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SEISMICITY OF THE NOTO PENINSULA: SPATIAL PATTERNS, SHALLOW SEISMIC ZONES, AND POSSIBLE VOLCANO-RELATED SIGNALS

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Background: Japan's complex tectonic setting produces intense seismicity, yet reliable earthquake prediction remains unresolved. Recent data-driven approaches suggest that classical models may be insufficient, highlighting the value of exploratory analysis of seismic parameters. The Noto Peninsula, despite its distance from major plate boundaries, exhibits persistent shallow seismicity and recent large events, making it a critical region for investigating potential precursory signals and improving forecasting methods. **Objectives:** This study aims to identify seismic anomalies in the Noto Peninsula that may act as precursors to large earthquakes, and to evaluate whether persistent elevation of the magnitude locator provides a more reliable forecasting indicator than scale variations. **Methods:** Earthquake data from the Japan Meteorological Agency catalogue (2007–2026) were analysed using an exploratory data analysis framework. Magnitudes were modelled as normally distributed, with location (μ) and scale (σ) parameters estimated via maximum likelihood. Spatial patterns were examined using a 1° latitude–longitude grid, with monthly aggregation of raw event counts and no smoothing applied. All recorded events, including low-magnitude earthquakes, were retained despite known detection limits. Statistical tools included Q–Q plots, regression, and distribution fitting to identify anomalies. Analyses were conducted in R, with full code publicly available to ensure reproducibility and transparency of the methodology. **Results:** Aftershock decay following the May 2023 earthquake showed two distinct phases inconsistent with classical Omori-type behaviour, while magnitude parameters exhibited atypical patterns, including a delayed and persistent increase in the locator. Spatial analysis revealed increasing seismicity near the Noto Peninsula since 2020, culminating in the January 2024 M7.6 event and rapid offshore propagation. Seismicity remained predominantly shallow, indicating stress accumulation in a near-surface zone rather than along the main plate boundary. Offshore regions displayed high locator and low scale values, resembling volcanic-type seismicity. Additional evidence suggests the presence of shallow seismic bands and possible structural links between Noto and adjacent regions. Post-2024 activity shows partial stabilization but continued complexity. **Conclusion:** Seismic activity in the Noto Peninsula exhibits distinct spatial and temporal patterns, with locator variations providing useful indicators of large events. Offshore anomalies and shallow seismic zones suggest complex tectonic or volcanic influences, highlighting the need for continued monitoring and data-driven forecasting approaches.

Keywords: seismicity; magnitude locator; shallow seismic zones; spatial patterns; seismic anomalies; volcanic-type seismicity; tectonic stress; spatial grid analysis.

INTRODUCTION

Japan is located at the convergence of multiple tectonic plates, making it one of the most seismically active regions in the world (JMA, 2023). Given the sudden and often devastating nature of earthquakes, the development of reliable prediction methods has long been a critical goal. Despite decades of research, however, earthquake prediction has remained elusive (JMA, 2024a).

Recent studies, including a new review by Konishi (2025a), suggest that prediction may be potentially feasible through the application of exploratory data analysis (EDA) to simple seismic measurements. In particular, Tong et al. (2025) demonstrate that observed earthquake magnitude distributions may deviate from the classical Gutenberg–Richter relation, thereby underscoring the potential value of flexible, nonparametric approaches for seismic data analysis. Moreover, exploratory data analysis (EDA) indicates that earthquake magnitudes may approximately follow a normal distribution—an observation that highlights a potential avenue for developing new approaches to seismic forecasting, complementing the long-established Gutenberg–Richter (GR) law (Konishi, 2025b; Konishi, 2026; Olsson, 1993; Okuda et al., 1992). Similarly, traditional models describing aftershock decay, such as the Omori rule, have been re-evaluated and significantly revised. These findings raise fundamental questions about how seismic energy should be characterized and assessed. Despite these advances, a robust, universally applicable method for earthquake prediction in Japan remains lacking. As a result, our theoretical understanding of earthquake processes may be on the cusp of substantial transformation.

However, significant challenges remain. Using the mesh-based visualization method together with three-dimensional inspection of seismicity (Konishi, 2026) provides two complementary perspectives for monitoring earthquake activity. These approaches have enabled the identification of precursory patterns associated with earthquakes above a certain magnitude (Konishi, 2025b). Nevertheless, practical experience is often required to interpret these signals reliably. A key challenge is the strong regional variability in seismic behaviour. I have not proposed a universal criterion for anomaly detection because such a standard is unlikely to be valid across Japan's diverse tectonic environments. If all regions shared identical geological structures, a single threshold might be feasible. In reality, however, some areas are inherently more prone to large earthquakes than others, making uniform criteria inappropriate.

One such region is the Noto Peninsula. Although located far from major plate boundaries, Noto lies above a complex interaction zone involving the Eurasian Plate, the Pacific Plate, and the Philippine Sea Plate. In particular, the shallow seismic zone associated with the Sanriku–Oki segment of the Pacific Plate's subduction extends beneath this region. This zone is interpreted as an area where compressive stress accumulates as the Pacific Plate pushes horizontally against the overriding Eurasian Plate. Such stress transfer is thought to generate a near-surface environment favourable for frequent shallow earthquakes (Konishi, 2026). Although the main plate boundary lies at depth, the mechanical coupling between the subducting and overriding plates may transmit stress upward into the crust, creating a persistent seismogenic zone beneath Noto.

In 2023, this region exhibited a marked increase in the magnitude locator, accompanied by a rise in event scale (Figure 1a–b).

Because earthquake magnitudes follow an approximately normal distribution (Konishi, 2025a), it is straightforward to track temporal variations in its two parameters: the mean (μ), represented by the locator, and the standard deviation (σ), represented by the scale. An increase in both parameters is typically associated with heightened potential for large earthquakes (Konishi, 2025a; Konishi, 2025e). Indeed, a magnitude 6.5 earthquake struck the area on 5 May 2023.

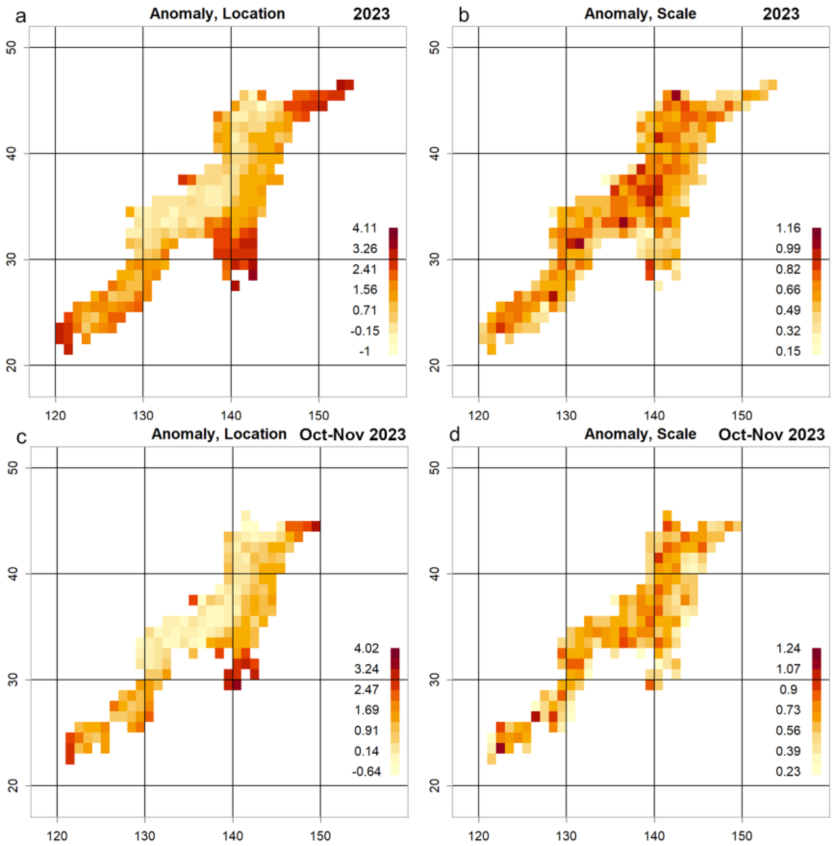

Figure 1. Magnitude-based anomaly metrics for earthquakes in 2023 around the Noto Peninsula (Konishi, 2025c): a – locator metric for all earthquakes in 2023; b – scale metric for all earthquakes in 2023; c – locator metric from October 2023 onward, after May 2023 aftershocks had largely subsided; d – scale metric from October 2023 onward, after May 2023 aftershocks had largely subsided (*Note: panels a and c show the locator metric, whereas panels b and d show the scale metric. Panels a–b cover the entire year 2023, while panels c–d correspond to the period after the May 2023 aftershocks had largely subsided*)

Elevated values in the locator metric (Figure 1a–c) are observed around the Noto Peninsula, particularly in the shallow offshore areas northwest of the peninsula (approximately 134°–136°E, 37°–38°N). Scale values (Figure 1b–d) are elevated over a broader region, with the most prominent region located at the tip of the Noto Peninsula (137°–138°E, 37°–38°N). During the period from October to December 2023, after the aftershock sequence from May 2023 had largely subsided, the locator metric remained elevated in some offshore panels (Figure 1c–d), whereas the scale metric had returned to near-normal levels. Shortly thereafter, on 1 January 2024, a magnitude 7.6 earthquake occurred. This observation indicates that persistent elevation of the magnitude locator (μ) may precede large earthquakes, suggesting a potential predictive signal.

In this study, seismic activity is examined using a 1° latitude–longitude grid in order to develop a method for identifying seismic anomalies that may serve as precursors to significant earthquakes in the Noto Peninsula. Based on empirical experience, this resolution offers a practical balance for analysing earthquakes in Japan: smaller grids tend to yield insufficient data for statistical analysis, while larger grids reduce the spatial precision of event localization (Konishi, 2025c). A more detailed justification for this approach is provided in the following section.

While many theoretical frameworks in seismology, such as the Gutenberg–Richter law and the Omori rule, have historically shaped understanding of earthquake behaviour, recent studies suggest that these models may require substantial revision (Konishi, 2026; JMA, 2024a). Moreover, many theoretical approaches rely on assumptions that are difficult to test or falsify (Thornton, 2023), limiting their utility for empirical validation. In this study, an alternative, data-driven analytical framework is adopted, which does not rely on these traditional models.

To illustrate the application of this data-driven approach, the Noto Peninsula is examined as a case study. Although distant from major plate boundaries, it lies above a complex tectonic intersection involving the Eurasian, Pacific, and Philippine Sea Plates. The shallow seismic zone associated with the Sanriku–Oki segment of the Pacific Plate's subduction extends beneath this area, creating a persistent seismogenic environment.

In 2023, the region exhibited a notable increase in the magnitude locator, followed by a magnitude 7.6 earthquake on 1 January 2024 that damaged approximately 165,000 homes. As of January 2026, 90% of those affected remain in temporary housing, highlighting the urgent need for effective forecasting methods in regions with complex tectonic settings. While prediction cannot eliminate disasters, it can help mitigate their consequences; as with weather forecasting, seismic prediction must rely on the best available data, even if imperfect.

Based on previous observations of the locator (μ) and scale (σ) parameters (Figure 1), the study is guided by two working hypotheses: (i) persistently elevated locator values in the Noto Peninsula are predictive of large earthquakes, and (ii) variations in the scale parameter alone are insufficient to forecast major seismic events.

The aim of this study is to develop a method for identifying seismic anomalies that may serve as precursors to significant earthquakes in the Noto Peninsula. Insights gained here may also contribute to improving preparedness and risk mitigation in other earthquake-prone areas.

MATERIALS AND METHODS

Data sources

Earthquake data were obtained from the seismic catalogue published by the Japan Meteorological Agency (JMA), covering the period from January 2007 to January 2026. The complete dataset includes all recorded earthquakes across Japan, with magnitudes down to approximately M = –1, and was downloaded daily from the official JMA repository. For each analysis, the specific spatial and temporal subsets used are indicated in the corresponding figure captions.

In addition, monthly summary data (JMA, 2025a) were used in Figure 11b of Appendix A (Konishi, 2026). These summary data include only perceptible earthquakes and are considered fundamentally complete, showing a strong linear relationship even for magnitudes as low as M = 1.

Data pre-processing

In this study, earthquake magnitudes are modelled using a normal distribution characterized by two parameters: the location parameter (μ) and the scale parameter (σ). The location parameter μ corresponds to the logarithmic mean of the magnitude distribution, while σ represents its standard deviation. These parameters were estimated using maximum likelihood estimation for each spatial and temporal subset of the data.

Figure 11b in Appendix A of Konishi (2026) is based on monthly summary data (JMA, 2025a), which includes only perceptible earthquakes. As this figure exhibits a strong linear relationship, the summary data can be considered fundamentally complete and reliable even for magnitudes as low as M = 1. However, no magnitude threshold or filtering was applied; all available events, including those below M = 1, were retained. Although data gaps are known to occur at lower magnitudes, particularly in offshore regions with sparse seismometer coverage, the analytical method was designed to be robust to such incompleteness (Konishi, 2025c).

This decision was informed by preliminary diagnostic checks, including normal Q–Q plots of the full catalogue. These plots revealed a downward deviation in the lower magnitude range, resulting in a concave curve a pattern consistent with detection limitations rather than data error.

Despite these limitations, the Latitude–Longitude Mesh Analysis (Figure 1) focuses primarily on land areas, where detection is more reliable. Therefore, the inclusion of low-magnitude events does not significantly affect the validity of the predictive analysis. The method accommodates such data characteristics without requiring uniform completeness across all regions.

Spatial analysis

To examine spatial patterns in seismic activity, a Latitude–Longitude Mesh Analysis was conducted (Figure 1). A grid with one-degree intervals in latitude was applied. This resolution was selected based on empirical testing: finer grids often result in insufficient data density, while coarser grids obscure local features. For Japan, this scale provides a practical balance between spatial resolution and data availability.

Within each grid cell, earthquake events were counted based on the number of individual events recorded in the JMA catalogue. Each event corresponds to a discrete seismic occurrence as defined by JMA's detection and classification system; no additional clustering or filtering was applied.

The time window for aggregation was typically one month, though this varied depending on the specific analysis and is indicated in the relevant figure captions.

No weighting or smoothing was applied; the analysis used raw event counts per grid cell and time window. This straightforward approach allows for transparent interpretation and avoids introducing assumptions that may obscure underlying patterns.

The spatial extent of each analysis is also specified in the corresponding figures, with particular focus on the Noto Peninsula, the primary region of interest in this study.

Statistical analysis

Statistical analyses included Q–Q plots, regression analysis, and distribution fitting to identify structural patterns in the seismic data. The exploratory data analysis (EDA) framework was adopted, following the principles outlined by Tukey (1977) and NIST/SEMATECH (2012). This approach is well suited for identifying anomalies and trends in complex scientific datasets without relying on strong parametric assumptions.

Following the principles of Exploratory Data Analysis (EDA) (Tukey, 1977), this study emphasizes pattern discovery and visualization over formal hypothesis testing. While statistical tests often require strong assumptions that may not hold in complex geophysical data, EDA provides a flexible framework for identifying structural patterns and anomalies without imposing rigid parametric constraints.

Software and reproducibility

All computations were performed using the R statistical environment (V.4.5.1) (R Core Team, 2025). The full R code used in this study is available via Zenodo (Konishi, 2025e), ensuring transparency and reproducibility.

RESULTS AND DISCUSSION

Aftershock decay patterns

Figure 2a shows a linear decrease on a semi-logarithmic plot following the earthquake on 5 May 2023. Two distinct segments are evident, indicating different decay rates with distinct half-lives, a pattern commonly observed in aftershock sequences from many other earthquakes (Konishi, 2026). The observed decay rate shows deviations from classical Omori-type behaviour (Omori, 1895; Utsu, 1957). Such deviations are increasingly recognised in modern seismology, where aftershock sequences are often modelled using Epidemic-Type Aftershock Sequence (ETAS) frameworks and multi-timescale relaxation approaches. These models account for factors such as heterogeneous stress accumulation, rate-and-state friction, and cascading aftershock triggering, and can naturally reproduce multi-phase decay patterns like those observed in Noto, providing a more flexible representation of post-mainshock activity. In this context, the two-segment decay observed in the Noto sequence (Konishi, 2026) may reflect multiple relaxation processes rather than a simple violation of the Omori law. Similar multi-phase decay patterns have been reported in other subduction zone earthquakes, such as the 2011 Tohoku event (Sun et al., 2014) and the 2016 Kumamoto sequence (Pollitz et al., 2017), where the initial fast decay is followed by a slower, long-term relaxation linked to afterslip and viscoelastic relaxation of the crust. This suggests that the observed behavior in Noto may similarly involve multiple physical processes operating at distinct timescales.

In contrast to typical large events, where the magnitude locator rises sharply by 2–4 units and decays rapidly (Konishi, 2026), the subdued initial response in Noto and the delayed increase in September–October suggest the possibility of spatially heterogeneous stress release or temporally staggered aftershock activation (Figure 2b). The figure displays hourly averages; when the window is extended to 12 hours, the transient increase nearly disappears. Instead, the locator rises again around September–October, exceeding the level observed on 5 May (corresponding to the anomaly in Figure 1c). This behaviour appears atypical compared with previously reported patterns. Comparable delayed anomalies have been noted in the 2015 Nepal earthquake aftershock sequences (Adhikari et al., 2015), where complex fault geometries and stress interactions delayed the peak energy release.

To further interpret these observations, it is useful to consider the statistical properties of earthquake occurrence and energy release. Both earthquake frequency and earthquake energy in our dataset are better described by log-normal distributions (Konishi, 2025a), implying that these quantities may result from the multiplicative interaction of several underlying physical factors. While the classical Gutenberg–Richter relation predicts an exponential (power-law) magnitude–frequency behaviour well established in global seismicity studies (Taroni, 2025), recent research has shown that the Gutenberg–Richter exponential model may not universally hold across all seismic environments and datasets (Serra & Corral, 2017; Krushelnitskii et al., 2024; Kostoglou et al., 2025). For example, magnitude distributions in certain anthropogenic or clustered seismicity datasets diverge significantly from exponentiality, exhibiting complex, multimodal, or inflected shapes (Serra & Corral, 2017) that challenge a simple power-law fit (Geffers et al., 2023). Such deviations highlight the limitations of a pure exponential model and the potential utility of alternative statistical forms in specific contexts. In this study, the differing half-lives associated with frequency and energy further suggest that the processes controlling earthquake occurrence times may be distinct from those governing magnitude, reinforcing the relevance of a log-normal representation in addition to the conventional power-law framework (Mitsui, 2024).

Collectively, these observations indicate that while the 5 May mainshock partially released stress, the incomplete relaxation and temporally staggered magnitude increase point to a system with complex stress interactions and variable susceptibility to further seismic activation, emphasizing the need for multi-model analyses beyond classical Omori or Gutenberg–Richter descriptions.

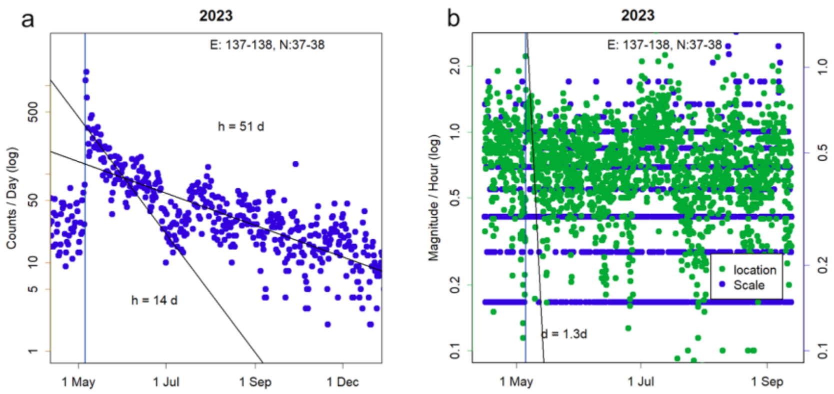

Figure 2. Aftershock activity and temporal evolution of magnitude parameters following the 5 May 2023 earthquake: a - Number of aftershocks observed in 12-hour intervals; the semi-logarithmic plot exhibits an approximately linear decay, consistent with previously reported half-life behaviour (Konishi, 2026); b - Hourly estimates of the magnitude parameters; the locator shows only a brief and minor increase immediately after the 5 May event, returning rapidly to baseline levels, whereas a more pronounced and persistent increase is observed from September onward

Spatial distribution of seismicity

A rare sequence of earthquakes, reminiscent of the Noto case, was recently observed in a separate region. These events occurred near the northern end of the Sanriku boundary, slightly shifted toward the subducting Pacific Plate rather than directly along the boundary (Figure 3), suggesting that local stress concentrations within the upper plate may have played a key role in triggering these events. Two earthquakes occurred in adjacent areas on 9 November 2025 (M6.9) and 8 December 2025 (M7.5), representing significant releases of accumulated strain in this offshore segment. Although this region has historically exhibited elevated locator values, the offshore setting limits the density and reliability of observations, often resulting in sparse data coverage. Consequently, these earthquakes occurred without any clearly identifiable precursory anomalies, consistent with observations in other offshore subduction zones, where seismic swarms and moderate-magnitude events frequently precede larger earthquakes without detectable surface or geophysical precursors (Zaccagnino et al., 2024).

The Figure 3 illustrates two moderately strong earthquakes in the Sanriku region and the associated seismic activity, allowing for an assessment of both the spatial distribution of events and their temporal evolution. The regional map (Figure 3a) shows the geographical setting of the study area, providing context for the analysis of epicentres presented in Figure 3b. The epicentral distribution from October 2025 to January 2026 reveals the formation of clusters corresponding to the two main seismic events.

The temporal evolution of aftershock activity (Figure 3c–d) is characterized by a decrease in the number of events over time. The semi-logarithmic representation of the data reveals an approximately linear relationship, indicating a typical decay of aftershocks following the main shocks. Although the aftershocks of these events decayed with a half-life (Figure 3c–d), the increase and subsequent decay in magnitude parameters were not particularly pronounced (Figure 3e–f). The magnitude locator parameters (Figure 3e–f) do not exhibit a pronounced increase either prior to or during the main events. As a result, the subsequent decay of the signal is weakly expressed and difficult to quantify. The extremely short half-life implies that these parameters are estimated with low precision, limiting robust statistical characterization of the decay. When averaged over longer time intervals, such subtle changes become almost undetectable, indicating that the characteristic decay rate of these aftershocks is brief relative to the monitoring intervals used. Under these conditions, conventional aftershock models may not fully capture the complexity of the sequence, especially if the seismicity exhibits swarm-like behaviour rather than a single dominant aftershock sequence (Lolli & Gasperini, 2006; Lolli et al., 2011). The absence of significant precursory signals in these parameters suggests a stationary behaviour in this case.

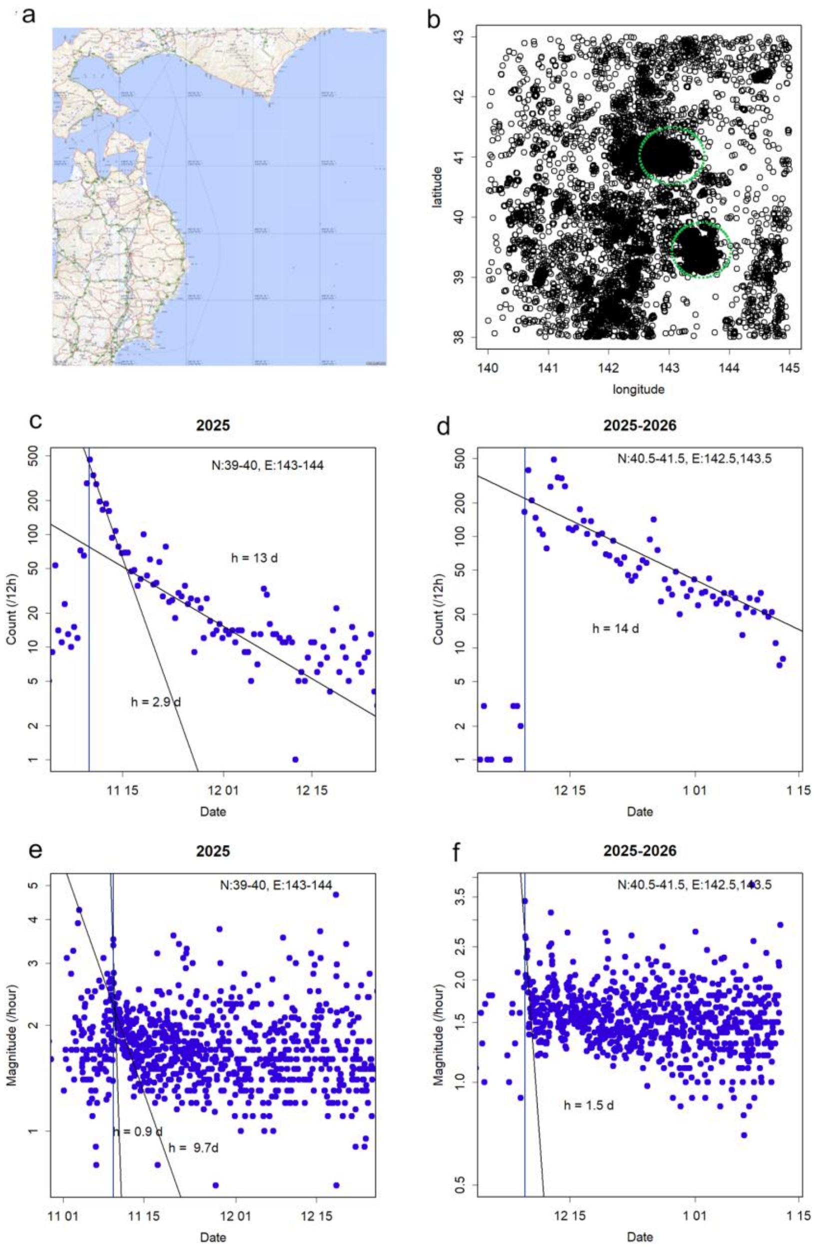

Figure 3. Two recent earthquakes near the Sanriku boundary: a – regional map of the Sanriku area; b – epicentral distribution from October 2025 to January 2026; c–d – number of aftershocks per 12-hour interval; e–f – magnitude locator parameters

A comparison of these results with observations from other regions, in particular the Noto Peninsula, indicates that precursory changes, such as a sustained increase in locator values and a complex structure of aftershock activity, are not universal. Thus, the analysis highlights the variability of seismic processes and underscores the need for region-specific approaches to the interpretation of precursors and seismic monitoring.

The observation that the hypocentres may not have fully released accumulated energy, coupled with the absence of a pronounced decay pattern, suggests that this sequence could represent a precursory swarm rather than a typical aftershock sequence (Petrillo et al., 2024). In seismology, swarms are characterised by multiple events of comparable magnitude without a single mainshock dominating the sequence, and they can reflect complex stress adjustments or aseismic processes within the crust while occasionally preceding larger mainshocks in some tectonic environments (Evison & Rhoades, 1998; Console & Mele, 2026). Although not all swarms reliably precede larger events, their occurrence at moderate magnitude, especially in a stressed subduction zone, raises the possibility that a larger mainshock could follow, given the elevated magnitudes already reached (Kato & Nakagawa, 2014). This interpretation highlights the need for cautious assessment of such sequences as potential precursors in similar geodynamic settings.

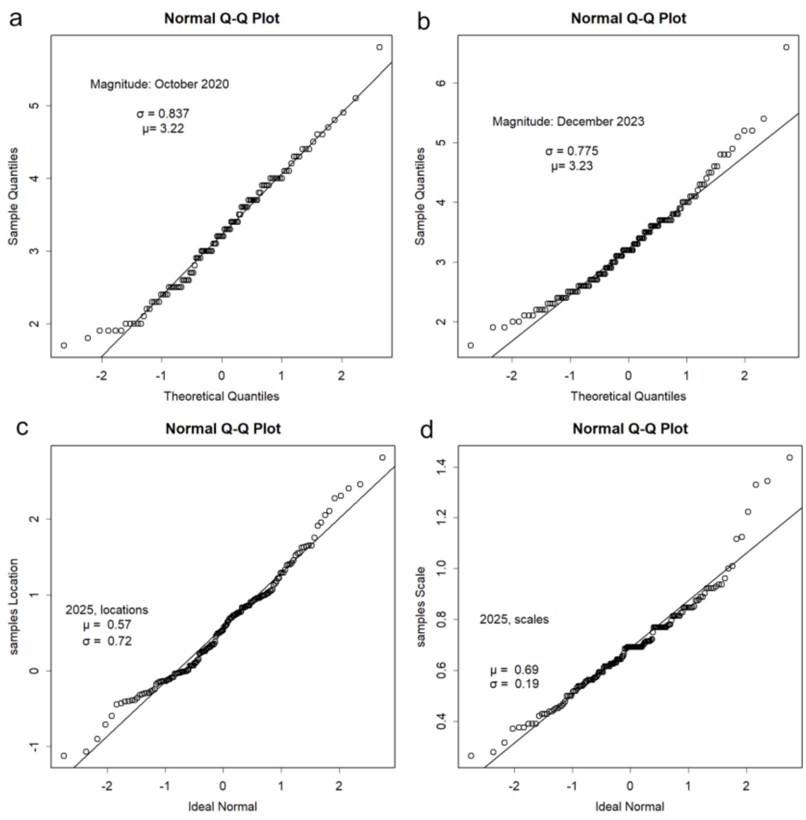

Figure 4. Exploratory data analysis of earthquake magnitude and spatial parameter distributions based on Q–Q plots and Kolmogorov–Smirnov tests

Figure 4a–b present normal Q–Q plots based on monthly catalogues of perceptible earthquakes for October 2020 and December 2023, respectively. In these plots, the x-axis corresponds to theoretical quantiles of a normal distribution, while the y-axis represents the ordered observed magnitudes. The near-linear alignment of the points suggests that earthquake magnitude distributions are approximately consistent with a normal distribution. These variables generally remain stable over time unless influenced by a major seismic event. The slight increase observed in December 2023 may therefore be interpreted as a potential precursory signal preceding the January 2024 Noto earthquake. Given that earthquake magnitude is defined as the logarithm of seismic energy, these results further imply that seismic energy may follow a log-normal distribution.

Figure 4c–d show the distributions of the location (μ) and scale (σ) parameters obtained from grid-by-grid calculations, as presented in Figures 2b and 7. These parameters also approximately follow normal distributions across spatial grids, which is useful for identifying local deviations and potential anomalies.

This visual assessment is consistent with the principles of Exploratory Data Analysis (EDA), which emphasizes pattern recognition with minimal assumptions (Tukey, 1977). The clear linear structure observed in the Q–Q plots provides empirical support for the assumed distributional form.

To complement the graphical analysis, the Kolmogorov–Smirnov (K–S) test was applied using the ks.test() function in R. The results are as follows:

– Figure 4a: D = 0.95560, p-value < 2.2e–16
– Figure 4b: D = 0.96462, p-value < 2.2e–16
– Figure 4c: D = 0.30857, p-value = 4.522e–14
– Figure 4d: D = 0.62631, p-value < 2.2e–16.

Although these low p-values formally reject the null hypothesis of normality, such outcomes are expected given the discrete and bounded nature of magnitude data as well as the large sample sizes involved. It should also be noted that even when Q–Q plots suggest an approximately normal structure, statistical tests may still indicate significant deviations. This highlights a known limitation of strict normality testing in geophysical datasets and underscores the complementary role of exploratory data analysis in such contexts.

As shown in Figure 3b, the nationwide mesh used for the 2026 assessment is shifted by 0.5°, while maintaining a grid size of 1°. This adjustment was made because the original mesh boundaries would otherwise intersect four tiles, complicating the analysis. The 1° tile size remains consistent throughout, as it provides a practical resolution for analysing seismic activity in Japan. For further details, see also Figure 5. Figure 5a shows a regional map of the study area based on the Ministry of Land, Infrastructure, Transport and Tourism dataset (GSI, 2025). The map spans a 2 degree grid in both latitude and longitude, matching the scale used in Figures 5 and 6. The peninsula shown is Noto, and the island in the upper right is Sado Island, separated from Honshu. Figure 5b–f show annual distributions of earthquake epicentres. Green symbols indicate events with magnitudes M > 4. An increase in seismicity is evident near the eastern tip of the Noto Peninsula beginning around 2020. The year 2023 shows a particularly high number of events due to the M6.5 earthquake on 5 May and its subsequent aftershocks.

The annual distribution of earthquake epicentres indicates a progressive intensification of seismic activity near the northeastern tip of the Noto Peninsula. Over the study period, events with magnitudes exceeding M > 4 become increasingly frequent and more spatially clustered, suggesting a transition from diffuse swarm-like activity toward localized strain concentration. This evolution culminates in 2023 (Figure 5f), when both the number and spatial density of moderate-magnitude events peak, immediately preceding the 5 May 2023 M6.5 earthquake and its subsequent aftershock sequence. This pattern is fully consistent with previously reported swarm evolution in the Noto Peninsula, where fluid-driven migration and progressive stress localization clearly and systematically preceded the 2023 M6.5 mainshock (Asano & Iwata, 2025; Tanaka et al., 2025).

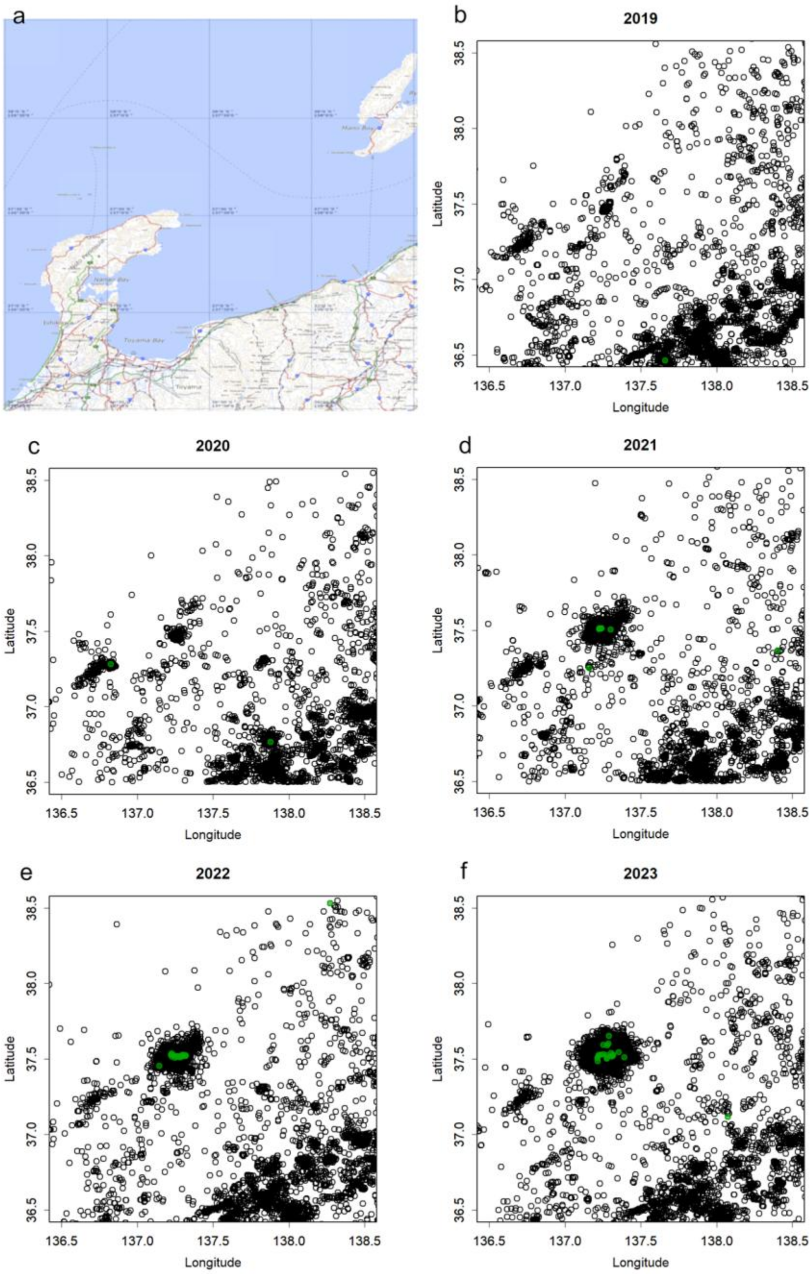

Figure 5. Spatial distribution of earthquake epicentres in the Noto Peninsula region: a – standard map from the Ministry of Land, Infrastructure, Transport and Tourism (GSI, 2025); b–f – annual distributions of earthquake epicentres for 2019–2023 (*Note: green symbols denote events with magnitudes M > 4*)

The spatial extent of panels b–f in Figure 5 lies almost entirely within the reference map shown in Figure 5a, which provides geographic context for the observed patterns.

Following the 1 January 2024 earthquake, the spatial pattern of seismicity changed markedly, with epicentres expanding from the Noto Peninsula westward into the adjacent offshore region (Figure 6a). The M7.6 mainshock nucleated near the tip of the peninsula at 16:10, and within approximately one hour, seismic activity had propagated into the offshore domain. Such rapid spatial expansion of seismicity is consistent with previously documented cases of dynamic stress transfer and rupture-induced triggering, where stress perturbations generated by a large earthquake can activate surrounding fault systems over short timescales (Toda et al., 2011; Kato & Ben-Zion, 2021). Notably, the offshore area affected in 2024 coincides with the epicentral region of the 25 March 2007 M6.9 earthquake (Figure 6b), suggesting spatial reactivation of a pre-existing seismogenic structure.

Both in 2007 and throughout the period up to 2023, earthquakes in this region have been predominantly shallow, typically occurring at depths of approximately 20 km and rarely extending to the Mohorovičić discontinuity (Figure 6c–d), indicating that seismicity is largely confined to the brittle upper crust, consistent with global observations of intraplate seismic regimes (Teng et al., 2014; Spooner et al., 2022). The deeper seismicity corresponds to the Sanriku boundary. The relationship between this boundary and the earthquakes in 2023 and 2024 remains unclear. No large earthquakes have been recorded along the boundary itself, and the number of events does not appear to have increased significantly. These earthquakes are therefore interpreted as originating within the shallow seismic zone (Konishi, 2026), reflecting stress accumulation associated with the horizontal thrusting of the Pacific Plate.

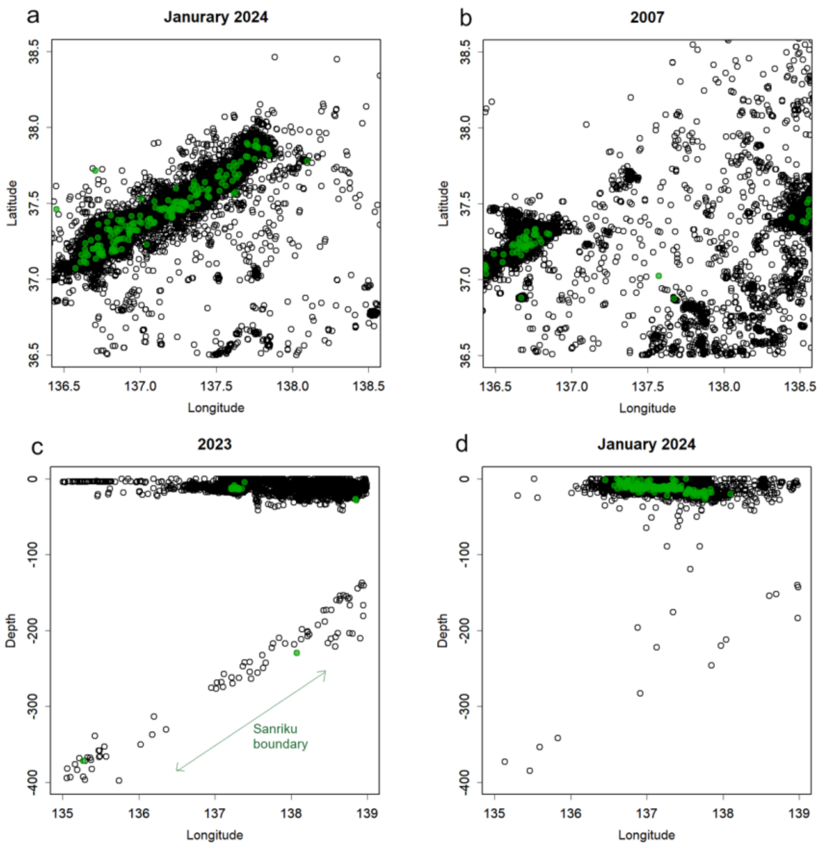

Figure 6. Spatial and depth distribution of seismic activity following the 1 January 2024 earthquake in the Noto Peninsula region: a – spatial distribution of seismic activity within one month after the M7.6 earthquake on 1 January 2024, showing expansion into the offshore region west of the Noto Peninsula; b – correspondence of the offshore seismic area with the epicentral region of the 25 March 2007 M6.9 earthquake; c – distribution of earthquake hypocentres; d – depth distribution of earthquake hypocentres

Following the M7.6 earthquake on 1 January 2024, seismic activity expanded into the offshore region west of the Noto Peninsula within one month, consistent with the documented approximately150 km along-strike aftershock distribution of the sequence (Shiina et al., 2025). This offshore cluster coincides with the epicentral area of the 25 March 2007 M6.9 earthquake, suggesting spatial recurrence of seismic activity in this region (Honda et al., 2025). The depth distribution shows that earthquakes are predominantly shallow, typically occurring above approximately 20 km, whereas deeper events exceeding 200 km are confined to the Sanriku boundary. Along this boundary, neither the frequency of events nor the occurrence of large earthquakes shows a notable increase.

Offshore seismic activity

A characteristic feature of the offshore region west of the Noto Peninsula is the frequent occurrence of relatively high locator values. Although this tendency is more pronounced on the Pacific side, where the onshore portion of the plate boundary lies, this particular area on the Sea of Japan side stands out for exhibiting exceptionally high locator values and elevated event frequency (Figure 7a–c). In contrast, the scale in this region is often very low (Figure 7d). Figure 7d corresponds to the same data shown in Figure 1b but with inverted colouring to highlight areas of low scale. Please refer to Figure 5 for details regarding the characteristics of the data underlying these calculations.

The combination of high earthquake frequency and low scale resembles the patterns observed prior to volcanic activity in the Tokara Islands, Miyakejima, and Mount Aso (Konishi, 2025b; Konishi, 2025d; Konishi, 2025e). These regions commonly exhibit swarms of small earthquakes, which have been associated with processes such as magma or hydrothermal fluid migration (Nakajima, 2022; Liu et al., 2024; Hiramatsu et al., 2026). Such processes generate frequent low magnitude events, and in some cases, larger earthquakes can occur without clear warnings (Konishi, 2025b; Konishi, 2025e).

Bathymetric data indicate that the seafloor in the offshore area adjacent to the Noto Peninsula is relatively shallow (approximately 100 m), which may be consistent with the presence of a submarine volcanic structure or other geological features. Although direct evidence is currently limited, several observed seismic characteristics in this region resemble those reported in volcanic or fluid-influenced seismic systems. These include the presence of a bank of fine silt and low Bouguer anomalies, as reported in geological surveys (Geological Survey of Japan, 2010).

While these features do not confirm the existence of a volcanic structure, they suggest a geological environment that may support such an interpretation. Determining the presence of a submarine volcano would require more detailed seafloor investigations using additional geophysical methods, but such data are not currently available in the public domain.

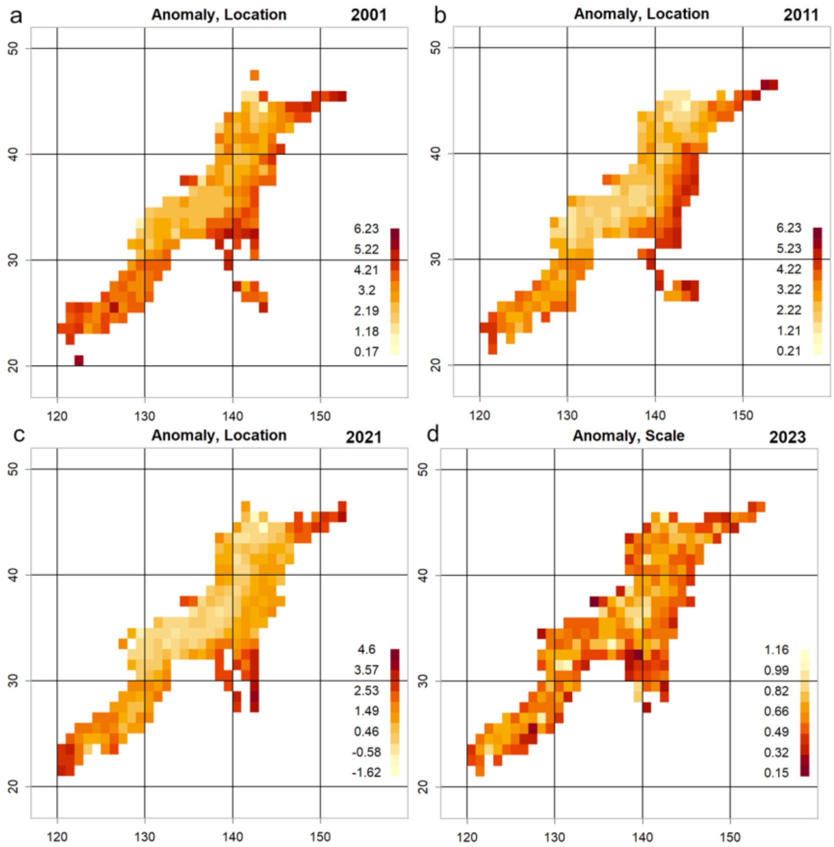

Figure 7. Magnitude-based anomaly metrics in the offshore region west of the Noto Peninsula: a–c – locator metric in the offshore region west of the Noto Peninsula, showing consistently elevated values; this tendency is more pronounced here than in other areas on the Sea of Japan side (Konishi, 2025c); d – scale metric for 2023 in the same region; data are shown with inverted colouring to highlight areas of low scale. High earthquake frequency combined with low scale is characteristic of seismic patterns observed in volcanic regions during periods of heightened volcanic activity (Konishi, 2025b; Konishi, 2025d; Konishi, 2025e)

It is plausible that the 1 January 2024 earthquake occurred in a region where unreleased tectonic stress at the tip of the Noto Peninsula coincided with elevated offshore seismic activity exhibiting volcanic- or fluid-like characteristics, potentially contributing to the observed event. The Noto Peninsula is located approximately between 136.7°E–137.3°E and 36.8°N–37.5°N, and the offshore region northwest of the peninsula consistently exhibits elevated locator values corresponding to the two adjacent grid panels spanning 134°–136°E and 37°–38°N. In 2023, the scale metric in this region reached unusually low values (Figure 7d), and the spatial overlap of high locator values and low scale suggests a combination of frequent seismic activity with low variability.

These observations highlight the shallow offshore area northwest of the Noto Peninsula as a zone of pronounced seismic anomalies, more notable than in other areas on the Sea of Japan side. Although unconfirmed, the observed patterns may be compatible with volcanic or fluid-related processes. It should be noted, however, that the reverse relationship does not always hold: some volcanic regions, such as Sakurajima, exhibit active volcanism without a corresponding decrease in scale (Figures 1c and 7d).

Shallow seismic zones

Shallow seismic zones form discontinuous bands, a pattern that becomes particularly clear when analysis is restricted to very shallow hypocentres (Okada et al., 2012). Figure 8 displays earthquakes shallower than 5 km, thereby emphasising events often associated with volcanic or near-surface processes (for example, Cape Erimo in the Kurils; Mount Akita Komagatake; the Hida Mountains including Mount Norikura and Mount Ontake; Miyakejima; Mount Aso; and the Tokara Islands) (Nanjo et al., 2025; Nishimura, 2026). The offshore sources shown in Figure 3 are also visible because they occurred during the same interval. A band immediately south of these features follows the Pacific coastline. These shallow seismic zones lie closer to the Pacific Plate side than the surface tangent to the Sanriku boundary, suggesting that similar structures can form on the advancing plate as well (Gamage et al., 2009; Du et al., 2023).

At plate boundaries, elastic strain is primarily accommodated through frictional locking and episodic stick–slip failure along the interface. In contrast, shallow seismic zones appear to reflect localized regions of strain concentration within the upper crust, where stress is not efficiently released along a single planar boundary. Instead, deformation is partitioned into discrete, laterally segmented bands. This behaviour is consistent with the discontinuous shallow seismic belts observed in Figure 8, which run approximately parallel to structural block boundaries.

Also apparent is a line extending from the Noto Peninsula to Sado Island. This feature may represent a distinct, unusually shallow segment among the shallow seismic zones and could accommodate Pacific Plate thrusting more readily than adjacent zones. The cause of this behaviour is unclear; one possibility is that it marks a marginal segment of the Eurasian Plate analogous to the Amur Plate (Bird, 2003; Malyshev et al., 2007). A long, active fault is known along the northern coast of the Noto Peninsula (Geological Survey of Japan 2010), and seismic activity in the region has been associated with uplift of the peninsula (Fujiwara, 2024; JMA, 2024b). Such plate driven orogenic processes contribute to the formation of the Japanese archipelago. Alternatively, continued uplift could eventually extend Noto eastward toward Sado Island. Historical precedent exists: an 1804 earthquake on the same Sea of Japan coast produced a 25 km wide uplifted strip at Kisakata that remains a notable landscape feature today (Hirano et al., 1979).

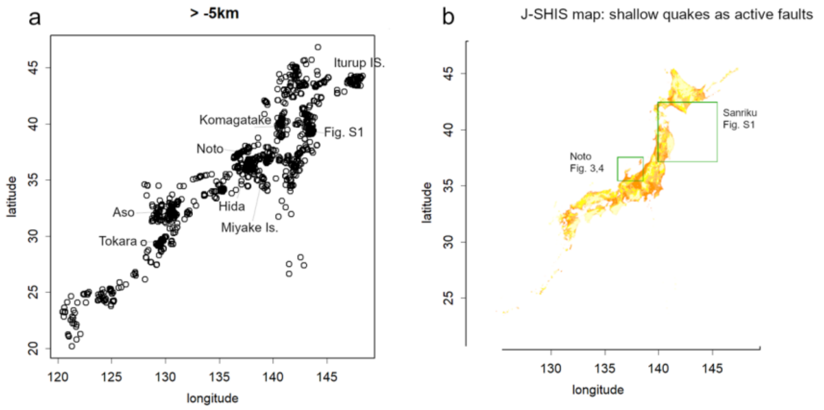

Figure 8. Shallow earthquake epicentres and seismic hazard context in Japan (October 2025 – January 2026): a – epicentres shallower than 5 km, observed from October 2025 to January 2026; b – J-SIS Japan Seismic Hazard Information, showing shallow earthquakes and active faults (National Research Institute for Earth Science and Disaster Resilience, 2025), at the same scale as panel a

Shallow earthquakes (<5 km) from October 2025 to January 2026 are concentrated in regions of reported volcanic activity. Offshore clusters visible in Figure 3 occurred during the same interval and correspond to those shown here. A shallow band immediately south of these features follows the Pacific coastline, while the line extending from the Noto Peninsula to Sado Island, which lies on the Eurasian Plate and is subject to compressive loading, is unusually dominated by very shallow events under the current filtering criteria. The seismic hazard map in panel b contextualizes these observations by showing the distribution of shallow earthquakes relative to active faults and highlighting the areas previously illustrated in Figures 3 and 4. The inset (green outlines) indicates the regions shown in Figure 5 (left outline) and the approximate extent of Figure 3 (right outline).

Recent activity and monitoring

In the 2024 event, the locator rose prior to declining with a characteristic half-life (Figure 9a), a behaviour commonly observed following mainshocks (Konishi, 2026), suggesting substantial energy release.

The subsequent aftershock sequence, however, displays an unusual trajectory. After an initial decay consistent with a half-life, the rate of aftershocks ceased declining after roughly two weeks and, unexpectedly, began to increase again. The cause of this resurgence is unknown, and no contemporaneous large earthquake has been identified to account for it. As of 2026, magnitudes remain relatively low (Figure 9c), and although aftershocks continue, their activity appears to have partially stabilized (Figure 9d). No clear small scale or high/low locator patterns have been detected (Figure 9e–f). Nevertheless, the region remains susceptible to major earthquakes and may be undergoing ongoing orogenic processes; continued vigilant monitoring is therefore warranted.

While the Noto sequence exhibited persistent elevation in locator values and complex aftershock dynamics (Figure 9a), similar behaviour was not observed in recent events near the Sanriku boundary (Figure 3). This contrast suggests that the nonstationary features identified in Noto may not be universally applicable across all tectonic settings in Japan. The absence of comparable precursory signals in Sanriku underscores the importance of tailoring seismic monitoring approaches to the specific characteristics of each region.

Figure 9b shows that, following an initial linear decrease, the aftershock rate stabilized after roughly three weeks and subsequently increased, an unusual pattern contrasting with the behaviour observed in Figure 1a. Figure 9c–d indicate that both the twelve-hour average magnitudes and aftershock counts remained at low levels throughout the interval from October 2025 to January 2026. Similarly, Figure 9e–f demonstrate that mesh-derived locator values near the Noto Peninsula were not elevated, and no decrease in scale was observed, indicating that no significant anomalies were present in the region during this period.

During the M7.6 earthquake on 1 January 2024, twelve-hour average magnitudes reached clear peaks, followed by a roughly linear decline, more pronounced than the trends shown in Figure 2b. Aftershock counts initially decreased linearly, but then stabilized after about three weeks and subsequently increased, reflecting the unusual behaviour highlighted in Figure 9b. In contrast, from October 2025 to January 2026, both the twelve-hour average magnitudes and aftershock counts remained low, and mesh-derived locator and scale metrics show no elevated values or anomalies near the Noto Peninsula, indicating a return to baseline seismic activity.

CONCLUSION

This study examined the spatial and temporal characteristics of seismic activity in the Noto Peninsula region, with a focus on the major seismic events of 2023–2024. The results revealed distinctive patterns in aftershock decay, spatial migration of epicentres, and variations in magnitude-related parameters, particularly the locator (μ) and scale (σ). These findings suggest that earthquake occurrence and magnitude may be governed by different underlying processes, each with distinct temporal dynamics.

The offshore region west of the Noto Peninsula exhibits persistent seismic activity and elevated parameter values, indicating that it may be an important zone of ongoing crustal deformation. While the available data do not permit a definitive interpretation, the observed patterns may be consistent with complex tectonic or volcanic-related processes, including the possible presence of submarine volcanic structures.

These results indicate that the seismic system in the Noto Peninsula cannot be adequately described by a single homogeneous process, but instead reflects the superposition of at least two partially decoupled mechanisms governing earthquake occurrence and magnitude distribution. The persistence of elevated activity offshore to the west of the peninsula suggests that this domain plays a structurally distinct role in regional deformation, likely associated with sustained stress accumulation and heterogeneous crustal properties. Although the current dataset does not allow a unique physical interpretation, the consistency of spatial clustering and parameter variability supports the existence of a long-lived deformation zone that continues to influence seismicity beyond the mainshock–aftershock sequence.

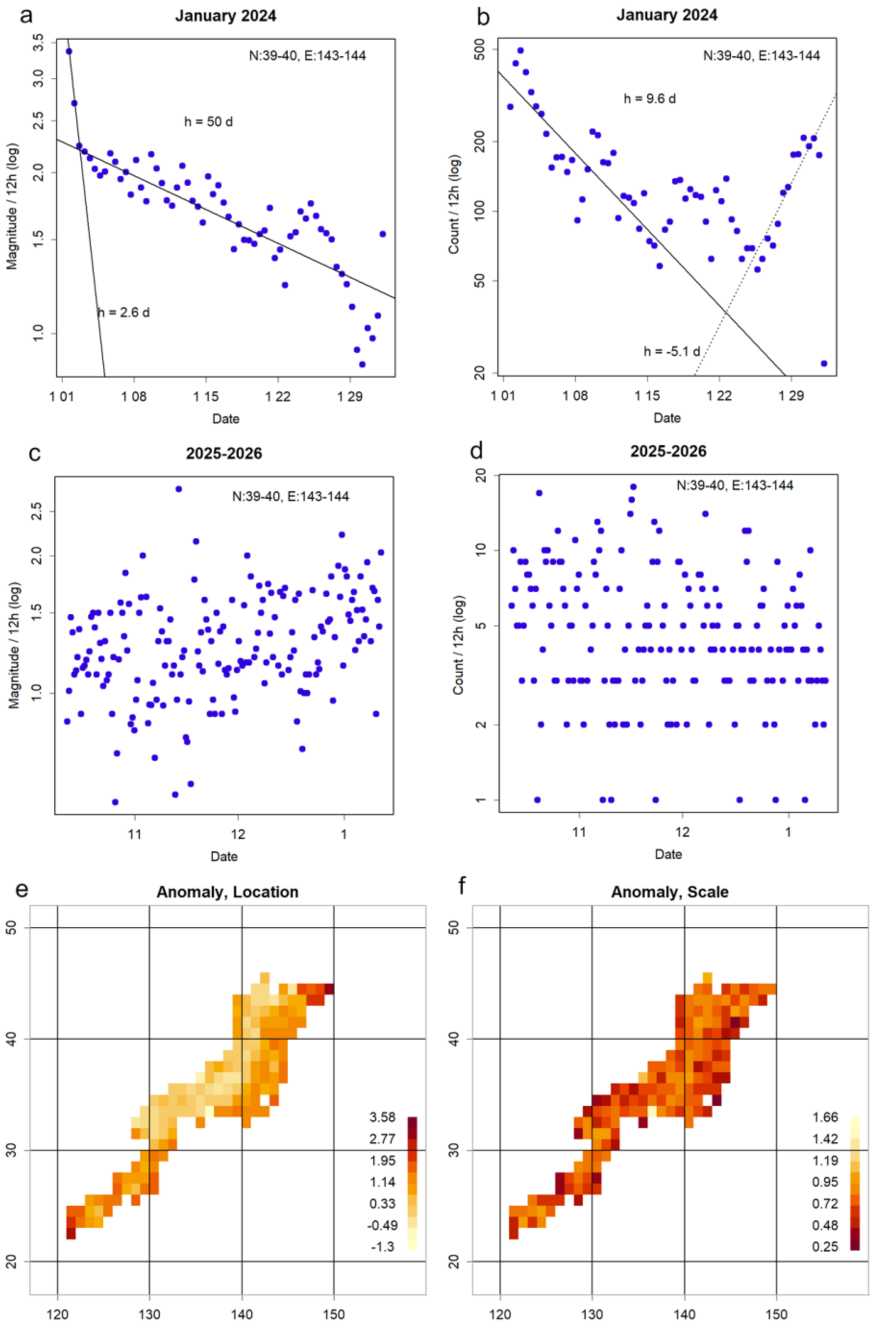

Figure 9. Temporal evolution of earthquake magnitude, aftershock activity, and magnitude-based metrics around the Noto Peninsula: a – twelve-hour average magnitude during the M7.6 earthquake on 1 January 2024 (magnitudes peak during the mainshock and then decline approximately linearly, a trend more pronounced than that shown in Figure 2b); b – aftershock counts in 12-hour intervals; c–d – twelve-hour average magnitude and aftershock counts from October 2025 to January 2026; e–f – mesh-derived locator and scale data for 2025–2026

Finally, this study demonstrates that exploratory data analysis (EDA) and visualization-based approaches in seismology can effectively reveal statistically robust spatial and temporal patterns that are not always apparent from conventional event-based analysis. Such patterns provide additional constraints on short-term seismic behaviour and contribute to a more refined characterization of regional seismicity and hazard structure. In particular, the integration of visual and quantitative diagnostics enables a more systematic identification of migration trends, clustering, and parameter variability, which may improve the interpretability of complex seismic sequences.

Author's statements

Contributions

Not applicable.

Declaration of conflicting interest

Not applicable.

Financial interests

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Data availability statement

All the data used can be downloaded from JMA homepage (JMA, 2025b; JMA, 2025c). R source code is available in Zendo https://doi.org/10.5281/zenodo.17983155.

AI Disclosure

The authors declare that generative AI was not used to assist in writing this manuscript.

Ethical approval declarations

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Additional information

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