PAKISTAN SEISMICITY IN 2025

Slab-Dominated Deformation within the Hindu Kush–Pamir–Makran Plate System

Technical Research Monograph

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National Seismic Monitoring Centre (NSMC)
Pakistan Meteorological Department (PMD)
Islamabad, Pakistan

Authored by

Nasir Mahmood
Meteorologist & Seismologist
National Seismic Monitoring Centre (NSMC)
Pakistan Meteorological Department
Islamabad, Pakistan

Reviewed and Endorsed by

Najeeb Ahmed Amir
Director
National Seismic Monitoring Centre (NSMC)

Mehwish Nadeem Butt
Deputy Director
Research & Development Division (R&D)
Pakistan Meteorological Department

Pakistan Meteorological Department (PMD)
Headquarters Office, Sector H-8/2
Islamabad, Pakistan

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Pakistan Seismicity in 2025: Slab-Dominated Deformation within the Hindu Kush–Pamir Collision System

Nasir Mahmood[1]*

[1] National Seismic Monitoring Centre (NSMC), Pakistan Meteorological Department (PMD), Islamabad, Pakistan

Corresponding author: Nasir Mahmood
Email: earthq5@yahoo.com

Abstract

Seismicity in Pakistan during 2025 was governed primarily by deformation within the deeply subducting Indian lithosphere beneath the Hindu Kush - Pamir region, with additional contributions from the Himalayan - Kabul transpressional arc and the Makran - Chaman - Sulaiman oblique plate-boundary system. Using a mechanically defined tectonic zonation (Zones A - H) and integrating PMD/NSMC solutions with reviewed regional/global catalogs, Gutenberg - Richter statistics, centroid moment tensors, GNSS velocities, Coulomb stress metrics, and strong-motion/MMI constraints, we quantify where and how strain was released. More than 70% of $M_w \geq 4$ earthquakes originated within the Hindu Kush slab (Zone A), confirming intermediate-to-deep slab deformation as the dominant mode of seismic energy release. Activity persisted throughout the year with moderate variability and episodic $M_w > 5$ events, indicating sustained plate-driven loading rather than short-lived episodic activation. The 31 August 2025 Mw 6.0 Asadabad earthquake, although centered in eastern Afghanistan, generated MMI V - VI shaking across northern Pakistan, highlighting the transnational footprint of slab - arc sources. The combined seismological and geodetic evidence depicts a mechanically coherent deformation regime in which slab processes strongly modulate Pakistan's regional hazard, superimposed on active shallow crustal deformation along collision and transform margins.

Keywords: Pakistan seismicity 2025; Hindu Kush slab; tectonic zonation; b-value; GNSS; Coulomb stress; Makran subduction; transpressional deformation

1. Introduction and Tectonic Framework

1.1 Tectonic framework

Pakistan occupies a first-order plate boundary region at the junction of the Indian, Eurasian, and Arabian plates. This setting generates a spectrum of deformation styles including:

1. Intermediate-to-deep slab seismicity in the Hindu Kush - Pamir system
2. Continental collision along the Himalayan - Kabul arc
3. Oblique convergence and strike-slip partitioning along the Chaman - Sulaiman system

4. Megathrust subduction along the Makran margin

During 2025, seismicity reflects the mechanical interaction of these systems within a unified plate-driven framework.

To enable consistent spatial comparison, we subdivide the region into eight mechanically defined tectonic domains (Zones A - H; Fig. 1 as detailed in Table 1). This zonation is based on deformation style and lithospheric behavior rather than political boundaries, allowing physically meaningful comparison of strain release.

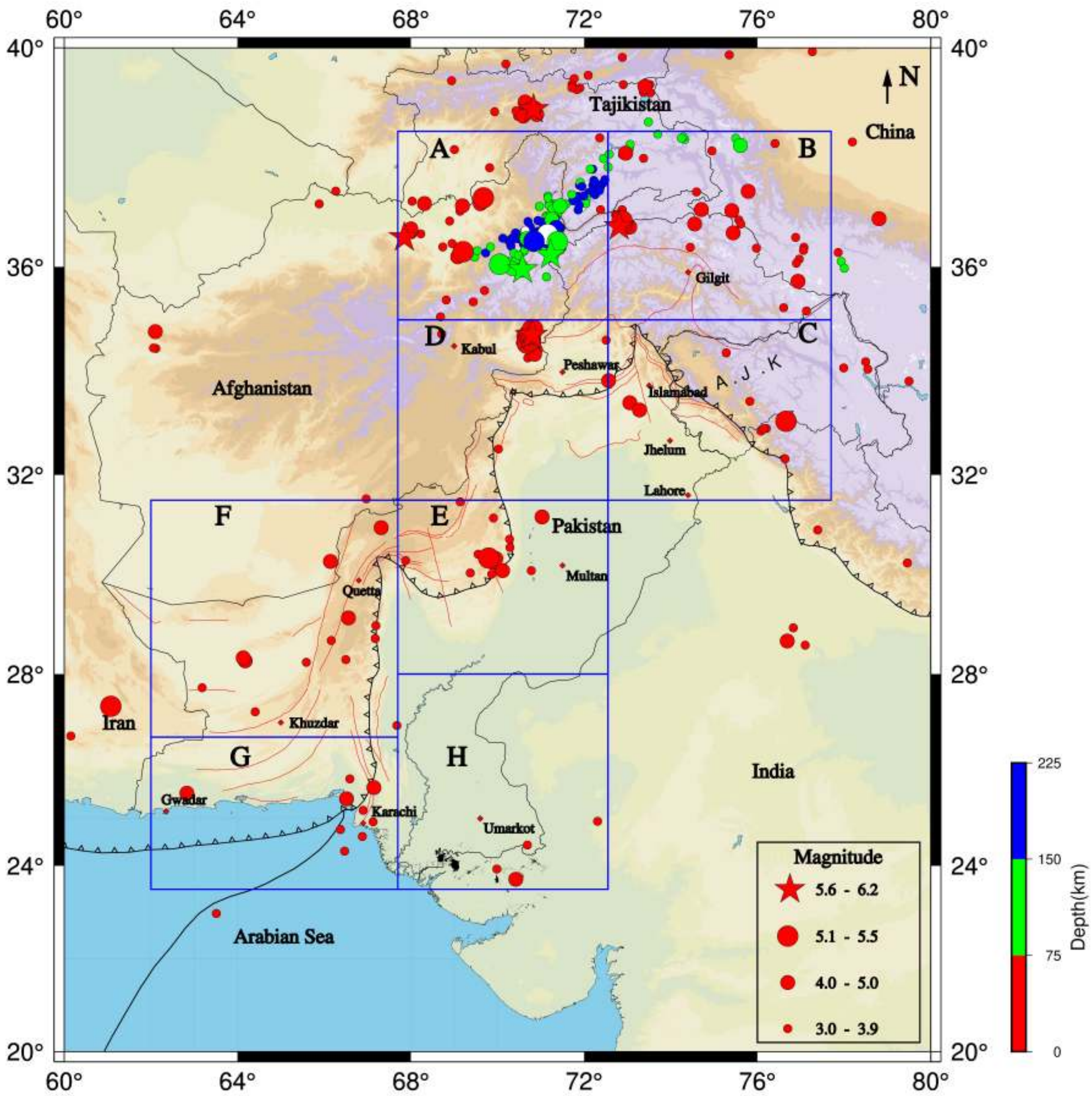

Figure 1. Tectonic zonation and earthquake distribution in the Pakistan - Hindu Kush - Pamir - Makran region during 2025. Epicenters (Mw ≥ 3.0) are plotted on shaded relief; symbol size scales with magnitude and color denotes focal depth. Rectangles delineate tectonic Zones A - H: A Hindu Kush - Pamir slab; B Karakoram - Pamir; C Kashmir - Hazara; D Kabul - KPK arc; E Sulaiman fold belt; F West Balochistan; G Makran subduction zone; H Lower Indus foreland. The clustering of intermediate-to-deep events in Zone A demonstrates slab-dominated seismicity.

Table 1. Mechanically Defined Tectonic Domains (Zones A–H) Used in This Study

Zone	Tectonic Domain	Dominant Deformation Regime	Representative Regions
A	Hindu Kush–Pamir Slab	Intermediate-to-deep slab deformation; down-dip compression and possible slab tearing	Hindu Kush, Pamir
B	Karakoram–Pamir Transition	Slab–collision interaction; mixed thrust and oblique faulting	Karakoram Range
C	Kashmir–Hazara Arc	Continental collision; compressional thrusting and crustal shortening	Kashmir, Hazara
D	Kabul–Khyber Pakhtunkhwa (KPK) Arc	Transpressional deformation; oblique India–Eurasia convergence	Eastern Afghanistan, KPK
E	Sulaiman Fold Belt	Thin-skinned fold–thrust deformation; frontal shortening	Western Pakistan
F	West Balochistan Domain	Distributed upper-crustal faulting; mixed strike-slip and compressional deformation	Chagai–Raskoh region
G	Makran Subduction Zone	Megathrust subduction; variable coupling and partial locking	Makran coastal margin
H	Lower Indus Foreland	Stable foreland basin; localized intraplate deformation	Sindh Plain

2. Data and Analysis Strategy

This study integrates seismological, geodetic, and mechanical datasets to evaluate the spatial and mechanical state of deformation across Pakistan during 2025.

2.1 Earthquake Catalog and Source Parameters

The earthquake catalog combines PMD/NSMC operational solutions with reviewed regional and global solutions (USGS/ISC where available). The final working catalog includes events of Mw 2.0 - 6.2, with completeness assessed monthly and by tectonic zone. Centroid moment tensors (CMTs) were computed for selected Mw ≥ 4 events using regional waveform inversion. Mechanisms were used to constrain stress regime, rupture style, and tectonic partitioning.

2.2 Magnitude - Frequency Statistics

Gutenberg - Richter relations were calculated annually and by tectonic zone (A - H).

- Magnitude of completeness (Mc) was estimated using MAX_C and goodness-of-fit methods.
- b-values were computed using maximum likelihood estimation (MLE).
- Temporal stability of Mc and b was evaluated monthly to distinguish tectonic signals from detection bias.

These statistics provide a first-order proxy for stress state and mechanical heterogeneity across domains.

2.3 GNSS Kinematic Constraints

Continuous GNSS stations (Eurasia-fixed reference frame) were processed using GAMIT/GLOBK to derive horizontal velocities. Stations across northern Pakistan show coherent NE - NNE convergence (~17 - 23 mm yr^{-1}), consistent with India - Eurasia plate motion. Velocity gradients between the Karakoram - Hindu Kush region and the foreland are used to infer strain partitioning and coupling variability.

2.4 Strong-Motion and Intensity Analysis

Strong-motion records from representative events were analyzed to compute peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), cumulative absolute velocity (CAV), Arias intensity, and spectral energy distribution. These parameters quantify amplitude, duration, and frequency content of shaking. Modified Mercalli Intensity (MMI) fields were derived from observed reports and empirical attenuation modeling to relate source characteristics to spatial patterns of ground shaking and expected damage.

Methodological Framework

All workflows followed established procedures using:

- **SAC** for waveform processing
- **SEISAN v13** for catalog management
- Regional moment-tensor inversion tools
- **GAMIT/GLOBK** for GNSS analysis
- **GMT v6.5** for mapping and visualization

This integrated multi-dataset approach enables consistent evaluation of slab, collision, and transpressional deformation within a unified mechanical framework.

3. Results

3.1 Spatial Distribution and Slab Geometry

The 2025 earthquake catalog comprises ~350 events (Mw 2.0 - 6.2) across Pakistan and adjacent regions. Seismicity is strongly concentrated within the **Hindu Kush - Pamir slab (Zone A)**, where intermediate-to-deep earthquakes (70 - 300 km) delineate a steeply northward-dipping Indian lithospheric slab (Fig. 1). Shallow crustal earthquakes (<40 km) are distributed along the **Chaman - Sulaiman transpressional system**, the **Himalayan - Kabul arc**, and the **Makran subduction margin**, reflecting active oblique convergence and strain partitioning. The spatial contrast between deep slab clustering and distributed shallow crustal events demonstrates that 2025 strain release was primarily slab-controlled rather than dominated by upper-crustal faulting within Pakistan.

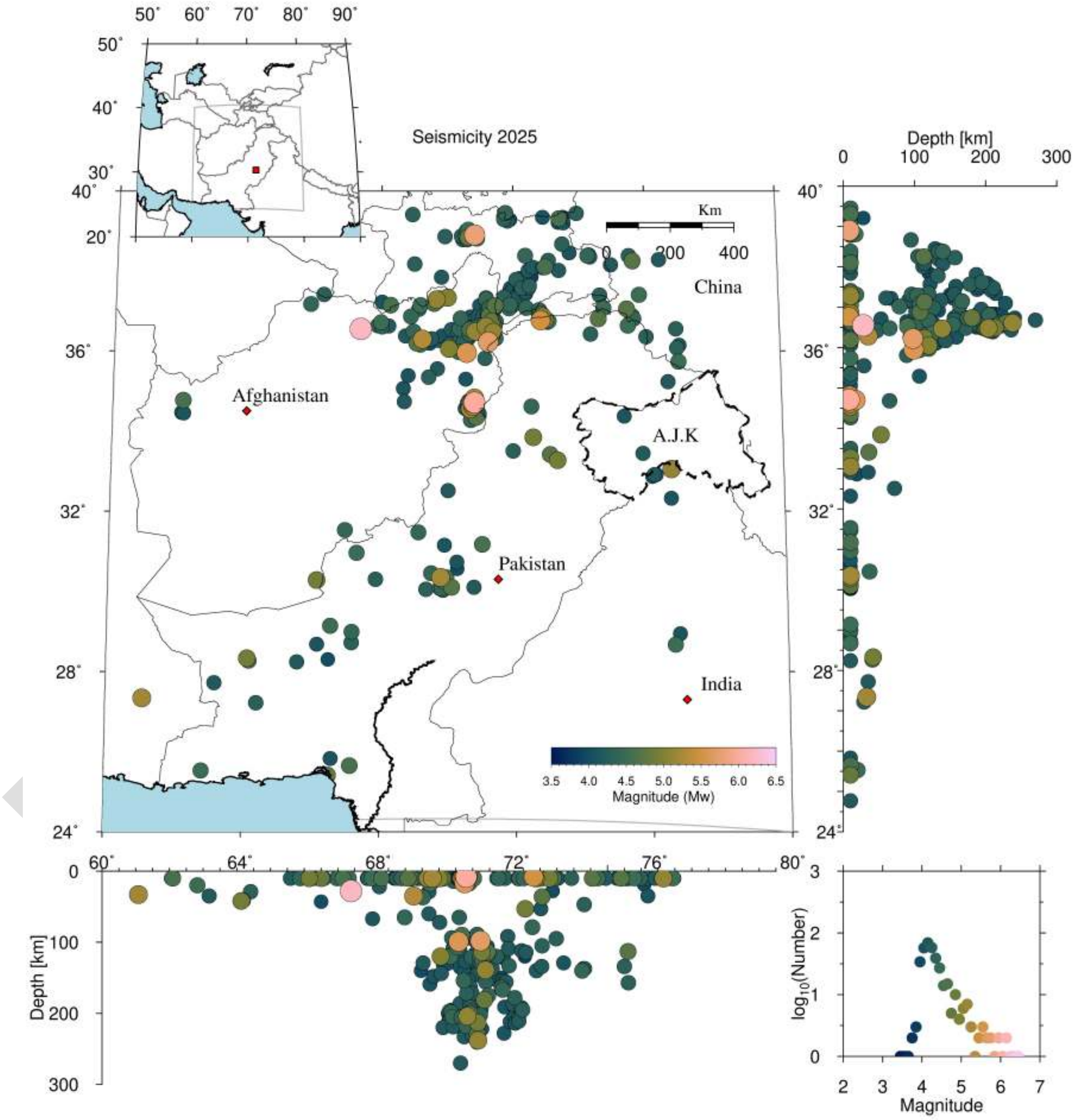

Figure 2a. Depth cross-section of 2025 seismicity. Hypocenters (Mw ≥ 2.0) define a steeply dipping Indian slab beneath northern Pakistan and Afghanistan. Shallow crustal earthquakes are concentrated along the Chaman transform system and the Makran subduction margin.

3.1.1 Depth Structure and Slab Geometry

A vertical cross-section through the Hindu Kush - Pamir region (Fig. 2a) reveals a coherent slab geometry extending from ~70 km to >300 km depth. Clustering at 150 - 250 km suggests internal slab deformation, consistent with down-dip compression and possible slab tearing. In contrast, crustal seismicity remains confined to shallow depths along western Pakistan and the Himalayan - Kabul collision front.

3.2 Zones Distribution of Mw ≥ 4 Earthquakes

Zones statistics confirm the dominance of the slab domain. Zone A accounts for >70% of Mw ≥ 4 earthquakes in 2025 (Table 2), establishing it as the primary source of seismic moment release.

Secondary contributions arise from:

- Zone D (Kabul - KPK arc)
- Zone E (Sulaiman fold belt)

Makran seismicity (Zone G) remained comparatively limited during 2025.The zonal partitioning quantitatively supports the interpretation of 2025 as a slab-dominated year.

Table 2. Significant seismicity in 2025 by tectonic zone (Mw ≥ 4.0).

Zone	Domain	Number of Events	Maximum Mw
A	Hindu Kush - Pamir slab	172	6.2
B	Karakoram - Pamir	67	5.5
C	Kashmir - Hazara	12	5.1
D	Kabul - KPK arc	39	6.0
E	Sulaiman fold belt	24	5.2
F	West Balochistan	3	4.9
G	Makran subduction zone	5	5.2
H	Lower Indus foreland	4	4.8

3.3 Mechanical State Inferred from b-values

Annual Gutenberg - Richter analysis yields a slab-wide b-value of ~1.06 (Fig. 2b&c), consistent with a coherent, highly stressed lithospheric slab. Domain-specific b-values (Fig. 2b) show lower values (<1) in:

- Zone A (Hindu Kush slab)
- Zone D (Kabul arc)
- Zone E (Sulaiman belt)

These values suggest comparatively elevated differential stress or stronger mechanical coupling in these domains.

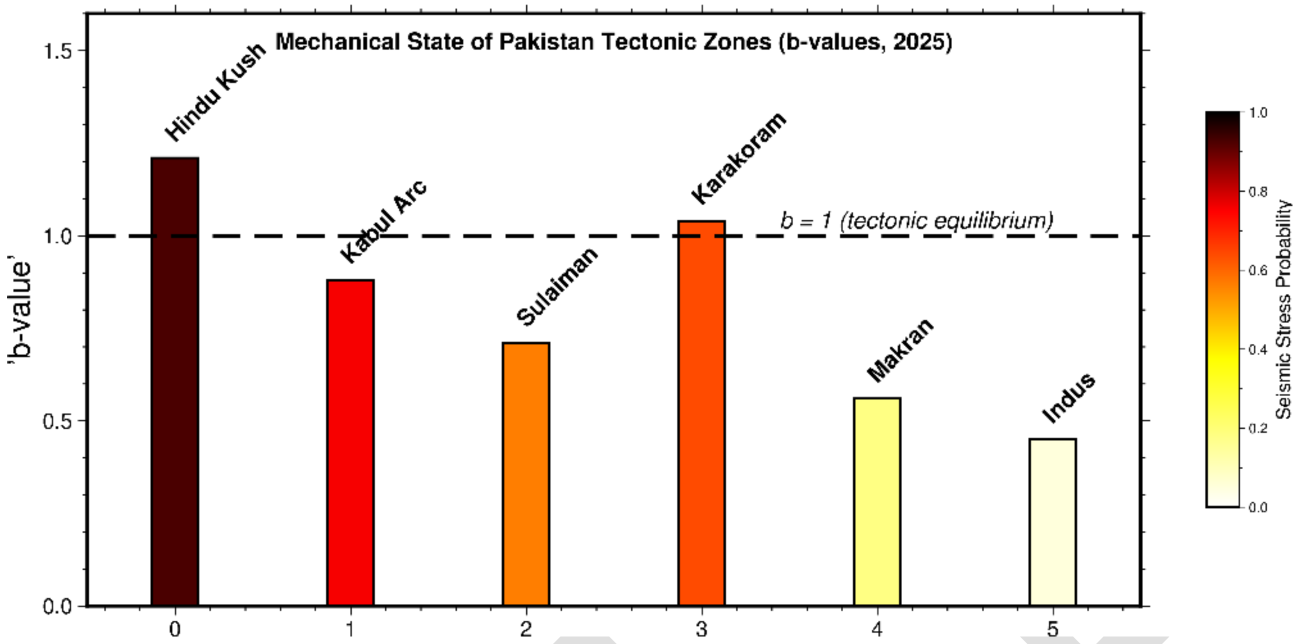

Figure 2b. Gutenberg - Richter b-values by tectonic domain for 2025. The dashed line (b = 1) represents approximate tectonic equilibrium. Lower b-values in Zones A, D, and E indicate elevated stress or stronger fault coupling.

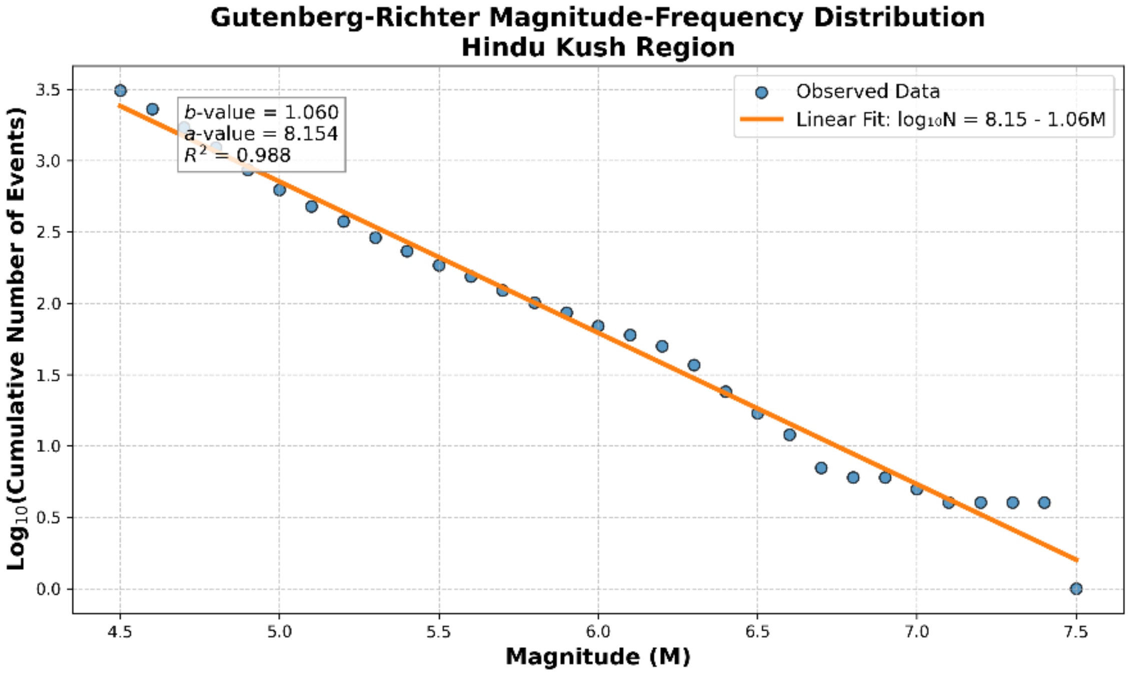

Figure 2c. Gutenberg–Richter magnitude–frequency relation for the Hindu Kush slab domain (Zone A) based on the compiled historical and instrumental earthquake catalog. The fitted relation ($\log_{10}N = a - bM$) yields a b-value of ~1.06, representing aggregated seismicity across multiple depth levels (70–300 km) and rupture styles within the subducting Indian lithosphere beneath the Hindu Kush–Pamir region. The high linearity ($R^2 \approx 0.99$) indicates statistical robustness and mechanical coherence of slab-controlled deformation over the analyzed period. This long-term magnitude–frequency behavior provides the stress-state framework within which the 2025 seismicity is interpreted.

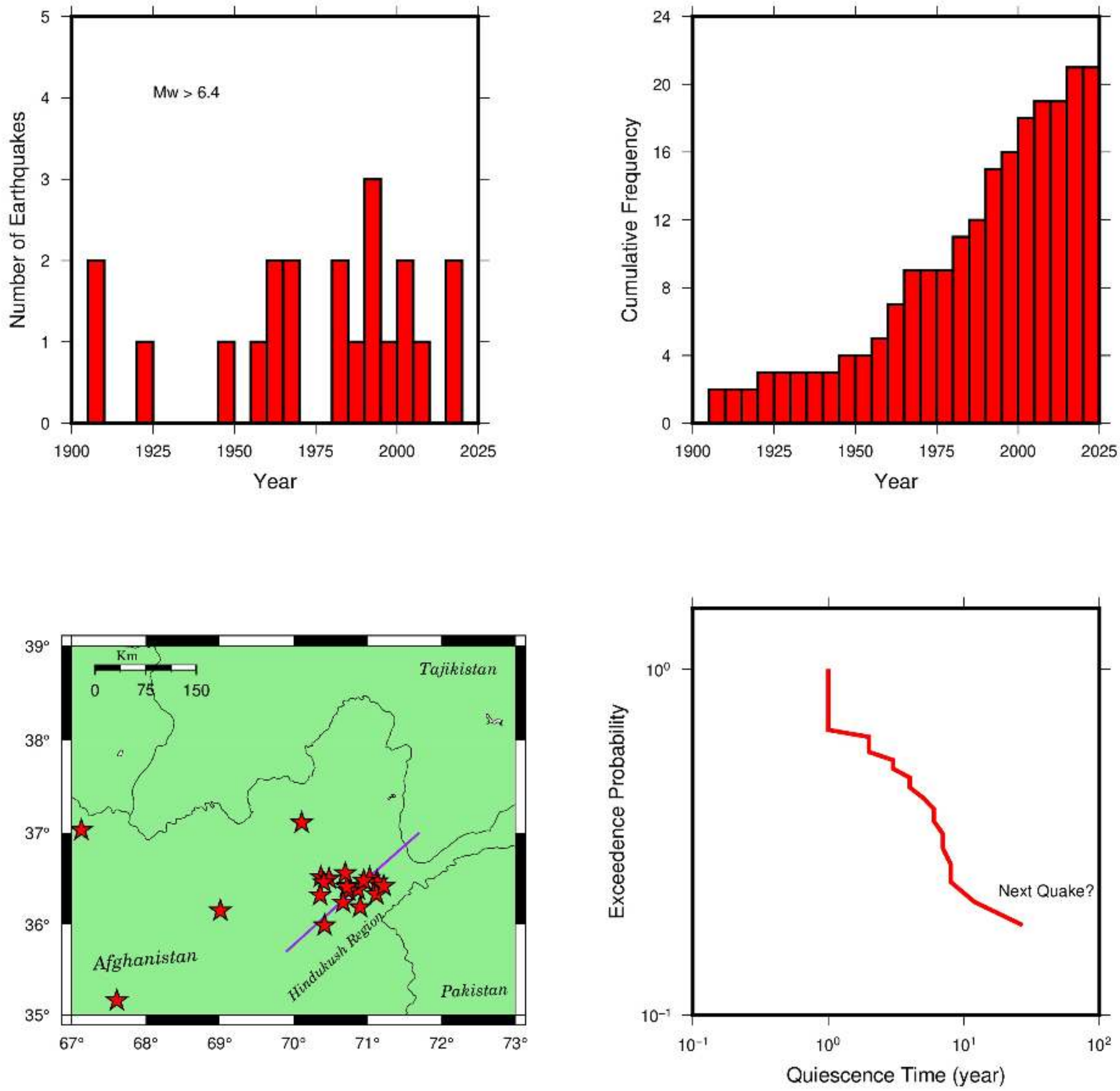

Figure 2d. Long-term seismic behavior of the Hindu Kush slab (Mw ≥ 6.4) in Afghanistan and northern Pakistan. (a) Annual occurrence of large earthquakes since 1900, illustrating episodic clustering rather than periodic recurrence; (b) cumulative frequency curve showing progressive moment release through time; (c) spatial distribution of major intermediate-to-deep earthquakes delineating the steeply north-dipping Indian slab beneath the Hindu Kush; (d) exceedance probability versus quiescence time, demonstrating irregular recurrence intervals and decadal-scale episodic slab deformation.

The combined panels highlight the non-periodic, internally driven mechanical behavior of the Hindu Kush slab and provide the long-term tectonic background against which the 2025 slab-dominated seismicity is evaluated.

3.4 Temporal Evolution and Catalog Stability

Seismicity during 2025 was persistent throughout the year, with continuous moderate activity punctuated by occasional stronger earthquakes (Mw > 5.0) (Fig. 3). While fluctuations in monthly counts are observed, no prolonged quiescent intervals occurred. The overall temporal pattern reflects sustained slab-controlled deformation, with intermittent contributions from shallow crustal systems.

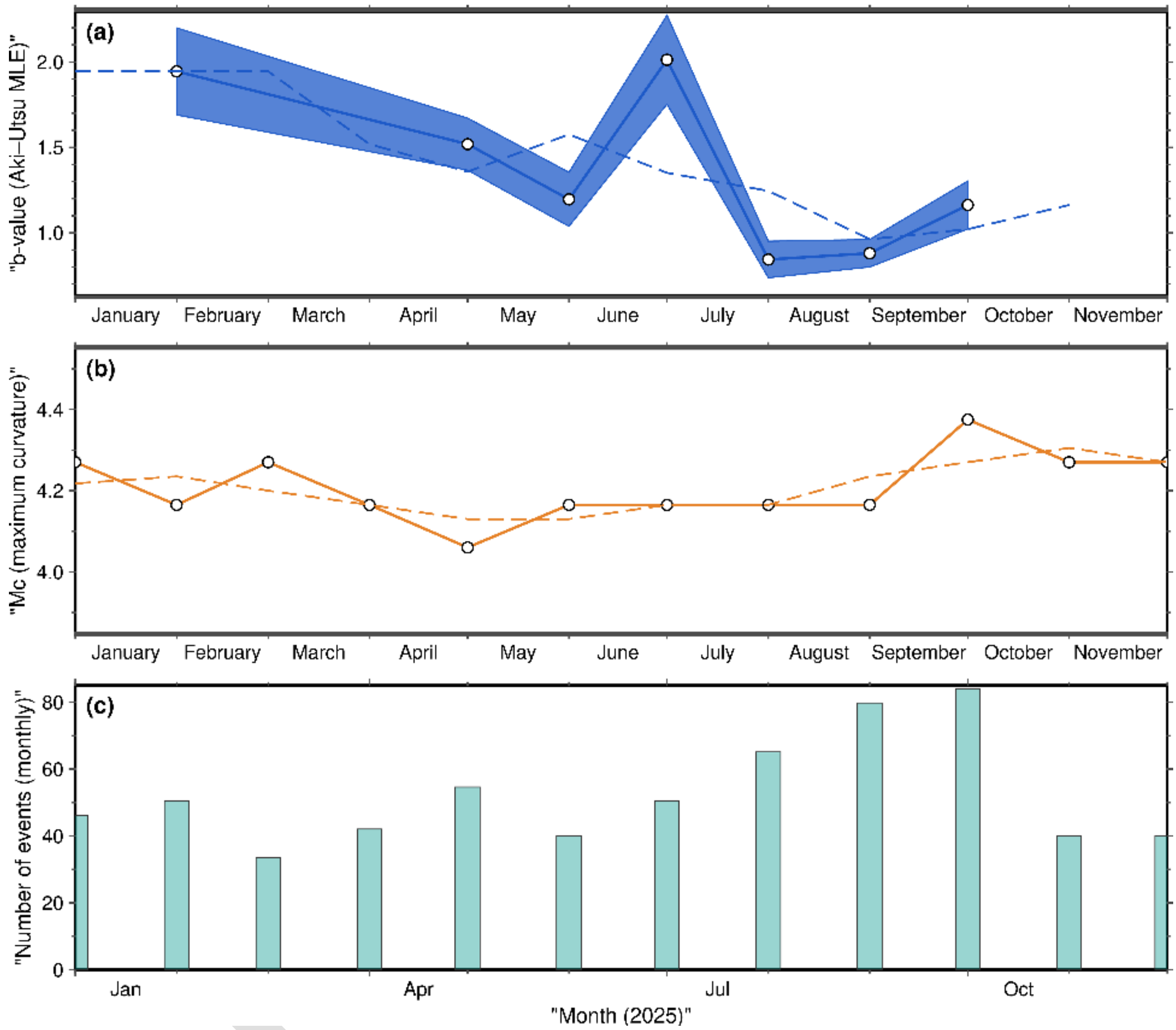

Figure 3. Temporal evolution of seismicity and catalog stability during 2025.

(a) Monthly b-values; (b) magnitude of completeness (Mc); (c) monthly earthquake counts (Mw ≥ Mc). Seismicity persisted year-round with variable monthly rates; peaks are primarily associated with Hindu Kush - Kabul slab/arc earthquakes, superimposed on steady background crustal activity in western Pakistan.

To verify that temporal variations represent tectonic processes rather than detection artifacts, magnitude of completeness (Mc) and monthly b-values were evaluated (Fig. 3a - b). Mc remained stable within expected thresholds, and b-values exhibited normal statistical variability without systematic shifts. Monthly earthquake counts (Mw ≥ Mc) show moderate variability but no abrupt catalog instability. These results indicate that seismicity in 2025 reflects continuous plate-driven deformation rather than short-lived episodic phases or network-related bias.

3.5 Stress Field and GNSS Constraints

GNSS velocities (Eurasia-fixed reference frame) indicate coherent NE - NNE convergence across northern Pakistan at ~17 - 23 mm yr^{-1} (Table 3; Fig. 4), consistent with India - Eurasia plate motion. Higher velocities in the Karakoram - Hindu Kush region relative to the foreland suggest spatial strain partitioning and variable coupling.

Table 3. Preliminary GNSS-Derived Horizontal Velocities (2024 - 2025)

Station	E - W (mm/yr)	N - S (mm/yr)	Azimuth (°)	Speed (mm/yr)
ISBA	12.78 ± 0.31	11.98 ± 0.28	46.85	17.52 ± 0.30
CHRT	14.56 ± 0.35	13.43 ± 0.32	47.31	19.81 ± 0.34
TBLA	13.50 ± 0.33	12.00 ± 0.30	48.37	18.06 ± 0.32
JHLM	13.07 ± 0.30	12.64 ± 0.29	45.96	18.18 ± 0.30
LAHR	12.35 ± 0.29	11.92 ± 0.27	46.02	17.16 ± 0.28
GLGT	16.49 ± 0.38	15.82 ± 0.36	46.19	22.85 ± 0.37
SKRD	15.23 ± 0.37	14.88 ± 0.35	45.67	21.29 ± 0.36
CHTL	13.99 ± 0.34	13.12 ± 0.31	46.84	19.18 ± 0.33
PATN	13.90 ± 0.36	12.10 ± 0.33	48.96	18.43 ± 0.35

Focal mechanisms and GNSS vectors jointly define the regional stress regime:

- **Zone A (Hindu Kush slab):** intermediate-to-deep slab-internal deformation, including down-dip compression and possible tearing.
- **Zone D (Himalayan - Kabul arc):** thrusting and transpressional faulting consistent with active collision.
- **Zones E - F (Chaman - Sulaiman system):** left-lateral strike-slip with compressional component.
- **Zone G (Makran):** long-term strain accumulation on a partially locked megathrust.

The consistency between kinematic (GNSS) and dynamic (focal mechanism) observations confirms that 2025 seismicity was primarily plate-driven and mechanically coherent across slab, collision, and transform domains.

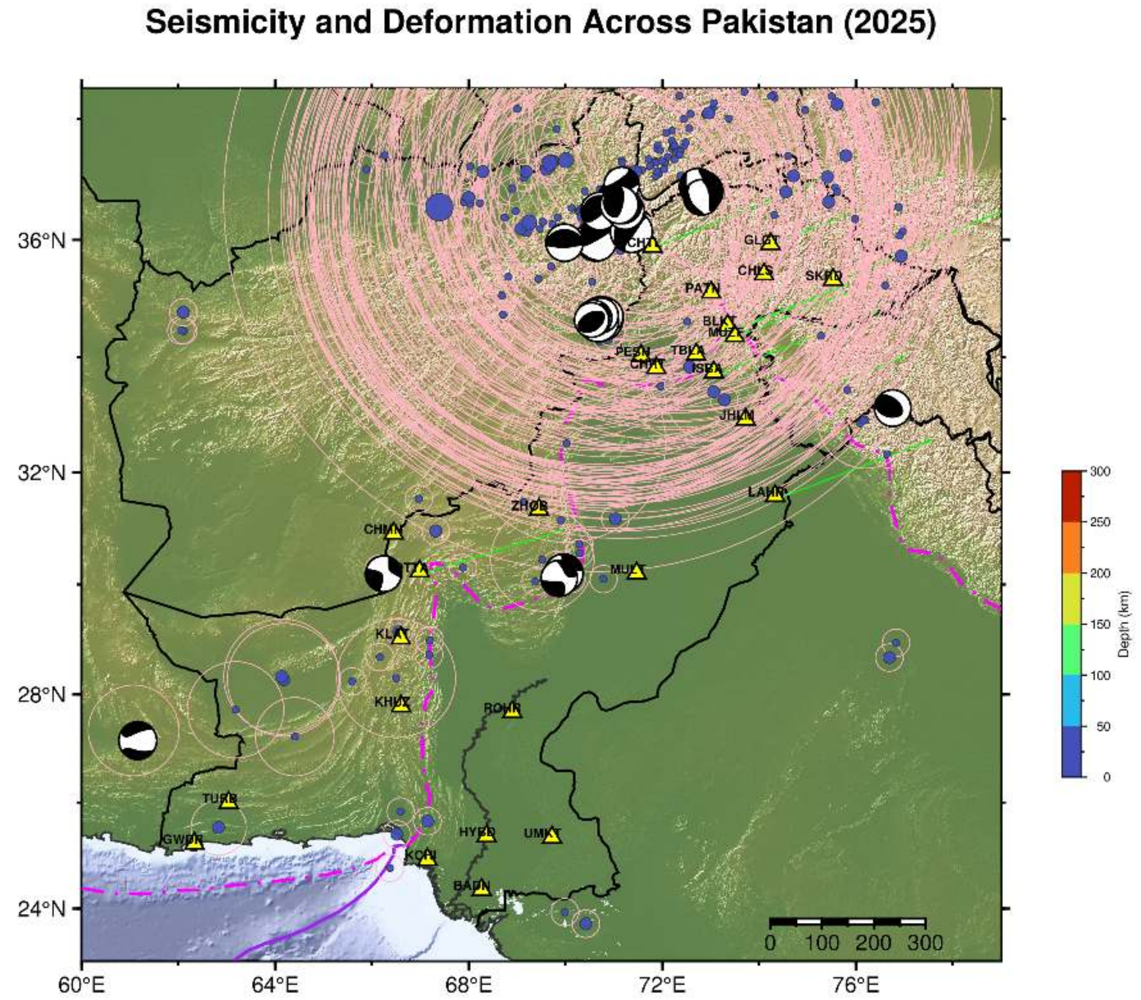

Figure 4. Integrated seismicity and deformation across Pakistan (2025). Hypocenters are color-coded by depth; focal mechanisms illustrate compressional faulting in the northern arc and mixed strike-slip to oblique mechanisms in western Pakistan. GNSS vectors indicate coherent NNE convergence (~17 - 23 mm yr^{-1}). The combined dataset supports plate-driven deformation.

4. Key Events and Shaking Consequences

Although seismicity persisted throughout 2025, composite ground-shaking patterns (Fig. 5) demonstrate that a limited number of moderate earthquakes controlled the national hazard footprint. Maximum intensities (MMI V - VII) are concentrated in northern Pakistan and are primarily associated with Hindu Kush - Kabul arc events, reflecting efficient regional wave propagation from intermediate-to-deep slab sources. In contrast, shallow crustal earthquakes in the Chaman - Sulaiman system and along the Makran margin produced more localized intensity fields, generally confined to MMI IV - V. The spatial distribution of composite MMI highlights the dominant influence of slab-related earthquakes on regional shaking, while also illustrating basin amplification effects in major urban centers including Islamabad and Karachi.

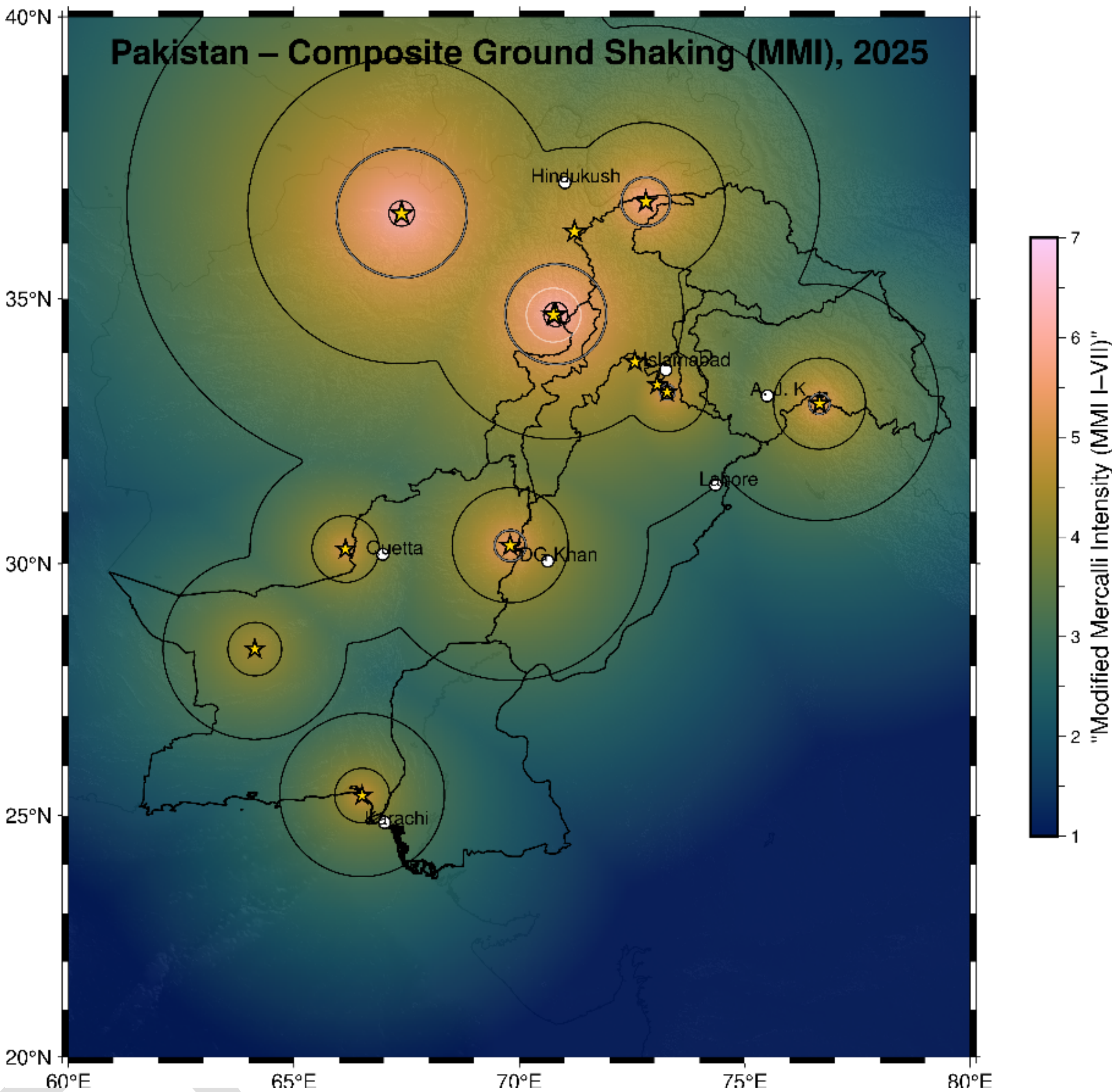

Figure 5. Composite Modified Mercalli Intensity (MMI) patterns in Pakistan during 2025. Highest intensities (MMI V - VII) are concentrated in northern Pakistan and primarily associated with Hindu Kush - Kabul arc earthquakes.

4.1 Mw 6.0 Asadabad Earthquake (31 August 2025)

The 31 August 2025 Mw 6.0 earthquake near Asadabad, eastern Afghanistan, was the most destructive event affecting the Pakistan - Afghanistan region in 2025. Although moderate in magnitude, the earthquake resulted in more than 2,000 fatalities and caused substantial economic and infrastructure losses across eastern Afghanistan.

Despite its epicenter outside Pakistan, the event produced widespread MMI V - VI shaking across northern Pakistan (Fig. 5), with strong ground motion reported in

Peshawar, Kohat, Islamabad, and surrounding districts of Khyber Pakhtunkhwa and northern Punjab. The broad spatial extent of perceptible to strong shaking underscores the transnational hazard posed by slab - arc earthquakes within the Hindu Kush - Kabul system.

Broadband waveforms recorded across Pakistan show prominent S-wave arrivals and prolonged coda durations (Fig. 6a), indicating efficient regional wave propagation and sustained energy release. This event exemplifies a key characteristic of 2025 seismicity: intermediate-to-deep and arc-related earthquakes, even of moderate magnitude, exerted disproportionate regional impact compared to localized shallow crustal events.

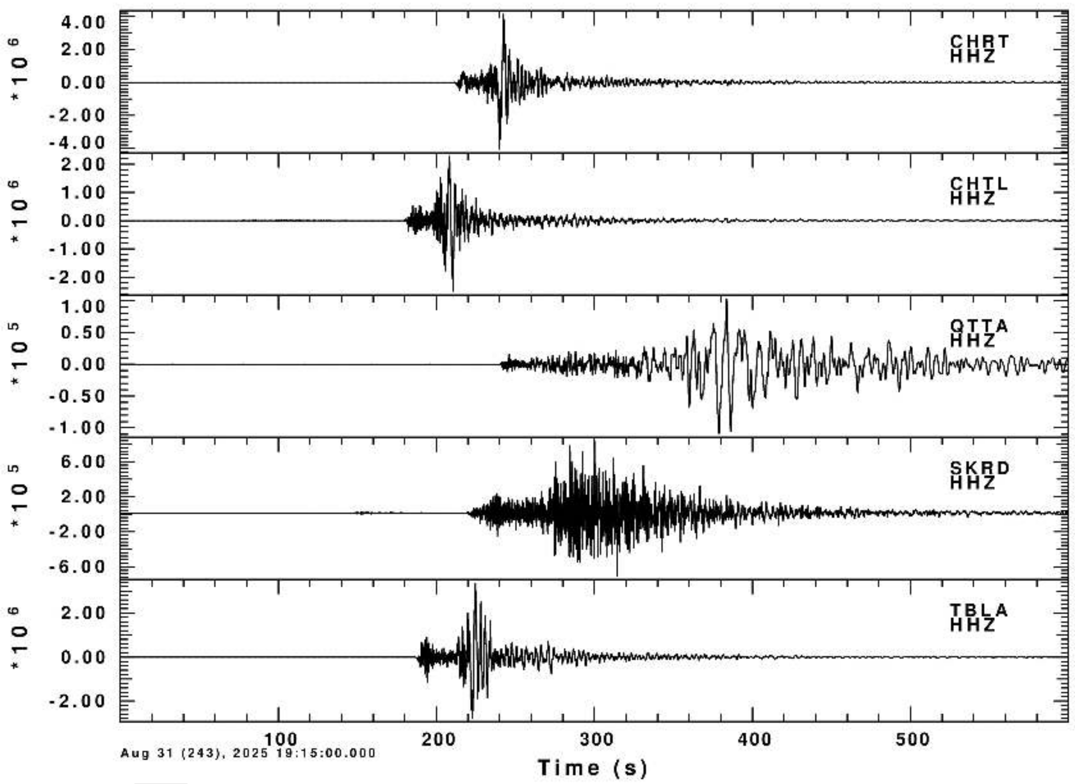

Figure 6a. Broadband vertical-component (HHZ) waveforms of the 31 August 2025 Mw 6.0 Asadabad earthquake recorded at regional stations (CHRT, CHTL, QTTA, SKRD, TBLA) across Pakistan. Clear, high-amplitude S-wave arrivals followed by prolonged coda are observed at epicentral distances spanning northern Pakistan, indicating efficient regional wave propagation from a shallow arc source. The extended duration and coherent amplitude decay are consistent with the widespread MMI V–VI shaking documented in northern Pakistan and highlight the strong transnational impact of this moderate-magnitude slab–arc earthquake within the Hindu Kush–Kabul system.

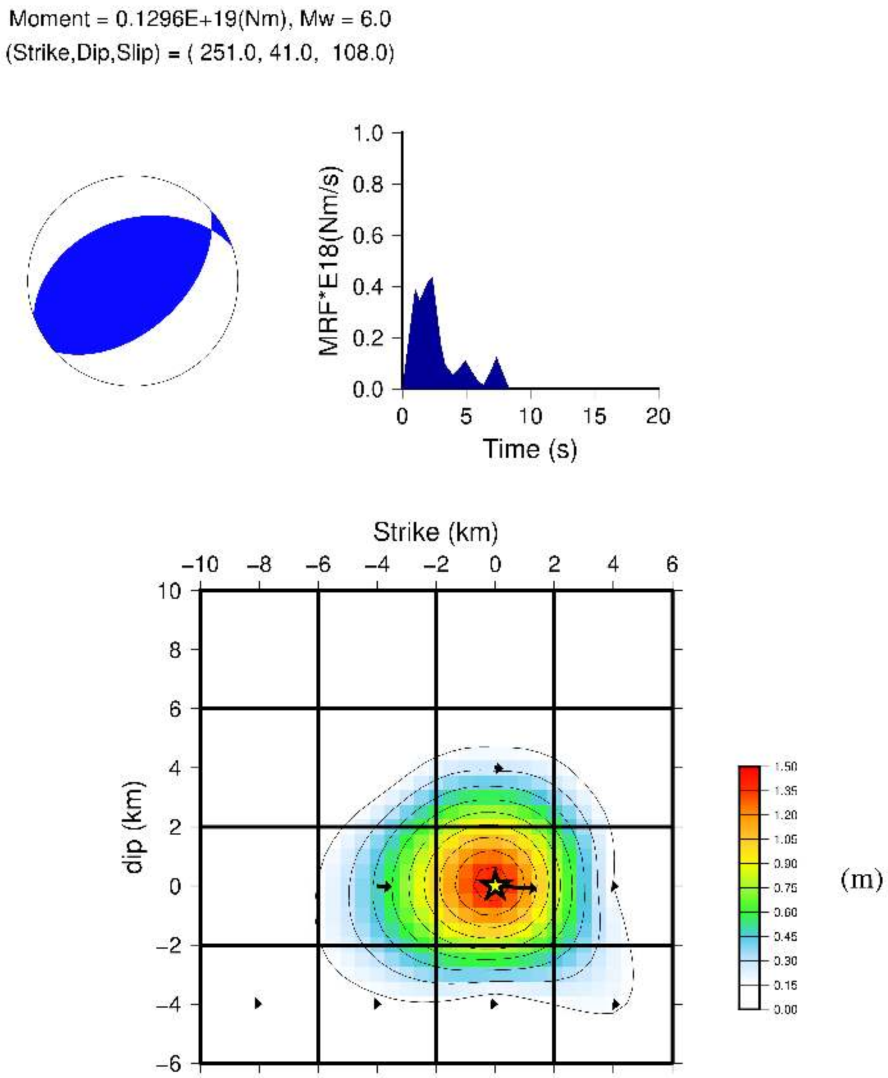

Figure 6b. Source mechanism, moment-rate function, and finite-fault slip distribution of the 31 August 2025 Mw 6.0 Asadabad earthquake. The focal mechanism indicates oblique reverse faulting (strike 251°, dip 41°, rake 108°) with seismic moment 1.30 × 10^{18} Nm (Mw 6.0). The moment-rate function shows a short-duration rupture (~8 - 10 s). The finite-fault model reveals a compact slip patch with maximum displacement ~1.5 m near the hypocenter, consistent with a shallow crustal rupture within the Hindu Kush - Kabul arc system.

Source inversion indicates that the 31 August 2025 Mw 6.0 Asadabad earthquake involved oblique reverse faulting within the Hindu Kush - Kabul arc system. The estimated seismic moment (1.30 × 10^{18} Nm) corresponds to a compact rupture with concentrated slip near the hypocentral region. The short-duration moment release and localized slip distribution are consistent with a shallow crustal event capable of generating strong regional shaking despite moderate magnitude.

4.2 Mw 4.8 Rawat Earthquake (15 February 2025)

The 15 February 2025 Mw 4.8 Rawat earthquake occurred southeast of Islamabad within the Himalayan - Kabul transpressional arc (Zone D). Although moderate in magnitude, the event represents an important example of shallow crustal deformation affecting a major urban corridor during 2025.

Moment-tensor inversion indicates predominantly oblique strike-slip faulting at ~11 km depth, consistent with partitioned India - Eurasia convergence along the active collision front. Strong-motion recordings at ISBA show moderate near-field shaking (PGA ~0.036 g; PGV ~2.3 cm s^{-1}) with dominant energy in the 0.5 - 5 Hz band, typical of shallow crustal sources. Modeled intensities reached ~MMI IV near the epicenter, with perceptible shaking across Islamabad - Rawalpindi and the Potwar Plateau.

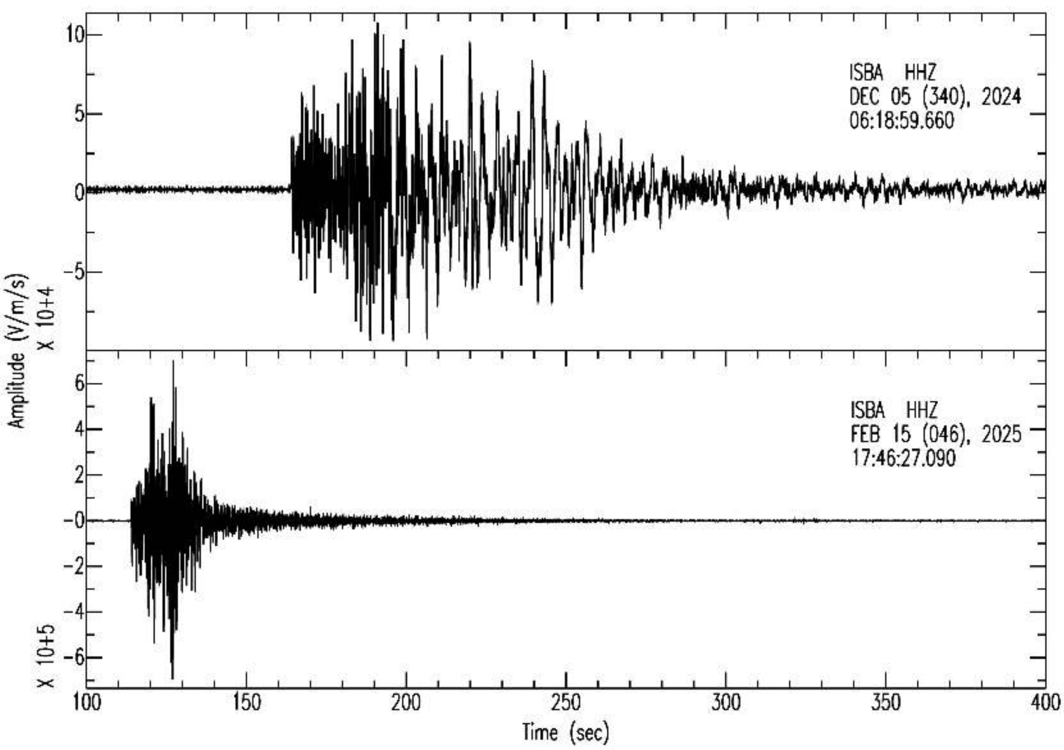

Figure 7a. Vertical-component (HHZ) broadband waveforms at ISBA for the Mw 5.2 Kharian earthquake (5 December 2024; upper) and the Mw 4.8 Rawat earthquake (15 February 2025; lower). The Kharian event shows higher peak amplitudes and longer coda, indicating greater moment release and sustained energy radiation, whereas the Rawat event displays lower amplitudes and shorter duration, consistent with a smaller, shallow crustal source within the Himalayan–Kabul arc.

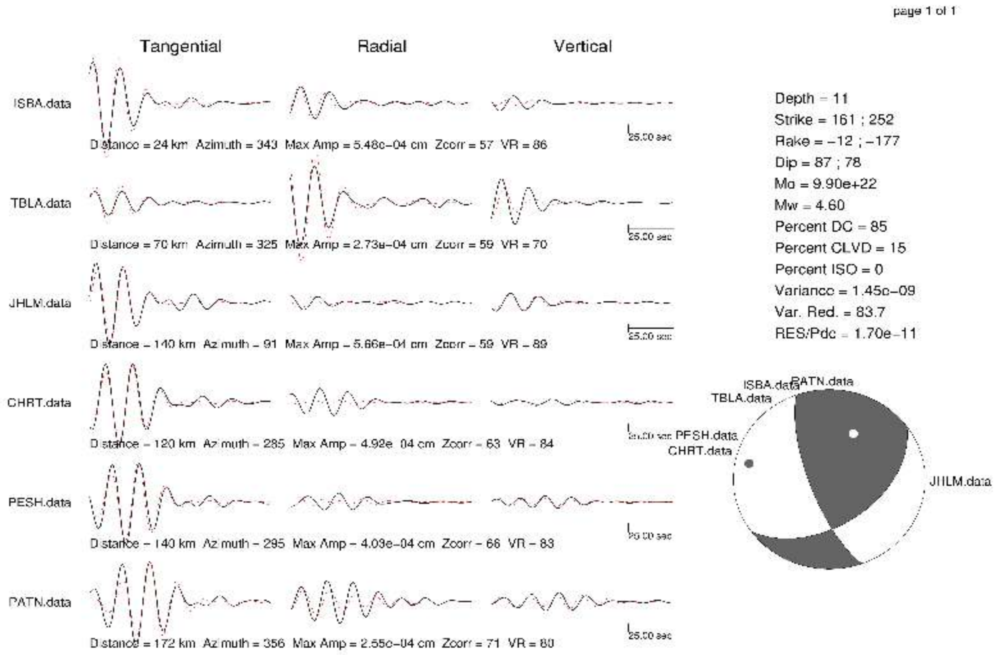

Figure 7b. Moment tensor solution and three-component waveform fits for the 15 February 2025 Mw 4.8 Rawat earthquake. Observed (black) and synthetic (red dashed) seismograms at regional stations (ISBA, TBLA, JHLM, CHRT, PESH, PATN) show good agreement, yielding an oblique strike-slip mechanism at ~11 km depth with 85% double-couple component and 83.7% variance reduction, consistent with a shallow crustal source within the Himalayan–Kabul arc.

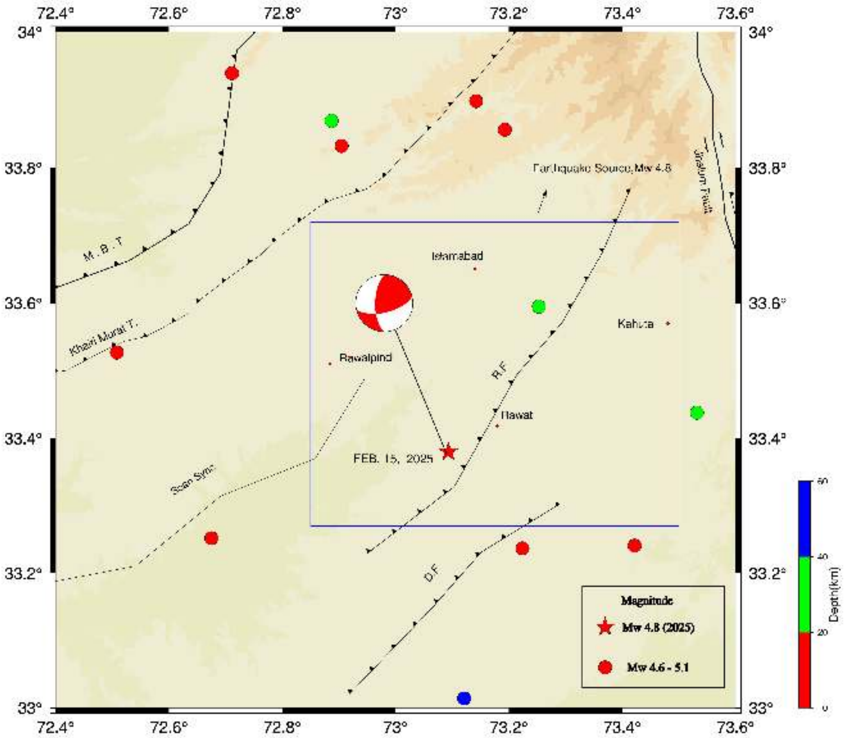

Figure 7c. Structural setting and local seismicity of the Mw 4.8 Rawat earthquake. The mainshock (red star) and surrounding events (color-coded by depth) are plotted with mapped

active faults near Islamabad. The focal mechanism is consistent with transpressional deformation within the Himalayan - Kabul arc (Zone D).

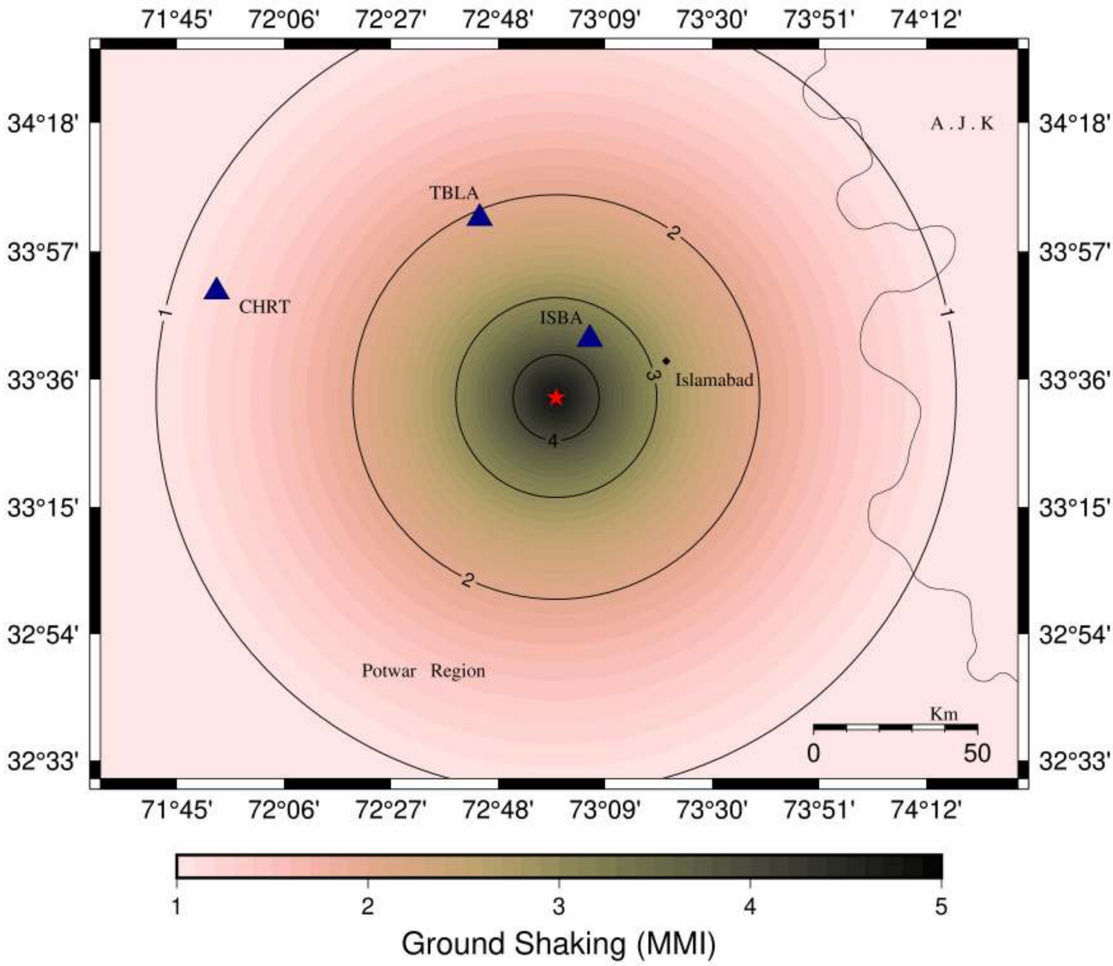

Figure 7d. Modeled ground shaking (MMI) for the 15 February 2025 Mw 4.8 Rawat earthquake. Maximum intensities of ~MMI IV occur near the epicenter, with perceptible shaking across Islamabad - Rawalpindi and the Potwar Plateau. Concentric decay patterns reflect attenuation typical of shallow crustal sources.

This event illustrates how localized crustal deformation, superimposed on the broader slab-dominated 2025 regime, can generate significant shaking within densely populated urban regions.

4.3 Karachi Microseismic Episode (June 2025)

A localized Mw 2.0 - 3.6 swarm occurred during June 2025 along the Malir - Quaidabad - Landhi corridor in eastern Karachi (Zone H). Although small in magnitude, this episode represents an important urban-scale manifestation of shallow crustal deformation within the broader Makran - Karachi tectonic domain.

The largest event (Mw 3.6) indicates predominantly oblique strike-slip faulting at shallow depth (~4 km), consistent with reactivation of a buried structure beneath the eastern Karachi basin. Broadband recordings at KCH1 show clear P - S arrivals with high signal-to-noise ratios and short-duration, high-frequency waveforms characteristic of shallow microseismic sources. Strong-motion parameters (PGA ≈ 24 cm s^{-2}; PGV ≈ 0.41 cm s^{-1}) confirm weak but well-resolved near-field shaking.

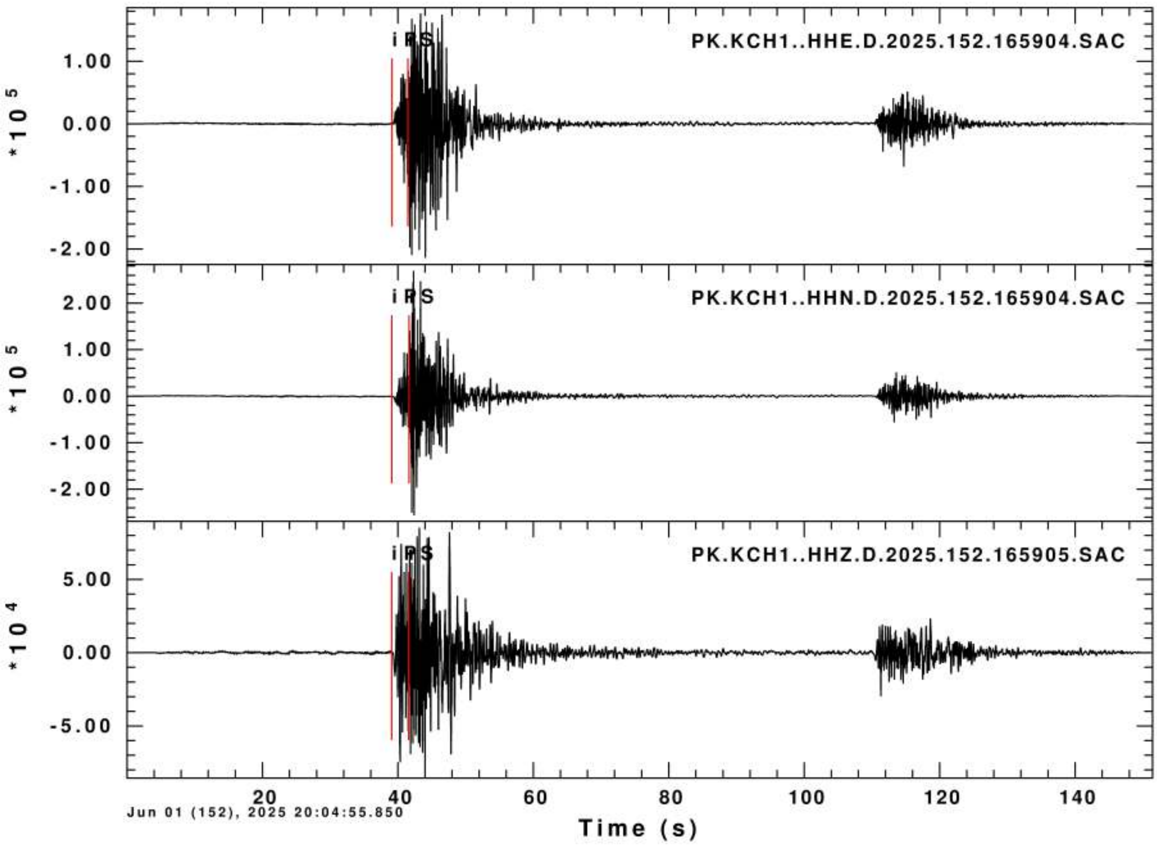

Figure 8a. Three-component broadband waveform of a representative June 2025 Karachi micro-earthquake recorded at station KCH1. Clear P - and S-wave arrivals and short coda duration indicate a shallow, high-frequency crustal source beneath eastern Karachi.

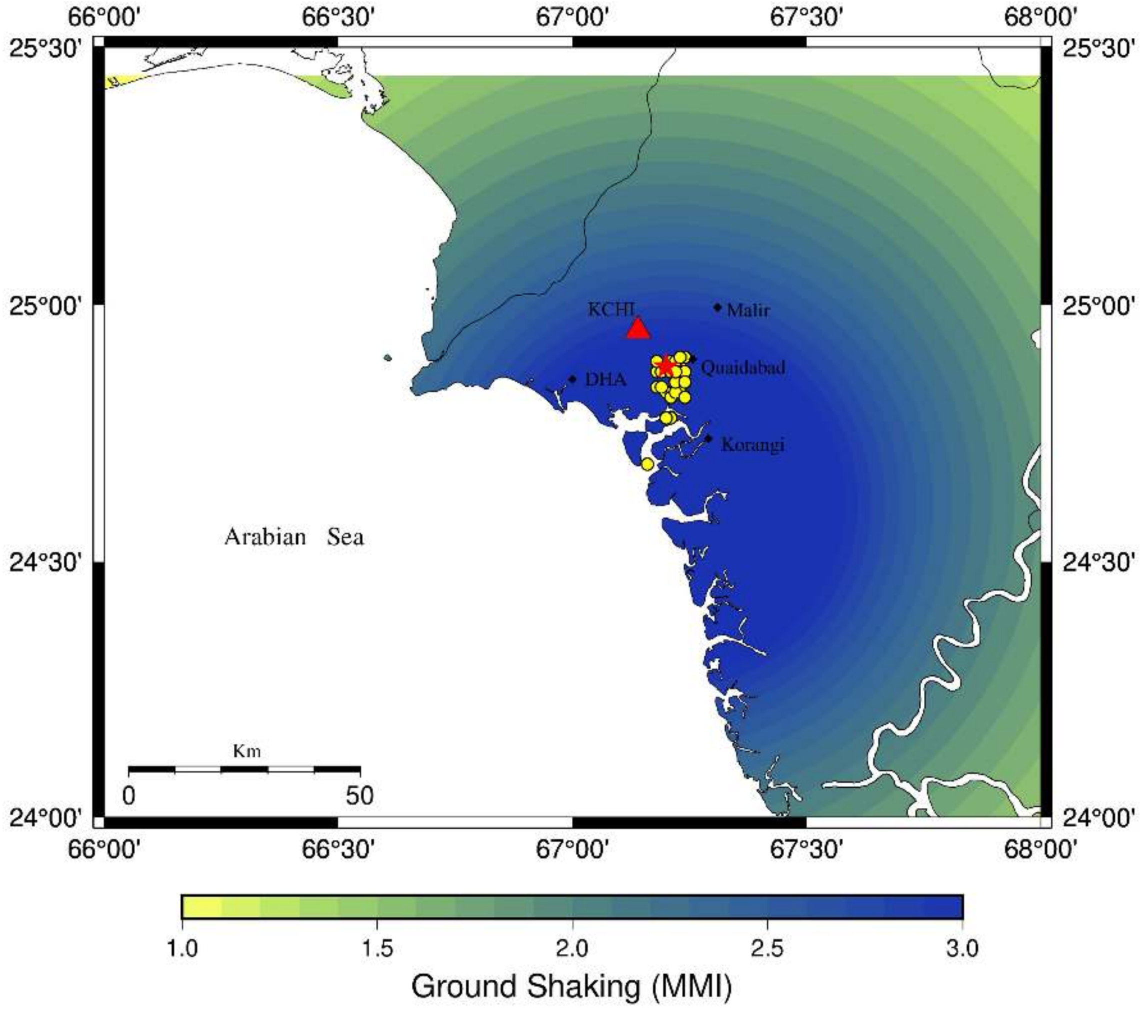

Figure 8b. Modeled MMI distribution for the Karachi - Malir microseismic event. Localized shaking (MMI ~2.5 - 3.0) is concentrated over Korangi - Quaidabad - DHA, reflecting basin-controlled amplification.

Modeled intensities remain low (MMI ~2.5 - 3.0), yet spatial patterns suggest localized sedimentary basin amplification across Korangi - Quaidabad - DHA. This swarm illustrates that, alongside slab-dominated regional deformation, 2025 seismicity also included persistent shallow microseismic activity affecting major metropolitan areas.

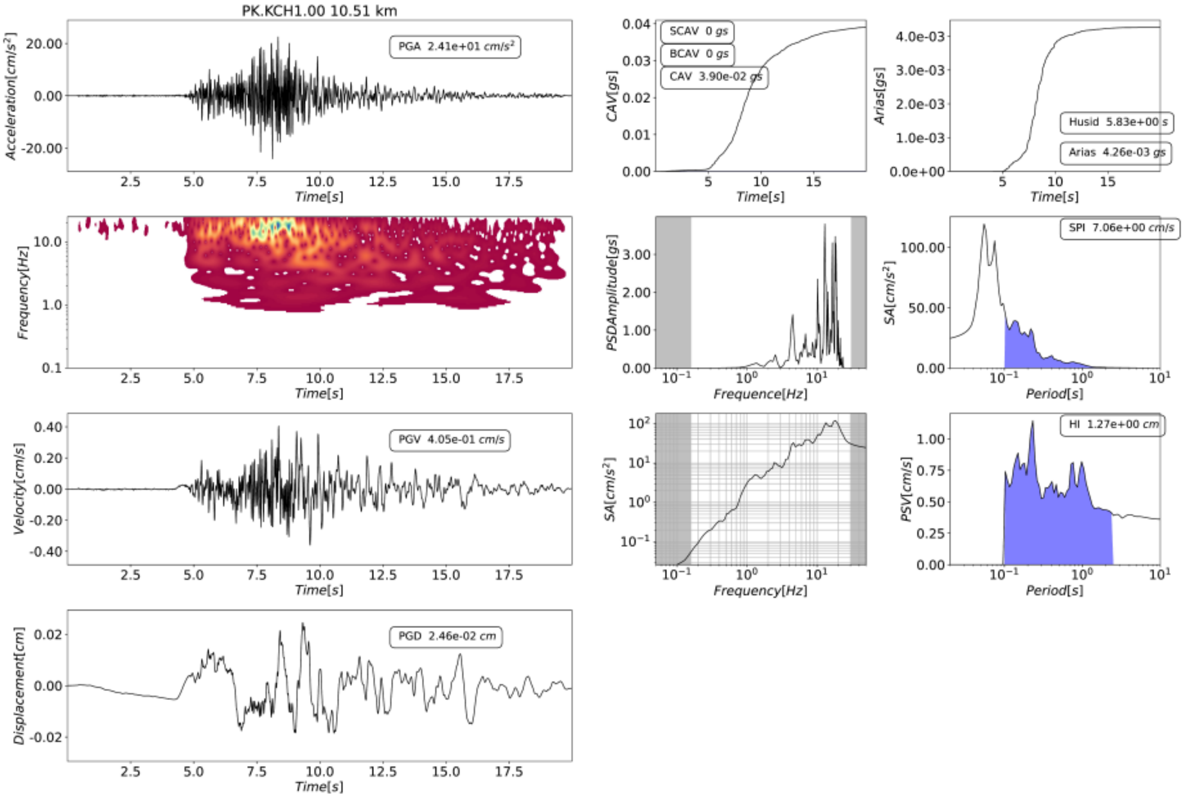

Figure 8c. Strong-motion characteristics of a June 2025 Karachi micro-earthquake (KCH1, ~10.5 km). Acceleration, velocity, displacement, spectrogram, CAV, Arias intensity, PSD, and response spectra indicate weak but well-resolved shaking dominated by ~1 - 10 Hz energy and short Husid duration (~6 s).

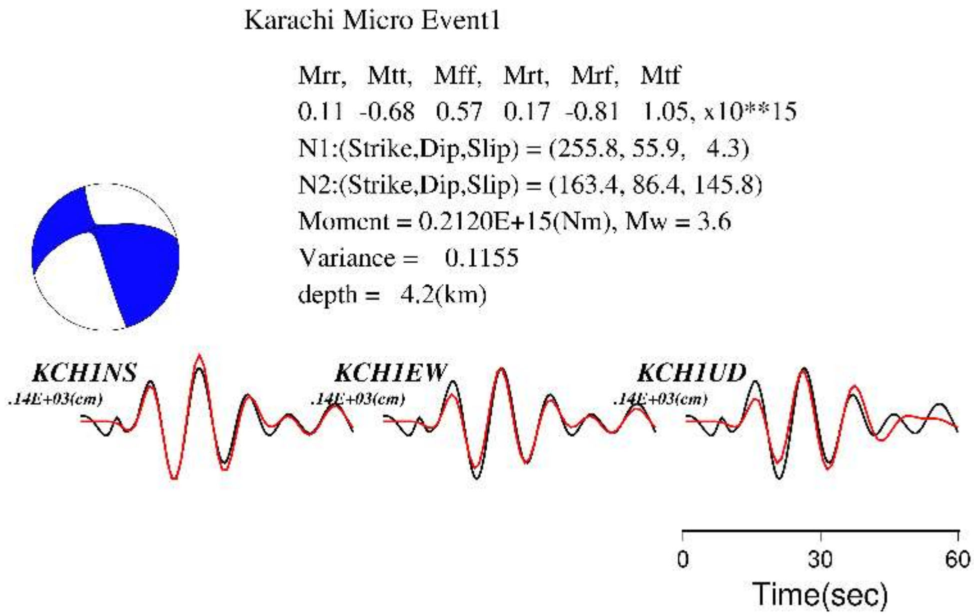

Figure 8d. Moment tensor solution and waveform fits for a representative Mw 3.6 Karachi micro-earthquake. The focal mechanism indicates shallow oblique strike-slip faulting (~4.2 km depth). Observed and synthetic waveform agreement supports a localized crustal source beneath the Malir - Quaidabad - Landhi corridor.

6. Long-Term Slab Context and Seismic Cycle

Seismicity in 2025 must be interpreted within the broader long-term behavior of the Hindu Kush slab. Historical records document multiple large intermediate-to-deep earthquakes (Mw ≥ 7) in 1983, 1985, 1993, 2004, and 2015, indicating episodic, decadal-scale slab deformation (Fig. 9).

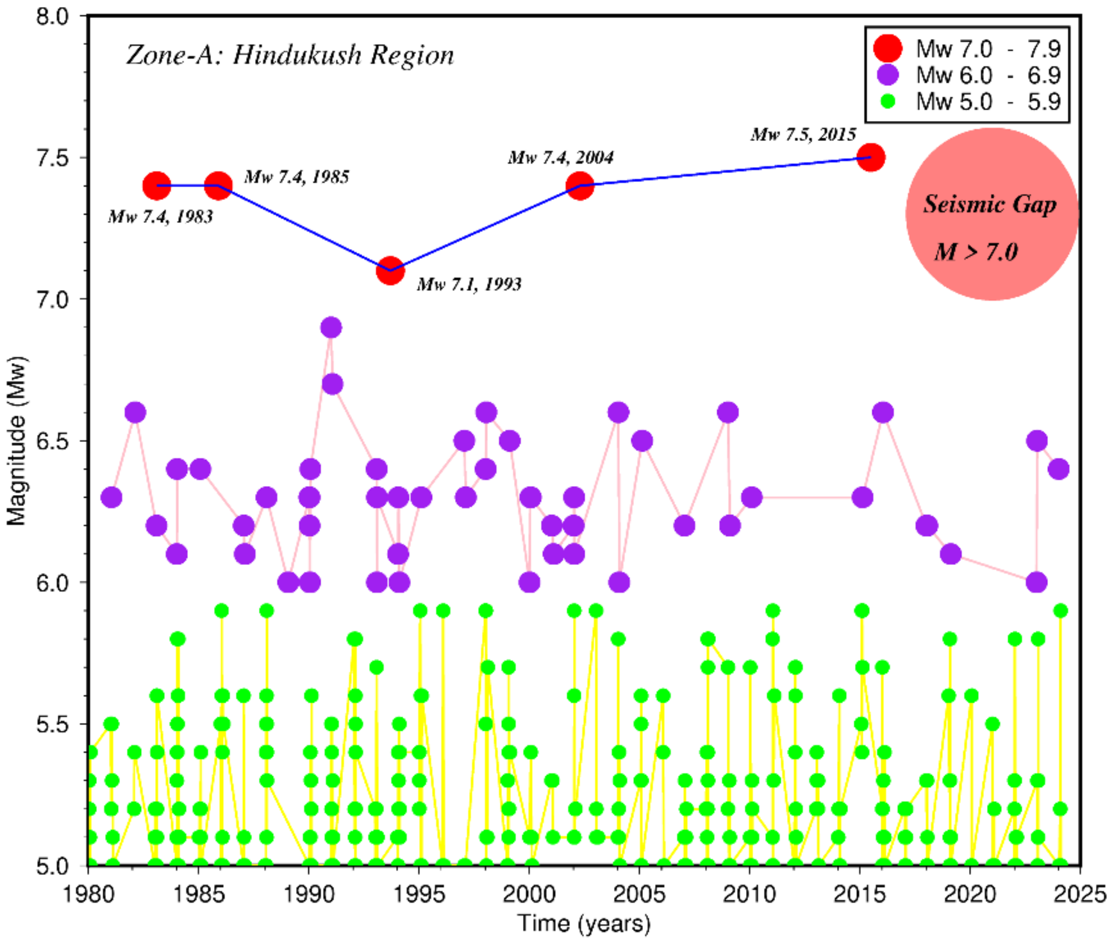

Figure 9. Long-term seismic cycle of the Hindu Kush slab (Zone A). Temporal distribution of Mw ≥ 7 earthquakes since 1980 illustrates episodic decadal-scale rupture. Moderate Mw 6 - 6.2 events in 2025 reflect continued slab re-loading.

The 2025 activity, including Mw 6.0 - 6.2 events, does not represent a major rupture phase but is consistent with continued slab re-loading following the 2015 large event. The slab-wide Gutenberg - Richter relation for 2025 yields a b-value of ~1.06 (Fig. 2c), suggesting a mechanically coherent and persistently stressed lithospheric slab.

The recurrence pattern of large Hindu Kush earthquakes is irregular rather than periodic, reflecting complex slab rheology and internal deformation processes. Moderate events in 2025 therefore represent ongoing stress redistribution within a long-lived, high-strain subducting lithosphere rather than an isolated anomaly.

7. Global Context

Seismicity in 2025 occurred within an active global plate-boundary framework (Fig. 10). Notable sequences included the 28 March 2025 Mw 7.7 central Myanmar earthquake within the Sunda - Burma arc system and the 30 July 2025 Mw 8.8 Kamchatka, Russia megathrust earthquake, followed by numerous large foreshocks and aftershocks along the northwest Pacific subduction margin. Additional Mw ≥ 6 earthquakes clustered along the Pacific "Ring of Fire," the Mediterranean - Himalayan belt, and major transform systems.

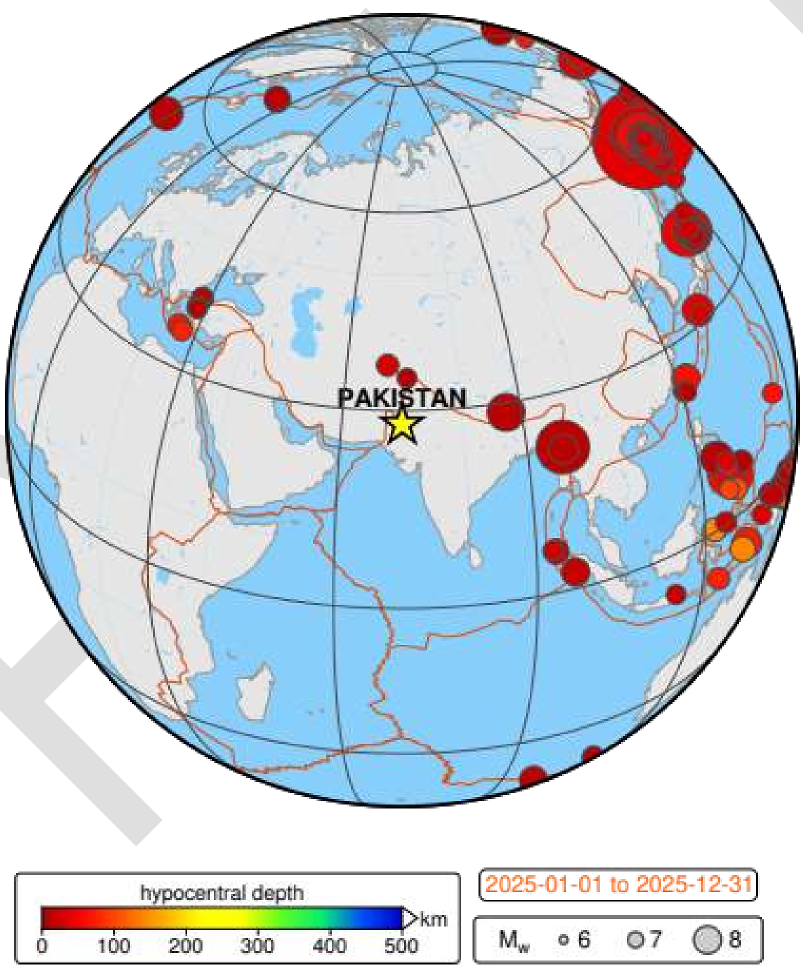

Figure 10. Global Mw ≥ 6 earthquakes during 2025. Major events cluster along subduction zones and collision belts, including the 28 March 2025 Mw 7.7 Myanmar earthquake and the 30 July 2025 Mw 8.8 Kamchatka earthquake sequence. Pakistan lies within the Indian - Eurasian convergence system, consistent with slab-driven regional deformation.

These global events reflect ongoing strain release along first-order plate boundaries and emphasize the dynamic nature of subduction-dominated tectonic systems. Pakistan lies within the Indian - Eurasian convergence zone, a major segment of the Alpine - Himalayan collision belt. The dominance of intermediate-to-deep slab earthquakes beneath the Hindu Kush in 2025 is therefore consistent with global subduction-related deformation patterns.

While no direct causal linkage is inferred, the occurrence of multiple large earthquakes worldwide highlights sustained plate-scale stress redistribution during 2025. Within this framework, Pakistan's seismicity represents a regional expression of continued Indian plate underthrusting beneath Eurasia, superimposed on active collision and transpressional crustal deformation.

8. Conclusions

Seismicity affecting Pakistan during 2025 was governed primarily by deformation within the deeply subducting Indian lithosphere beneath the Hindu Kush - Pamir region, with additional contributions from the Himalayan - Kabul transpressional arc and the Makran - Chaman - Sulaiman oblique plate-boundary system. The principal findings are:

1. **Slab-dominated strain release:** Intermediate-to-deep earthquakes in the Hindu Kush slab (Zone A) contributed >70% of Mw ≥ 4 events, confirming slab deformation as the dominant mode of seismic energy release during 2025.
2. **Mechanically consistent deformation across domains:** Agreement between GNSS velocities, focal mechanisms/moment tensors, and magnitude - frequency characteristics supports a coherent, plate-driven deformation regime linking slab processes with shallow arc and transform/collision tectonics.
3. **Persistent year-round seismicity:** Activity continued throughout 2025 with moderate temporal variability and episodic Mw > 5 earthquakes, indicating sustained regional loading rather than short-lived episodic activation.
4. **Transnational shaking footprint:** The 31 August 2025 Mw 6.0 Asadabad earthquake generated MMI V - VI shaking across northern Pakistan despite its Afghan epicenter, underscoring that damaging ground motion in Pakistan can be produced by slab - arc sources beyond national borders.
5. **Makran margin implications:** The comparatively low Makran seismicity during 2025 is compatible with spatially variable coupling and/or partial locking; short-term quiescence should not be interpreted as reduced long-term seismic or tsunami-genic potential.

Overall, the 2025 pattern demonstrates that Pakistan's hazard is strongly influenced by transnational slab-controlled sources superimposed on active shallow crustal deformation. Robust hazard assessment for major population centers—particularly Islamabad - Rawalpindi, Khyber Pakhtunkhwa

- Hazara, Azad Jammu & Kashmir, and key urban corridors along the western boundary—should therefore integrate intermediate-depth slab earthquakes with shallow crustal sources within a unified plate-tectonic framework.

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Appendix A – GNSS Quality Control and Residual Diagnostics

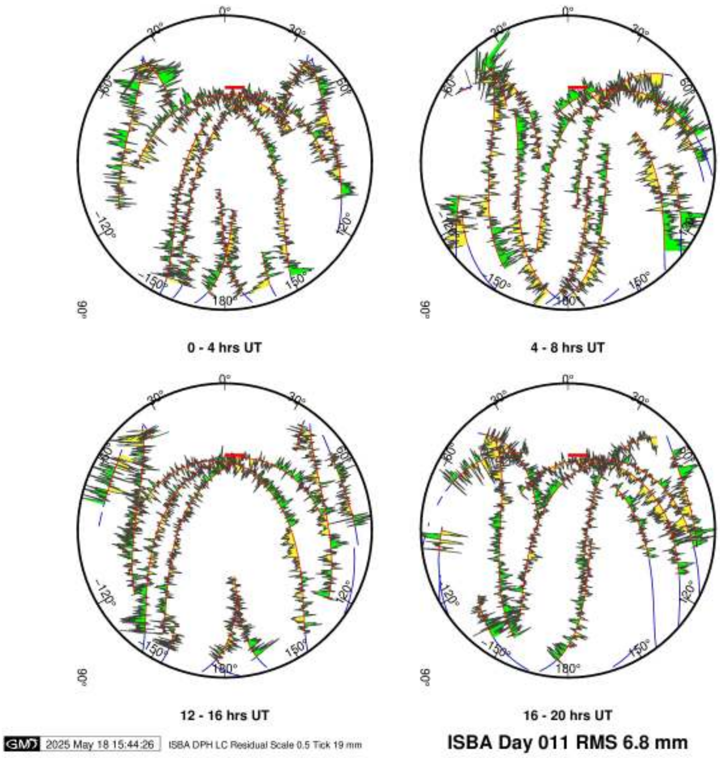

Figure A1. Daily GNSS residual sky plots (ISBA, Day 011; RMS 6.8 mm). *24-hour residual distributions shown in 4-hour UT intervals, demonstrating stable phase residuals and absence of systematic bias.*

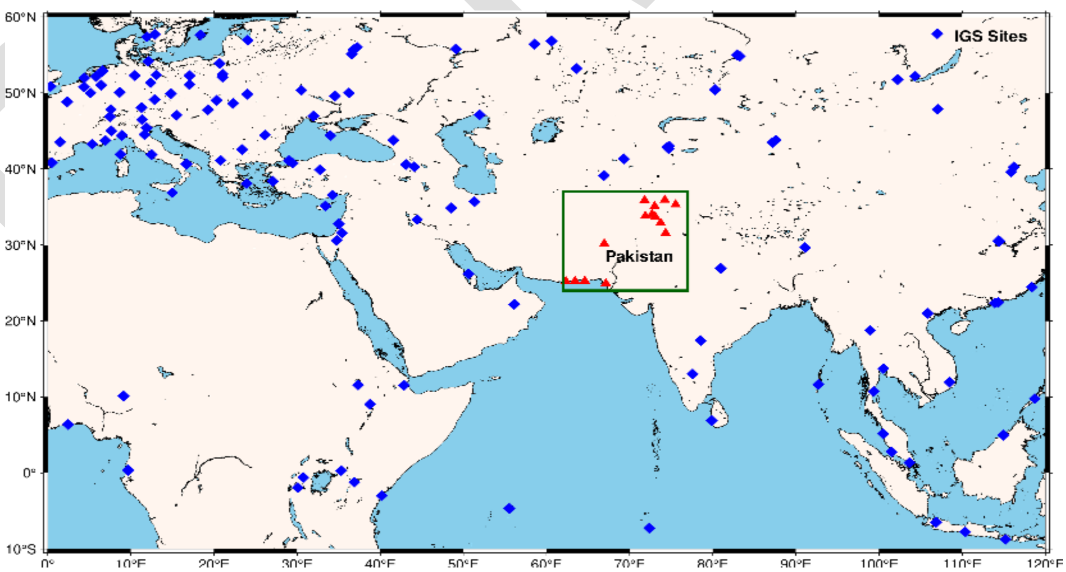

Figure A2. Regional GNSS network configuration. *IGS reference sites (blue) and Pakistan regional stations (red triangles) used in Eurasia-fixed velocity solution.*

Appendix B: **Supplementary Ground-Shaking Model**

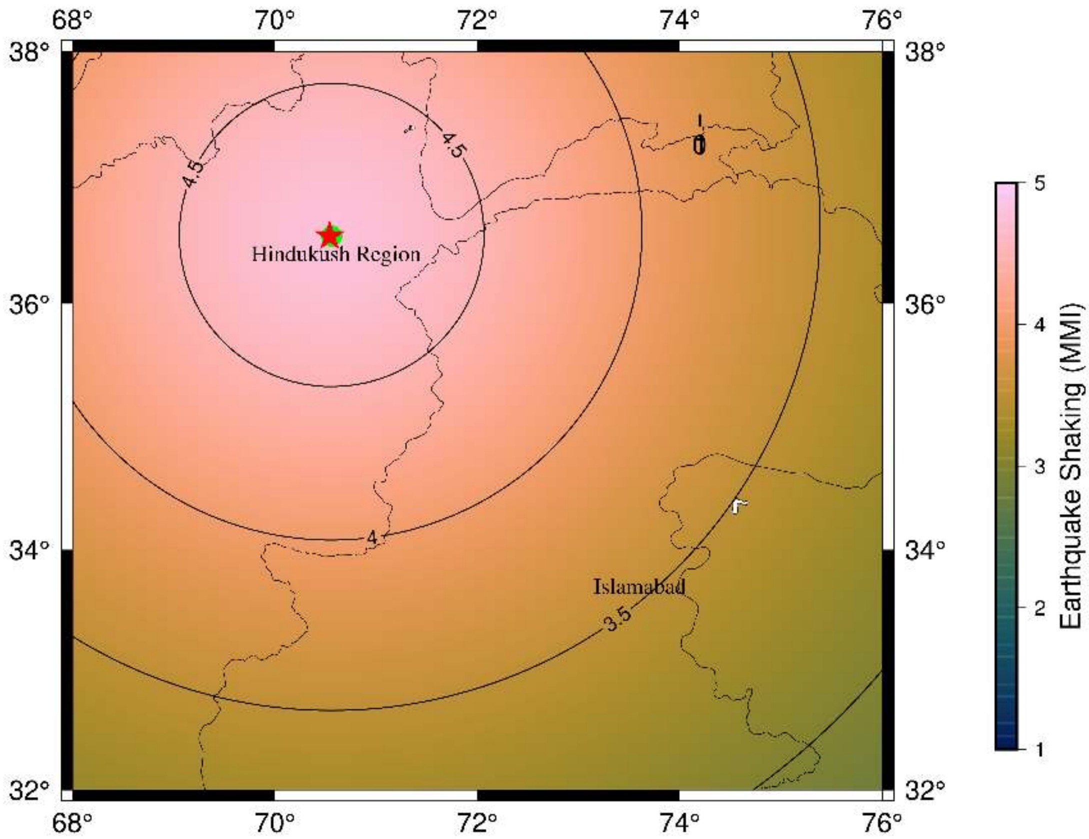

Figure B1. Modeled Modified Mercalli Intensity (MMI) distribution for a representative Hindu Kush slab earthquake affecting northern Pakistan. *The epicenter (red star) is located within the Hindu Kush region. Concentric intensity contours illustrate radial attenuation of shaking, with peak intensities (MMI ~4.5–5.0) concentrated near the source and gradual decay toward Islamabad and northern Punjab (MMI ~3–3.5). The smooth spatial gradient reflects regional wave propagation from an intermediate-depth slab source and highlights the broad transnational shaking footprint characteristic of Hindu Kush seismicity.*