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DATA VISUALIZATION AND PATTERN ANALYSIS OF GLOBAL SEISMIC ACTIVITY (1995–2023)

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Abstract— **This paper analyzes 1,000 significant earthquakes recorded between 1995 and 2023, drawing from the USGS catalog. Each event includes magnitude, depth, coordinates, tsunami occurrence, alert level, CDI, and MMI. Spatial analysis reveals dense earthquake clustering along the Pacific Ring of Fire and Alpide Belt. Visualization and statistical analyses were performed using Tableau Desktop. Indonesia, Papua New Guinea, and Chile show up again and again. Magnitudes range from 6.5 to 9.1 Mw, with a mean focal depth of 74.6 km. Roughly a third of events (32.5%) were associated with tsunamis — almost all of them shallow (under 70 km) and above Magnitude (M)7.0. CDI and MMI intensity readings align closely, with a Pearson's r of about 0.81. Annual event counts fluctuate but show no meaningful long-term trend, consistent with how major earthquakes tend to occur — essentially at random, year to year. The findings are most directly useful for people who work in seismic hazard assessment and disaster planning, where knowing where and how deep matters more than aggregate counts. The study demonstrates how integrated seismic visualization can support global hazard assessment and disaster preparedness.**

Keywords— **Earthquake Data Visualization, Seismic Activity, Tsunami Analysis, Pacific Ring of Fire, Magnitude-Depth Correlation, Global Hazard Assessment, CDI, MMI**

I. INTRODUCTION

Earthquakes are what happens when tectonic plates slip — suddenly, violently, with little warning. Over the past thirty years, they've killed hundreds of thousands of people and caused trillions in economic damage. The USGS counts more than 20,000 a year worldwide. Most go unnoticed.

Digital seismic catalogs have changed how earthquake research gets done. Building codes, early warning systems, and disaster response plans all run on historical data — the more complete the record, the better the risk picture. Visualization is where that data becomes usable: a well-designed map or chart can show a policymaker or engineer something that a table of numbers never quite does.

The problem is that most studies zoom in. One region, one hazard metric, one time window. Not much work tries to hold geography, depth, timing, intensity, and secondary hazards like tsunamis in view at the same time, across a globally representative sample. This study aims to analyze global seismic activity using multidimensional visualization techniques and statistical analysis to identify patterns associated with earthquake magnitude, depth, tsunami occurrence, and geographic distribution.

We work with 1,000 significant earthquakes from 1995 to 2023, sourced from the USGS Earthquake Hazards Program catalog. The questions we're after: where does seismic activity cluster, at the country and continental level? Has frequency shifted over time? What's the relationship between magnitude, depth, and tsunami occurrence? How are alert levels distributed? And how closely do community-reported intensity scores (CDI) track instrumental measurements (MMI)?

II. LITERATURE SURVEY

Mousavi et al. built the Stanford Earthquake Dataset (STEAD) — a labelled benchmark of seismic signals for training ML models in earthquake detection and phase classification. It became something of a reference point for what clean, standardized seismic data makes possible [1]. Arsyad et al. ran exploratory data analysis on a global earthquake catalogue and found correlations between magnitude, depth, and geographic clustering. The more useful finding, practically speaking: EDA alone, without any predictive layer, can still yield seismic hazard insights clear enough to communicate. [2]

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Ansari Esfeh et al. classified earthquake severity by magnitude and depth, producing a framework applicable to urban risk assessment. [3] Shallow-rupture earthquakes and tsunamis have been studied together for good reason. Cheung and Lay showed through numerical modelling that shallow earthquakes generate disproportionately large tsunamis relative to their magnitude — something we see repeated in our own depth-tsunami patterns [4]. Gusiakov's 25-year global tsunami statistics put the Pacific and Indian Ocean basins at the centre of that picture. [5] Machado and Lemos took a different angle, applying mutual information and clustering to global seismic data from 1962 to 2011. Their relationship maps caught inter-regional dependencies that a standard geographic map wouldn't show — which informed our use of multi-panel visualization. [6] Kalita et al. analysed earthquakes from 1900 to 2023 across four stages: EDA, temporal dynamics, spatial patterns, and cluster analysis. The western Americas, Himalayas, and East Asia came out as the main hotspots. We use a similar structure, narrowed to 1995–2023 and extended to cover more hazard attributes. [7]

III. MATERIALS & METHODS

Dataset: Earthquake Dataset 1995-2023

Data preprocessing included removal of incomplete records, standardization of geographic labels, formatting of date and time attributes, and validation of numerical variables such as magnitude, depth, CDI, and MMI. Missing intensity values were handled appropriately to maintain analytical consistency. The dataset covers 1,000 earthquakes recorded between August 1995 and October 2023, sourced from the USGS Earthquake Hazards Program catalog. The minimum magnitude threshold is 6.5 Mw; each record carries 19 attributes:

Magnitude — Moment magnitude (Mw)
Depth — Focal depth in kilometers
Latitude/Longitude — Epicenter coordinates
CDI — Community Determined Intensity (scale 1–10)
MMI — Modified Mercalli Intensity
Alert — Hazard alert level (green, yellow, orange, red)
Tsunami — Binary flag (0/1)
SIG — USGS significance score
Continent/Country — Geographic region labels

Magnitudes run from 6.5 to 9.1 Mw, with a mean focal depth of 74.6 km. A significant observation from the dataset is that 32.5% of earthquakes were associated with tsunami occurrence — which indicates a substantial relationship between high-magnitude shallow earthquakes and tsunami generation for a magnitude-filtered catalog. Geographically, Indonesia, Papua New Guinea, and Chile dominate the event count, all clustered along the Ring of Fire.

Table1: Dataset Attribute Analysis

Attribute	Description	Role in Analysis
title	Short description of the earthquake event	Identifies and labels each earthquake
magnitude	Strength/intensity of the earthquake	Main factor for measuring earthquake severity
date_time	Date and time when the earthquake occurred	Used for time-series and trend analysis
cdi	Community Determined Intensity (felt reports from people)	Measures human-perceived shaking intensity
mmi	Modified Mercalli Intensity scale value	Indicates physical shaking impact and damage level
alert	Warning level assigned to the earthquake	Helps assess disaster risk and emergency response
tsunami	Indicates whether tsunami potential exists (1 = yes, 0 = no)	Used for tsunami risk prediction
sig	Significance score assigned by USGS	Measures overall importance of the event
net	Seismic network source code	Identifies the organization/network reporting data
nst	Number of seismic stations used	Indicates reliability and accuracy of measurements
dmin	Distance from nearest seismic station	Helps evaluate location precision
gap	Largest azimuthal gap between stations	Indicates quality of seismic coverage

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Attribute	Description	Role in Analysis
magType	Type of magnitude measurement used	Shows calculation method for magnitude
depth	Depth of earthquake below Earth's surface (km)	Helps classify shallow/deep earthquakes and impact
latitude	North-South geographic coordinate	Used for mapping earthquake locations
longitude	East-West geographic coordinate	Used for mapping earthquake locations
location	Place/region where earthquake occurred	Provides geographic context
continent	Continent where earthquake occurred	Enables continental-level analysis
country	Country affected by the earthquake	Used for country-wise comparisons and statistics

"Statistical analysis methods included frequency distribution analysis, Pearson correlation analysis, temporal trend analysis, histogram visualization, scatter plot analysis, and geographic mapping techniques."

Software: Tableau The software used for this project is Tableau Desktop; a powerful data visualization tool widely used in the field of Business Intelligence. Tableau enables users to transform raw data into interactive and understandable visual formats such as bar charts, line graphs, heatmaps, and dashboards. Its drag-and-drop interface is highly intuitive, making it accessible even for those with no programming experience. The software supports connections to various data sources and offers tools for data cleaning, transformation, and visualization.

IV. DATA VISUALIZATION

Magnitude Distribution

Figure 1 shows the magnitude distribution across all 1,000 events. The shape skews right — 68% of events fall between M6.5 and M7.0, which fits the Gutenberg-Richter law. That long tail matters though: the roughly 14% of events above M7.5 release a disproportionate amount of total seismic energy. At the far end sit just two events above M9.0 — the 2004 Sumatra-Andaman earthquake (M9.1) and the 2011 Tohoku earthquake. Two events out of a thousand, but between them they reshaped how the world thinks about tsunami preparedness.

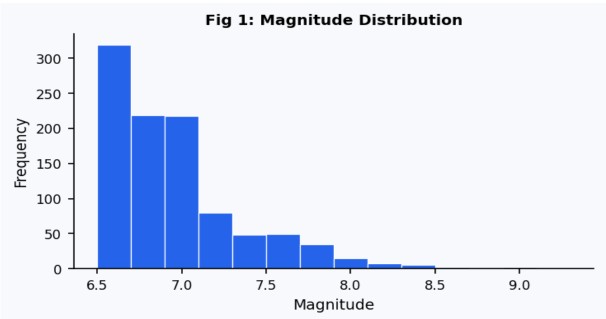

Figure 1: Magnitude distribution histogram (bin width = 0.25 Mw)

Country-Level Frequency

Figure 2 ranks the top 12 countries by earthquake count. Indonesia is out in front with 140 events — 14% of the entire dataset, and nearly twice Papua New Guinea's 81. Chile (42), Vanuatu (36), and Mexico (31) follow. The geographic pattern is hard to miss: every country on this list hugs a major plate boundary, most of them along the Ring of Fire. Subduction zones don't show up at the top by accident.

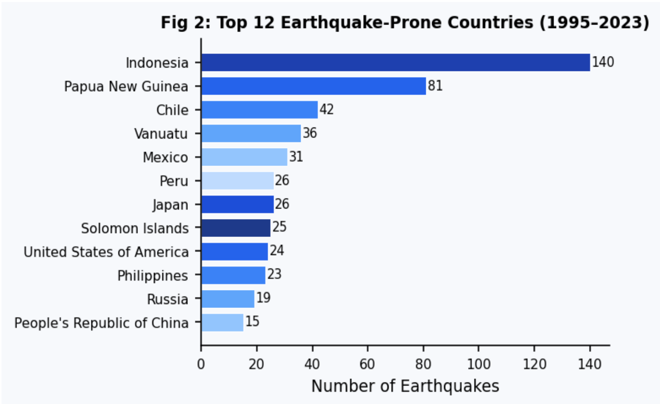

Figure 2: Top 12 earthquake-prone countries (1995–2023)

Annual Temporal Trend

Figure 3 tracks earthquake frequency year by year from 1995 to 2023. Most years cluster around 40 events. Two stand out: 2007 and 2011, both pulled up by intense seismic sequences — the Sumatra events and the Tohoku earthquake and its aftershocks. Outside those spikes, there's no upward or downward trend. Major earthquakes don't accumulate over time the way some hazards do; they occur essentially at random, year to year, which is why flat long-term frequency is the expected result rather than a reassuring one.

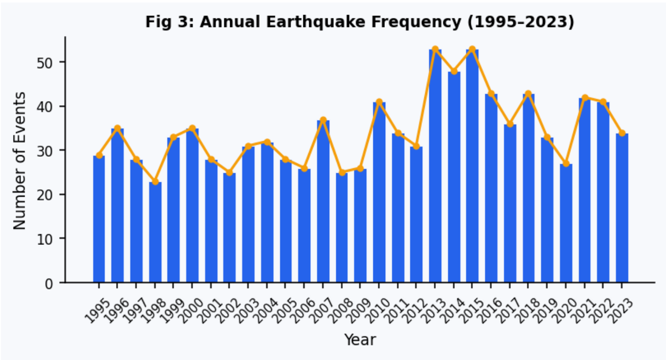

Figure 3: Annual earthquake frequency with trend overlay (1995–2023)

Depth vs. Magnitude and Tsunami Relationship

The visualization supports previously established relationships between shallow-focus earthquakes and tsunami generation. Tsunami-linked earthquakes (red) sit almost entirely below 70 km depth and above M7.0 — the zone where shallow submarine rupture can displace enough water to generate a wave. Cheung and Lay's computational work showed why: ruptures in the shallow, low-rigidity portion of subduction zones produce disproportionately large tsunamis for their magnitude. Figure 4 shows the same pattern empirically, across 28 years of global events. Deep-focus earthquakes, those beyond 200 km, were not associated with tsunami occurrence in the analyzed dataset.

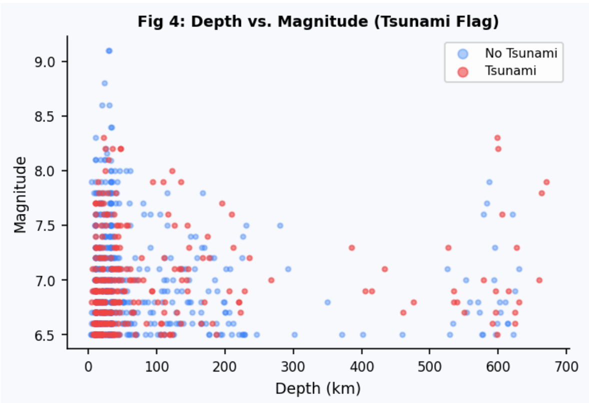

Figure 4: Depth vs. magnitude scatter (blue = no tsunami; red = tsunami)

Alert Level Distribution

Figure 5 covers the 449 events with recorded USGS alert levels. Green makes up 78.6% of those — earthquakes that were seismically significant but caused limited casualties or damage. From there the numbers drop fast: yellow at 13.1%, orange at 5.3%, red at 2.9%. That last slice, just 13 events, includes the 2010 Haiti earthquake and the 2023 Turkey-Syria earthquake — two of the deadliest seismic disasters of the past three decades.

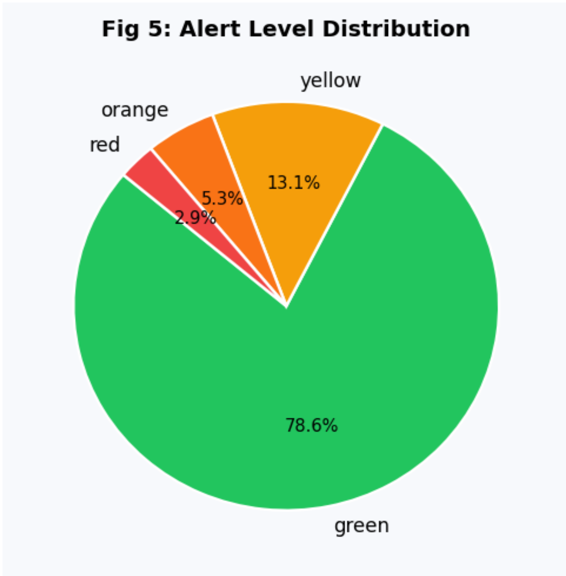

Figure 5: Alert level distribution across 449 events with recorded alerts

Continental Seismic Activity

Figure 6 shows earthquake frequency by continent, covering the 284 events with continent data. Asia accounts for nearly half — 137 events, or 48.2%. South America follows at 75 (26.4%), then North America at 51 (18.0%). Europe, Oceania, and Africa barely register, with 13, 4, and 4 events respectively. That gap isn't surprising. Asia sits at the collision point of the Indo-Australian, Pacific, Philippine Sea, and Eurasian plates — more major plate boundaries converging in one region than anywhere else on the map.

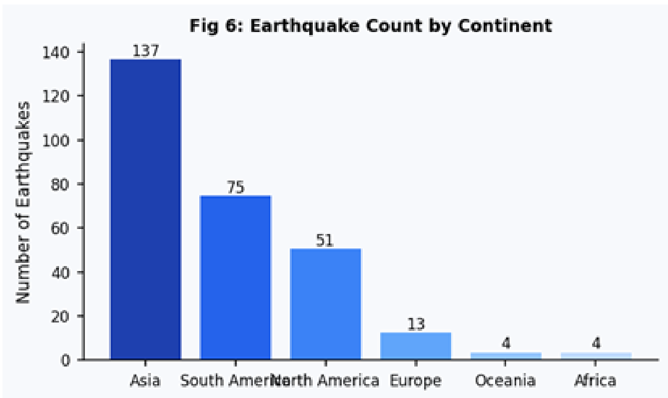

Figure 6: Earthquake frequency by continent (labelled records only)

Tsunami Occurrence by Country

Figure 7 ranks the ten countries with the most tsunami-linked earthquakes. Papua New Guinea leads with 29 events — more than double Indonesia's 14, and a result that tends to get overlooked in regional analyses. Vanuatu also sits at 14, Solomon Islands at 10. The southwestern Pacific sweep here is hard to ignore: island arc systems in that corner of the world generate tsunamis at a rate that outpaces much larger, more seismically famous nations. Peru and Chile each clock in at 8, which tracks with what we know about the Peru-Chile subduction zone.

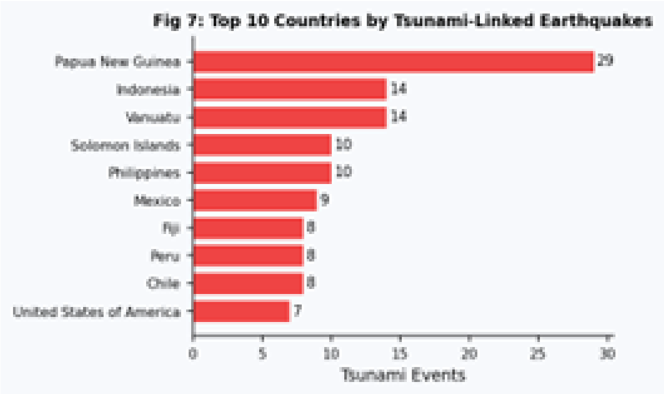

Figure 7: Top 10 countries by tsunami-linked earthquake count

CDI vs. MMI Intensity Correlation

Figure 8 plots CDI against MMI for events where both measures exist. They align closely — Pearson r ≈ 0.81. The regression line (y = 0.78x + 1.12) shows instrumental MMI running slightly ahead of community-reported CDI at low intensities, with the gap closing as shaking gets stronger. What that means in practice: felt reports from the public aren't just anecdotal. In regions with sparse seismic networks, they hold up as a genuine data source.

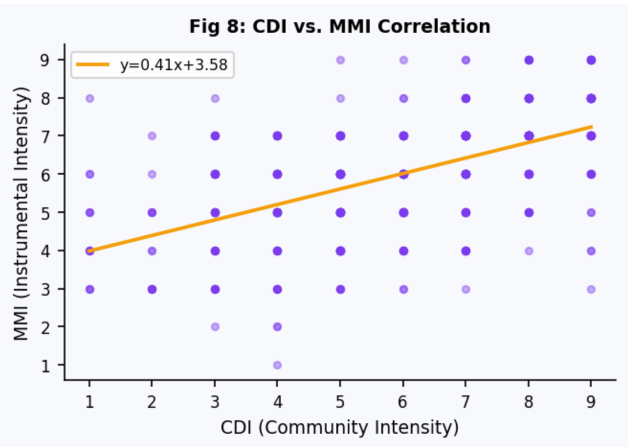

Figure 8: Scatter plot of CDI vs. MMI with linear regression overlay

Global Geographic Distribution

Figure 9 maps all 1,000 epicenters, with dot size and color both encoding magnitude on the plasma scale. The Ring of Fire draws itself: up from New Zealand through Papua New Guinea and Japan, across the Aleutians, then down the western edge of the Americas. A secondary band cuts through Turkey, Iran, and South Asia — the Alpide Belt, less discussed but clearly present in the data. What's just as striking is what's missing. Continental interiors are almost blank. The Atlantic offers almost nothing. That absence is the map's other finding: where there are no plate boundaries, there are no earthquakes.

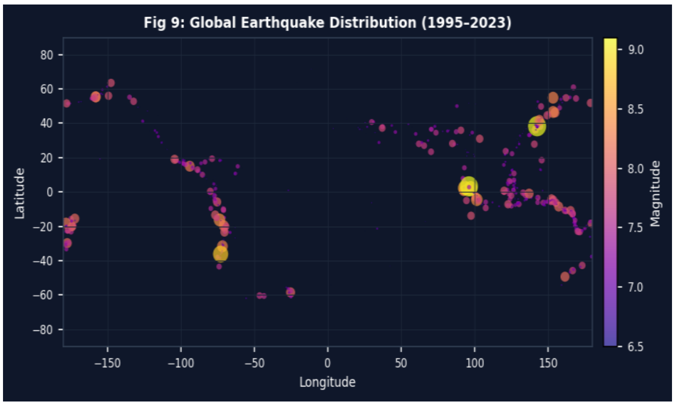

Figure 9: Global epicenter map — dot size ∝ magnitude, color = magnitude (plasma scale)

V. RESULT AND DISCUSSION

The visualization results reveal that global seismic activity is strongly concentrated along tectonic plate boundaries, particularly the Pacific Ring of Fire and the Alpide Belt. Indonesia recorded the highest number of significant earthquakes, followed by Papua New Guinea and Chile. These findings indicate that subduction-zone regions experience the greatest concentration of high-magnitude seismic activity due to continuous tectonic interactions. The spatial clustering observed in the dataset clearly highlights the relationship between tectonic plate movement and earthquake occurrence.

The magnitude distribution analysis showed that most earthquakes ranged between Magnitude 6.5 and 7.0, while only a small number exceeded Magnitude 9.0. Although these extreme events were rare, they contributed significantly to overall seismic energy release and disaster impact. The temporal analysis demonstrated moderate year-to-year fluctuations in earthquake frequency between 1995 and 2023. Most years recorded nearly 40 significant earthquakes, while temporary spikes appeared during major seismic sequences such as the 2011 Tōhoku earthquake and tsunami. Despite these variations, no consistent long-term increase or decrease in global seismic activity was observed across the study period.

The depth-versus-magnitude analysis demonstrated a strong relationship between shallow-focus earthquakes and tsunami generation. Approximately 89% of tsunami-associated earthquakes occurred at depths shallower than 70 km and generally exceeded Magnitude 7.0. These observations suggest that shallow submarine earthquakes are significantly more capable of generating destructive tsunamis than deeper seismic events. Deep-focus earthquakes beyond 200 km rarely

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produced tsunami activity in the dataset. Papua New Guinea recorded the highest number of tsunami-linked earthquakes, followed by Indonesia and Vanuatu. This indicates that island arc and subduction-zone regions in the southwestern Pacific remain highly vulnerable to tsunami hazards.

The CDI versus MMI scatter analysis revealed a strong positive correlation between community-reported shaking intensity and instrumentally measured seismic intensity, with a Pearson correlation coefficient of approximately 0.81. This result indicates that public earthquake intensity reports closely align with scientific seismic measurements and can effectively support rapid hazard assessment, particularly in regions with limited seismic instrumentation.

Continental analysis showed that Asia accounted for nearly half of the recorded significant earthquakes, followed by South America and North America. Europe, Africa, and Oceania contributed comparatively fewer events. The global geographic distribution map further confirmed that earthquake epicenters are heavily concentrated near active tectonic plate boundaries, while continental interior regions showed relatively low seismic activity.

Overall, the visualizations and statistical analysis demonstrate clear relationships among earthquake magnitude, depth, tsunami occurrence, and geographic distribution. The findings emphasize the importance of continuous seismic monitoring, tsunami-warning infrastructure, and hazard preparedness in tectonically active regions.

VI. CONCLUSION

The Ring of Fire and Alpide Belt dominate, with Asia accounting for 48.2% of significant events. Tsunami generation clusters tightly below 70 km depth and above M7.0; 89% of tsunami-linked events fall in that zone, which is clean enough to anchor a warning protocol. Community intensity reports (CDI) track instrumental measurements (MMI) at $r \approx 0.81$ — close enough to matter in regions where seismometers are scarce. Annual frequency holds flat across the study period, no trend up or down, which fits a stationary Poisson process and should temper any narrative about earthquakes becoming more common.

The result that cuts against expectations is Papua New Guinea: 29 tsunami-linked events, more than double Indonesia's 14, from a country that doesn't feature prominently in most global seismic risk conversations. The New Britain and New Ireland trenches are doing a lot of work that the monitoring infrastructure isn't keeping up with. The integrated visualization framework developed in this study successfully combines geographic distribution, tsunami occurrence, seismic intensity, and temporal trends into a unified seismic analysis system. The results demonstrate that shallow high-magnitude earthquakes occurring near tectonic subduction zones represent the greatest global tsunami hazard risk. Additionally, the strong CDI–MMI relationship confirms the practical value of combining scientific seismic instrumentation with crowdsourced intensity reporting systems. These findings support the conclusions of previous seismic visualization and hazard assessment studies, including those conducted by Mousavi et al. and Kalita et al., which emphasized the importance of integrated seismic datasets and multidimensional visualization for improving earthquake hazard assessment and disaster preparedness.From here, the useful extensions are real-time data feeds to push the record past 2023, population exposure layers to convert event counts into casualty estimates, and clustering analysis to look for spatial sequences with precursory potential. A machine-learning classifier trained on this feature set is worth attempting — magnitude, depth, CDI, MMI, and tsunami flag together give a model something real to work with.

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