



Book of Abstracts

**Earthquake Source:  
Mechanics, Seismology  
and Geology**

2026



NISER Bhubaneswar

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# **Strain, Seismicity and Hazards in the Himalaya**

# Strain map of the Himalayan region

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The Himalayan arc is amongst the most seismically active regions of the world, with the majority of earthquakes occurring along the Main Himalayan Thrust (MHT). A few seismic gaps have been identified along the arc, and the central seismic gap has not experienced a major earthquake in the past few hundred years, covering a significant portion of this area. Therefore, it is crucial to study the current strain accumulation rates along the arc. Several studies have employed Global Navigation Satellite System (GNSS) data to examine strain accumulation rates using dense networks; however, some regions still lack sufficient coverage. We utilized the most recent compilation of GNSS data along the Himalayan arc to obtain a more robust estimate of strain accumulation rates and their relation with seismicity in the region. Our analysis indicates strain rates ranging from ~70 to 100  $\mu\text{strain/yr}$ , with the principal axes predominantly reflecting compression across the arc due to the collision between the Indian and Eurasian tectonic plates. For seismic hazard assessment, we analyzed the correlation between geodetic strain rates and several factors, including seismicity, topography, and population density. We found a strong correlation between strain and seismicity, indicating that areas with high seismicity are also characterized by high strain rates. For hazard assessment, we propose that it is better to consider the locking map rather than the crustal strain map, as the former is derived from earthquake process-based modelling and the latter is only a surface effect of the former.

# Unraveling paleoshortening directions from leading edge of thrust sheets in an active orogen by integrating mechanical, kinematic inversion of slickenlines and penetrative strain: A case study from the Ramgarh thrust sheet, Darjeeling- Himalaya

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Slickenlines on fault surfaces are reasonable paleoshortening indicators in fractured rocks. Reconstructing spatio-temporal variation of paleoshortening directions in rocks recording prolonged deformation within active orogens is challenging due to difficulty in ascertaining relative timing among fracture-sets, genetic association with larger structures, reactivation, heterogeneity, non-coaxiality, overburden, footwall structure growth. Mechanical inversion treats slickenlines as finite deformation markers (Angelier, 1984), while kinematic inversion as incremental strain markers (Marrett and Allmendinger, 1990). We estimated penetrative strain from quartz grains to test the more suitable approach for reconstructing progressive deformation. The Ramgarh thrust (RT) is the roof thrust of the lower Lesser Himalayan duplex with ~58-65 km translation and folds into a thrust-related antiform at its leading-edge (Bhattacharyya et al., 2015; Parui and Bhattacharyya, 2018). We deciphered a first-order relative timing among the fracture-sets from the RT zone upto ~3.4km into the RT sheet and established that fracturing progressed from low-angle, shear, to high-angle, opening mode and shear fractures (Ammu and Bhattacharyya, 2025). We analyzed fault-slips from the same rocks and used PBT analysis suite, Win\_Tensor (Delvaux and Sperner, 2003), Linked Bingham distribution analysis tool, FaultKin (Allmendinger et al., 2012), strain ellipsoid Mathematica to reconstruct paleoshortening directions.

The RT fault, oriented ~72°, 304°, along a cross-section (~130-310°) has a top-to-the south vergence. Fault-slips (n=208) record normal (~61%), inverse (~39%), sinistral (~54%), dextral (~46%), oblique- (~74%), dip- (~18%), and strike- (~8%) slip movement, representing heterogeneous population. Fractures exhibit spatial variation of intensity, orientation, and slip-sense with increasing distance from the fault. We segregated heterogeneous fault-slip data into fourteen homogeneous subsets which formed during pre-, syn-, and post-folding. Pre-tilting deformation is characterized by low-angle, layer-parallel shortening. With progressive thrust-related folding and tilting, axial and transverse extension, and strike-slip fault-slips formed at high angles to bedding. Present-day regional shortening signatures are recorded at the post-folding state, but are not the most dominant. Penetrative strain indicates that strain initiated before thrusting and folding of the sheet.

**Keywords:** Fault-slip, paleostress, strain

# Geodetic insights to the Himalayan megathrust kinematics unravel increased earthquake hazard

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Subduction zone megathrusts host many of the largest and most damaging earthquakes through release of strain energy accumulated over centuries. Unlike oceanic subduction zones, continental megathrusts, such as the Himalayas, are easier to monitor because they occur on land. Measurements of both horizontal and vertical surface displacements allow for rigorous estimation of the moment deficit and the spatial distribution of fault locking. Earlier Himalayan studies mostly relied on horizontal velocities from Global Navigational Satellite Systems, leaving details of how the megathrust transitions from locked to steady interseismic creep poorly constrained. We present new observations of surface deformation from interferometric synthetic aperture radar for approximately 800 km along Himalaya. The interseismic velocity field along arc-perpendicular transects suggests a 5-8 mm/yr uplift in the higher Himalayas. We employ an Elastic Subduction Plate Model (ESPM) based approach to model the vertical and horizontal deformation data as elastic response of the medium to frictional locking along the Main Himalayan Thrust (MHT) and a smooth transition to the underthrusting rate of the Indian plate. The width of transition from frictional locking to creep is modelled as a stress-free crack within this model framework. We infer that the megathrust accommodates 20-22 mm/yr convergence over a width of ~115 km from the frontal thrust followed by a ~40 km transition zone. Sufficient strain has accumulated over the past five to seven centuries in the central seismic gap that could be released by two Mw 8.8 earthquakes.

**Keywords:** Interseismic deformation, InSAR, Himalaya, plate coupling, seismic hazard

# **The role of Himalayan deformation and structural architecture in understanding Himalayan Seismic Hazards**

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The Himalayan mountain belt is an active fold characterised by a basal decollement known as the Main Himalayan thrust. Slip along the basal decollement has been the crux of Himalayan deformation, resulting in the generation of Himalayan topography through the emplacement of in-sequence thrust sheets since ~55 Million Years Ago. The hinterland of the Himalayas has been uplifted to more than 8 km above mean sea level. Parts of this topography continue to be uplifted along the active Lesser Himalayan duplex, which has evolved as the dominant active structure in the Himalayas. This Himalayan structural architecture is the key to understanding the topographic development and associated natural hazards, such as earthquakes. This paper examines the relationships between Himalayan deformation, topography development, and associated seismic natural hazards in the Himalaya, within the context of how Earth's surface processes and deformation kinematics interact. Understanding these connections and incorporating them into developmental activities is key to achieving sustainable development in the Himalayas.

# **Locked Frontal and Lateral Ramps on the Main Himalayan Thrust beneath NW Himalaya illuminated by precisely located seismicity**

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The Kashmir 'seismic gap' in the NW Himalaya, between the 1905 Kangra and 2005 Muzaffarabad earthquake rupture zones, has been replete with moderate-to-small earthquakes. GPS geodetic measurements across the Himalayan arc reveal arc-normal convergence of  $\sim 11$  mm/yr, which decreases towards the foreland in the India-fixed reference frame. In 2013, the Jammu And Kashmir Seismological NETWORK (JAKSNET) and later the Himachal Pradesh Seismological NETWORK (HiPSNET) were established to study the seismological characteristics of this 'seismic gap'. Using continuous waveform data from these networks, an earthquake catalog has been created using the Regressive ESTimator (REST) algorithm. Following this, seismic phases were manually checked for  $\sim 1100$  earthquake records to determine the accurate arrival-times. A subset of these events, based on the quality of picked phases, is relocated using a probabilistic Non-Linear Location (NLL) method. These earthquakes have magnitudes between 0.5 and 4.5 and are distributed throughout the crust, with the majority concentrated at shallow depths ( $< 25$  km). These shallow earthquakes are concentrated beneath the Higher Himalaya with lateral variations south of the Kishtwar window and in a region to its east. In arc-normal cross-section, the hypocenters lie on and above the MHT, and the depth increases hinterlandward. Two distinct clusters of seismicity with increasing depth coincide with the mid-crustal frontal ramp observed in Vs structure beneath the Kishtwar window. The arc-parallel cross-section shows two eastward-dipping dipping hypocenter-clusters on and above the MHT. The one west of the Kishtwar window coincides with the lateral ramp observed in the Vs model. We conjecture that the one to the east also illuminates a similar transverse structure within the Himalayan wedge. Comparison of our hypocentral distribution with GPS velocities across this region reveals a frictionally locked shallow segment of the MHT, with the down-dip unlocking-zone highlighted by the across-arc clustering of seismicity beneath the Higher Himalaya. The locked-to-creep transition occurs immediately north of the mid-crustal frontal ramp. We compute strain-rate from the sparse GPS data, which reveals a predominant NE-SW compression and high strain-rates in regions of clustered shallow-seismicity.

# Earthquake hazard in the Himalaya: Lessons learnt from recent earthquakes

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The tectonically active Himalayan mountains have produced some of the most devastating earthquakes in the recent past, viz. Kangra (1905), Assam (1950), Uttarkashi (1991), Chamoli (1999), Kashmir (2005), Sikkim (2011) and Nepal (2015). These earthquakes have caused enormous loss of lives and property, highlighting the vulnerability of civilizations in areas where major earthquakes occur. More than a sixth of the world's population live in India. This population is growing rapidly and is accompanied by rapid urban development in regions of high seismic hazard. Recent advances in instrumentation and computational techniques have enabled geoscientists, particularly seismologists, structural geologists and tectonic geomorphologists, to better understand active faults, earthquake source properties, seismic velocity structure and attenuation of seismic energy. This knowledge is used to quantify seismic hazards in the Himalaya and the adjoining Indo-Gangetic plains, the most densely populated regions of the country. I will present studies of recent moderate-to-major Himalayan earthquakes from this century (eg. 2005 Kashmir, 2011 Sikkim, 2013 Kishwar and 2015 Nepal) and how this knowledge should be incorporated in estimation of future seismic hazard.

# Probabilistic Seismic Hazard Assessment of Himalayan region Using Zoning, Zone-Free and Moment Slip Approaches

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The Himalayan arc, located in the northernmost part of the Indian subcontinent, forms a key segment of the extensive Alpine–Himalayan convergent tectonic belt and is one of the most seismically active regions in the world. The region has experienced several strong to moderately strong earthquakes in the past. Considering its active seismic regime and the rapid developmental activities underway in the mountainous states, updating seismic hazard knowledge using the latest insights on earthquake occurrence and ground-motion attenuation is essential.

This study aims to generate updated PSHA information for the northwest and central Himalayan region by employing multiple methodological approaches. The adopted procedures incorporate improved magnitude conversion techniques, updated ground-motion prediction equations, and three different hazard computation methods: Cornell's (1968) zoning method, Woo's (1996) zone-free method, and Bungum's (2007) moment-slip method. Seismic activity rates were estimated following the techniques proposed by Cornell, Bungum, and Woo, while standard probabilistic empirical relations were used for hazard assessment. Peak ground accelerations (PGAs) were computed at the centers of grid points for return periods of 475 years and 2475 years (corresponding to 10% and 2% probability of exceedance in 50 years) using new-generation attenuation relationships.

In the zoning method, seismogenic zones were delineated by integrating earthquake clustering with tectonic characteristics, and zone boundaries were defined based on natural breaks in seismicity and structural features. The zone-free method employed kernel density estimation to derive spatially varying seismicity rates, where the anisotropic kernel parameters influenced the elongated shape of predicted hazard zones, aligning them with Himalayan structural trends. The moment-slip method estimated mean annual earthquake occurrence rates from fault slip parameters, resulting in comparatively higher ground motions due to uncertainties in fault length, which increase the estimated maximum magnitude.

For the 2475-year return period, the zoning approach estimated maximum PGAs of 0.545g–0.597g in western Nepal, northeastern Himachal Pradesh, and parts of Tibet and the Kashmir valley. The zone-free method predicted PGAs of 0.547g–0.609g in the Kashmir valley, eastern Uttarakhand, and western Nepal. The moment-slip method predicted higher PGAs of 0.687g–0.749g in western Nepal.

Overall, the bedrock-level ground motions estimated for Maximum Considered

Earthquake (MCE) and Design Basis Earthquake (DBE) conditions appear consistent with the expected seismic potential of the Himalayan tectonic belt.

**Keywords:** Himalaya; PSHA; Seismogenic Zones; Zone-Free Method; Moment-Slip Method

# Constraints On The Lithospheric Deformation In Northwest Himalaya Using Core-Mantle Boundary Refracted Shear (SKs) And Direct Shear (S) Waves

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The study of seismic anisotropy provides a first-order understanding of deformation in the crust and the upper mantle. The tectonically active Himalayan orogen, a region of tectonic activity, serves as a prime natural laboratory for the study of ongoing continent-continent collisional processes and the geodynamic evolution of the region. We investigate the pattern of seismic azimuthal anisotropy beneath the northwest Himalaya using an unprecedented broadband seismic dataset from 15 stations of the JAKSNET network. The quantification of azimuthal seismic anisotropy is achieved through core-mantle refracted shear waves (SKS) and direct S- waves (S). The subsequent interpretation of these results aims to elucidate the prevailing geodynamics. The SKS splitting parameters (fast polarization azimuth and delay time) are estimated using the Rotation-Correlation and the Minimum Transverse energy method, from 2323 ray paths with  $M_w > 5.5$ . The analysis yielded 205 non-null and 131 null splitting measurements. The limited backazimuthal distribution of the SKS dataset is compensated for by analyzing the direct S waves using the reference-station technique in which the SKS splitting results serve as the a-priori receiver-side measurements

beneath the reference station. The issue of receiver-side splitting is addressed by implementing the inverse a-priori splitting measurements at the reference station. Assuming that the source-side anisotropy is identical for both the reference and the target station, a grid search on the splitting parameter space is performed to identify the maximum waveform similarity between the target station and the receiver-side splitting-corrected reference station seismograms. Therefore, the splitting parameters that maximize the similarity correspond to the condition where the target station seismograms only contain the source side anisotropy. This condition allows for the isolation and recovery of the receiver-side anisotropy beneath the target station. In comparison to the 336 SKS ray paths, 1383 S ray paths contributed to the station-averaged splitting estimates. The results from both the methods demonstrate a coherent deformation fabric in the NW Himalaya with fast axes predominantly aligned in the direction of the Indian Absolute Plate Motion vector. Nevertheless, a comparison

of the splitting studies from the central and the eastern Himalayan sectors reveals lateral variation in the mean splitting orientation, ranging from NE (in the NW sector ) to ENE (in the eastern sector). Our findings provide new constraints on the geometry and mechanical segmentation of the deformation field, offering valuable insights into the tectonic evolution and mantle structure of the Northwest Himalayan orogen.

**Keywords:** Northwest Himalaya, Seismic anisotropy, lithospheric deformation, SKS splitting, direct S splitting

# Co-seismic Source Radiation Characteristics for the March 2025 Myanmar Earthquake through Temporal Polarity Effects

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On March 28 2025, a shallow earthquake measuring 7.7 Mw struck the Sagaing fault (N S) located on the Burma microplate. This event released a portion of the strike-slip motion along the central-south segment of the Sagaing Fault. This earthquake is particularly notable as initial research in multiple sub-event models suggests that the last phase of the mainshock ended in an oblique-slip mechanism, arresting the rupture. This 3rd subevent has a consistent super-shear rupture velocity signature. Laboratory experiments have confirmed that super-shear speeds can manifest in all types of fault systems. While evidence for super-shear velocities is plentiful in nature among strike-slip faults, it remains insufficient when it comes to dip-slip faults. The frequency-dependent radiation pattern in the longer periods is associated with higher amplitudes in the source-time function and cumulative energy release, in the multi-array back-projection results.

The study aims to utilize the polarity effects of the co-seismic phase across time-averaged intervals to deduce whether the ground motions are characteristic of a dip-slip fault. To compare and contrast how polarity distribution varies over time, a time window range of 10 seconds was chosen to obtain the average amplitudes of the seismogram traces from 0 to 100 seconds. The averages are further classified into dilatational or compressional, subsequently filtered through a series of cutoffs to improve spatial resolution and incur an accurate representation. Good azimuth coverage and large takeoff angles are of high priority so that the body wave signature can be better isolated for temporal polarity analysis. Refined investigation of the azimuthal effects, especially the statistical relevance, is to be established to differentiate the dip-slip signature from the predominant strike-slip fault dynamics.

**Keywords:** Mw 7.7 Myanmar Earthquake, super-shear rupture, polarity effects, fault dynamics

# Constraining the Crystallographic Vorticity Axis Using Kernel-Scale Orientation Dispersion in Mineral Phases: Implications for Reconstructing Progressive Deformation Events

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Recently, a new method for determining the position of a Kernel-scale orientation of vorticity axis using intragranular crystallographic orientation data has been proposed (Kruckenberg et al., 2019). These axes are quantified from electron backscatter diffraction (EBSD) data using crystallographic orientation statistics (Michels et al., 2015) from a thin section of a deformed monomineralic as well as polymineralic rock. The calculations of Crystallographic Vorticity Axis (CVA) is involved applying a 3×3 matrix of orientations that is used to capture grid-scale variations in lattice orientation of a mineral phase. This methodology enables structural geologists to confidently identify vorticity-normal surface from lattice rotation axes.

A polycrystalline rock deformed under ductile conditions contains mineral phases that exhibit crystallographic distortion, as indicated by microstructural evidence of kinking, undulose and patchy extinction, and subgrain formation. In such plastically deformed grains, crystallographic orientations are typically dispersed along small circles on a stereographic lower hemisphere equal-area projection. It can be considered that an intragranular dispersion axis aggregated from many grid-scale calculations can be analyzed to calculate a preferred vorticity axis. This method utilizes rotational statistics, specifically principal geodesic analysis, to determine a single optimal rotational axis that aligns with the rotational dispersion of the crystallographic orientations of a deformed grain (Michels et al., 2015). In this study, we determine the preferred dispersion axis for each constituent phases of a polished thin section of a deformed quartzofeldspathic mylonite, using kernel density estimation with a de la Vallée Poussin kernel and a 10° halfwidth. This procedure calculates the orientation density (i.e., multiples of uniform density) of a population of axes relative to an orientation grid-space.

The bulk CVA plots, which considers all mineral phases in a polycrystalline rock, reveal similar deformation geometries across different field sites, primarily dominated by the quartz CVA as quartz is the dominant mineral phase in our samples. However, the CVA data generated from other constituent mineral phases (plagioclase, orthoclase, albite, micas, and garnet) reveal how the flow kinematics evolved over time, from triclinic pure shear to monoclinic pure shear-dominated deformation. While quartz and anorthosite consistently record monoclinic simple-shear. Our study indicates that mineral-fabrics corresponding to different constituent mineral phases in

a large-displacement shear zones under mid-crustal conditions may form at different times during the progressive evolution of the shear zone.

**Keyword:** EBSD, Shear zone, Vorticity axis

**References:**

1. Kruckenberg, S. C., Michels, Z. D., & Parsons, M. M. (2019). From intracrystalline distortion to plate motion: Unifying structural, kinematic, and textural analysis in heterogeneous shear zones through crystallographic orientation-dispersion methods. *Geosphere*, 15(2), 357-381.
2. Michels, Z. D., Kruckenberg, S. C., Davis, J. R., & Tikoff, B. (2015). Determining vorticity axes from grain-scale dispersion of crystallographic orientations. *Geology*, 43(9), 803-806.

# Complex deformation of India-Eurasia collision zone: Insights from Anisotropy, stress and strain rate

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The collision of the Indian -Eurasia plate forms a one of the most extensive continental deformation zones, the Himalayan-Tibetan Collision Zone (HTCZ). Previous studies [e.g., Ghosh et al., 2008; Singh & Ghosh, 2019] explored the dynamics of this region by examining two main stress contributors: topography and crustal density structure, and basal tractions due to density-driven mantle convection. These studies had used strain rates, plate velocities, and SHmax directions from the World Stress Map database to constrain the relative importance of these two primary sources of stress in the region. With the availability of high-resolution full waveform regional (Liu et al., 2024) and global (Solvi et al, 2024) tomography models and latest geodetic data, we can gain greater insight into the complex dynamics of this region. Abhirami et al. [2025] have shown that stress and strain could be related in an anisotropic manner in various parts of the HTCZ. Recent seismic anisotropy observation of SKS splitting parameters can help us understand the deformational history of the region. In this study, using global mantle convection models, we re-visit the sources of stress in this region by incorporating the constraints of SHmax directions, strain rates, GPS velocities and SKS splitting observations.

**Keywords:** Complex deformation, anisotropy, HCTZ, stress

# **An integrated geological and geophysical model of the Rampur Tectonic Window: Implications for seismic hazard**

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The Rampur-Bushahr region in Himachal Pradesh hosts the Rampur Window, where the Lesser Himalayan metasediments are exposed amongst the high-grade metamorphic rocks of the Upper Himalayan Crystalline sequence. Tectonic windows may form by erosion of overlying thrust sheets, anticlinal uplift, or duplex formation, possibly enhanced by foreland ridge interactions (e.g., the Delhi Ridge) and tectonic denudation along ramps. Despite being documented, the kinematic evolution and structural relationship of the Rampur Window with the MHT remain poorly constrained. Understanding its subsurface architecture and its relation to the Main Himalayan Thrust (MHT) is essential for assessing strain partitioning and seismic hazard in this segment of the Himalayas.

This study integrates multiple geophysical datasets—including gravity, seismic tomography, seismicity, and topography with surface geology to model the geometry of the Rampur window, using both surface geological data and geophysical data through integrated geophysical petrological modelling using LitMod2D 2.0. The integrated analysis enabled us to create a detailed cross-section of the window and derive the depth-dependent variation of Temperature, density, and P and S wave velocities. The findings are then utilised to draw a contrast with the adjacent regions of the Kishwar Window on the West and the Garhwal Himalayas on the east, highlighting along-strike variations in thrust architecture. The findings will advance our understanding of the accommodation of Himalayan strains and contribute to improved assessment of seismic hazards in the region.

**Keywords:** Integrated geophysical modelling, strain partitioning, seismic hazard

# Modelling the Coseismic Phase of the Earthquake Cycle using the Burridge Knopoff Model

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Large earthquakes release accumulated strain on faults over very short timescales, and understanding the physics of this coseismic phase is essential for interpreting rupture propagation, source-time functions (STFs), and the role of fault-zone heterogeneity in real seismic events. The classical Burridge-Knopoff (BK) model, which represents a fault as a chain of elastically coupled blocks sliding under velocity-weakening friction, has long been used to study stick-slip dynamics. However, because the traditional model includes a constantly moving loader plate, it inherently mixes interseismic loading with coseismic failure, making it difficult to isolate the rupture physics alone.

In this work, we modify the BK model to focus exclusively on the coseismic stage by removing the loading plate and instead applying a finite, impulsive stress perturbation through a driving spring. After this initial push, the system evolves freely under elastic coupling and dynamic friction, mimicking the self-driven rupture seen in real earthquakes. We then introduce spatial heterogeneity in spring stiffness, including decreasing, increasing, and multi-segment stiffness gradients to investigate how variations in elastic properties control rupture propagation.

Our simulations demonstrate that weak (low-stiffness) regions hinder stress transfer, leading to rupture arrest, reflections, and multi-peaked STFs. In contrast, stiffening regions enhance coupling and produce coherent, system-spanning ruptures with smooth single-peaked STFs. These behaviours offer a physically intuitive explanation for the multi-burst energy release inferred for the 2015 Gorkha earthquake, where rupture propagated through heterogeneous upper-crustal layers.

By isolating the coseismic dynamics, our model reveals that even simple 1D stiffness heterogeneity can fundamentally shape the evolution of rupture, providing a potential insight into why large Himalayan earthquakes often exhibit multi-peaked source time functions.

**Keywords:** earthquake rupture, Burridge-Knopoff model, heterogeneity, source-time function, rupture dynamics

# Effect of 1D and 3D Velocity Models on Moment Tensor Solutions for the 2015 Nepal Aftershocks

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The 2015 Gorkha earthquake was followed by numerous moderate aftershocks that offer valuable information about strain release and active faulting in central Nepal. Accurate moment tensor estimations are essential for determining the source parameters of these seismic events. One of the key factors that affects moment tensor inversion is the choice of velocity model. This work aims to understand how 1D and 3D velocity models influence the solutions of the 2015 Nepal aftershocks.

The waveform data recorded by the NAMASTE temporary broadband network are used to analyze 51 aftershocks with magnitude greater than 3.5. For the 1D scenario, we constructed a composite velocity profile by integrating parameters from Yamada (2019) and Timsina (2025) models, both of which are region-specific velocity structures developed for the Nepal Himalaya. A library of Green's functions is generated using the fk method for the composite velocity model. Synthetic waveforms derived from the Green's functions are used to invert the waveform data for the moment tensor estimation. We constrain the inversion to only double-couple sources considering shear dislocations without opening.

In the subsequent step, we integrate the Timsina (2025) 3D velocity model to represent the lateral heterogeneity in the study area. Green's functions for the 3D structure are computed using the spectral element method (SPECFEM3D).

Comparison of the solutions obtained from the 1D and 3D velocity models helps determine whether the 3D model improves waveform fit and key source parameters such as centroid depth and fault-plane orientation. It also provides insights for refining the 1D model to better represent the crustal structure.

This study shows how the choice of the velocity model influences moment tensor solutions in the Himalayan region, where significant lateral variations are expected. The results contribute to a better understanding of the aftershock behavior and earthquake source processes in the Nepal Himalaya.

**Keywords:** Moment tensor, Source parameters, Velocity model, Spectral element method, Gorkha earthquake, Nepal Himalaya.

# **Spatial variations in the low-velocity layer above the 410-km discontinuity and their relationship to mantle dynamics**

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Constraining the seismic velocity discontinuities at 410 km depth (D410) and 660 km depth (D660) is key to understanding mantle dynamics. Receiver functions (RFs) have been the primary tool for imaging these structures and have revealed widespread low-velocity layers (LVLs) atop D410, supporting the global “water filter” model. Numerical experiments have also predicted double LVLs in specific settings. However, the link between LVL occurrence and regional tectonic processes remains poorly understood, and RF analyses typically depend on subjective trace selection and alignment using theoretical travel times from reference Earth models. Here, an automated, data-driven, machine-learning approach is applied to RFs from global seismic stations to image the velocity structure near D410. Our method aligns P-to-S converted phases from D410 without invoking theoretical travel times, and we demonstrate that the resulting alignment is physically meaningful and reflects the underlying velocity structure. This automated workflow enhances both the efficiency and reproducibility of RF-based studies. The global stations reveal three distinct patterns of seismic velocity near D410: (1) a thick LVL atop D410 associated with cold mantle regions, (2) a double LVL atop D410, with interlayer spacing varying between stations and corresponding to hot mantle or fast upwelling, and (3) a thin LVL atop D410 linked to slower upwelling. These observations indicate that LVLs above D410 are a global feature consistent with the water-filter concept, while their spatial variability reflects regional mantle dynamics and upwelling style.

# **Intraplate Earthquakes — Occurrence, Processes and Geology**

# **Seismogenic fault reactivation and intraplate earthquakes: a synthesis of ideas from ancient pseudotachylyte veins in the rock record**

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Continental intraplate earthquakes are most dangerous for the society as they often strike in densely populated areas inside the 'apparently stable' cratonic domains (Stable Continental Region: SCR) which are normally not intensely monitored by seismologists and disaster management authorities. In cratonic areas, the long-term inter-seismic strain accumulates at a considerably slow rate compared to the active plate boundary zones. As a result, SCR earthquakes recur after a large time gap (often a few hundred years to more than 1000 years), and therefore, have a poor instrumentally recorded history. On the other hand, continental plates, because of their long survival, are riddled with a complex network of pre-existing faults/shear zones and ancient rift systems which are quite prone to reactivation and seismic fault movement under the current crustal stress regime. Sudden and unexpected movement on such faults have historically caused some very devastating earthquakes within the cratonic part of India (e.g. 1819 Runn of Kutch, 1993 Latur, 1997 Jabbalpur earthquakes, among others) and in other parts of the world (e.g., 1811-12 Charleston earthquake in New Mexico, USA, 1976 Tangshan earthquake in China, and many others). One way of studying ancient shear/rift systems for potential history of seismogenic fault movement is through the systematic study of exhumed fault zones laced with pseudotachylyte – a relatively rare fault rock produced by partial (and non-equilibrium) melting of the host rock along a fault plane due to locally intense frictional heating generated by rapid, seismic-rate fault slip. A detailed study of pseudotachylyte not only helps understand the history of seismic fault movement, but also divulges a lot of important information on the fracture propagation, directivity, compositional control on frictional melting of rocks, along with a number of seismic source parameters like slip- weakening distance, dynamic shear strength of the fault zone, and even an approximate estimate of the seismic energy released during the earthquake. A lot of experimental work and theoretical modeling have been carried out on frictional hearing and melting of rocks in the last couple of decades. As a result, a holistic view of ancient seismic faulting in cratonic areas is now shaping up through a combination of field, laboratory and modeling data. Study of pseudotachylyte in ancient, exhumed fault zones can provide important clues of crustal seismogenic processes in the geological past, and can guide modern seismological studies as well as disaster and/or risk assessment practices in the continental interiors. Critical examples come from exhumed fault zones within the Central Indian Tectonic Zone, and from the Aravalli-Delhi Mobile belt in western India.

**Keywords:** Fault reactivation, seismic movement, flash heating and melting, pseudotachylyte, intraplate (SCR) earthquakes, central and western India.

# Unraveling Intraplate Strike-Slip Kinematics in the Eastern Himalayan and Indo-Burman Plate Boundary Systems

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North-East India, at the eastern extremity of the Himalayas, constitutes one of the world's most rapidly deforming intraplate regions. The geodynamics of this region is dominated by oblique convergence between two nearly perpendicular plate boundaries of the Eastern Himalaya and the Indo-Burman convergence zone. This region of distributed deformation is associated with intraplate strike-slip and oblique-slip earthquakes. We model the source mechanisms of six recent moderate-to-strong intraplate earthquakes ( $5.0 \leq M_w \leq 6.7$ ) using teleseismic P- and SH-waveform inversion and use source directivity and rupture back-projection, for the largest event, to isolate the fault plane. We combine these mechanisms with previous earthquake source studies, GPS-geodetic-velocity vectors, and GPS-derived strain-rate field, to build a kinematic model. Majority of the earthquakes have strike-slip to oblique-slip (thrust) motion and originate in the middle-to-lower crust. These reveal that the entire NE-Indian crust is seismogenic. The oblique-thrust earthquakes occur due to high in-plane compressive stresses in the flexed Indian Plate. The region north of the Dawki Fault, in the vicinity of the Kopili and Dhubri-Chungthang Fault Zones, deforms through dextral strike-slip faulting and anticlockwise rotation of blocks along NW-SE trending transverse structures. The transitional crust of the Bengal Basin has several NE-SW trending paleo-rifts which are reactivated as sinistral strike-slip faults and the intervening blocks undergo clockwise rotation. The oblique convergence between the Indian and Eurasian Plates is partitioned into dextral and sinistral strike-slip motions across NE-India. The GPS velocity vectors and the strain-rate field indicate that the region north of the Dawki Fault has strong coupling between the surface deformation and the earthquake faulting. However, south of the Dawki Fault, the coupling is weaker. A complex interplay between lateral-shear forces created by the strike-parallel components of the interplate-coupling resistance and mantle-drag forces and trench-normal slab-pull forces is the likely cause of the strike-slip earthquakes beneath Indo-Burma.

**Keywords:** Intraplate earthquakes, Strike-slip earthquakes, North-East India.

# Dynamics of Aseismic Slip, Fluid Flow, and Fault Interaction in the Palghar Earthquake Swarm

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The Palghar earthquake swarm in western India provides an exceptional opportunity to investigate active faulting within a region traditionally regarded as tectonically stable. Since late 2018, the Palghar swarm has produced sustained seismicity within a compact area, revealing ongoing deformation in an intraplate setting. Although the sequence was recorded by two independent seismic networks (NGRI and NCS), their initial catalogs were produced separately and suffered from limited azimuthal coverage. By integrating both datasets, we generated a unified catalog with significantly improved network geometry, enabling the development of a regional 1D velocity model and the precise relocation of the core seismicity.

The refined locations illuminate two closely spaced, steeply dipping N–S faults at 6–8 km depth that host most of the swarm. Seismicity initiates on the western structure, migrates eastward, and eventually fills the corridor between them, defining a coherent spatiotemporal progression indicative of linked fault behaviour. Migration rates of ~0.1–0.3 km<sup>2</sup>/day exceed values expected for pore-pressure diffusion alone, suggesting that aseismic or slow-slip transients contributed to transferring stress across the system.

To capture the full evolution of the swarm, automated detection recovered tens of thousands of additional earthquakes, revealing broadband rupture behaviour from low-frequency to classical shear events. The earthquakes exhibit low stress drops, and moment tensor solutions for larger events show predominantly normal faulting, consistent with geodetically inferred aseismic slip rake angles. InSAR-derived geodetic moment release exceeds the seismic moment by roughly two orders of magnitude, implying that aseismic slip accounts for most of the observed strain.

Taken together, these observations show that the Palghar swarm reflects a dynamic intraplate fault system governed by fluids, transient slip, stress transfer, and fault–fault interaction. The sequence provides rare empirical evidence that stable continental interiors can host fault processes typically associated with plate boundaries, offering broader insight into the mechanics and hazards of intraplate deformation globally.

# **Intraplate Earthquakes and their relations with plate boundary forces**

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According to the theory of Plate Tectonics, maximum release of tectonic strain energy occurs along plate boundaries, whereas plate interiors are rigid. Intraplate earthquakes, though fewer in number compared to their plate boundary counterparts, defy that paradigm. Although there is agreement that these earthquakes owe their activity to the reactivation of ancient faults that were created during previous tectonic events, there is no comprehensive model to explain how these faults get reactivated. Several hypotheses have been put forward to explain their occurrences, which include glacio-isostatic adjustment, buoyancy forces within the lithosphere, transient perturbation of local stresses along pre-existing fracture zones, and large-scale convection within the mantle. A persistent question that exists is, how analogous are these earthquakes to their plate boundary counterparts? Here, I will give a brief summary of the existing views as to what could cause these anomalous seismicity within the plate interiors and present some of my earlier studies on the earthquakes that have taken place in the stable cratonic Eastern North America. We had found (Ghosh et al., 2019) that large scale tectonic effects, which arise from forces due to topography and lithosphere structure coupled with large scale mantle flow, could be a likely cause for seismicity in the eastern US.

# **Scientific deep drilling in the Koyna intraplate seismic zone, Maharashtra: towards a paradigm shift in earthquake science**

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Scientific drilling investigations in recent times have driven a paradigm shift in earthquake science by allowing for direct, in-situ observations of fault zone properties, monitoring of active fault zones at seismogenic depths, and sampling fault rocks for laboratory studies to achieve unprecedented insights into the mechanical behaviour of faults that challenge previous conceptual models based on surface observations alone. The reservoir-triggered seismicity (RTS) site in Koyna, western India with recurrent activity over the past six decades confined to a ~20 km x 30 km area and 2-10 km in depth within a largely stable intraplate setting offers a natural laboratory to conduct such experimentation.

Recurrent seismicity in the Koyna region, western India is attributed to the initial impoundment of the Koyna (Shivajisagar) water reservoir in 1962 and subsequent water level variations corresponding to the annual loading and unloading cycles of the Shivajisagar and nearby Warna reservoirs. The activity includes the largest triggered earthquake of magnitude M6.3 in 1967, ~20 earthquakes of M>5, ~400 earthquakes of M>3.5 and thousands of smaller earthquakes. The M6.3 earthquake was associated with the development of Donichawadi fissure zone, the surface manifestation of a deeper crustal fault that remains seismically active to this day.

The pilot phase of the drilling project has been completed. This phase included drilling of a 3 km deep scientific borehole KFD1 in the seismic zone, downhole measurements of and laboratory studies on cores from the fault damage zones as well as intact rocks. The downhole measurements provide robust constraints on (i) physical, mechanical and chemical properties of the Deccan traps and underlying granitoid basement rocks, (ii) petrological and geochemical properties of the granitoid basement that primarily host the seismic activity, (iii) heat flow and thermal structure, (iv) in-situ stress regime from three independent datasets, (v) subsurface fracture orientations and their correspondence with stress orientations, (vi) chemical and noble gas isotope compositions of formation gases, (vii) presence of fault-damage zones below 2 km, (viii) evidence of deep percolation of meteoric water down to 3 km, (ix) rock strength properties of basement granitoids at ambient and high temperatures, and (x) frictional properties of fault zone rocks. Combined with seismological observations from a local seismic network in the vicinity of KFD1, the borehole datasets reveal new insights into the disposition of seismically active fault zones and their complexity, and provide a solid foundation to undertake deeper drilling and experimentation in the near field of earthquakes.

In the next phase of operations, it is planned to drill a ~6 km deep hole in the seismically active source region, conduct downhole measurements, and equip the

borehole for long-term near-field monitoring to capture pre-seismic, co-seismic and post-seismic processes as well as physical and chemical properties of the seismically active formation. Such datasets can offer unique insights for advancing our understanding of physics of reservoir-triggered earthquakes (and earthquakes in general), seismic hazard assessment, and complementing current developments in forecasting seismogenic processes.

***Acknowledgements.*** The work presented in the paper is a summary of the collective work of a number of past and present colleagues of MoES-BGRL.

# Revisiting some global examples of Reservoir Triggered Seismicity (RTS): What makes Koyna unique?

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Although there are thousands of artificial water reservoirs globally, only about a hundred of them are known to be associated with triggered earthquakes. Among them only four have generated  $M > 6$  earthquakes; Kremasta (Greece), Kariba (Zambia–Zimbabwe), Hsinfengkiang (China), and Koyna (India). In all these cases, temporal associations with the filling of the reservoir are evident and the earthquakes are spatially confined to the immediate vicinity of the reservoirs, typically within about 10–20 km from the dam axis or reservoir margins. These and the other examples of RTS have demonstrated how relatively small anthropogenic stress perturbations associated with reservoir impoundment can activate pre-existing faults in critically stressed brittle crust. These perturbations include (i) instantaneous elastic response to the increased load in the reservoir, (ii) undrained response due to the instantaneous increase in pore pressure following the filling, and (iii) delayed drained response due to diffusion of pore-pressure to the seismogenic depths. It is also observed that RTS generally decline substantially or ceased altogether within years to a few decades after the initial onset. Koyna, stands as an exception where seismicity continues, even after six decades of initial onset.

In an effort to address the question of continuing seismicity at Koyna, we investigate its history in the context its geological background and filling history using updated geologic and seismologic data. We analyse the spatial and temporal patterns of earthquakes in response to the elastic, undrained and drained responses and report that the seismic activity at Koyna is mostly associated with the delayed response controlled by pore-pressure diffusion. From the general absence of earthquakes in the deeper parts of the reservoir and its immediate peripheries, we conclude that the effects from elastic loading and undrained response are insignificant. As the only known example of RTS associated with reservoirs built on basaltic rocks globally, Koyna makes a special case where the local geology may be an influencing factor. We believe the fracture-controlled permeability within the Deccan trap basalts may be playing a crucial role in the percolation of water as well as sustaining the diffusion of pore pressure, which facilitates slip on the pre-existing, critically stressed faults.

**Keywords:** Reservoir Triggered Seismicity (RTS), elastic response, undrained response, pore-pressure diffusion, Koyna-Warna seismic zone.

# Thermomechanical Model of the Indian Lithosphere: Implications for Intraplate Seismicity

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The stable continental regions of the Indian lithosphere, although situated away from the active Himalayan plate boundary, experienced notable intraplate seismicity, particularly in regions such as the Peninsular Shield, the Kutch Rift Zone, and the Indo Gangetic Plain. The drivers of this seismicity remain inadequately understood, particularly given the low strain rates and extended recurrence intervals characteristic of these earthquakes. Intraplate seismicity in the Indian lithosphere is further complicated by the presence of inherited tectonic structures, strong spatial variations in crustal structure and mantle composition, and differences in thermal and rheological strength.

We aim to quantify whether present-day variations in lithospheric density, thermal structure, and thermomechanical properties exert a dominant control on intraplate seismicity. To achieve this, we computed the density, temperature, and strength from a physical interpretation of seismic tomography, utilising mineral physics to inform major crustal and mantle compositions in the Indian lithosphere, based on laboratory derived rheological laws. We aim to compare the obtained models with the observed seismicity patterns and assess whether intraplate earthquakes tend to occur above lateral density/strength gradients or in regions characterised by upper-mantle heterogeneities, highlighting the importance of mantle lithosphere buoyancy forces for crustal seismicity. This work aims to explore the role of such internal lithospheric heterogeneities (second-order controls) in localising seismicity in Stable Continental Regions of the Indian lithosphere relative to far-field tectonic forces such as Indian-Eurasia convergence and ridge push. In this contribution, we will discuss the preliminary results of the proposed research plan.

**Keywords:** Intraplate earthquakes, Indian Shield, Strength, Mantle heterogeneities.

# **Applications of Artificial Intelligence and advanced image analysis techniques to study fault rocks and fracture zones**

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Quantitative investigation of fracture networks and related fluid flow in a fault zone is a difficult task due to their apparently random/chaotic nature. Many workers have argued that there certainly lie some patterns within this apparent randomness. Similarly, genetic processes involved in many fault rocks (e.g. pseudotachylyte and cataclasite) can be understood only by a quantitative analysis of their textural elements. We have tried to quantify these patterns and decipher the order in this chaos, using Convolutional Neural Networks (CNNs) and advanced image analysis techniques including binarization, thresholding, box counting etc.

We used two prominent types of fault rocks namely, pseudotachylyte, formed by frictional melting at the slip surface due to rapid fault movement, and cataclasite, formed by comminution/crushing due to fault movement. Fracture zone (undeformed, damaged zone & core zone) rocks were also utilized in the study. Our goal was to quantitatively discriminate melt-origin pseudotachylyte from crush-origin cataclasite and characterize fracture networks geometrically and topologically along with calculating fluid flow through them.

We estimated the grain boundary fractal dimension (Df) of the relict clasts of quartz in pseudotachylyte (of Sarwar-Junia Fault Zone, Rajasthan) and in cataclasite (of Gavilgarh-Tan Shear Zone, Central India). For this, we captured images of these rocks under a petrographic microscope and SEM (BSE images) and segmented the clasts using a U-Net model (trained by transfer learning) and histogram thresholding. We divided these clasts into 2 size classes for SEM-BSE images: XS (area<2000 $\mu\text{m}^2$ ), MS (2000<area< 20000 $\mu\text{m}^2$ ) and 3 size classes for optical microscope: S (area<0.02mm<sup>2</sup>), M(0.02mm<sup>2</sup><area<0.04 $\mu\text{m}^2$ ), & L (area>0.04mm<sup>2</sup>). Through postprocessing, we extracted clast boundaries from the segmented clasts and calculated their clast boundary fractal dimension using the FracLac plug-in of ImageJTM software. For fracture zone rocks, we tried to segment the fracture networks using another U-Net model (again trained by transfer learning).

Our results show that Df of all size classes in cataclasite are almost equal with an average value of 1.1203 whereas in pseudotachylyte, the Df value increases with decreasing size and has an average value of 1.2288 which is higher than cataclasite. These results show that clast boundaries in pseudotachylyte become rougher than cataclasite due to melt-clast interaction which is more intense for smaller clasts that have higher surface area to volume ratio. Further, we also plan to quantitatively determine fluid flow through fracture networks by determining their geometry, topology and connectivity and how it alters the fault zone properties. These observations prove that AI and advanced image analysis techniques can be efficiently used to quantify

fault zones and help us understand the underlying genetic processes better.

**Keywords:** Artificial intelligence, CNNs, image analysis, fault rocks, pseudotachylyte, cataclasite, fracture network, grain boundary fractal dimension.

# Localized Deformation in Ductile Regimes: a Possible Mechanism of Deep Focus Earthquakes

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Deep-focus earthquakes, occurring at depths greater than ~300 km, constitute a significant part of the global earthquake distribution, which has emerged as a major area of interest to geologists and seismologists. However, the earthquake-triggering mechanism remains an enigma in solid Earth geophysics as the process operates under physical conditions that largely suppress brittle failure in the lithospheric materials. At such depths, they undergo deformations largely by viscous flows, posing critical question- what causes them to produce ruptures required for seismic events? This study provides a plausible explanation for shear localization during progressive viscous deformations with increasing shear rate ( $\dot{\gamma}_b$ ), effective viscosity ( $\mu_b$ ), and cohesion (C). The shear localization eventually results in narrow, high-strain shear band formation. This localization enhances strain heating and thermal softening that can lead to runaway viscous instability. Associated metastable phase transformations, such as the olivine-to-spinel transition, can further amplify this instability, producing transient stress release and seismic energy generation within the viscous regime. The presentation reports field observations from mid-to lower-crustal shear zones in eastern India, together with 2D viscoplastic numerical simulations incorporating strain-softening rheology, support this mechanism. The findings suggest that variations in  $\dot{\gamma}_b$ ,  $\mu_b$  and C govern the transition from distributed viscous deformation features to localized shear band formation controlling the extent of strain concentration. This study finally discusses the origin of deep-focus earthquakes as a consequence of internal viscous instabilities within shear zones, switching the mechanical continuum behaviour from slow viscous flows to rapid seismic rupturing in the mantle.

# **Physics of Earthquakes: Theory and Experiments**

# **Spectrum of slip dynamics, scaling & statistical laws for earthquakes emerge from simplified models of faults and damage zone architecture**

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Seismological and geodetic observations of a fault zone reveal a wide range of slip dynamics, scaling, and statistical laws. However, the underlying physical mechanisms remain unclear. In this study, we show that incorporating an off-fault damage zone-characterized by distributed fractures surrounding a main fault-can reproduce many key features observed in seismic and geodetic data. Using quasi-dynamic boundary integral simulations accelerated by hierarchical matrices, we simulate slip dynamics of this system and analyze the events produced both on and off the main fault. Despite the spatially uniform frictional properties, we observe a natural continuum from slow to fast ruptures, as observed in nature. Our simulations reproduce the Omori law, the inverse Omori law, the Gutenberg-Richter scaling, and the moment-duration scaling. We also observe seismicity localizing toward the main fault when an event is about to nucleate on the main fault. During slow slip events, off-fault seismicity migrates in a pattern resembling a fluid diffusion front, despite the absence of fluids in the model. We also show that tremors, Very Low Frequency Earthquakes (VLFs), Low Frequency Earthquakes (LFEs), Slow Slip Events (SSEs), and earthquakes (EQs) can all emerge naturally in the 'digital twin' framework.

# Tectonic Tremor Analogs During High-Pressure Experiments at Relevant Subduction Zone Conditions

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Non-volcanic, i.e., tectonic, tremors are a unique kind of earthquakes that occur in certain subduction zones. They are characterized by long durations and particularly low frequencies. Some of these events are located at great depths, beyond the seismogenic zone. They are often associated with regions of high  $V_p/V_s$  and thought to be closely related to the presence of fluids released by dehydration reactions. Some of their properties scale distinctively differently than those of regular earthquakes. Notably, their seismic moment is proportional to their duration, whereas it is proportional to duration cubed for regular earthquakes.

Here, we have performed experiments on olivine samples containing varying amounts of antigorite, the high-pressure form of serpentine. We used a Griggs-type apparatus, a solid pressure-medium device, equipped with acoustic capability. Pressure and temperature (PT) were ramped up together according to a rather warm subduction zone geotherm (e.g. Cascadia), where tremors are typically detected. Thousands of acoustic emissions were collected along the PT-path. At low PT, acoustic emissions have regular earthquake characteristics, while at high PT, they are tremor-like, with longer durations and lower frequency contents. Furthermore, these tremor-like acoustic emissions also possess a moment magnitude that scales proportionally with their duration. And most importantly, these events were also collected in dry samples containing nothing but dry olivine, which demonstrates that they do not simply originate from the presence or the migration of fluids. However, the comparison between the dry experiments and those performed with the presence of dehydrating serpentine suggests that the release of dehydration fluids promotes their appearance.

**Keywords:** non-volcanic tremors, scaling laws, high-pressure experiments, acoustic emissions

# Effect of Damage Zone on Earthquake Rupture Dynamics on Planar Fault: Insights from Direct Experimental Observations

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Fault damage zones around natural faults contain dense networks of small fractures with diverse sizes and geometries that strongly influence earthquake rupture dynamics. Numerical models have shown that these fractures can modify rupture velocity, style, and extent, but direct experimental evidence remains limited. In this study, we directly demonstrate how damage geometry controls rupture behavior in laboratory-scale shear ruptures. We use laser engraving to create controlled damage patterns in polymethyl methacrylate (PMMA) plates that contain a pre-cut planar fault. We vary the damage geometry by changing the number of layers, crack spacing, and crack angles within arrays of sub-parallel cracks. Each crack measures about 3–5 mm in length and 0.2–0.3 mm in width. We generate spontaneous shear ruptures along the main fault and record them using an ultra-high-speed camera operating at one million frames per second. Using Digital Image Correlation (DIC), we map the full-field displacement and velocity during rupture propagation. Our experiments show that structured damage zones significantly increase peak slip velocity, transform rupture style from pulse-like to crack-like, and accelerate rupture speed from sub-Rayleigh to supershear. We also perform numerical analyses to explore how small-scale cracks modify the stress field on the main fault. The analyses show that the cracks, depending on their size, angle, and distance from the fault, locally amplify the shear-to-normal stress ratio, which may explain the increased rupture intensity and the sub-Rayleigh to supershear transition. These findings provide new insights into how damage zone characteristics affect earthquake rupture dynamics, enhancing our understanding of the complex interaction between fault structure and rupture processes.

**Keywords:** Fault damage zone, PMMA, Digital image correlation, Rupture, Sub-Rayleigh to Supershear transition.

# Aseismic rupture in elasto-frictional, rate-weakening interfaces: Relevance to earthquakes and landslides.

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The nucleation of earthquakes relies on an interfacial instability that facilitates the transition from slow fault slip to faster dynamic rupture. Fault sizes over which slip instabilities develop are identified through studies on the emergence of these instabilities from perturbations to steady-state sliding and the tip energetics of shear cracks. Here, we highlight scenarios in which rate-weakening, state-dependent interfaces exhibit a phase of slow aseismic slip—prior to slip instability—that propagates large distances compared to the usual nucleation length scales. Such aseismic slip propagation results from the response of rate-weakening interfaces to reach a state of steady sliding when forced to slide below steady-state conditions. We numerically simulate the slip cycle—aseismic creep, instability, dynamic rupture—driven by external loadings of either a constant dislocation rate at the end(s) or a constant stress rate within a small localized region. After the aseismic phase, while loading with a localized distribution of external stress (at a constant rate) provokes unstable slip over typical nucleation sizes, a fault with a constant rate of dislocation loading can nucleate an instability when its size exceeds a cutoff size. This cutoff fault size is considerably larger than the nucleation length scale, ( $2L_b$ ,  $2L_{b-a}$ ) or ( $2L_\infty$ ), depending on the friction parameters, the extent of initial contrast from steady state sliding, and the slip conditions toward which aseismic rupture progresses.

Furthermore, we find that slow slip transitions to early-stage instability through an intermediate breathing-type evolution of slip rate. This long-term phase of aseismic deformation of locked asperities increases the minimum size required to nucleate an earthquake, which differs from the usual instability nucleation length scales and can explain the lack of seismicity of strike-slip faults during the interseismic period.

We also highlight the relevance of the results to the transition from the creeping of thin, deformable landmasses to catastrophic landslides.

**Keywords:** slip instability, elasto-frictional systems, earthquake nucleation, catastrophic landslides.

# The 28 March 2025 Mw 7.7 Myanmar Earthquake: Spatio-temporal Rupture Evolution and Source Characteristics

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The 28 March 2025 Mw 7.7 earthquake in Myanmar occurred along the N–S striking Sagaing Fault near Mandalay and ruptured a previously identified 'seismic gap'. This shallow, bilateral rupture spanned ~400 km and lasted about 80s. The rupture initially propagated northward at sub-shear speed and then transitioning to a super-shear southward rupture, which likely sustained the rupture on such a long fault. The mainshock was followed by a significant Mw 6.7 aftershock just 11 minutes later. Teleseismic waveform data analysis of the mainshock revealed three distinct sub-events, with the central one (10–40 s) contributing the most energy and dominating the radiation pattern. A frequency-dependent radiation is observed for the super-shear southern rupture, which ended in oblique-slip. The mainshock seismic moment is  $\sim 6.26 \times 10^{20}$  N.m, and moment magnitude is 7.79. The average slip on the fault is ~2 m, with stress-drop of  $\sim 15 \pm 5$  bars. Source directivity analysis indicated stronger ground motion to the south, consistent with the super-shear rupture. The mainshock not only released the strain, accumulated over decades, on the Sagaing Fault, but potentially increased stress on the adjacent, fully-locked Rakhine-Bangladesh megathrust. This has major implications for seismic hazard in Bangladesh and northeast India.

**Keywords:** Mw 7.7 Myanmar Earthquake, super-shear rupture, bilateral rupture, earthquake source dynamics and kinematics

# Constraining the Physical Controls of Transient Fault Friction Using Acoustic Emissions

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The transient frictional behavior of fault gouge strongly influences fault stability in continuum fault-slip models. This behavior is typically described by rate-and-state friction, in which friction depends on slip velocity and the evolving state of the interface. Although various formulations for the state variable exist, none fully capture laboratory-observed frictional responses. Notably, the formulations that best match data—such as the Ruina (Slip) law—lack a complete physical basis. In this study, we examine the physical controls on transient friction in granular fault zones by integrating laboratory observations with concepts from granular physics and a thermally activated model previously proposed for the direct effect, the instantaneous frictional response to velocity changes. We conducted servo-controlled shear experiments on synthetic gouge composed of granular silica powder using a custom ring-shear rheometer with precise control of shear velocity, temperature, and humidity. A triaxial accelerometer mounted on the apparatus continuously recorded acoustic emissions (AEs). Voltage outputs were converted to calibrated accelerations using repeatable ball-drop tests performed with and without gouge to account for attenuation, boundary effects, and sensor response. AEs arise from rapid, localized energy release as grains slide, rotate, fracture, and reorganize within evolving force chains. Using a velocity-stepping protocol, we characterized both steady-state and transient friction. Persistent AE activity was observed across several orders of magnitude in slip velocity, and AE amplitudes were used to estimate granular kinetic energy within the shear layer. Finally, we assess whether AEs can serve as proxies for gouge kinetic energy and whether they can be used to estimate the direct-effect component of friction. This approach may improve understanding of the frictional state of granular fault gouge and provide a framework for using fault-core seismic emissions to better constrain earthquake nucleation and fault stability.

**Keywords:** Acoustic Emissions, Transient Friction, Fault Gouge

# Investigating Frictional Properties in NW Himalayan Faults: High Pressure-Temperature Experiments

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Seismic events are often closely linked to the frictional behaviour of fault gouges, widely modelled using rate-and-state friction (RSF) laws. Experimental observations suggest that frictional properties, including fault strength and stability, vary with mineralogy, temperature, overburden pressure, and pore-fluid pressure. We report the first such experimental setup in India and protocol for generating high-quality friction data to obtain reliable RSF parameters under seismogenic conditions.

Despite being one of the most seismically active orogenic belts, the Himalayan orogen lacks experimental studies on the frictional properties of its fault gouges. In this study, we present laboratory measurements of frictional strength of fault gouge from the major Himalayan thrust. To establish and calibrate our experimental protocol, we conducted frictional sliding tests on pure quartz gouge using a state-of-the-art, servo-controlled, oil-medium triaxial deformation apparatus at IIT Kanpur. The measured friction coefficients of pure quartz ( $\mu = 0.56$  to  $0.60$ ) were consistent with the previous studies under similar conditions (25MPa confining pressures (CP) with velocity  $0.1-1-10 \mu\text{m/s}$ ) (e.g., Mair & Marone, 1999; Frye & Marone, 2002). We conducted a series of velocity-stepping tests (VSTs) on the gouge collected from the Main Boundary Thrust (MBT) at constant CP (25-175MPa) and temperature (up to  $100^\circ\text{C}$ ) and velocity (1-10 mm/s). Shear strength of the gouge increases with increasing CP at room temperature, while decreases with increase in temperature at constant CP. At room temperature, the gouge exhibited velocity-strengthening ( $a-b > 0$ ) behaviour across all confining pressures, indicating stable sliding. In contrast, at elevated temperatures, the gouge transitioned from velocity strengthening ( $a-b > 0$ ) at low confining pressure to velocity weakening ( $a-b < 0$ ) at higher confining pressure. This implies that increasing temperature and pressure together can shift the gouge from stable to potentially unstable slip, increasing the likelihood of earthquake nucleation.

**Keywords:** Rate and State Friction, Triaxial experiment, Frictional strength, Rate dependence

# Response of a fluid-saturated fault gouge to frequency varied cyclic pore pressure oscillations

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Cyclic fluid injection for industrial purposes within fault zones are commonly imposed, since they are observed to stabilize induced seismicity, often inducing aseismic slip along fault surfaces, without immediate seismic energy release (Zang et al., 2018; Noël et al., 2019; Ji et al., 2021a, 2021b, 2022). Even though dynamic variations of effective normal stress on fault zones due to both natural and anthropogenic causes are common (Chen et al., 2024), the impact of the perturbations and their frequencies on fault strength is less explored (Savage and Marone, 2007; Ferdowsi et al., 2015; Noël et al., 2019). The frequency of pore-pressure changes is expected to impose a characteristic timescale, controlling the crossover from a drained to an undrained response, which in turn will promote markedly different deformation modes and rates (Passelègue et al., 2018).

In this work we present results from a coupled hydromechanical-discrete element model that simulates the response of a pre-stressed, fully saturated fault, filled with a granular fault gouge, subject to cyclic pore-pressure variations across frequencies of three orders of magnitude. For lower frequencies we see nucleation-arrest-nucleation dynamics within the granular rupture and for higher frequency we observe cyclic creep, both driven by pore-pressure perturbations. Within the frequency parameter space, we see a crossover of the slip modes as we increase frequency, lower frequencies show unstable failure, while higher frequencies show creep. Our results might account for a) fluid induced slip stability in cyclic injection scenarios (higher frequencies) and b) low-frequency dynamic triggering of earthquakes.

**Keywords:** cyclic pore-pressure oscillations, fault gouge, dynamic triggering

# **A Micro-physical Model to explain the Rate Dependent Friction**

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Friction exhibits strong velocity dependence and slip-history dependence, which are described empirically by the Rate-State Friction (RSF) Law. This law characterizes the behavior of a wide range of materials, including polymers, glass, and rocks found in the Earth's crust. This work investigates the physical meaning of the parameters used in empirical RSF laws and attempts to connect them with material properties estimated in the lab by Nano-Indentation Experiments. We aim to explain the steady-state velocity dependence of friction by treating asperity interactions as Nano-Indentation events. We find that there is a competing evolution of contact strength weakening and contact area growth of the indentation substrate. This drives a transition in the kinetic friction coefficient from velocity-strengthening at low velocities to velocity-weakening at high velocities. Experiments of RSF have been done in the lab on the cm scale, and they show the same transition as Nano-Indentation Experiments.

# Landslide times-to-failure - Comparing rate-and-state friction laws

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Creeping-to-catastrophic transitions of rainfall-regulated landslides often occur over a characteristic time-to-failure (TTF) that can be independent of the time- history of the rainfall-induced pore-pressure changes that cause them. Landslide models with shear strength governed by the rate-and-state friction (RSF) laws naturally reproduce these characteristic timescales for failure independent of the pore-pressure history. Recent theoretical analyses of such creep-to-catastrophic transitions in models employing the RSF framework have used the "aging law" formulation to simulate landslide response to idealized pore-pressure perturbations. However, new velocity-step experiments on both synthetic and natural landslide materials show that frictional strength evolution better resembles the "slip law" version of RSF under low normal stress conditions relevant to landslides. Motivated by these observations, we theoretically analyze the creep-to-catastrophic transition of landslides governed by the "slip law" using a quasi-static, gravity-driven rigid block model on a velocity-weakening slope. We derive velocity evolution to instability and TTF for this model (semi-)analytically for both step and sinusoidal perturbations in pore-pressure which allow direct, quantitative comparison with prior aging law results. The solutions are entirely determined by a suite of non-dimensional numbers - magnitude of pore-pressure perturbation relative to frictional resistance, the ratio of evolution effect to direct effect, and the sinusoid period relative to a frictional timescale. We find that for large normalized pore-pressure perturbations, the slip law predicts systematically earlier onset and culmination of the instability compared to the aging law for both the step and sinusoidal histories. Also, the slip law predicted TTFs become progressively smaller compared to aging as the normalized perturbation period decreases. These results demonstrate that the choice of a particular version of RSF can significantly influence predictions of landslide behavior in these simple models. This in turn underlines the importance of generating laboratory friction data, under conditions and on materials relevant to landslides, which can provide diagnostic constraints between different RSF versions.

**Keywords:** Creeping landslides, slow-to-fast transition, rate-and-state friction, times-to-failure