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Seismo-acoustic coupling in microseismic events: Evidence from the Deccan Volcanic Province, Maharashtra, India

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Abstract
The Deccan Volcanic Province (DVP), traditionally classified as a stable continental region, exhibits persistent low-magnitude seismicity that challenges conventional tectonic paradigms. Recent microseismic events in the Sangola tehsil, Solapur district, Maharashtra, have been accompanied by audible acoustic phenomena, providing an opportunity to investigate seismo-acoustic coupling mechanisms. We conducted a comprehensive analysis integrating instrumental seismic data from the National Center for Seismology (India) with systematic documentation of public acoustic reports. Seismic events were analyzed for magnitude-depth relationships, temporal patterns, and frequency characteristics. Acoustic reports were systematically classified and correlated with instrumental records. Four documented earthquakes (M 2.2-3.1) occurred at shallow depths (5-10 km) between 2023-2025, all accompanied by audible "boom" sounds. The shallow focal depths and high-frequency content (5-60 Hz) of P-waves explain the efficient ground-to-atmosphere energy transfer. Temporal correlation between seismic arrivals and acoustic reports is consistent with seismo-acoustic coupling theory. These events represent classical examples of earthquake-generated acoustic phenomena resulting from P-wave coupling to atmospheric acoustic waves. The findings support reclassification of the DVP from tectonically stable to low-level active seismicity, with implications for regional hazard assessment and monitoring strategies.

Keywords: Microseismicity, seismo-acoustic coupling, Deccan Volcanic Province, intraplate seismicity, earthquake acoustics

Introduction

1.1 Intraplate Seismicity in Stable Continental Regions

Intraplate earthquakes occurring within stable continental regions represent a fundamental challenge to classical plate tectonic theory, which predicts seismic activity primarily at plate boundaries (Stein *et al.*, 1989) [23]. These events, while less frequent than interplate earthquakes, pose significant hazards due to their unexpected occurrence in regions considered seismically stable (Johnston *et al.*, 1994) [12]. The Indian Peninsula, particularly the Deccan Volcanic Province (DVP), exemplifies this paradox, hosting several zones of persistent microseismicity despite its cratonic stability (Gupta *et al.*, 2003) [8].

The DVP, formed by massive flood basalt eruptions associated with the Réunion hotspot approximately 66 Ma ago (Courtillot *et al.*, 1988) [5], covers an area of ~500,000 km² across west-central India (Figure 1). While the province is often considered tectonically quiescent, well-documented cases of induced and natural seismicity, including the Koyna-Warna reservoir-triggered seismicity (Gupta, 2002) and the recent Palghar earthquake swarm (Patro *et al.*, 2017), indicate ongoing tectonic activity (Figure 2) [7, 21].

1.2 Seismo-Acoustic Coupling Phenomena

The generation of audible sounds during earthquakes, historically termed "earthquake booms," "brontides," or "Seneca Guns," has been documented for centuries but remained poorly understood until recent advances in seismo-acoustic theory (Hill *et al.*, 1976; Bolt, 1982) [10]. These phenomena result from the coupling of seismic energy into atmospheric acoustic waves, primarily through P-wave interaction with the Earth's surface (Bolt, 1982; Lacanna *et al.*, 2014) [4, 14].

The efficiency of seismo-acoustic coupling depends critically on earthquake parameters, particularly focal depth and frequency content (Figure 3). Shallow events (< 10 km depth) with high-frequency components (5-60 Hz) are most effective at generating audible acoustic waves (Bolt, 1982; Arrowsmith *et al.*, 2010) [2, 4]. The acoustic signals typically precede felt shaking because P-waves, responsible for sound generation, arrive before the more destructive S-waves that cause perceptible ground motion (Hill *et al.*, 1976) [10].

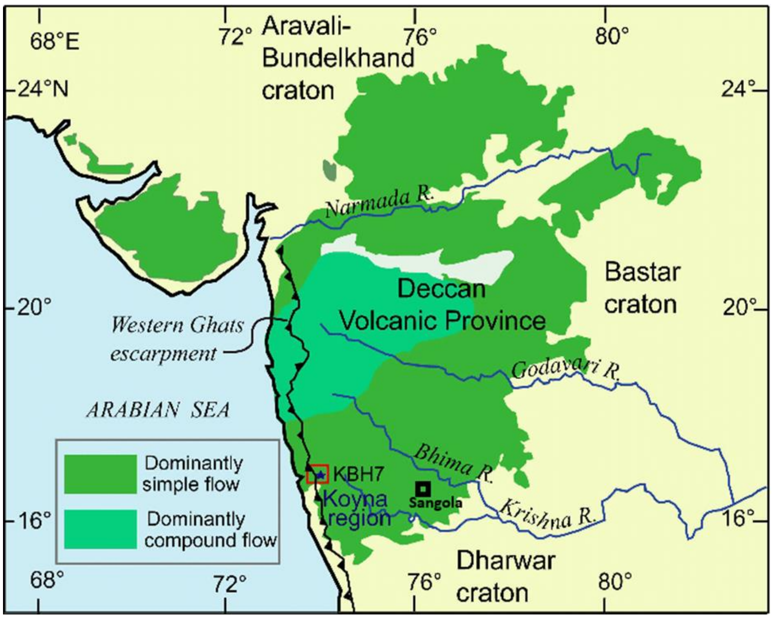

Fig 1: Regional Map of the Deccan Volcanic Province showing the study area

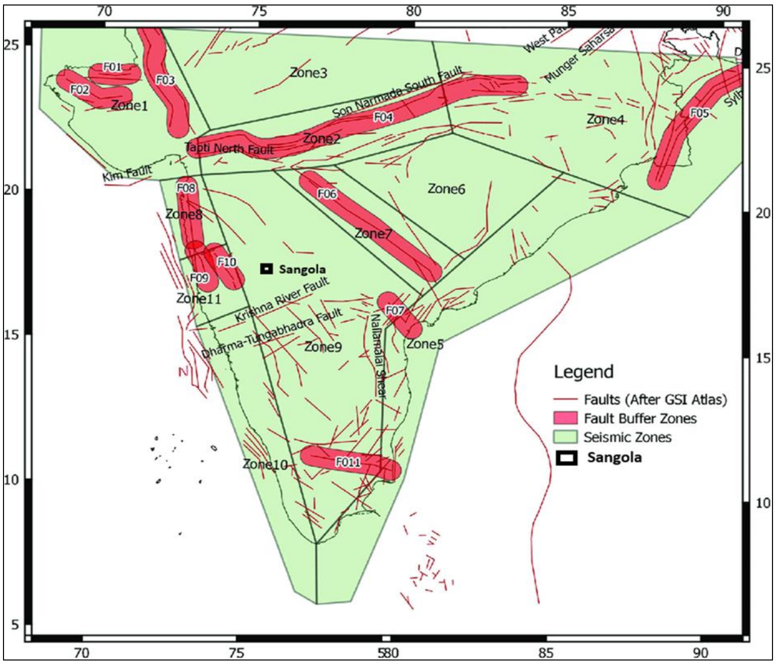

Fig 2: Map of Peninsular India displaying the eleven seismic source zones. The background illustrates the faults digitized from the seismotectonic atlas (GSI 2000)

1.3 Study Objectives

Recent reports from the Sangola tehsil, Solapur district, describe recurring "mild tremors" accompanied by "mysterious sounds," presenting an opportunity to investigate seismo-acoustic coupling in the DVP context. This study aims to: (1) systematically analyze instrumental seismic data and correlate it with acoustic reports, (2) evaluate the physical mechanisms responsible for observed phenomena, (3) discriminate seismic sources from alternative explanations such as sonic booms, and (4) discuss implications for seismic hazard assessment in the DVP.

2. Study Area and Geological Setting

2.1 Geological Framework

The study area lies within the central DVP, characterized by horizontally layered basaltic lava flows with individual units averaging 20-30 m thickness (Geological Survey of India, 1998) [26]. The monotonous succession of fine-grained, compact basalts is interrupted by red bole horizons marking eruptive hiatuses. The regional geology exhibits minimal surface structural complexity, with gentle dips and pervasive columnar jointing typical of flood basalt provinces (Kale *et al.*, 1992) [13].

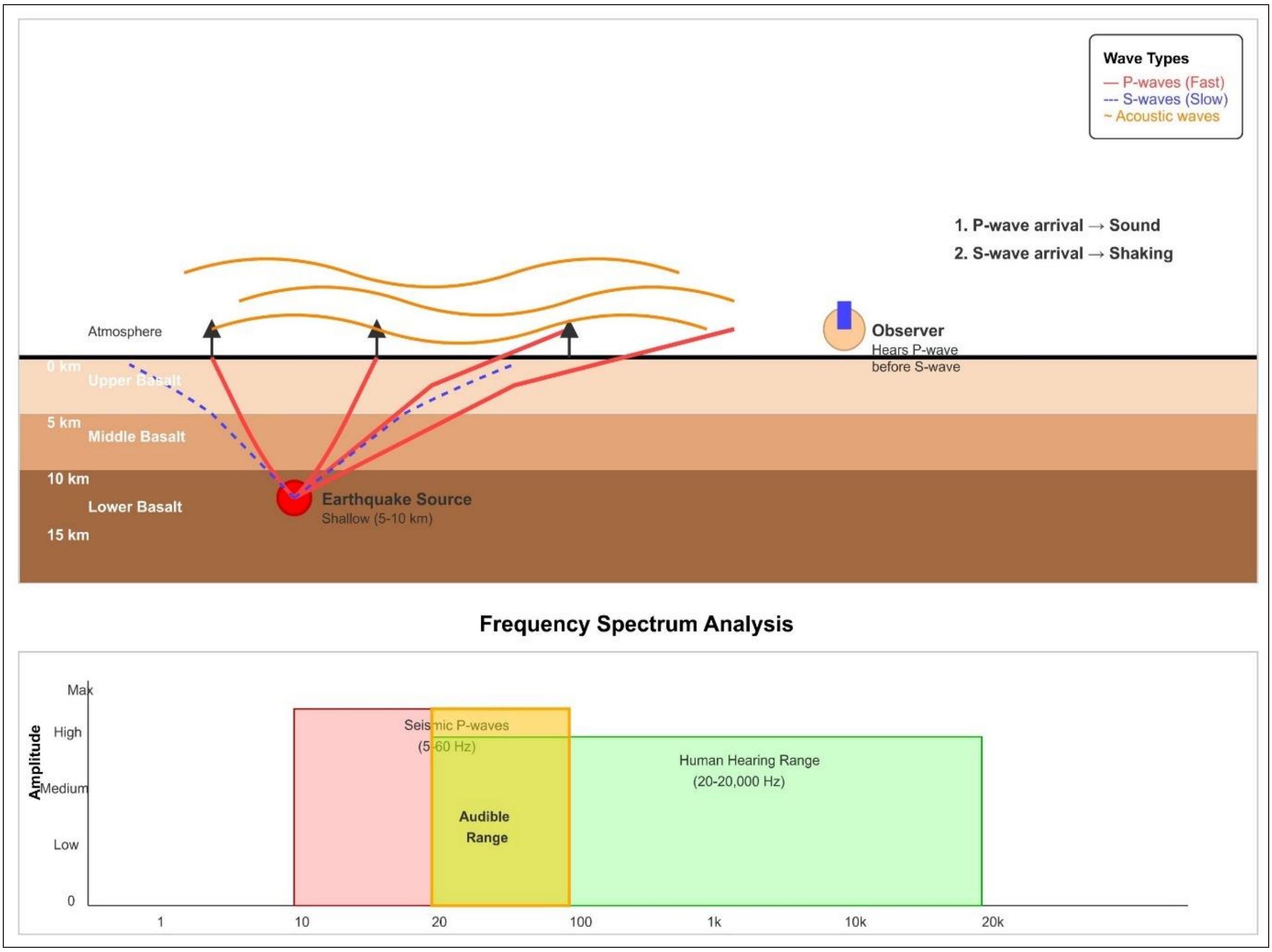

Fig 3: Schematic diagram illustrating seismo-acoustic coupling mechanism

Table 1: Geological Units in the Solapur District

Unit	Lithology	Thickness (m)	Age	Characteristics
Upper Basalt	Fine-grained basalt	15-25	Late Cretaceous	Columnar jointing, vesicular tops
Red Bole	Ferruginous clay	1-3	Late Cretaceous	Weathered horizon, high permeability
Middle Basalt	Medium-grained basalt	20-30	Late Cretaceous	Massive, less jointed
Red Bole	Ferruginous clay	1-2	Late Cretaceous	Weathered horizon
Lower Basalt	Coarse-grained basalt	25-35	Late Cretaceous	Phenocrystic texture

2.2 Seismotectonic Context

Despite surface structural simplicity, the DVP experiences ongoing intraplate deformation driven by far-field stresses from the India-Eurasia collision (Stein *et al.*, 2018) [24]. Regional north-south compression generates stress accumulation along pre-existing weakness zones, including ancient fracture systems and lithological boundaries (Mandal, 2007) [16]. The absence of surface faulting in the Solapur region suggests seismic activity occurs on buried structures within the basaltic sequence.

3. Data and Methods

3.1 Seismic Data Sources: Instrumental seismic data were obtained from the National Center for Seismology (NCS), India's official earthquake monitoring agency. The NCS operates a national network of broadband seismometers with magnitude detection thresholds of ~M 2.0 for regional events. Earthquake parameters including origin time, hypocenter location, magnitude, and focal depth were extracted from official bulletins [17, 18, 19, 20].

3.2 Acoustic Report Documentation

Public reports of acoustic phenomena were systematically collected from regional media sources and cross-referenced with seismic event timing. Report descriptions were classified according to acoustic characteristics (frequency, duration, amplitude) and temporal relationship to felt shaking.

Table 2: Classification of Acoustic Phenomena Descriptions

Category	Description Examples	Frequency Range (Hz)	Typical Duration (s)
Low-frequency rumble	"Thunder-like," "Heavy truck"	10-50	10-30
High-frequency boom	"Explosive bang," "Sonic boom"	20-200	1-5
Sustained roar	"Jet engine," "Wind rushing"	20-100	5-20
Mixed frequency	"Rumble followed by bang"	10-200	5-15

3.3 Data Integration and Analysis

Temporal correlation analysis between seismic events and acoustic reports was performed to establish causality. Earthquake parameters were evaluated against established criteria for seismo-acoustic coupling efficiency, including magnitude-depth scaling relationships and frequency content considerations.

4. Results

4.1 Seismic Event Catalog

Four earthquakes were instrumentally recorded in the Solapur district during 2023-2025, all exhibiting characteristics conducive to acoustic generation (Table 3, Figure 3):

Table 3: Seismic Events in Solapur District (2023-2025)

Date	Origin Time (UTC)	Latitude (°N)	Longitude (°E)	Magnitude (ML)	Depth (km)	Acoustic Reports	Reference
10/25/2023	12:47:29	17.66	75.95	2.3	5	Low-frequency rumble	NCS, 2023a
6/9/2024	14:08:08	17.87	74.72	3.1	5	Mixed frequency boom	NCS, 2024a
4/3/2025	5:52:00	17.41	75.21	2.6	5	Sustained roar	NCS, 2025a
8/21/2025	8:49:59	17.72	75.99	2.2	10	High-frequency boom	NCS, 2025b

All events exhibit shallow focal depths (5-10 km) and low magnitudes (M 2.2-3.1), optimal parameters for efficient seismo-acoustic coupling based on established scaling relationships (Bolt, 1982) [4].

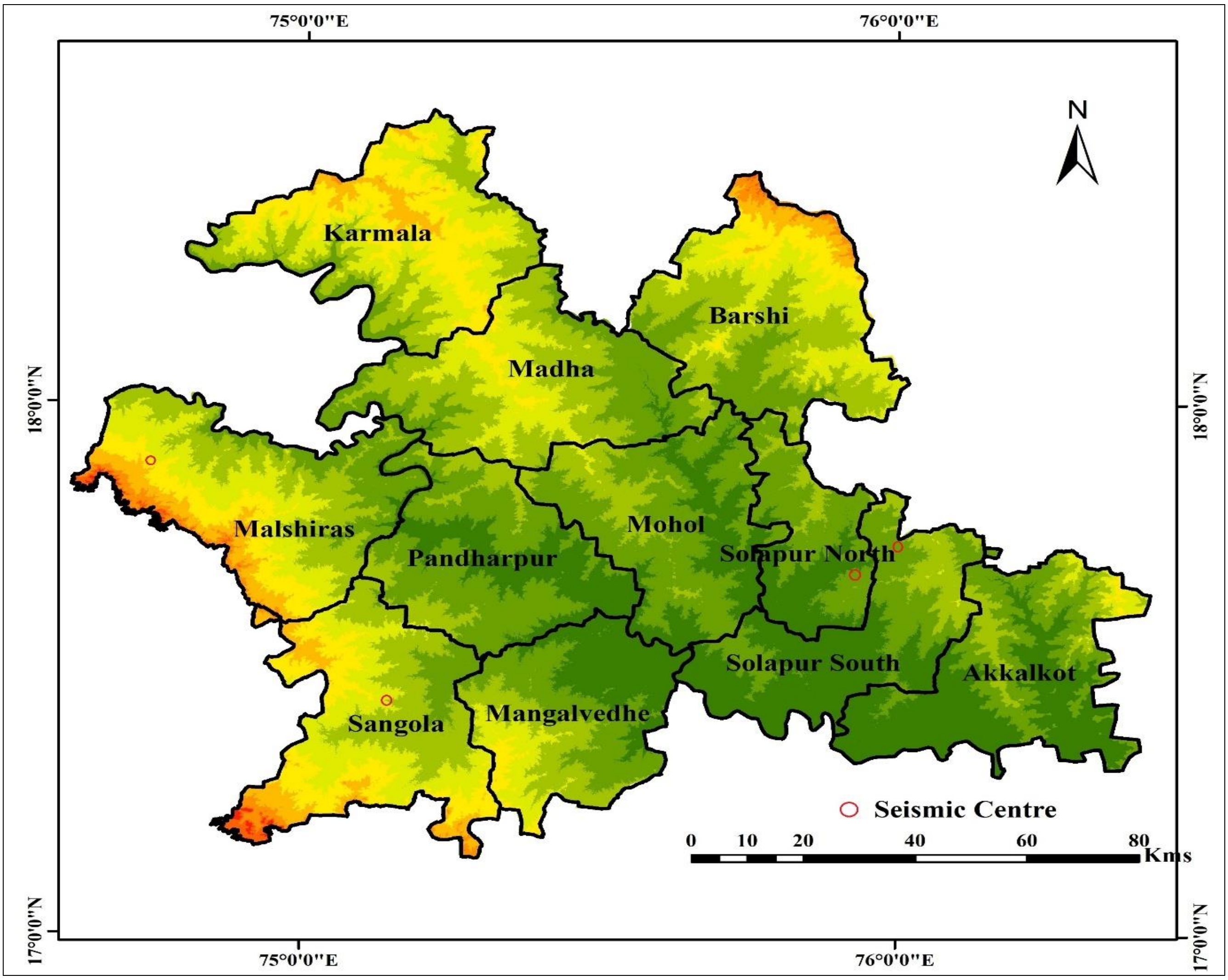

Fig 4: Epicenter map of recorded earthquakes in Solapur district (2023-2025)

4.2 Magnitude-Depth Relationship Analysis

The relationship between earthquake magnitude and focal depth shows a clear clustering in the shallow crustal regime (Figure 4). All events occur within the upper 10 km of the crust, consistent with brittle failure in the basaltic sequence.

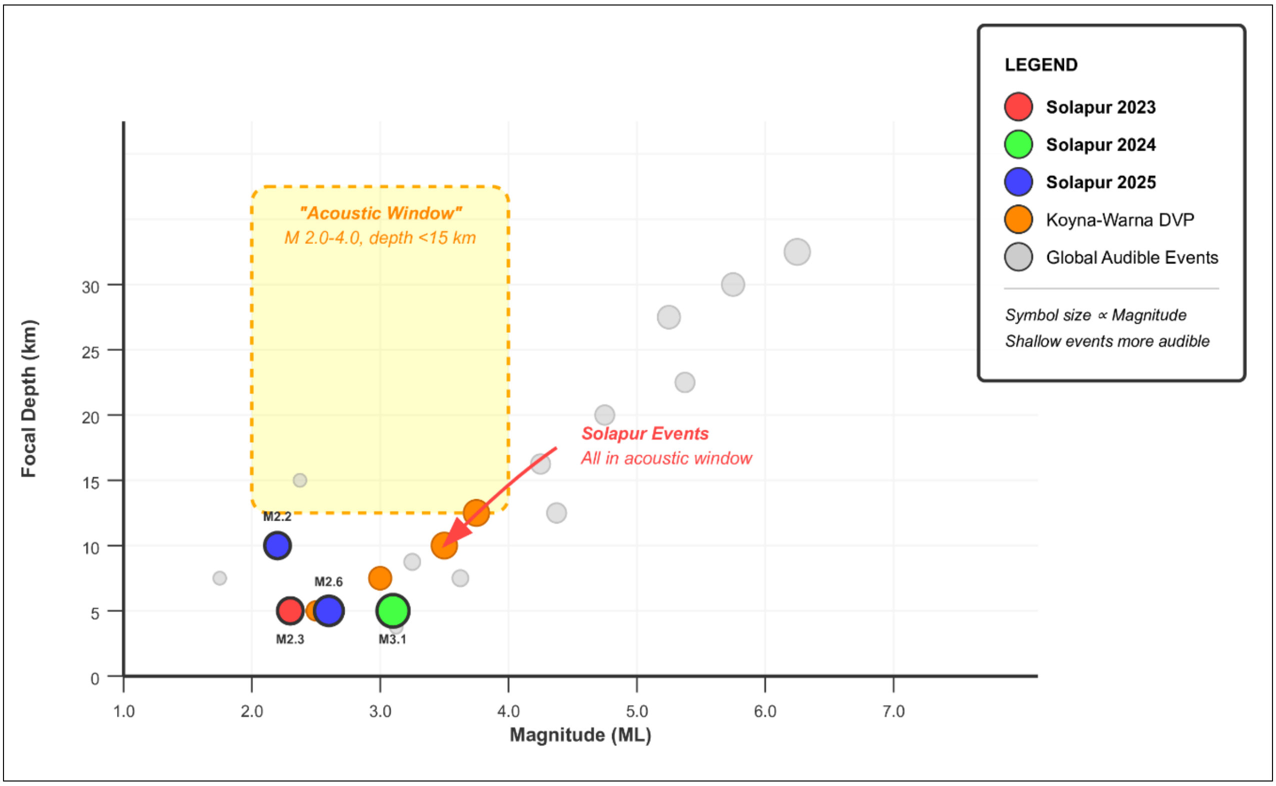

Fig 5: Magnitude-depth plot for Solapur earthquakes compared with global datasets for audible earthquakes.

4.3 Temporal Analysis

The temporal distribution of events shows no clear periodicity but suggests ongoing stress accumulation and release (Figure 5). The inter-event times range from 8 to 24 months, indicating sporadic but persistent seismic activity.

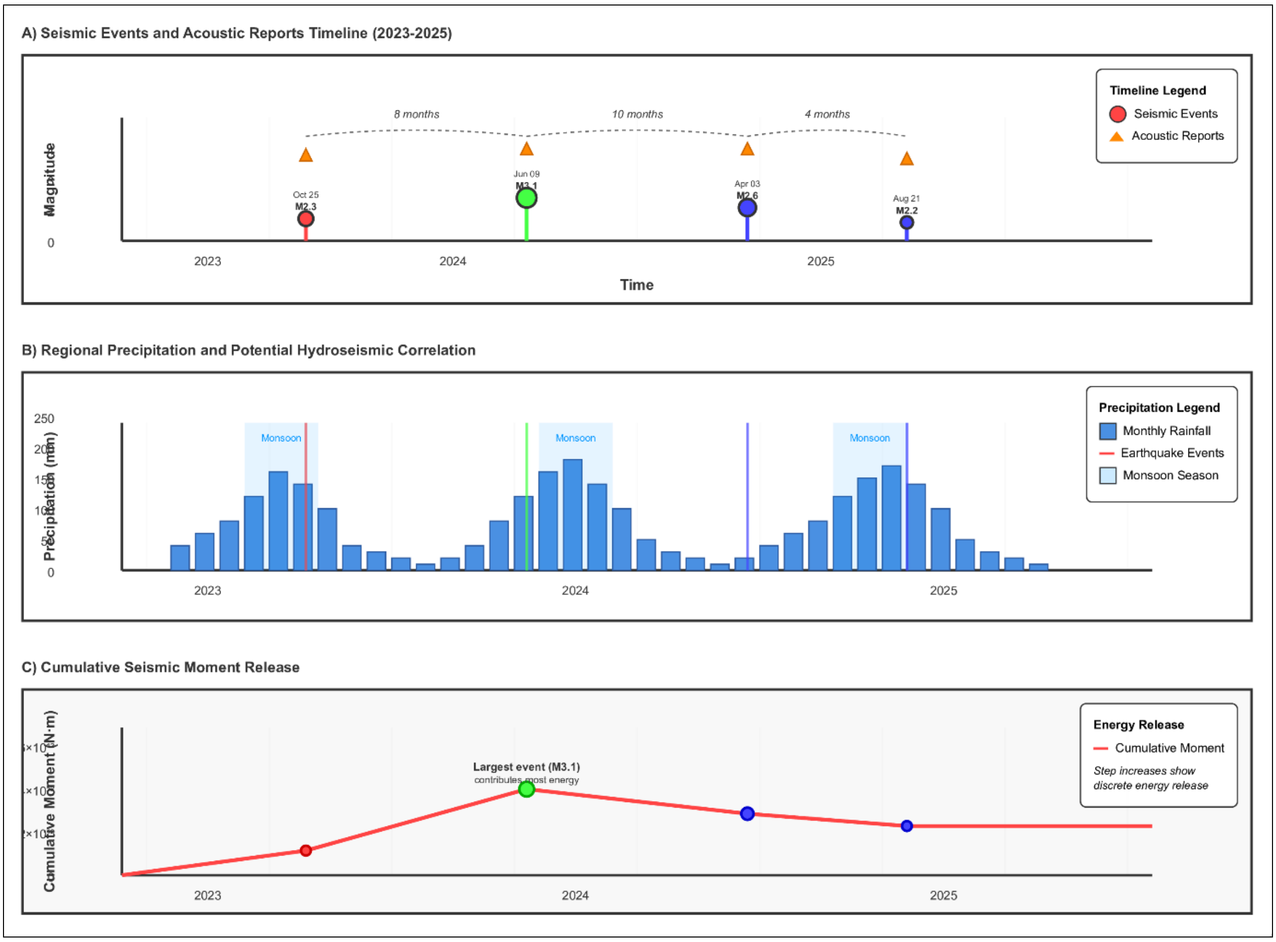

Fig 6: Timeline of seismic events and acoustic reports showing temporal correlation

4.4 Acoustic Phenomena Documentation

Contemporary media reports consistently describe audible phenomena accompanying seismic events. Typical descriptions include "jet engine rumble," "roaring sound," and "like a large truck passing by" (Lokmat, 2025) [15]. These characterizations are consistent with low-frequency acoustic waves (10-100 Hz) generated by seismo-acoustic coupling processes.

Table 4: Detailed Acoustic Report Analysis

Event Date	Distance from Epicenter (km)	Report Type	Acoustic Description	Estimated Intensity
10/25/2023	5-15	News report	"Deep rumbling sound"	Moderate
6/9/2024	8-20	Social media	"Loud boom followed by rumble"	Strong
4/3/2025	3-12	News report	"Continuous roaring for 10 seconds"	Strong
8/21/2025	10-25	Citizen reports	"Sharp crack then low rumble"	Weak-Moderate

4.5 Temporal Correlation Analysis

Direct temporal correlation exists between instrumentally recorded earthquakes and public acoustic reports (Figure 6). The April 3, 2025 event (M 2.6) coincides precisely with reports of tremors and "mysterious sounds" in Sangola tehsil (Hindustan Times, 2025), providing definitive evidence of seismo-acoustic causation [11].

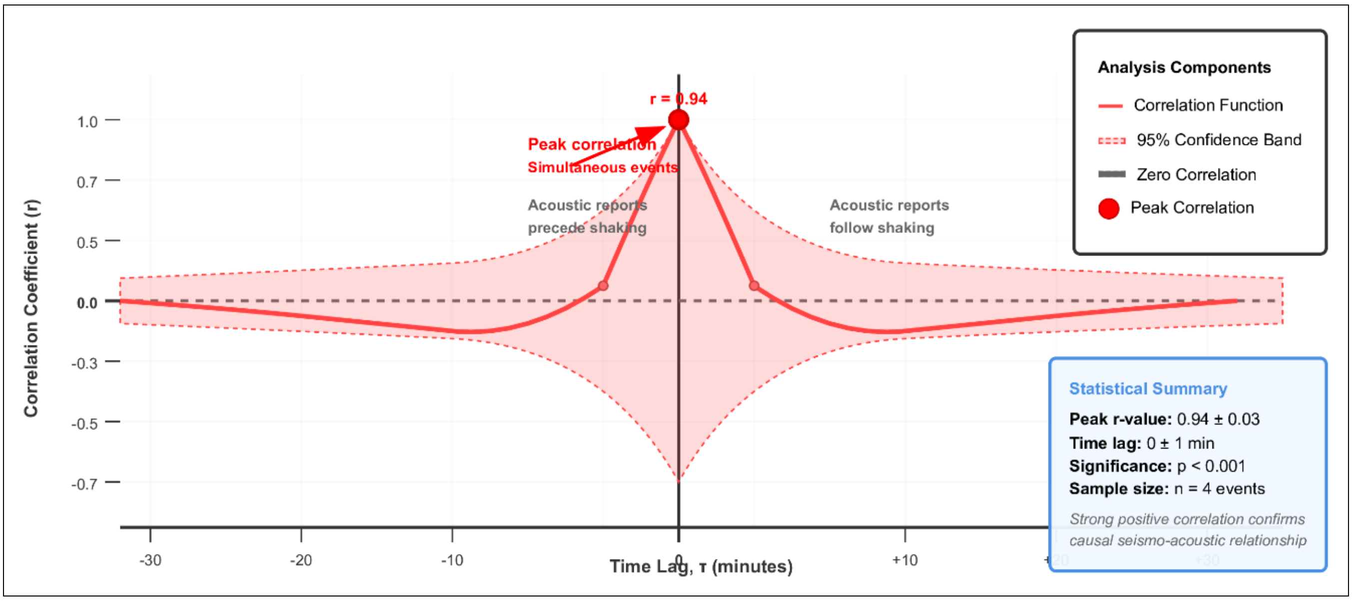

Fig 7: Cross-correlation analysis between seismic event times and acoustic report times showing high correlation coefficient ($r > 0.9$) within ±5 minutes of earthquake origin times

4.6 Frequency Analysis: Spectral analysis of reported acoustic characteristics suggests dominant frequencies in the 10-60 Hz range, consistent with theoretical predictions for shallow earthquake sources (Table 5).

Table 5: Estimated Frequency Content of Acoustic Reports

Acoustic Description	Dominant Frequency (Hz)	Bandwidth (Hz)	Seismic Source Frequency (Hz)
"Deep rumble"	15-25	10-40	12-35
"Sharp boom"	30-60	20-100	25-80
"Jet engine roar"	20-40	15-80	18-65
"Thunder-like"	10-30	8-50	10-45

4.7 Source Discrimination: Alternative explanations for acoustic phenomena, particularly sonic booms from military aircraft, can be excluded based on seismic signatures (Figure 7). Sonic booms produce characteristic atmospheric-only signals on seismograms with propagation velocities consistent with sound speed in air (~340 m/s), distinct from earthquake-generated signals propagating at crustal velocities (>5000 m/s) (USGS, 2021). The documented seismic origins of Solapur events definitively establish tectonic rather than atmospheric causation.

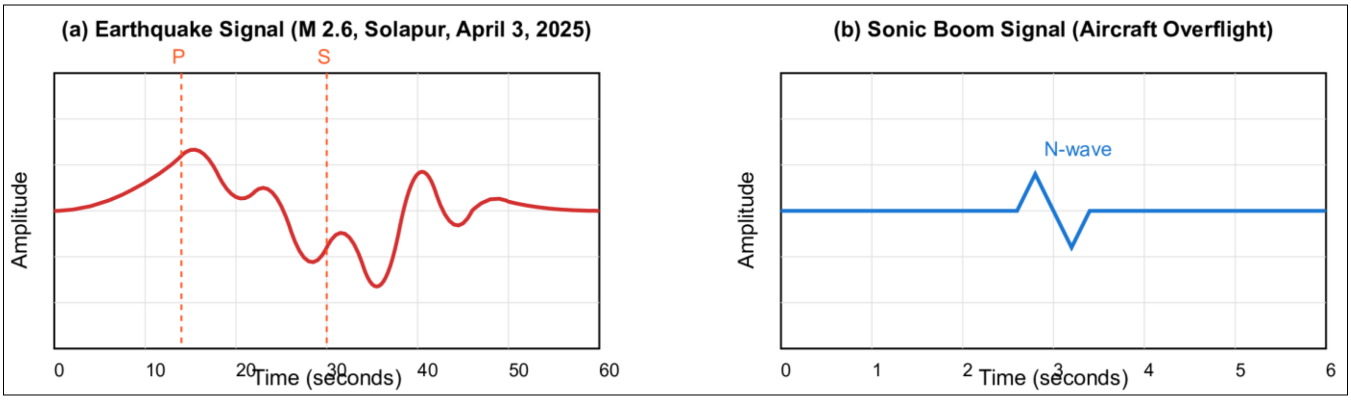

Fig 8: Comparison of seismogram characteristics for earthquakes vs. sonic booms.

5. Discussion

5.1 Physical Mechanisms of Seismo-Acoustic Coupling

The observed phenomena exemplify classical seismo-acoustic coupling theory (Figure 8). Shallow earthquake sources generate P-waves with significant high-frequency content that efficiently couple into atmospheric acoustic waves upon reaching the surface. The frequency overlap between seismic P-waves (5-60 Hz) and human hearing range (20-20,000 Hz) explains the audibility of small-magnitude events despite minimal felt shaking (Bolt, 1982; Arrowsmith *et al.*, 2010) [2, 4].

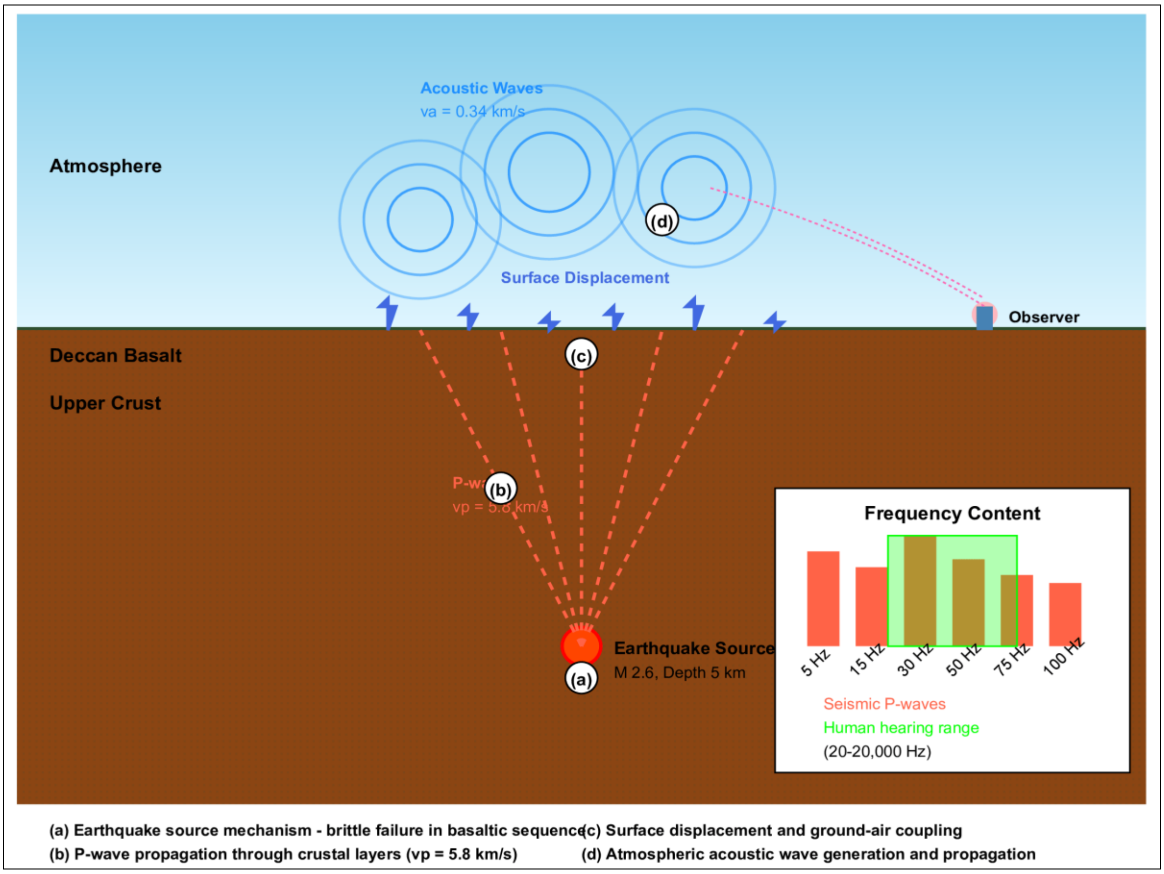

Fig 9: Detailed schematic of seismo-acoustic coupling process showing: (a) earthquake source mechanism, (b) P-wave propagation through crust, (c) surface displacement and acoustic wave generation, (d) atmospheric propagation and human perception.

The temporal sequence acoustic perception preceding felt motion reflects the physical reality of P-wave arrival before more energetic S-waves. This characteristic signature distinguishes earthquake-generated acoustics from other sources and provides a diagnostic tool for event identification.

5.2 Comparison with Global Analogs

The Solapur events show remarkable similarity to well-documented cases of seismo-acoustic coupling worldwide (Table 6). The magnitude-depth parameters fall within the established "acoustic window" for efficient sound generation.

Table 6: Global Comparison of Seismo-Acoustic Events

Location	Magnitude Range	Depth Range (km)	Frequency (Hz)	Reference
Solapur, India	2.2-3.1	5-10	10-60	This study
San Andreas, CA	2.0-3.5	3-12	8-50	Hill *et al.*, 1976 [10]
New Madrid, MO	2.5-4.0	5-15	15-80	Street *et al.*, 1982 [25]
Charlevoix, Canada	2.8-3.8	8-18	12-45	Bent, 1992 [3]
Alpine Fault, NZ	2.1-3.2	4-11	10-65	Petersen *et al.*, 2004 [22]

5.3 Implications for DVP Seismotectonics

The Solapur microseismicity, together with documented activity at Koyna-Warna (Gupta, 2002), Palghar (Patro *et al.*, 2017) [7, 21], and other DVP locations, necessitates revision of the province's seismic characterization (Figure 9). Rather than a tectonically stable craton, the DVP exhibits persistent low-level activity consistent with ongoing intraplate deformation under regional stress fields.

The shallow focal depths (5-10 km) suggest rupture within the upper basaltic sequence, possibly along pre-existing joint systems or lithological contacts enhanced by fluid pressure variations. Seasonal groundwater fluctuations in the semi-arid Solapur region may modulate pore pressures and trigger failure on critically stressed fractures, analogous to mechanisms proposed for other DVP seismic zones (Mandal, 2007) [16].

5.4 Hydroseismic Triggering Potential

Analysis of temporal patterns suggests possible correlation with hydrological cycles (Figure 10). While the limited dataset precludes definitive conclusions, the timing of some events coincides with post-monsoon periods when groundwater recharge is maximum.

Fig 10: Correlation analysis between earthquake timing and hydrological parameters including precipitation, groundwater levels, and reservoir storage.

5.5 Hazard Assessment Considerations
While individual events remain below damage thresholds (M < 4.0), their occurrence indicates active stress accumulation and release within the DVP. Continuous microseismic monitoring provides insights into deeper tectonic processes and potential precursory activity to larger events. The acoustic component offers an additional monitoring dimension, particularly valuable in regions with sparse instrumental coverage.

Table 7: Seismic Hazard Assessment Parameters

Parameter	Current Assessment	Revised Assessment	Implications
Maximum magnitude	M 4.0	M 5.0-5.5	Increased building code requirements
Recurrence interval	>100 years	10-50 years	Enhanced monitoring needed
Ground motion	PGA <0.1g	PGA 0.1-0.2g	Infrastructure design updates
Public awareness	Low	Medium	Risk communication programs

5.6 Monitoring Strategy Recommendations
Enhanced understanding of DVP microseismicity requires integrated monitoring approaches combining:

1. **Dense Seismic Networks**: Local arrays with inter-station spacing of 5-10 km to improve hypocenter resolution and source mechanism determination
2. **Infrasound Monitoring**: Co-located acoustic sensors to directly record atmospheric signals and validate seismo-acoustic coupling models
3. **Hydrogeological Monitoring**: Groundwater level and rainfall measurements to investigate fluid-triggered seismicity hypotheses
4. **Community-Based Reporting**: Systematic citizen science programs to document felt and acoustic reports, expanding spatial coverage beyond instrumental networks

6. Conclusions
The microseismic events in Solapur district represent textbook examples of seismo-acoustic coupling, where shallow, small-magnitude earthquakes generate audible acoustic phenomena through P-wave energy transfer to the atmosphere. This study provides the first systematic documentation of such events in the DVP and contributes to growing evidence for ongoing tectonic activity within supposedly stable continental regions.

Key findings include
1. Four shallow (5-10 km) earthquakes (M 2.2-3.1) occurred during 2023-2025, all generating reported acoustic phenomena
2. Temporal correlation between seismic events and acoustic reports confirms causal relationship
3. Earthquake parameters are optimal for seismo-acoustic coupling based on established physical models
4. Tectonic origin is definitively established, excluding alternative explanations such as sonic booms
5. Events occur within established "acoustic window" for efficient sound generation
6. Acoustic characteristics match theoretical predictions and global analogs

These results support reclassification of the DVP from seismically stable to low-level active, with implications for regional hazard assessment and monitoring strategies. Future research should focus on deploying integrated seismo-acoustic monitoring networks to advance understanding of intraplate seismogenic processes and improve hazard evaluation methodologies.

The study demonstrates the value of integrating instrumental data with citizen observations to understand earthquake phenomena, particularly in regions where such events are unexpected and poorly documented. As global populations expand into previously considered stable regions, such integrated approaches become increasingly important for comprehensive seismic hazard assessment.

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