables expected to be diagnostic of fault-controlled volcanism, and sign conventions s_k were used to encode inverse relationships (e.g. smaller distance to the SF implies higher affinity). The weighted influence matrix is:

$$I_w(j, k) = w_k s_k I(j, k) \quad (3)$$

where j indexes volcanoes and k parameters. In Eq. (4), a benchmark SF-related morphometric signature F was defined as the median of the weighted influence vectors of three volcanoes independently identified as SF-controlled (Sibualbuali, Lubukraya, Talang). The FAI for each volcano was then computed as the Pearson correlation between its weighted influence vector and the benchmark signature:

$$FAI_j = \text{corr} (I_w(j, :), F) \quad (4)$$

where FAI_j ranges from -1 (strong dissimilarity) to $+1$ (strong similarity). This index provides a reproducible relative measure of structural affinity to the Sumatran Fault across the volcanic arc.

Sensitivity analysis with different weighting configurations

To assess the sensitivity of the FAI to parameter weighting, we recalculated the index using three alternative weighting schemes (unweighted, 3, and 6) and compared them to the

reference weighting of 1.5. As described in the main text, weighting was applied only to the five morphometric variables most directly associated with fault-controlled edifice development (fault distance, $\Delta\beta$, number of vents, summit-to-basal width ratio, and height-to-basal width ratio). The resulting FAI values (Fig. 9) show that the overall ranking of volcanoes is broadly stable across weighting levels, with only limited shifts in intermediate cases. For example, Kerinci yields slightly higher FAI values under the stronger weighting schemes compared to its neighbour volcanoes on the plot (Sorikmarapi, Tandikat, Marapi and Sumbing), but remains consistently among the volcanoes with relatively high affinity. Sinabung shows a modest shift in sign, with a more pronounced positive value under the unweighted scheme and slightly negative values under the weighted schemes (3 and 6). Given independent geological evidence indicating that Sinabung is unlikely to be structurally controlled by the Sumatran Fault, the weighted results (including the reference 1.5 scheme) appear more consistent with expectations. Overall, the reference weighting of 1.5 reproduces the relative ordering observed in the more strongly weighted models while avoiding the amplification of end-member values, and therefore represents a conservative and geologically coherent choice compared to the unweighted alternative.

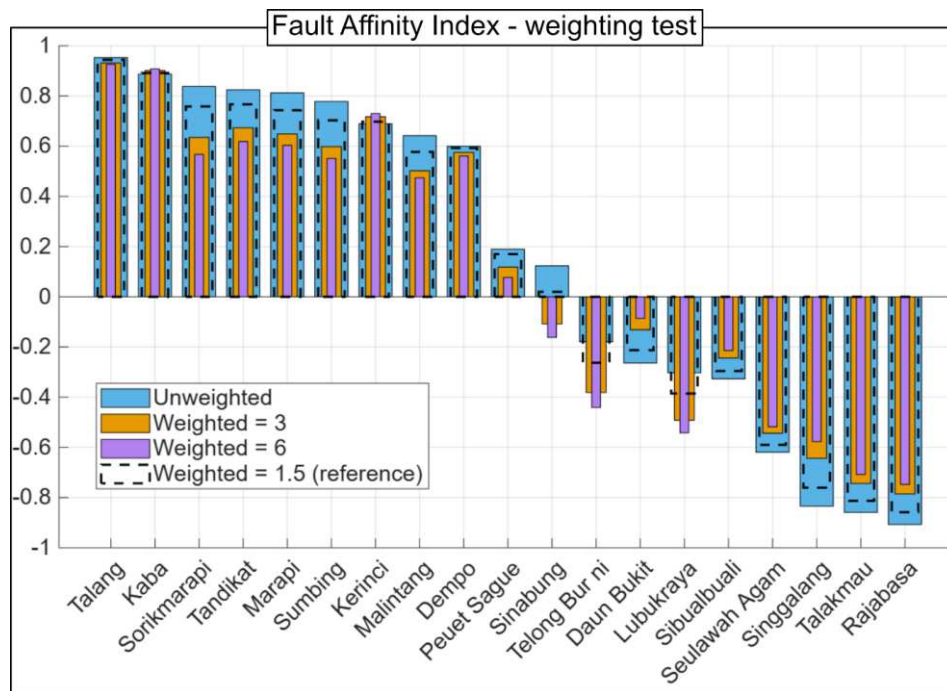


Fig. 9 Fault Affinity Index (FAI) test results for all volcanoes calculated under four weighting schemes, including the reference one (weight= 1.5) adopted in our work

Sensitivity analysis for fault affinity ranking

To evaluate the robustness of our parameterization and its influence on the resulting FAI per volcano, we conducted a sensitivity analysis. Specifically, we performed a 'leave-one-parameter-out' test following the same workflow described for the PCA and weighted matrix

creation (see Methods section). For each iteration, one parameter at a time was excluded and the remaining variables were standardized (zero mean, unit variance). This process did output 11 weighted matrices, as the total numbers of initial parameters considered. Subsequently, to quantify the stability of rankings across all sensitivity tests, we conducted a cumulative rank frequency analysis, in particular, we compiled the ordered volcano lists from each of the 11 leave-one-out runs. For each volcano, its row FAI position (1st–19th) in each test was recorded. A cumulative frequency matrix (19 × 19) was then constructed, with rows representing volcanoes and columns representing rank positions. Each cell records the number of times a given volcano occupied a given rank across all tests. For example, if Lubukraya ranked first in 10 tests and second in one test, its row contained values of ten in column 1, one in column 2, and zeros elsewhere (Fig. 10).

A broad distribution of rank frequencies, particularly when multiple rank positions show counts ≥ 2 , indicates that a volcano's placement is sensitive to the removal of individual parameters. Conversely, a narrow concentration of frequencies ≥ 2 reflects a stable ranking that is not strongly driven by any single morphometric variable. In our results, most volcanoes show relatively limited dispersion: for the majority of cases, frequencies ≥ 2 occur across no more than across 4 rank positions (Fig. 10). This pattern indicates that the ranking structure is generally robust. Volcanoes with positive FAI values (the top 10 volcanoes in Fig. 5) consistently fall within the upper portion of the ranking (e.g. Dempo ranked seven times in 6th position and twice in 8th position). The same applies to volcanoes with negative FAI values (e.g. Rajabasa shows the widest spread, across six rank positions, but always within the negative-affinity range, between 10th and 15th). One borderline case is Sumbing, which ranks mostly between 9th and 14th, broadly within the negative-affinity domain, whereas in the original analysis it ranked 10th with a low but positive FAI.

This sensitivity test largely supports our original FAI results.

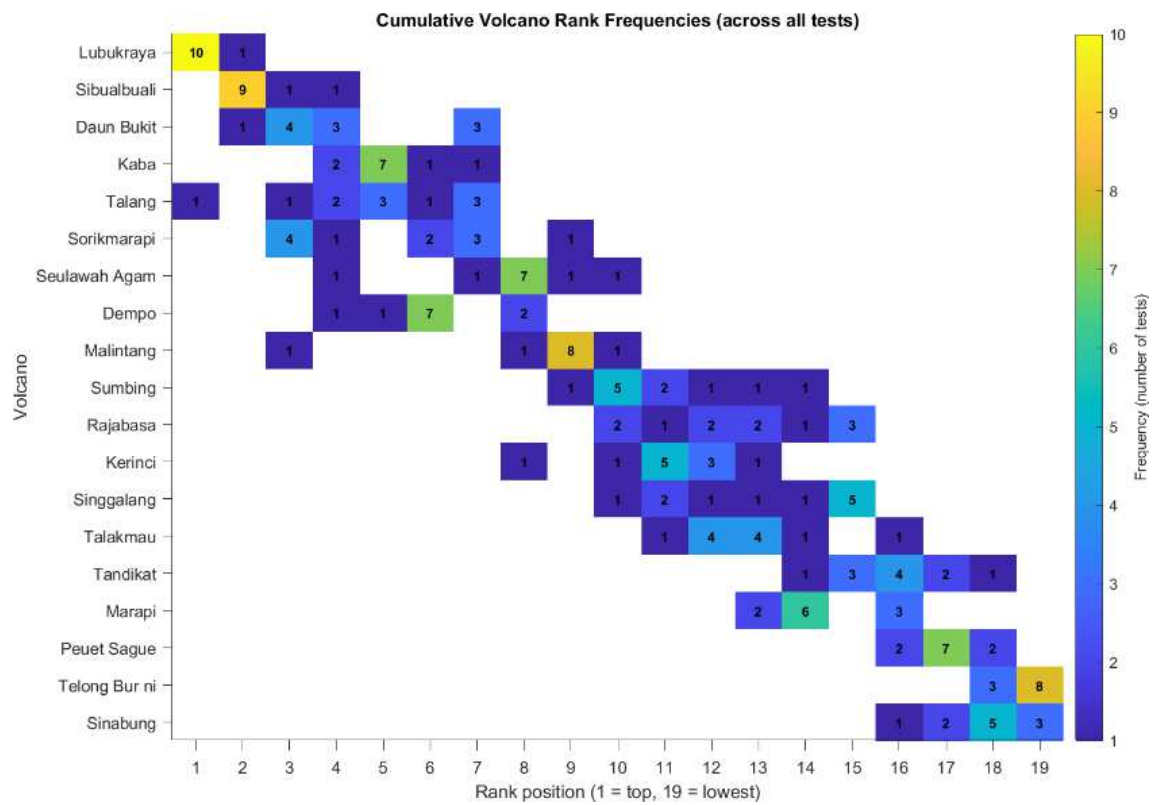


Fig. 10. Fault-related volcano ranking sensitivity matrix

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