

A magnitude–frequency kink maps a laterally varying brittle–ductile transition beneath the 2020–2024 Noto Peninsula earthquake swarm, Japan

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Research Article

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A magnitude–frequency kink maps a laterally varying brittle–ductile transition beneath the 2020–2024 Noto Peninsula earthquake swarm, Japan

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Abstract

Departures of earthquake magnitude–frequency distributions (FMDs) from a single Gutenberg–Richter (GR) law may reflect source heterogeneity or catalogue processing. We analyse the 2020–2024 Noto Peninsula swarm, Japan, with a public relocated catalogue (14,810 events of $M_{\text{JMA}} \geq 1.2$ in 2021–2023 and the full record to March 2024) and test the main results with the Japan Meteorological Agency (JMA) catalogue. Events deeper than 13 km follow a two-slope law ($b_1 = 1.57$, $b_2 = 0.75$; $\Delta\text{BIC} = -107$; bootstrap $p < 0.005$). Most of the steep branch lies below the JMA processing threshold M 1.7; correcting the counts with a step factor measured independently in Ibaraki and Nankai ($f \approx 1.9$) removes the break at 10–13 km ($\Delta\text{BIC} +14.5$) but not below 13 km ($\Delta\text{BIC} -42$). There a steep population ($b \approx 1.7$) rises from $\leq 2\%$ to 33–60% of events within 1 km, and it is present in every time window from 2021 to October 2023. We model each event as drawn from a depth-dependent mixture of a brittle ($b \approx 0.88$) and a steep ($b \approx 1.72$) population and map the depth z_{50} at which the two are equally common on a 1-km grid. z_{50} , a proxy of the brittle–ductile transition, lies at 12.45–13.5 km (10–90%; median 13.15 km) at 90 well-constrained nodes, varies laterally (tile permutation test $p < 0.005$; synthetic flat and dipping surfaces are recovered correctly) and deepens to the SE by 4.3° ($p = 5 \times 10^{-9}$), more steeply ($\approx 9^\circ$) near the 2023 M_j 6.5. Across this surface the steep share changes from ≈ 0.02 to ≈ 0.9 and b from 0.88 to 1.67 within about 1 km, a result confirmed by a split-half test. The JMA catalogue reproduces the lateral variation ($p = 0.01$), the pattern ($\rho = 0.67$ at 63 common nodes) and the SE deepening ($p = 5 \times 10^{-7}$), with a constant offset of 0.9 km; a deeper transition beneath the eastern cluster is not reproduced. Below the transition a seismicity-poor, bowl-shaped zone (≈ 14.5 – 16.5 km), the aseismic zone in which geodesy places slip and opening, separates the busy layer from the deep cluster where the swarm began; together they outline a SE-dipping structure ($\approx 38^\circ$) aligned with the 43 – 45° Suzu blind fault. All first $M \geq 5$ events nucleated 0.5–2.6 km above the local transition and 1.2–2.7 km above the local base of seismicity; because 86% of all events lie above the transition this is consistent with, but not evidence for, nucleation control. A reported b -value rise before the 2024 M_w 7.5 is reproduced at low completeness (Utsu $\Delta\text{AIC} = 2.6$), but 56% of ordinary 90-day blocks pass the same threshold, and the rise disappears above the processing threshold and within a single depth layer; it is a depth-mix and processing effect, not a precursor. For the inherited 43 – 60° reverse faults of the region, reactivation requires pore pressure above hydrostatic. Mantle helium is strongest directly above the deep onset cluster. We interpret the observations as a processing step superposed on a layered fault zone — brittle faults above a gently SE-dipping transition, a steep small-event population at the transition and a quiet, aseismically slipping, fluid-rich segment below — while several analyses were post hoc and are labelled as such.

Keywords: Noto Peninsula; earthquake swarm; magnitude–frequency distribution; b -value; brittle–ductile transition; catalogue processing; fault reactivation; fluid overpressure; inversion tectonics; b -value precursor; reproducibility

Key points

- The deep FMD of the Noto swarm breaks from a single GR law; correcting the JMA M 1.7 processing step with factors measured in other regions removes the break at 10–13 km but not below 13 km, where a steep small-event population ($b \approx 1.7$) appears.

- An event-level mixture model maps the depth z_{50} of the brittle–ductile transition in 3-D: it varies laterally (12.45–13.5 km), deepens 4.3° to the SE and is reproduced by the independent JMA catalogue ($\rho = 0.67$, constant 0.9 km offset).
- Across z_{50} the steep share rises from ≈ 0 to ≈ 0.9 and b from 0.88 to 1.67 within about 1 km; below it a bowl-shaped seismicity-poor zone (the geodetic aseismic zone) separates the busy layer from the deep onset cluster.
- A reported b -value rise before the 2024 Mw 7.5 is not a precursor: half or more of ordinary 90-day blocks show the same rise, and it vanishes above the processing threshold and within one depth layer.
- Steep inherited reverse faults ($43\text{--}60^\circ$) require supra-hydrostatic pore pressure to slip, and mantle helium is strongest above the deep onset cluster, linking fault inversion and deep fluids.

1. Introduction

The Gutenberg–Richter (GR) law, $\log_{10} N(M \geq m) = a - b m$, describes how earthquake numbers decrease with magnitude (Gutenberg and Richter 1944). Its slope, the b -value, is widely interpreted as a proxy for differential stress (Scholz 1968; Schorlemmer et al. 2005) and is used to discriminate foreshocks from aftershocks (Gulia and Wiemer 2019). These uses assume that one straight line describes the magnitude–frequency distribution (FMD) above the completeness magnitude. Departures from a single line can arise from incomplete detection, from changes in magnitude scaling for small events (Deichmann 2006; Uchide and Imanishi 2018), from mixing of earthquake populations, from heterogeneous catalogue processing (Tamaribuchi 2018), or from physical processes such as changes of stress or pore pressure with depth (Spada et al. 2013).

The 2020–2024 swarm beneath the northeastern tip of the Noto Peninsula is one of the best-documented fluid-related swarms that preceded a large earthquake. A low-velocity lower crust suggests fluid supply from depth (Nakajima 2022); hypocentres migrated diffusively (Amezawa et al. 2023) and upward from a deep ring-shaped cluster (Yoshida, Uno et al. 2023); geodetic data show tensile opening at about 16 km followed by aseismic slip (Nishimura et al. 2023); the 5 May 2023 Mj 6.5 earthquake ruptured a $\sim 45^\circ$ SE-dipping fault at 4–14 km and was followed by rapid up-dip aftershock migration interpreted as fault-valve behaviour (Kato 2024); and the 1 January 2024 Mw 7.5 earthquake started on the Suzu blind fault at the front of the swarm migration (Yoshida et al. 2024). Hirose et al. (2024) found a uniquely high b -value (1.85) and tidal sensitivity in the deepest part of the southern cluster and attributed both to high pore-fluid pressure. Fukuoka et al. (2024) found lower static stress drops in the medial parts of the northern-cluster faults, which they attributed to elevated pore pressure.

The tectonic setting favours fluid-assisted reactivation of old faults. The Japan Sea opened by back-arc rifting in the Miocene (about 15–25 Ma), forming normal faults that have been reactivated as reverse faults under compression since the late Miocene (inversion tectonics; Kato 2024 and references therein). The 25 March 2007 Noto Hanto earthquake (Mj 6.9, Mw 6.7) beneath the west coast ruptured an approximately 55° SE-dipping fault interpreted as such a reactivated structure (Kato 2024, citing Kato et al. 2008). Offshore, the Noroshi-oki fault of the AIST active-fault database is a NE–SW-trending, 60° SE-dipping reverse fault with a right-lateral component (Kato 2024), and the Suzu-oki and Wajima-oki faults lie near the swarm; a 1729 earthquake of magnitude 6.6–7.0 is believed to have occurred on the Wajima-oki segment (Yoshida et al. 2024). The 2023 and 2024 ruptures did not occur only on these mapped faults: the 2023 aftershock zone extended far north of the Noroshi-oki segment (Kato 2024), and the 2022 and 2023 events and the start of the 2024 mainshock lay on the Suzu blind fault, a few kilometres deeper than and roughly parallel to a known active fault (Yoshida et al. 2024). Takano et al. (2024) described an aseismic zone at 14–16 km between the southern cluster and the other clusters, in which the geodetic sources lie, and found misoriented faults with elevated pore pressure in the deep southern cluster; Okada et al. (2024) found high V_p/V_s at about 18 km beneath it and related it to a Tertiary magma reservoir, and a recent study proposed that rupture of solidified ancient magma that had

impeded the swarm migration led to the 2024 earthquake (Sci. Adv. 2025). The 2024 rupture broke a strong asperity at the edge of the swarm from two sides (Xu et al. 2024). Helium with a large mantle component ($^3\text{He}/^4\text{He} \approx 3.9 \text{ R}_A$) in borehole gas near the source region (Umeda et al. 2024) and changes of $^3\text{He}/^4\text{He}$ in groundwater before the 2024 earthquake (Kagoshima et al. 2025) indicate fluids of deep origin; Yoshida, Uno et al. (2023) discussed possible fluid leakage from a hidden magma system.

In an earlier analysis of the same catalogue we found that deep events follow a broken GR law, and then that the break lies close to a JMA processing threshold. Here we bring together all tests made since, under protocols fixed before each analysis: depth accuracy and boundaries, depth as a continuous variable, time relative to the 2023 earthquake, spatial clusters and the 2023 fault plane, the processing audit and bias simulations, replication on four other sequences, and a tidal test with the software used by Hirose et al. (2024). We ask four questions: (1) Is the break statistically real? (2) Where in depth, time and space is it? (3) Which explanations remain after all tests? (4) Why does the break depend on depth, and why do depth–b profiles from the JMA catalogue (Hirose et al. 2024) differ from those of the relocated catalogue? In this version we add (5) a correction of the processing step with factors measured outside Noto, (6) the evolution of the break from 2021 to March 2024, across both mainshocks, and (7) the structure below the busy layer — a quiet band at about 14.5–16.5 km — and its relation to the faults, the geodetic sources and the nucleation of the large earthquakes. In this version we ask in addition (8) whether the depth of the transition between the two populations can be mapped in three dimensions, whether it varies laterally and whether an independent catalogue reproduces it, and (9) whether the b-value rise reported before the 2024 Mw 7.5 (Li et al. 2025; Noda et al. 2024) survives a false-alarm test and the processing correction.

2. Data

2.1 Relocated catalogue

We use the double-difference relocated catalogue of Yoshida et al. (2024; Zenodo, <https://doi.org/10.5281/zenodo.12799165>; CC BY 4.0): 31,158 events from March 2003 to March 2024, relocated from JMA unified-catalogue events of $M_{\text{JMA}} \geq 1$ (our copy is byte-identical to the published file, MD5 a5a994e039832ccda3aed53903bcefb5). Magnitudes are M_{JMA} rounded to 0.1. The authors report a mean 95% relative location uncertainty of about 0.13 km in depth. The analysis set contains 14,810 events of $M \geq 1.2$ between 1 January 2021 and 31 December 2023 (JST): 1,787 shallow (< 10 km), 9,993 middle (10–13 km) and 3,030 deep (≥ 13 km). Events were assigned to the four swarm clusters of Hirose et al. (2024; S, W, N, E) using boxes read from their Fig. 1a; with these boxes we reproduce their b-values (Sd 1.86 against 1.85; N 1.14 against 1.16; E 1.13 against 1.10; W 1.12 against 1.11; all 1.15 against 1.16). JMA and relocated depths of 6,437 matched events differ by a median of 0.17 km. Sections 4.12–4.15 also use the swarm from 1 December 2020 to 31 March 2024 (the end of the catalogue); one entry with M 0.0 (1 January 2024 16:10:08.4, magnitude not determined) is excluded. We also use the three-dimensional Vs model of Takagi, Yoshida and Okada (ambient-noise surface-wave tomography; Dryad, doi 10.5061/dryad.zcrjdfnm3), the helium isotope data of Kagoshima et al. (2025, supplementary tables) and, for comparison, the relocated hypocentres and tomographic sections published by Nakajima (2022). The 2024 Mw 7.5 itself (JMA origin 16:10:22.5 JST) is not in the catalogue; the M 5.9 at 16:10:09.4 is its pre-event about 13 s earlier (Aochi 2024).

2.2 JMA processing classes

Since April 2016 the JMA unified catalogue flags the processing class of each hypocentre: fully checked (K, S) for events at or above a threshold magnitude M_{th} , simply checked (k, s) and automatic (A, a; PF method) below it (Tamaribuchi 2018; JMA catalogue notes). On and near land $M_{\text{th}} = 1.7$. We matched relocated events of $M \geq 1.5$ to the JMA catalogue ($M \geq 1.5$, 2000–2023) by origin time (≤ 1 s) and magnitude (< 0.05): 6,437 of 6,668 events matched one-to-one. The same JMA extract was used for the Ibaraki and Nankai regions.

2.3 Other sequences

For replication we used pre-mainshock catalogues of L'Aquila 2009 (Mw 6.1), Central Italy 2016 (Amatrice, Mw 6.2) and Kahramanmaraş 2023 (Mw 7.8) published with Karimpouli et al. (2026; Family_based_features repository, commit 5e67f5a, Apache-2.0), and of Iquique 2014 (Mw 8.1) from GFZ Data Services (doi 10.5880/GFZ.4.1.2023.004; events within 100 km of 19.90°S, 70.50°W before the mainshock). These sequences are among those reviewed by Martínez-Garzón and Poli (2024).

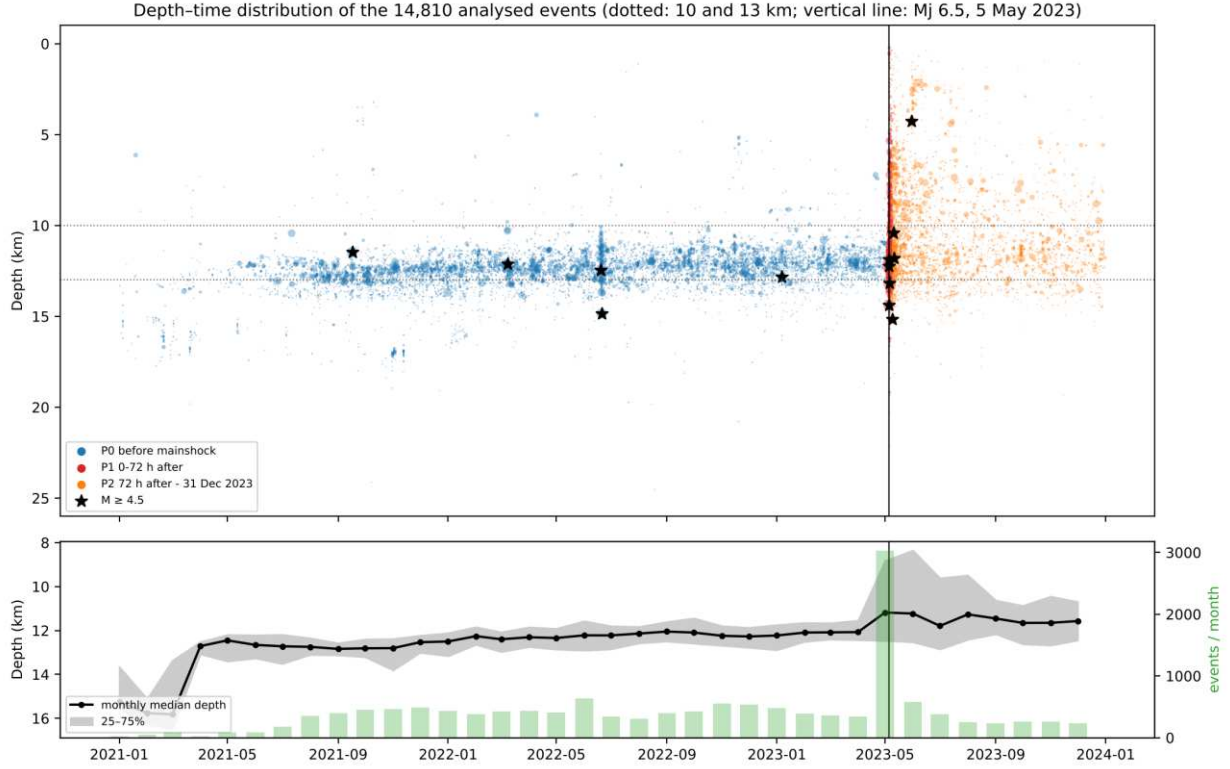


Figure 1. Depth–time distribution of the 14,810 analysed events (top; blue before, red 0–72 h after and orange later than the 5 May 2023 Mj 6.5 earthquake; stars $M \geq 4.5$) and monthly median depth and event count (bottom). Dotted lines: 10 and 13 km.

3. Methods

3.1 Completeness and b-value

The completeness magnitude was estimated by maximum curvature plus 0.2 and by goodness of fit (Wiemer and Wyss 2000); both give $M_c \leq 1.2$ in all depth bands, and $M_c = 1.2$ is used throughout unless stated. Where needed we also report M_c from b-value stability (Woessner and Wiemer 2005), noting that this estimator moves above any break by construction. The maximum-likelihood b-value (Aki 1965) with the binning correction of Utsu (1965) and the uncertainty of Shi and Bolt (1982) are

$$b = \log_{10} e / [\bar{M} - (M_c - \Delta M/2)], \quad \Delta M = 0.1; \quad \sigma_b = 2.30 b^2 \sqrt{[\sum (M_i - \bar{M})^2 / (N(N-1))]}$$

3.2 FMD models and model selection

With $m_0 = M_c - 0.05$ we compare three survival functions $S(m) = P(M > m)$:

$$S_1(m) = 10^{(-b(m - m_0))} \quad (\text{single GR, } k = 1)$$

$$S_2(m) = 10^{(-b_1(m - m_0))} \text{ for } m < M_k; \quad 10^{(-b_1(M_k - m_0) - b_2(m - M_k))} \text{ for } m \geq M_k \quad (\text{broken GR, } k = 3)$$

$$S_3(m) = w \cdot 10^{(-b_a(m - m_0))} + (1 - w) \cdot 10^{(-b_b(m - m_0))} \quad (\text{two-population mixture, } k = 3)$$

The probability of the 0.1 bin centred at v is $P(v) = S(v - 0.05) - S(v + 0.05)$ and the binned log-likelihood is $\ln L = \sum n_v \ln P(v)$. Models are compared with $BIC = k \ln N - 2 \ln L$; $\Delta BIC = BIC(\text{broken or mixture}) - BIC(\text{single}) < -10$ is taken as strong support. M_k was searched from 1.8 to 3.5 in steps of 0.1 (the original specification) and, as a sensitivity test, from 1.4 to 3.5. Because M_k is searched, significance is assessed by a parametric bootstrap: catalogues of the same size are simulated from the fitted single law and both models are refitted with the full break search; $p = (\text{number of simulated LR} \geq \text{observed LR} + 1) / (\text{number of simulations} + 1)$, $LR = 2(\ln L_2 - \ln L_1)$. A break is called present only if $\Delta BIC < -10$ and $p < 0.05$. Intervals of M_k , b_1 and b_2 come from resampling the events. The false-positive rate of the ΔBIC rule was calibrated with 4,000 single-law catalogues (four settings of N , b and M_c).

3.3 Depth analyses

Depth accuracy was tested by perturbing all depths (Gaussian noise of 0.13, 0.5 and 1.0 km, 50 realisations each; uniform shifts of ± 0.5 and ± 1 km). Boundary dependence was tested with five pairs (8/11, 9/12, 10/13, 11/14 and 12/15 km). For depth as a continuous variable, events were sorted by depth and fitted in windows of 1,000 events moved by 500. Because neighbouring windows share events, the uncertainty of window estimates was obtained by resampling the whole catalogue 200 times and refitting all windows; the resulting covariance matrix C (shrunk 10% toward its diagonal) was used in generalised least squares, $\hat{\beta} = (X^T C^{-1} X)^{-1} X^T C^{-1} y$, to compare constant, linear, quadratic and single-step trends of b_1 with depth by AIC.

3.4 Time, clusters and the 2023 fault plane

Periods were defined relative to the Mj 6.5 earthquake of 2023-05-05 14:42:04 JST: before (P0), 0–72 h after (P1) and from 72 h after to the end of 2023 (P2), with P0 also split by year. Because later periods contain fewer events, we compared each later result with 200 random subsamples of the corresponding pre-mainshock group of the same size (added after the first results). A plane was fitted by principal components to the first-72-h aftershocks (three trimming passes at 2 km), and events within 1.5 km of the plane and inside its extent were labelled as on the 2023 fault. Cluster-by-depth FMDs were fitted for the four clusters of Hirose et al. (2024).

3.5 Processing audit and bias simulations

For each depth band, year and period we computed the share of automatic hypocentres by 0.1 bin among matched events, and the count ratio across the threshold, $r = n(1.7)/n(1.6)$, compared with its GR expectation $10^{-(0.1/b)}$ for the band's b above M_{th} ; a 95% interval was obtained from the Clopper–Pearson interval of $n(1.7)/[n(1.6) + n(1.7)]$. The same ratio was computed by year (2005–2023) for the Noto, Ibaraki and Nankai regions. Fits were repeated with M_c raised to 1.5, 1.7, 1.8 and 2.0. Three bias models were simulated: (i) an excess factor f of events below 1.7 in a GR catalogue ($b = 0.9$, $N = 3,030$); (ii) a shift δ of the magnitudes of 75% of events below 1.7 ($b = 0.8$); (iii) a magnitude-scale compression below $M_{1.9}$ of the size needed to reproduce the deep break, applied at all depths, to find whether it would be detected in groups of the size of the shallow groups.

3.6 Replication on other sequences

The same model comparison was applied to the whole pre-mainshock catalogue of each other sequence, to depth thirds and to depth windows, at the completeness magnitude stated by the data authors and at the more conservative b -stability value; for L'Aquila the period 1 January 2009 to the mainshock (the foreshock swarm) was also tested separately. Magnitudes given to 0.01 were rounded to 0.1. The break was searched from $M_c + 0.3$ to $M_c + 2.5$.

3.7 Tidal test

Tidal strain and stress were computed with TidalStrain.2 (Hirose et al. 2019): solid tide plus ocean-tide loading (GOTIC2; Matsumoto et al. 2001) with PREM elastic constants, on a fault of strike 45° , dip 45°

and rake 90° as in Hirose et al. (2024), every 10 min from 2021 to May 2023 at the median location of each group. Indices were volumetric strain ΔV , shear stress $\Delta\tau$, normal stress $\Delta\sigma$ and $\Delta\text{CFF}(\mu') = \Delta\tau + \mu'\Delta\sigma$ for $\mu' = 0.1\text{--}0.9$. Each event received a phase ψ (-180° at the tidal minimum before it, 0° at the maximum, $+180^\circ$ at the next minimum). Tidal sensitivity was tested with the Schuster statistic, $D^2 = (\sum \cos \psi_i)^2 + (\sum \sin \psi_i)^2$, $p = \exp(-D^2/N)$. Because this p assumes independent events, a clustering-preserving null was added after the first results: all event times of a group were shifted by the same random offset ($\pm 3\text{--}60$ days; 2,000 offsets) and $p_{\text{shift}} = [\#(D^2_{\text{shifted}} \geq D^2_{\text{obs}}) + 1]/2,001$. The method was to be accepted only if it reproduced the published Sd signal ($p < 0.05$ for ΔV and $\Delta\tau$), a rule fixed before the computation.

3.8 Depth-slice tests of the depth dependence

These tests were added after the depth dependence was known (post hoc, under a fingerprinted protocol). (i) Depth- b profile: for the selection of Hirose et al. (2024) — 2018–2022, $37.41\text{--}37.58^\circ\text{N}$, $137.13\text{--}137.35^\circ\text{E}$, depth < 20 km, flags K, k, A — b was computed in 1-km bins for the same 3,492 events of $M \geq 1.5$ once with JMA depths and once with relocated depths, and the depth difference $d = z_{\text{JMA}} - z_{\text{relocated}}$ was compared between processing classes. (ii) Cluster N before the 2023 mainshock was divided into slices of 0.5–1 km between 10 and 14 km, plus ≥ 14 km. In each slice we fitted, besides the three models of Section 3.2, an end-member mixture with both slopes fixed from pure groups and only the weight w free ($k = 1$):

$$S_{\text{em}}(m) = w \cdot 10^{-(b_{\text{high}}(m - m_0))} + (1 - w) \cdot 10^{-(b_{\text{low}}(m - m_0))}, \quad \Delta\text{BIC}_{\text{em}} = -2(\ln L_{\text{em}} - \ln L_1)$$

with $b_{\text{low}} = 1.09$ (single-law fit to N 10–12 km) and $b_{\text{high}} = 2.80$ ($N \geq 14$ km; variant: Sd, $b = 1.71$). Five explanations were confronted with explicit predictions: depth-error leakage of the deep population (the excess of small events at 13–14 km, $N_{\text{obs}}(< M_k) - N_{\geq M_k} [10^{(b_2(M_k - M_c))} - 1]$, must not exceed the number of events below 14 km that could be mislocated upward); a smooth b -gradient inside a slice (200 simulations each with b varying linearly by 0.23, 0.40 or 1.00 per km); two-population mixing across the brittle–ductile transition (w must increase with depth and the steep component must match the deep population); rupture-size truncation (predicts $b_2 > b_1$); and depth-dependent processing (count deficit relative to the fitted mixture, $r_{\text{mix}} = P_{\text{em}}(1.7)/P_{\text{em}}(1.6)$, automatic share and number of stations must change with break strength).

3.9 Correction of the processing step with external factors

To test whether the processing step alone can produce the break, we measured the step independently of Noto. In the JMA catalogue of the Ibaraki and Nankai regions (depth ≤ 20 km) the share q of events at M 1.5 and 1.6 relative to $M \geq 1.7$ was compared before and after April 2016; the step factor $f(m) = q_{\text{post}}/q_{\text{pre}}$ (pooled: $f(1.5) = 1.89$, 95% CI 1.77–2.01; $f(1.6) = 1.86$, 1.74–1.99) was used to weight the Noto counts at $M \leq 1.6$ by $1/f$. Variants: weights only at 1.5–1.6, and the upper-CI factors. The prediction, fixed before the run (protocol SHA-256 a5fa8b56...), was that the break at 10–13 km disappears while the steep component at 13–14 km (end-member weight w) survives with its lower 95% bound above the upper bound at 11–13 km.

3.10 Evolution in time

Periods were defined relative to both mainshocks (P0 before the 2023 Mj 6.5; P1 0–72 h after, split 0–6, 6–24, 24–72 h; P2 72 h – 31 December 2023; Q1 0–72 h, Q2 72 h – 7 d and Q3 7 d – 31 March 2024 after the Mw 7.5), and consecutive windows of 1,000 events (all depths) and 250 events (13–14 km, for w) were analysed. For each later group we report the size control (median ΔBIC of 200 P0 subsamples of the same size), the completeness MAXC (modal bin + 0.2), the count ratio $r = n(1.7)/n(1.6)$ against $10^{(-0.1b)}$, the deficit of small events $D_{\text{small}} = 1 - n_{\text{obs}}(1.2\text{--}1.4)/n_{\text{GR}}(1.2\text{--}1.4)$ extrapolated from the $M \geq 1.8$ law, and the shape ($b_1 > b_2$: Noto type; $b_1 < b_2$: incompleteness). Protocol SHA-256 a6529513...

3.11 Structure below the busy layer

Depth distributions in 0.25-km bins were compared between the relocated and the JMA catalogue ($M \geq 1.5$, depth not fixed) for 1 December 2020 – 1 January 2024 16:06. Events were projected onto sections normal to strike 53° (the strike of the Suzu blind fault; Yoshida et al. 2024). In 2-km cells we mapped $N(14.5\text{--}16.5\text{ km})/N(11\text{--}13\text{ km})$ and the 90th-percentile depth (base of seismicity). For each $M \geq 5$ event we measured the 90th-percentile depth of earlier events within 3 km horizontally (local base) and its height above it. The GNSS source models of Nishimura et al. (2023; centres, depths, strikes, dips) were projected onto the same sections. Migration from the onset point (median of the 30 November 2020 events deeper than 15 km) was tested by comparing diffusive growth of the 95% quantile of distance, $r = a + \sqrt{(4\pi Dt)}$ (Shapiro et al. 1997), with constant-velocity growth, $r = a + v \cdot t$, fitted by linear quantile regression ($q = 0.95$; Koenker and Bassett 1978) over the first 90 days and scored by blocked five-fold cross-validation of the pinball loss, with a day-block bootstrap (1,000 draws) of the loss difference; diffusion or constant velocity was to be favoured only if both criteria agreed (protocol SHA-256 12709345...; an earlier one-year fit of $r = \sqrt{(4\pi Dt)}$ used protocol 33b178ec...). The steep-population weight w was tested as a precursor with the last 250 events at 13–14 km before each large sequence, compared with all other non-overlapping windows and with 5,000 sets of random target times (protocol SHA-256 cc00e176...). These analyses are post hoc except the migration and precursor tests.

3.12 Mechanical condition for reactivation

For reverse slip with σ_1 horizontal and $\sigma_3 = \sigma_v$ on a cohesionless plane of dip δ and friction μ , slip requires the effective stress ratio (Sibson 1985)

$$R(\delta) = \sigma_1'/\sigma_3' = (1 + \mu \cot \delta) / (1 - \mu \tan \delta), \quad \text{optimum } \delta^* = \frac{1}{2} \arctan(1/\mu), \quad \text{lock-up } \delta = \arctan(1/\mu)$$

If the differential stress cannot exceed the value that slips an optimally oriented plane at hydrostatic pore pressure ($\lambda_v = 0.4$), a plane of dip δ needs the pore-fluid factor $\lambda_v(\delta) = 1 - 0.6(R^* - 1)/(R(\delta) - 1)$. This is a consistency calculation, not a measurement of fluid pressure.

3.13 Shear velocity and helium

V_s was interpolated trilinearly at each hypocentre and expressed as $dV_s = V_s - \bar{V}_s(z)$, with $\bar{V}_s(z)$ the mean of resolved grid points ($N_{\text{data}} > 0$) at the same depth in $37.3\text{--}37.7^\circ\text{N}$, $137.0\text{--}137.5^\circ\text{E}$. For each layer (11–13, 13–14, 14.5–16.5 and 16.5–18 km) the mean dV_s was compared with 2,000 sets of depth-matched random points in the swarm area ($37.40\text{--}37.60^\circ\text{N}$, $137.15\text{--}137.40^\circ\text{E}$); an anomaly was considered only if it exceeded half the model standard deviation. Helium ratios corrected for air (R/R_A) were compared with the distance of each site from the deep onset point and, at the two monitored sites, with the number and median depth of swarm events within 10 km in the preceding 30 days (Spearman correlation). Mantle fraction = $(R/R_A - 0.02)/(8 - 0.02)$. Protocol SHA-256 a025d288...

3.14 Event-level mixture model and three-dimensional map of the transition

The depth-slice mixtures of Section 3.8 treat each slice separately. To map the transition we fit one model to the individual events. Each event i of magnitude $m_i \geq M_c$ and depth z_i belongs to the steep population with probability $w(z_i)$ and to the brittle population otherwise; w changes with depth as a logistic function centred on z_{50} with width s :

$$w(z) = 1 / (1 + \exp(-(z - z_{50})/s))$$

$$P_i = w(z_i) \cdot p_{\text{high}}(m_i) + (1 - w(z_i)) \cdot p_{\text{low}}(m_i), \quad p(m) = \beta e^{(-\beta(m - M_c))} \Delta m, \quad \beta = b \ln 10$$

$$\ell(z_{50}) = \sum_i c_i \ln P_i, \quad c_i = 1/f \text{ for } m_i < 1.7 \text{ (processing-step weight)}, \quad c_i = 1 \text{ otherwise}$$

The weights c_i remove the excess of small events produced by the JMA processing step ($f = 1.886$ in Ibaraki and 1.864 in Nankai; Section 3.9). The slopes b_{low} and b_{high} and the width s were estimated once from all events ($b_{\text{low}} = 0.88$, $b_{\text{high}} = 1.72$, $s = 0.25$ km, $N = 9,576$ events of $M \geq 1.2$ in December 2020 – 31 December 2023 in the rotated box, global $z_{50} = 13.35$ km) and then held fixed. At

each node of a 1-km grid in rotated coordinates (x along strike 53°, positive NE; y across strike, positive SE; origin 37.5°N 137.25°E) we used the events within a horizontal radius R that grows from 2.5 to 4 km until $N \geq 300$, and found z_{50} by maximising ℓ on a 0.05-km grid; the 90% interval comes from 200 bootstrap resamples of the node events. A node is "below seismicity" when the likelihood increases monotonically to the deepest events, and it is then not used. Because the likelihood is flat across the seismicity gap, a post hoc quality rule (labelled) classifies a node as well constrained only if its profile interval is ≤ 1.5 km and at least 20 events lie within ± 0.5 km of z_{50} ; the other nodes are "gap-limited".

Lateral variation was tested with a tile statistic. The area was divided into 5-km tiles with ≥ 300 events; $G = 2 \sum_{\text{tiles}} [\ell_{\text{tile}}(z_{50}, \text{tile}) - \ell_{\text{tile}}(z_{50}, \text{global})]$ measures the likelihood gain of tile-wise transition depths. The null distribution was obtained by permuting magnitudes among events within 0.5-km depth bins (keeping the depth distribution of each tile and the overall magnitude–depth relation but removing any lateral difference), 200 times. Two synthetic catalogues tested the method: one with a flat surface at 13.2 km and one with a surface dipping from 12.7 to 13.7 km, both with the real hypocentres, magnitudes drawn from the mixture and the processing step imitated by adding small events (factor f). In the specification the step was written as a thinning; this sign error was corrected before the synthetic results were used and is disclosed. The across-strike dip of z_{50} was estimated by least squares on the well-constrained nodes, overall and in along-strike strips at -3 , $+1$ and $+5$ km.

The same code was applied, without change of settings, to the JMA unified catalogue ($M \geq 1.5$, the completeness of that catalogue in the swarm; $N = 4,084$), under a separate protocol fixed before the run. Four pre-specified tests were made: J1 lateral variation (tile test); J2 the same pattern (Spearman ρ of z_{50} at common nodes); J3 a deeper transition beneath the eastern cluster than beneath the centre; J4 the SE deepening. A control catalogue with a constant transition depth was analysed in the same way. All maps and three-dimensional views in this paper are drawn with NW positive ($-y$), because the coordinate triple (NE, SE, up) is left-handed and an earlier rendering with SE positive was mirrored.

3.15 Test of a b-value precursor

Li et al. (2025) and Noda et al. (2024) reported that b rose before the 2024 Mw 7.5. We repeated this comparison in consecutive 90-day blocks ending at each mainshock and compared each block with the preceding one using the Utsu (1992) test:

$$\Delta\text{AIC} = -2(N_1 + N_2) \ln(N_1 + N_2) + 2N_1 \ln(N_1 + N_2 b_1/b_2) + 2N_2 \ln(N_2 + N_1 b_2/b_1) - 2, \quad P \approx \exp(-\Delta\text{AIC}/2 - 2)$$

with $\Delta\text{AIC} > 2$ regarded as significant. Four settings were fixed in advance: S1, M_c from maximum curvature $+0.2$ (1.4) and all depths, which imitates the published approach; S2, $M_c = 1.8$ (above the processing threshold); S3, $M_c = 1.2$ with the step-corrected counts; S4, $M_c = 1.8$ and the 10–13 km layer only (one population). The false-alarm rate is the share of ordinary blocks, not followed by a mainshock, that pass the same threshold. In the JMA catalogue the last block was compared with the 5–95% range of all earlier blocks. A precursor is supported only if the last block is significant in S2–S4 and the false-alarm rate is low.

3.16 Pre-specification and reproducibility

Each analysis was specified in a written protocol fingerprinted with SHA-256 before it was run; additions made after seeing results are labelled post hoc in the text. All raw data, scripts, Excel workbooks with live recalculations of the key likelihoods and statistics (agreeing with Python to 0.000), figures and protocols are provided in the reproducibility packages listed under Availability of data and materials.

4. Results

4.1 The break and its statistical support

Table 1. Model comparison, $M_c = 1.2$, 2021–2023. Negative ΔBIC favours the broken or mixture model. Bootstrap p from 200 simulations with the full break search (floor 1/201).

Depth band	N	b (Aki)	b_1 / b_2	M_k (95%), grid ≥ 1.8	ΔBIC broken / mixture	Bootstrap p	M_k , ΔBIC (grid ≥ 1.4)
Shallow < 10 km	1,787	0.92 ± 0.02	—	—	+12.5 / +15.0	0.47	— (+12.0)
Middle 10–13 km	9,993	1.05 ± 0.01	1.11 / 0.84	1.8 (1.8–2.0)	−96.8 / −67.1	< 0.005	1.7 (−117.5)
Deep ≥ 13 km	3,030	1.45 ± 0.03	1.57 / 0.75	1.9 (1.8–2.3)	−107.3 / −111.8	< 0.005	1.7 (−113.8)
All depths	14,810	1.09	1.17 / 0.84	1.8 (1.8–1.9)	−202.7 / −162.3	< 0.005	1.7 (−243.1)

Shallow events follow a single GR law, whereas middle and deep events strongly prefer a broken or mixture model (Table 1, Fig. 2). In the deep band the best mixture consists of 94% of events with $b_a = 1.71$ and 6% with $b_b = 0.43$. A single law fitted to the deep band predicts 7.6 events of $M \geq 3$ (95% range 2–14) and 0.3 of $M \geq 4$, against 37 and 12 observed. In 4,000 simulated single-law catalogues no case reached $\Delta BIC < -10$, so the rule has a very low false-positive rate. With the original grid (≥ 1.8) the best deep break is M 1.9; when the grid is extended down to 1.4 the best break moves to 1.7 in the middle, deep and all-depth sets, with ΔBIC improving by 6.5–40 units.

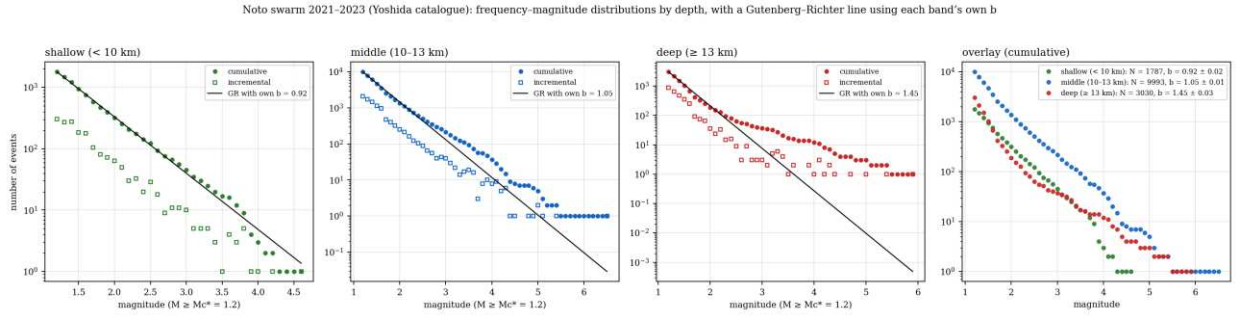


Figure 2. Frequency–magnitude distributions by depth band ($M \geq 1.2$, 2021–2023): cumulative (dots) and per-bin (squares) counts with the single GR line of each band’s own b -value. Right: overlay of the three bands.

4.2 Robustness: depth errors, boundaries, declustering, magnitude type and years

Table 2. Robustness of the break (details in the four-test and processing reports of the reproducibility packages).

Test	Result for the deep / steep break
Depth noise 0.13, 0.5, 1.0 km (50 runs each)	Bend in 100% of runs (median ΔBIC −114 to −118); shallow never
Depth shift $\pm 0.5, \pm 1$ km	Deep group 720–8,754 events; bend in all (ΔBIC −35 to −197)
Five boundary pairs 8/11 ... 12/15 km	Deepest group bends in all; at 12/15 km (431 events) only by bootstrap; groups entirely above 11 km never
Declustering (nearest neighbour), catalogue B / C	ΔBIC −102.9 (mixture) / −34.2 (broken), M_k 2.0 / 1.8
Single magnitude type (V only, $M \geq 1.5$)	Mixture ΔBIC −35.5, M_k 1.8, $M \geq 3$: 26 observed / 8 expected
Each year 2021, 2022, 2023 (deep)	ΔBIC −14.6, −24.6, −46.6; best M_k with grid ≥ 1.4 : 2.2, 1.7, 1.7
M_c raised to 1.5	Deep ΔBIC −97.7, middle −106.0 (break still at 1.8–1.9)

4.3 Depth and time are confounded

Of the 1,787 shallow events, 1,633 occurred after the 2023 Mj 6.5 earthquake; before it there were only 154 (Fig. 1). Shallow seismicity therefore mostly represents the up-dip and shallow activation that followed the 2023 rupture (Kato 2024), whereas most deep events occurred before it. The shallow-versus-deep contrast of Table 1 is thus largely a contrast between post- and pre-mainshock events.

Table 3. N and ΔBIC (broken – single) by period and depth, $M_c = 1.2$. * bend present ($\Delta\text{BIC} < -10$ and bootstrap $p < 0.05$). Last row: median and 5–95% range of 200 random subsamples of the pre-mainshock group with the size of the P2 group (post hoc).

Period	Shallow < 10	Middle 10–13	Deep ≥ 13	All depths
Before mainshock (P0)	154: +7.1	7,256: -83.7*	2,204: -57.2*	9,614: -170.2*
2021 / 2022	— / —	-13.7* / -39.3*	-14.5* / -24.7*	-50.3* / -73.7*
1 Jan 2023 – mainshock	—	-3.4	-0.1	-15.4*
0–72 h after (P1)	560: +3.5	879: +11.7	302: -3.5	1,741: +10.3
72 h after – end 2023 (P2)	1,073: +3.3	1,858: +6.8	524: -7.0	3,455: -18.9*
P0 subsampled to P2 size	—	-11.7 (-26.4 to +0.4)	-4.3 (-24.3 to +7.2)	-54.8 (-81.3 to -31.4)

The break existed before the 2023 earthquake, in 2021 and in 2022 separately (Table 3, Fig. 3), so neither the 2023 rupture nor the fluid discharge that followed it (Kato 2024) can be its origin. In the first 72 h no group bends; completeness then varies rapidly and b is low (0.72–0.94). Kato (2024) recovered many immediate aftershocks by matched filtering that are absent from the catalogue, so the low b of this period most likely reflects short-term incompleteness rather than a change of source physics. Later, the break is weaker at 10–13 km and in the whole set than the pre-mainshock events would give with the same number of events, whereas the deep group shows no measurable change.

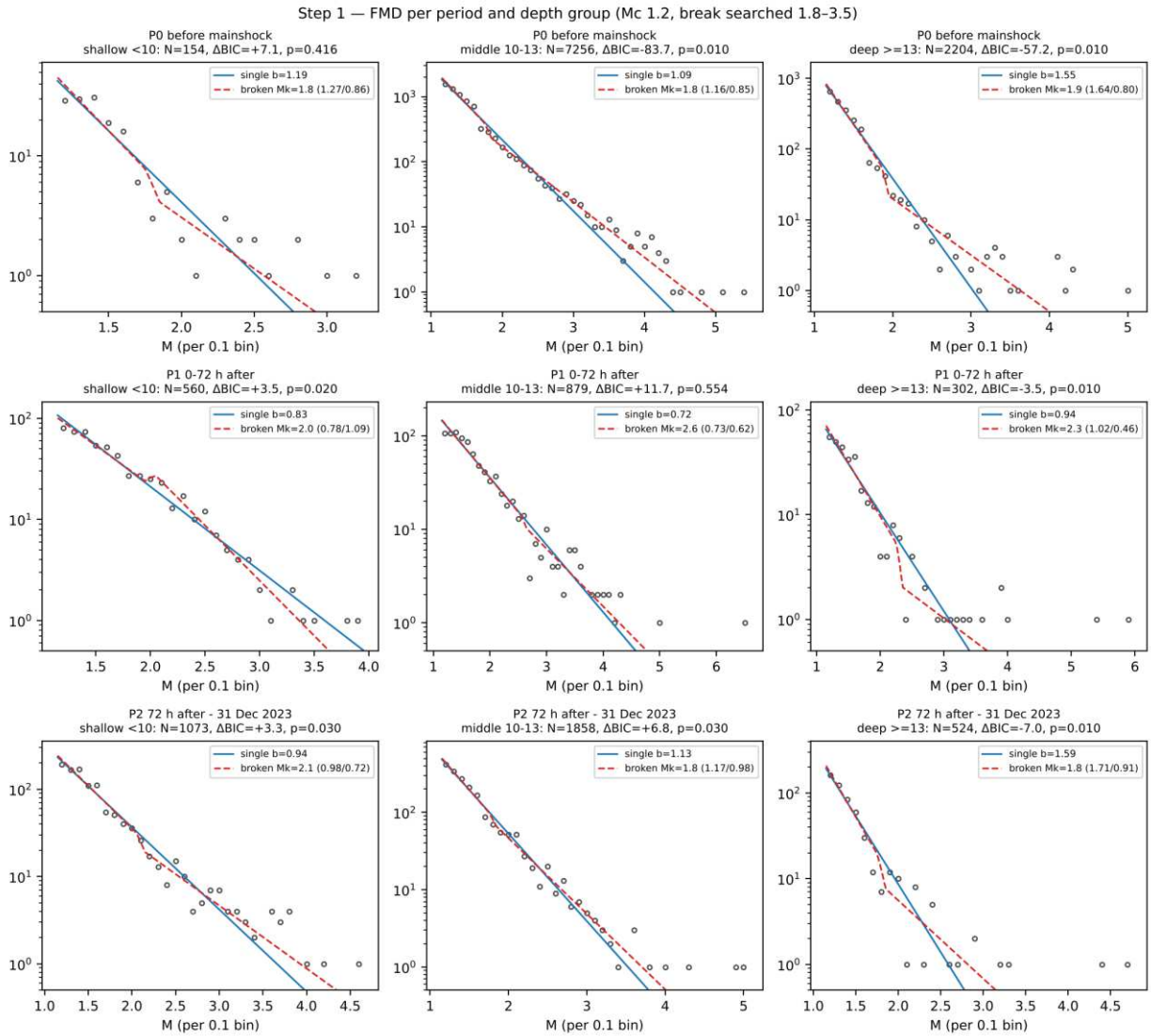


Figure 3. FMD by period (rows: before, 0–72 h after, 72 h after – end of 2023) and depth band (columns), with single (blue) and broken (red dashed) fits, $M_c = 1.2$.

4.4 Depth as a continuous variable

Neighbouring 1,000-event windows are correlated ($r \approx 0.4\text{--}0.5$ for b_1), and this correlation is included in the trend models. In the pre-mainshock swarm, which spans mainly 11–14 km, b_1 increases with depth by 0.23 per km (95% interval 0.19–0.27); a quadratic trend is preferred over linear and single-step trends (AIC -35.1 , $+18.0$ and -9.1). In the full set the slope is 0.094 per km (0.081–0.105), again best described by a curved trend that steepens below about 13 km. b_2 and M_k show no depth trend (Fig. 4). The break becomes consistently strong (bootstrap share with $\Delta\text{BIC} < -10$ above 0.7) in windows with median depth ≥ 13 km in the full set and from about 13.2 km before the mainshock, with isolated strong windows from 12.3 km.

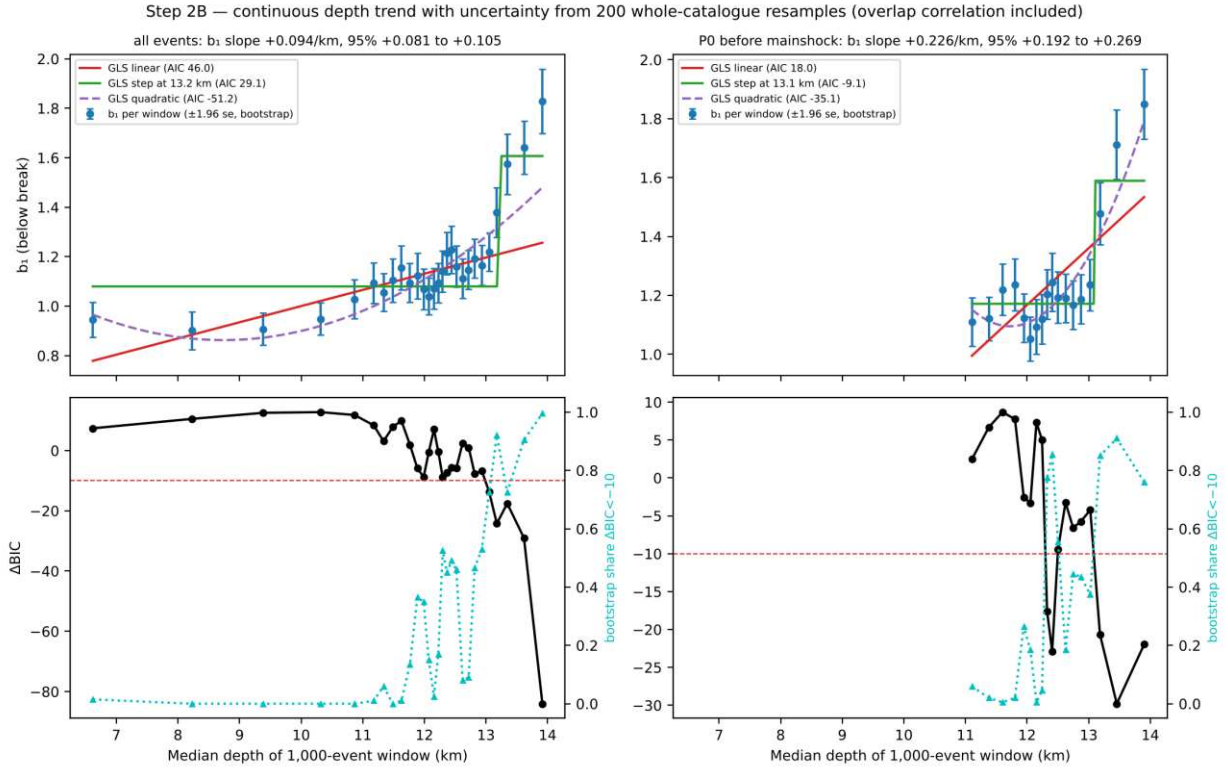


Figure 4. b_1 against the median depth of 1,000-event windows with bootstrap uncertainty (± 1.96 se) and generalised-least-squares trends (top), and ΔBIC with the bootstrap share of $\Delta\text{BIC} < -10$ (bottom), for all events (left) and events before the 2023 mainshock (right).

4.5 Clusters and the 2023 fault

Table 4. Break strength by cluster (boxes of Hirose et al. 2024), depth slice and position relative to the 2023 fault plane, $M_c = 1.2$, break searched 1.8–3.5.

Group (before the 2023 mainshock unless stated)	N	$M_{\max}$	b_1 / b_2	ΔBIC
S cluster ≥ 14 km (Sd, 2021–2023)	324	2.6	1.69 (single law)	+10.8
N cluster 10–12 km	1,501	4.2	1.15 / 0.83	-4.9 (11–12 km: -1.1)
N cluster 12–13 km	3,009	5.4	1.17 / 0.78	-44.0
N cluster 13–14 km	1,077	4.3	1.63 / 0.62	-28.6
N cluster ≥ 14 km	157	1.7	2.80 (single law)	+10.1
E cluster 12–13 / 13–14 km	1,088 / 514	4.3 / 4.3	1.11 / 0.75; 1.39 / 0.89	+0.2 / +1.0
W cluster (all depths)	982	4.4	1.15 / 0.87	+2.8
N + E + W, deep ≥ 13 km (2021–2023)	2,679	5.9	1.55 / 0.73	-107.2
On / off the 2023 fault plane (before mainshock)	6,106 / 3,508	—	1.22 / 0.82; 1.31 / 0.88	-113.1 / -38.7

The deep southern cluster Sd, where Hirose et al. (2024) found $b = 1.85$, follows a single steep law ($b \approx 1.7$) with no event larger than M 2.6; it does not bend (Table 4, Fig. 5). Removing the S cluster leaves the deep break unchanged ($\Delta\text{BIC} -107.2$), so the break is not a mixture of Sd with the other clusters. Before the 2023 earthquake the break lies mainly in the northern cluster at 12–14 km, where events of all sizes

up to M 5.4 occur; there the slope below the break at 13–14 km (1.63) is close to the S_d slope. The plane fitted to the first-72-h aftershocks strikes 61° and dips 37° toward 151° between 5.0 and 14.3 km (bootstrap 95%: dip $35.2\text{--}38.5^\circ$, strike $58\text{--}63^\circ$). Kato (2024) describes an approximately 45° SE-dipping plane at 4–14 km, a parallel and slightly deeper fault that hosted the M_j 5.9 aftershock, and poorly constrained offshore depths that produce an apparent gentle dip. Fitting only the 529 events that preceded the M_j 5.9 aftershock gives a steeper plane (dip 39° , strike 56°), so our lower dip is mainly a consequence of fitting one plane to two faults and to offshore events; the plane is used only to classify events. Before the mainshock 64% of events lie within 1.5 km of it, against a median of 19% for randomly oriented planes through the same centroid (97.8th percentile) and 31% for planes of the same dip and random strike (92.9th percentile): the swarm was preferentially, but not exclusively, organised along the future rupture plane, consistent with the 2022 M_j 5.4 aftershocks near its base (Kato 2024). The break is present both on and off the plane (Supplementary Fig. S1).

At depths of 13 km and more the two sides differ (Supplementary Fig. S7). On the plane, deep events (median 13.3 km) bend ($\Delta\text{BIC} -40.3$; b_1 1.56, b_2 0.70); off the plane they lie deeper (median 15.1 km) and do not bend ($\Delta\text{BIC} -1.8$). This contrast alone is within sample-size variability (on-plane events subsampled to the off-plane size give a median of -15.8 , 5–95%: -31.1 to $+0.4$). More informative is the content of the two sides: off-plane events below 14 km (N 457, median 16.1 km) follow a single steep law ($b = 1.91$, $\Delta\text{BIC} +11.3$) with no event of $M \geq 3$ (largest M 2.6), whereas events of $M \geq 4$ deeper than 12 km are about three times more frequent on the plane (21 of 4,479) than off it (4 of 2,412; Fisher $p = 0.06$).

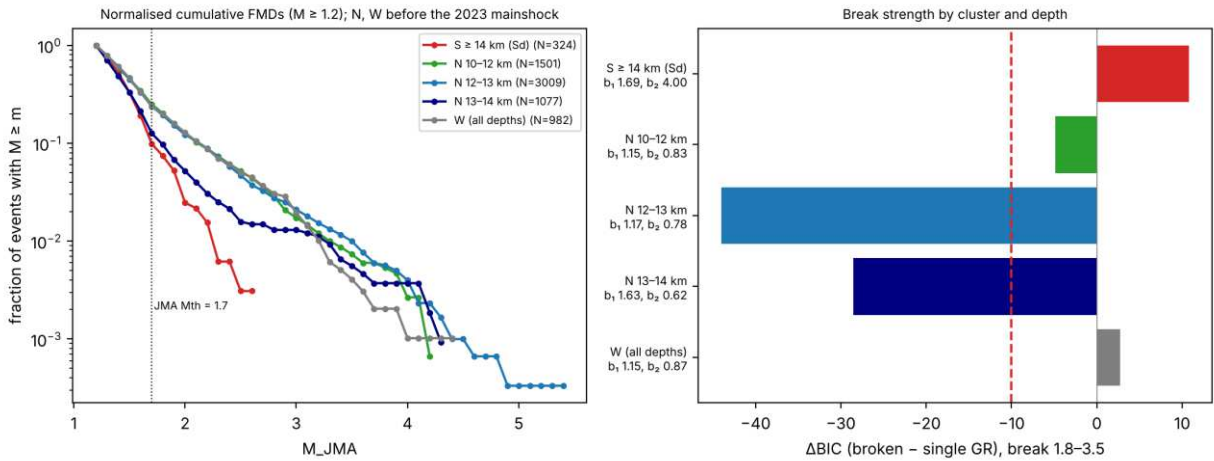


Figure 5. Left: normalised cumulative FMDs of cluster and depth groups; dotted line $M_{\text{th}} = 1.7$. Right: break strength (ΔBIC) with fitted slopes; red dashed line $\Delta\text{BIC} = -10$.

4.6 The JMA processing threshold

Table 5. Processing classes and the count ratio $r = n(1.7)/n(1.6)$ across the JMA threshold $M_{\text{th}} = 1.7$ (2021–2023), and the same ratio in the JMA catalogue before and after automatic hypocentres were introduced in April 2016.

Depth band	Automatic share at M 1.5 / 1.6 / ≥ 1.7	$n(1.6) \rightarrow n(1.7)$	r (95% CI)	GR expectation
Shallow < 10 km	70% / 65% / 0%	179 $\rightarrow$ 104	0.58 (0.45–0.74)	0.82
Middle 10–13 km	82% / 71% / 0%	967 $\rightarrow$ 473	0.49 (0.44–0.55)	0.82
Deep ≥ 13 km	77% / 74% / 0%	257 $\rightarrow$ 93	0.36 (0.28–0.46)	0.81
JMA catalogue, Noto region	r 2005–2015: 0.88	2016: 0.72	2017–2023: 0.56	—
JMA catalogue, Ibaraki / Nankai	r 2005–2015: 0.92 / 0.86	2016: 0.56 / 0.58	2017–2023: 0.56 / 0.54	—

Automatic hypocentres make up 65–82% of events at M 1.5–1.6 and none at $M \geq 1.7$, in every depth band, year and period (Table 5, Fig. 6). Across the threshold the count drops far more than a GR law allows, and the drop is largest at depth ($r = 0.36$ against 0.81). The same drop appeared in 2016 in the

Ibaraki and Nankai regions, far from Noto (Fig. 7), so it is a property of catalogue processing. The profile likelihood of the break magnitude has its minimum at 1.7 in the middle and deep bands and in 2022 and 2023 separately (Fig. 8). In simulations, an excess factor $f = 2.0$ – 2.5 of events below 1.7 reproduces the location of the break and ΔBIC values of -55 to -101 (-77 to -136 with the extended grid), with $b_1 = 1.23$ – 1.36 against the observed 1.57 (Supplementary Fig. S2). In contrast, shifting the magnitudes of automatic events by $\delta = -0.3$ to $+0.2$ produces either no break or one of the opposite shape ($b_1 < b_2$).

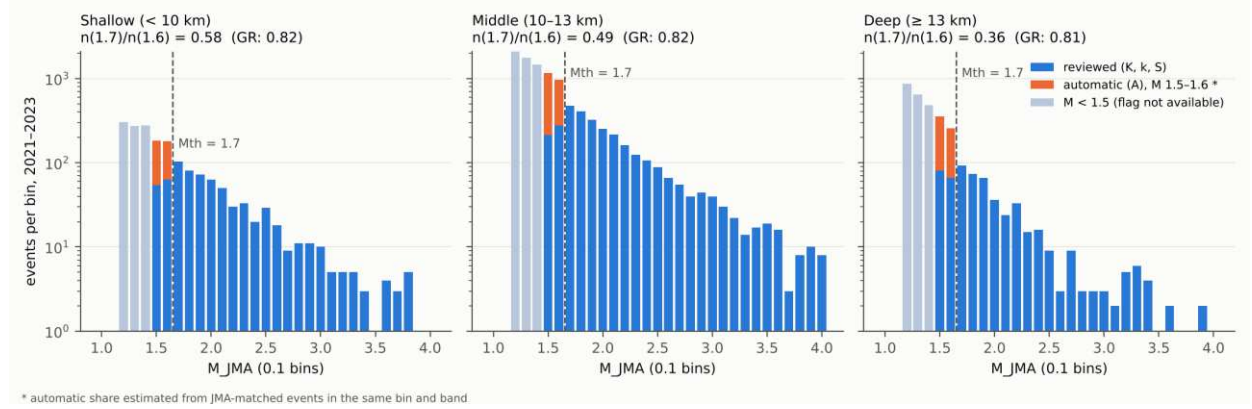


Figure 6. Counts per 0.1 bin by depth band with the estimated number of automatic hypocentres at M 1.5–1.6 (orange); dashed line $M_{\text{th}} = 1.7$. Titles give the observed ratio $n(1.7)/n(1.6)$ and its GR expectation.

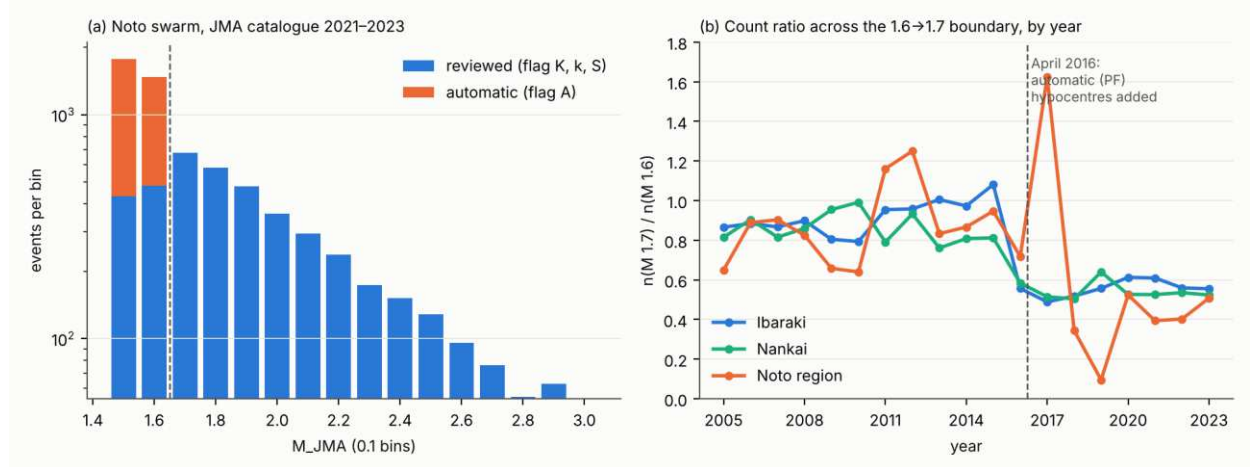


Figure 7. (a) Processing classes of the swarm events in the JMA catalogue; automatic hypocentres occur only below M_{th} . (b) Count ratio $n(1.7)/n(1.6)$ by year in three JMA regions; it fell when automatic hypocentres were introduced in April 2016.

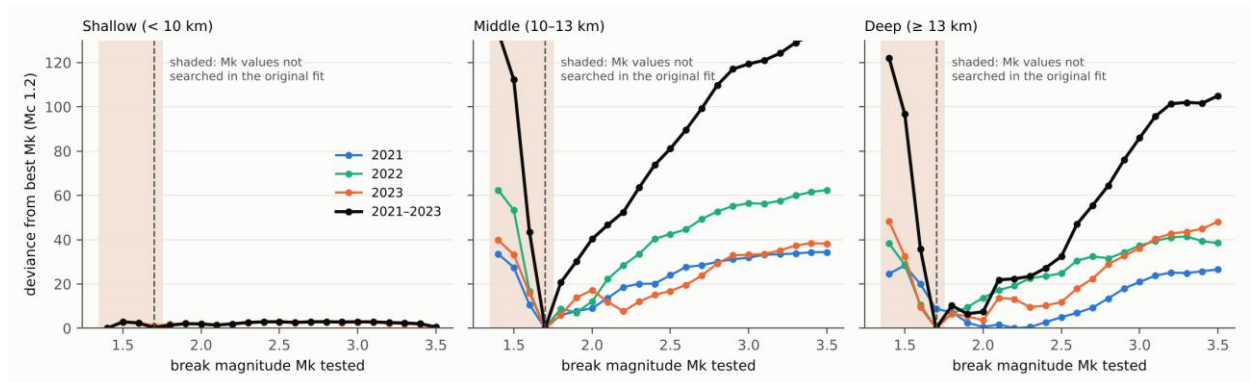


Figure 8. Profile likelihood of the break magnitude by depth band and year: deviance relative to the best M_k . Shaded: break magnitudes not searched in the original analysis; dashed: $M_{\text{th}} = 1.7$.

4.7 Above the processing threshold

Table 6. Fits using only fully checked events ($M_c = 1.7$; break searched 2.0–3.5). Positive ΔBIC favours a single law.

Band	Set	N	b (Aki)	b_1 / b_2	M k	ΔBIC	p	$M \geq 3$ obs / exp
Shallow	2021–23	576	0.86 ± 0.04	0.86 / 1.39	3.5	+9.5	0.31	45 / 42.8
Middle	2021–23	2,573	0.86 ± 0.02	0.91 / 0.79	2.2	+4.7	0.005	216 / 192.1
Deep	2021–23	421	0.92 ± 0.06	1.06 / 0.51	2.5	−18.6	< 0.005	37 / 26.7
Deep	2021 / 2022 / 2023	129 / 129 / 163	1.11 / 0.88 / 0.83	—	2.3 / 2.5 / 2.5	−4.0 / +6.5 / −6.4	—	10/4.6, 11/9.1, 16/13.5
Deep	catalogue B / C	302 / 230	$0.95 / 1.07$	1.14 / 0.43; 1.18 / 0.63	2.5	−24.9 / +1.4	—	23/17.4; 13/9.1

Using only fully checked events, the shallow and middle bands follow single laws with $b \approx 0.86$ in every analysable year (Table 6). The deep band keeps a weaker flattening above $M \approx 2.5$ (ΔBIC −18.6; 37 events of $M \geq 3$ against 27 expected), which is not significant in 2022, is not preferred by BIC in the background-only catalogue, and does not separate deep from shallow events within 2023 ($\chi^2 p = 0.15$). Over all three years deep and shallow FMDs above M_{th} differ ($p = 0.0014$). With $M_c \geq 1.7$ a break at 1.8–1.9 cannot be tested, because the search must start above M_c .

4.8 Other sequences

Table 7. Replication on other pre-mainshock sequences (whole catalogue; depth thirds and windows give the same conclusion).

Sequence	N (pre-mainshock)	Authors' $M_c \rightarrow \Delta BIC$, shape	Conservative $M_c \rightarrow \Delta BIC$	Noto-type break?
L'Aquila 2009	4,075	$1.5 \rightarrow -338$, $b_1 < b_2$ (break at $M_c + 0.3$)	$1.9 \rightarrow +12.2$	No
foreshock period 2009	607 / 250	$1.5 \rightarrow +4.9$	$1.9 \rightarrow +7.0$	No
Amatrice 2016	12,357	$1.8 \rightarrow +2.7$	$2.1 \rightarrow +7.1$	No
Kahramanmaraş 2023	5,686	$1.0 \rightarrow -87$, $b_1 < b_2$ (break at $M_c + 0.3$)	$1.3 \rightarrow +8.0$	No
Iquique 2014	5,398	$1.5 \rightarrow -2.1$	$1.9 \rightarrow +4.2$	No
Noto 2021–23, deep (reference)	3,030	$1.2 \rightarrow -107$, $b_1 > b_2$	—	Yes

No other sequence shows a break with $b_1 > b_2$ at either completeness magnitude, in any depth group or window, or in the L'Aquila foreshock period (Table 7, Fig. 9). The two significant results (L'Aquila and Kahramanmaraş at the authors' M_c) have the opposite shape, with the break at the lowest allowed value and per-bin counts that level off just above M_c — the signature of incompleteness — and disappear at the conservative M_c . The mixture model is never preferred (ΔBIC +6 to +17).

Test 4 — whole pre-mainshock catalogue, authors' M_c

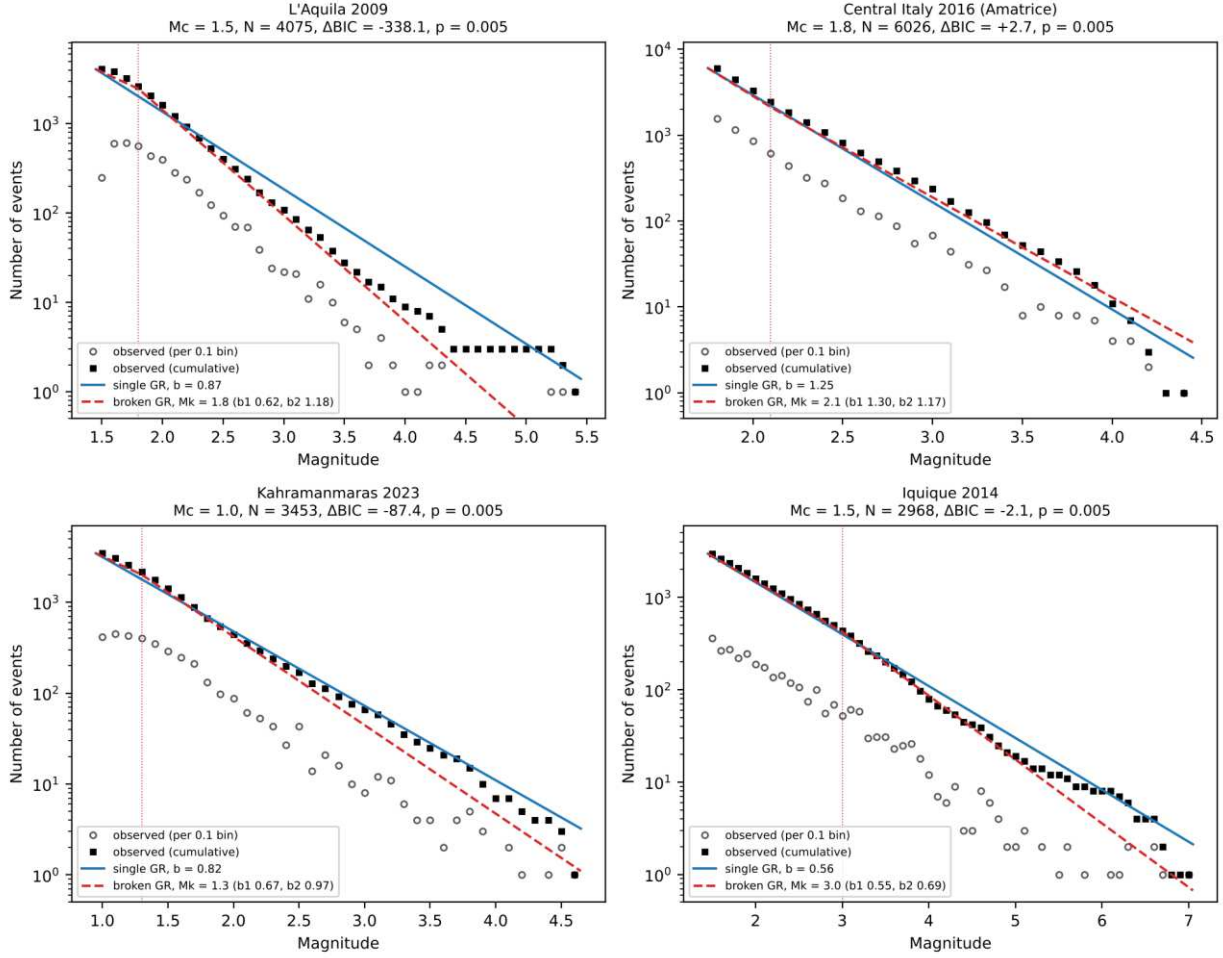


Figure 9. FMDs of four other pre-mainshock sequences at the completeness magnitude given by the data authors, with single (blue) and broken (red dashed) fits.

4.9 Tidal test

Our compiled TidalStrain.2 reproduces the reference output of the package (correlation ≥ 0.994 for ΔV , $\Delta \sigma$ and ΔCFF). The validation rule was not passed: in Sd the best results were $\Delta \tau$ $p = 0.053$ and $\Delta CFF(0.1)$ $p = 0.064$ with declustering at a 48-h threshold (46 events), and ΔV $p = 0.14$. The preferred phases agree in direction with Hirose et al. (2024) (ΔV about $+90^\circ$ to $+110^\circ$ against $+140^\circ$; $\Delta \tau$ about -60° to -90° against -40°). In the break volume (cluster N, 12–14 km, before the mainshock), the plain Schuster test gives $p = 0.0004$ for $\Delta CFF(0.1)$ among the small events ($M < 1.9$). The time-shift null shows this to be an artefact of clustering: for the same events moved in time D^2/N has a median of 3.6 instead of about 0.7, and $p_{\text{shift}} = 0.11$ ($\Delta \tau$ 0.08, ΔV 0.38). After this correction no index is significant in the break volume or in the control groups (Fig. 10). A day–night detection cycle is absent (24-h Schuster $p = 0.50$). With the clustering-corrected null, a tidal modulation of the small-event rate larger than about 5% (ΔV), 6% ($\Delta \tau$) or 12% ($\Delta CFF(0.1)$) would have been detected (post hoc). Because the published Sd signal was not confirmed with this catalogue and period, the test of the break volume is formally inconclusive.

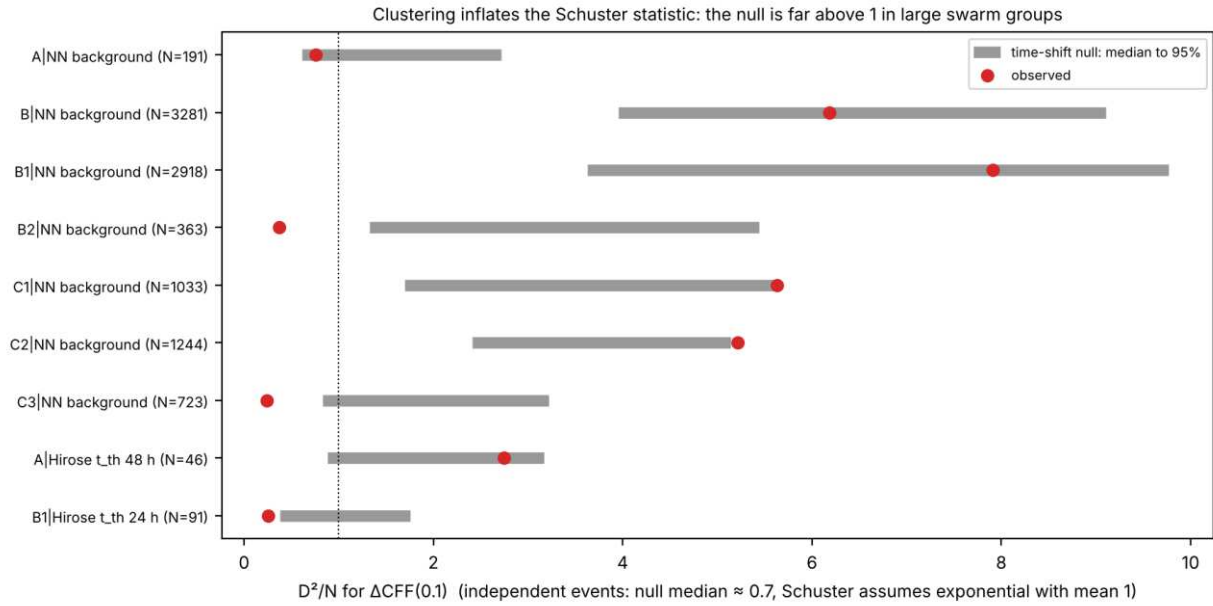


Figure 10. Observed Schuster D^2/N for $\Delta CFF(0.1)$ (red) and the range of D^2/N after random time shifts that keep event clustering (grey, median to 95th percentile). In large swarm groups the null lies far above the value for independent events.

4.10 Depth–b profiles: JMA versus relocated depths

Table 8. b-value ($M_c = 1.5$) by 1-km depth bin for the 3,492 events of the Hirose et al. (2024) selection, located with JMA and with relocated depths. Hirose values were read by eye from their Fig. 9a ($M \geq 1.3$).

Depth (km)	Hirose et al. 2024 (digitised)	JMA depth: N, b	Relocated depth (same events): N, b
9–10	1.47	44, 1.57 ± 0.32	19, 0.92 ± 0.19
10–11	1.38	183, 1.31 ± 0.13	97, 0.86 ± 0.10
11–12	1.17	765, 1.37 ± 0.06	791, 1.13 ± 0.05
12–13	1.09	1,481, 1.06 ± 0.03	1,839, 1.01 ± 0.03
13–14	1.05	722, 0.81 ± 0.04	531, 1.32 ± 0.08
14–15	1.06	117, 2.06 ± 0.26	27, 1.85 ± 1.01
15–17	1.89–1.99	109, 2.02–2.15	113, 1.88–2.54

With JMA depths the same events reproduce the profile of Hirose et al. (2024): b is high at 9–12 km (1.31–1.57), lowest at 13–14 km (0.81) and about 2 below 14 km (Table 8, Fig. 11). With relocated depths b is about 0.9–1.1 at 9–13 km, rises to 1.32 at 13–14 km and is about 1.9–2.5 below 14 km, close to our profile of the full relocated selection ($M \geq 1.3$). The two depth sources agree below 14 km and disagree above it. The difference is systematic by processing class: automatic hypocentres of M 1.5–1.6 lie 0.16 km shallower than their relocated positions (median; IQR 0.85 km), reviewed ones of the same magnitude 0.22 km deeper (IQR 0.70 km), and reviewed events of $M \geq 1.7$ 0.17 km deeper (Supplementary Fig. S4). In JMA depth, small events are therefore moved upward relative to large ones, which raises b at 9–12 km and lowers it at 13–14 km.

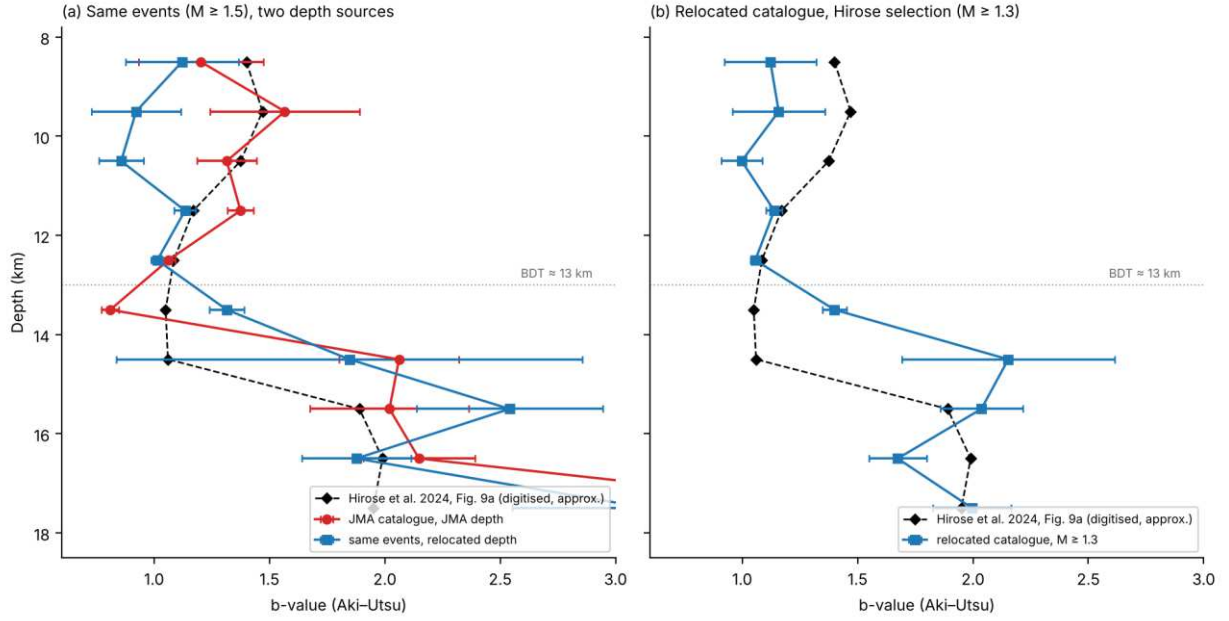


Figure 11. (a) b against depth for the same 3,492 events ($M \geq 1.5$) with JMA depths (red) and relocated depths (blue), and the values of Hirose et al. (2024, Fig. 9a; black, digitised). (b) Relocated catalogue with the Hirose selection, $M \geq 1.3$.

4.11 Which explanations of the depth dependence are admissible

Table 9. Cluster N before the 2023 mainshock by depth slice: broken-model fit, weight w of the steep end member in the end-member mixture ($k = 1$) and its ΔBIC , and the count deficit across M_{th} relative to the fitted mixture. The ≥ 14 km group is the steep end member itself.

Slice (km)	N	M_{max}	b_1 / b_2	ΔBIC broken	w (95%)	$\Delta\text{BIC}_{\text{em}}$	deficit vs mixture
10–12	1,501	4.2	1.15 / 0.83	−4.9	0.04 (0.00–0.11)	−1.5	0.36
11–12	1,370	4.2	1.17 / 0.86	−1.1	0.06 (0.00–0.12)	−1.7	0.39
12–12.5	1,728	5.4	1.18 / 0.79	−25.3	0.04 (0.00–0.11)	−1.6	0.39
12.5–13	1,281	4.5	1.17 / 0.79	−9.3	0.05 (0.00–0.14)	−1.7	0.35
13–13.5	710	4.2	1.54 / 0.75	−15.6	0.40 (0.29–0.50)	−8.2	0.58
13.5–14	367	4.3	1.88 / 0.44	−2.8	0.65 (0.52–0.77)	+8.4	0.36
≥ 14	157	1.7	2.80 / 0.70	+10.1	1.00 (1.00–1.00)	+0.0	0.62

Within 10–13 km all slices have the same steep branch ($b_1 = 1.15$ –1.18) and the same count deficit across M_{th} (0.35–0.39 relative to the fitted mixture; automatic share 0.72–0.79), yet only 12–12.5 km (and 12.5–13 km marginally) is significantly bent (Table 9, Fig. 12; Supplementary Fig. S5). That slice is the largest (1,728 events) and contains the largest events (M 5.4); its slope above M_{th} is 0.84 against 0.93 at 11–12 km, a difference of about 1.5σ . The end-member mixture does not improve these slices ($w \approx 0.04$ –0.06, $\Delta\text{BIC}_{\text{em}} \approx -1.5$). Between 13 and 14 km the picture changes: w rises to 0.40 (0.29–0.50) at 13–13.5 km and 0.65 (0.52–0.77) at 13.5–14 km, b_1 increases from 1.17 to 1.54 and 1.88, and the steep component of the free mixture at 13–13.5 km ($b_a = 1.70$) equals the Sd slope (1.71). With one free parameter the end-member mixture reaches $\Delta\text{BIC}_{\text{em}} = -8.2$ at 13–13.5 km (−12.6 with the Sd member) and, for all clusters, −16.3 and −10.5 at 13–13.5 and 13.5–14 km, where it fits better than the three-parameter broken model at 13.5–14 km (−6.8). The automatic share (0.73–0.86) and the median number of stations (19–20) do not change down to 14 km; fewer stations (11.5–13) record events only below 14 km.

The excess of small events at 13–14 km over the downward extrapolation of the b_2 law is 923, whereas only 47 events lie within the 95% relative depth error (0.13 km) below 14 km and 157 below 14 km in total, so leakage of the deep population cannot supply it; the steep population must be present at 13–14 km itself. Smooth b -gradients of 0.23 and 0.40 per km never produced $\Delta\text{BIC} < -10$ in 200 simulations (median ΔBIC +11.6 to +13.7), and even 1.0 per km did so in only 10% and 0% of simulations

(Supplementary Fig. S6). Rupture-size truncation predicts steepening at large magnitudes ($b_2 > b_1$), the opposite of the observed shape, although it is consistent with the small maximum magnitudes of the pure steep population ($M \leq 1.7$ in $N \geq 14$ km, ≤ 2.6 in Sd).

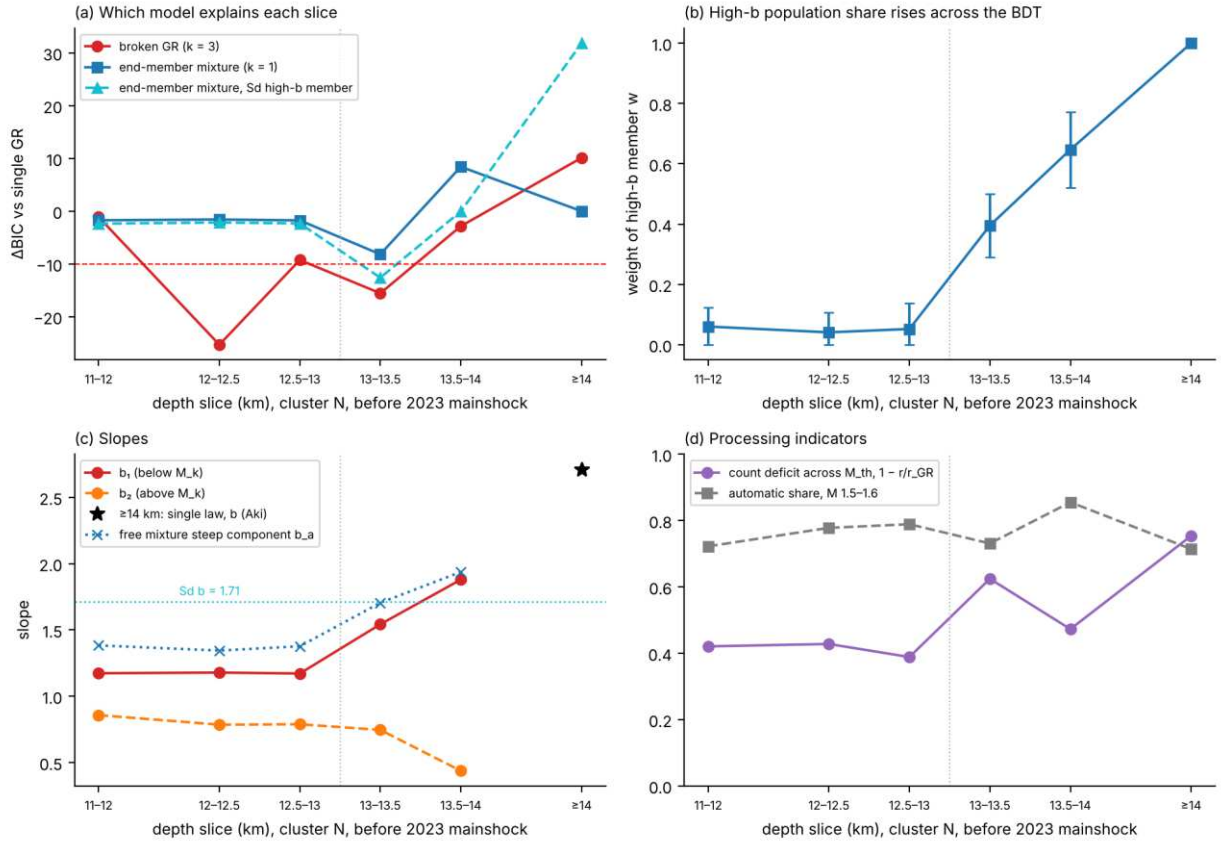


Figure 12. Cluster N before the 2023 mainshock by depth slice: (a) ΔBIC of the broken ($k = 3$) and end-member mixture ($k = 1$) models; (b) weight of the steep end member with 95% bootstrap interval; (c) slopes; (d) count deficit across M_{th} and automatic share. Dotted line: brittle–ductile transition (~ 13 km).

4.12 Correcting the processing step with external factors

Table 10. Break strength before and after weighting the counts at $M \leq 1.6$ by $1/f$, with f measured in Ibaraki and Nankai (main: $f(1.5)$ for all $M \leq 1.5$).

Depth band (2021–2023)	Uncorrected ΔBIC (b_1 / b_2)	Corrected, main	Corrected, 1.5–1.6 only	Corrected, upper-CI f
Shallow < 10 km	+12.5 (0.92 / 1.39)	−4.5 (0.67 / 0.89)	+12.1	−9.7
Middle 10–13 km	−96.8 (1.11 / 0.84)	+14.5 (0.84 / 0.77)	−94.3	+9.2
Deep ≥ 13 km	−107.3 (1.57 / 0.75)	−42.0 (1.23 / 0.53)	−125.0	−38.0

With the externally measured step removed, the middle band follows a single law ($\Delta BIC +14.5$; $+9.2$ with the upper-CI factor), whereas the deep band still bends (-42.0 ; -38.0), with M_k moving to 2.4 (Table 10, Fig. 13). In cluster N before the 2023 mainshock the corrected weight of the steep end member is 0.00–0.02 at 10–13 km and 0.33 (0.22–0.43) at 13–13.5 km and 0.60 (0.47–0.74) at 13.5–14 km; b_1 increases by 0.44 (0.35–0.56) from 12–13 to 13–14 km. The pre-registered survival rule was met for both cluster sets and all corrections. The steep population is a layer rather than the vicinity of the GNSS source ($p = 0.052$), and its events are not more clustered in time than those at 11–13 km (difference-in-differences of the background share $+0.03$, 95% CI -0.06 to $+0.11$).

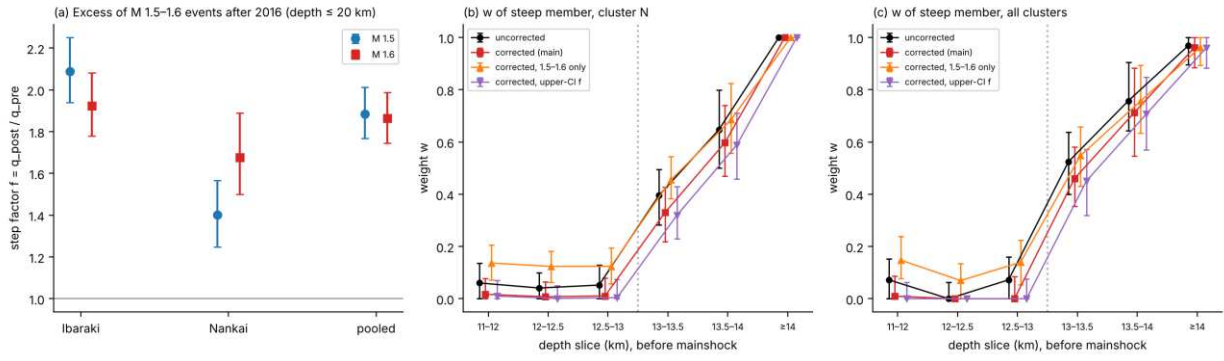


Figure 13. (a) Step factor of M 1.5 and 1.6 events after April 2016 in Ibaraki, Nankai and pooled. (b, c) Weight of the steep end member by depth slice before the 2023 mainshock, uncorrected and with three corrections, for cluster N and all clusters. Dotted line: ~13 km.

4.13 Evolution from 2021 to March 2024

Table 11. Break by period relative to the two mainshocks ($M_c = 1.2$). Size control: ΔBIC of 200 random pre-mainshock subsamples of the same size.

Period (all depths)	N	$\Delta\text{BIC} (b_1 / b_2)$	Size control: median (% < -10)	Reading
P0 before 2023 Mj 6.5	9,615	-170.3 (1.26 / 0.85)	—	break; corrected -3.7
P1 0–72 h after	1,741	+10.3 (0.80 / 0.64)	-19.0 (81%)	no break; first 6 h incomplete (MAXC 1.7)
P2 72 h – 31 Dec 2023	3,455	-18.9 (1.17 / 0.90)	-52.0 (100%)	weaker break; w(13–14 km) 0.68
1 Sep – 1 Jan 2024 16:06	1,002	-4.3 (1.16 / 0.69)	-7.4 (36%)	moderate; w 0.48; no acceleration
Q1 0–72 h after Mw 7.5	1,205	-412.0 (0.20 / 0.55)	—	incompleteness shape
Q2 72 h – 7 d	602	-174.1 (0.29 / 0.94)	—	incompleteness shape
Q3 7 d – 31 Mar 2024	3,683	+3.9 (0.92 / 1.06)	-56.4 (100%)	no Noto-type break

Before the 2023 mainshock the break was strongest in 2021 – early 2022 (1,000-event windows: ΔBIC -14.7, -26.2 and -21.7) and weaker in later windows of the same size, which sample mainly the 11–13 km layer where the break is the processing step. The steep population at 13–14 km, in contrast, was present in every 250-event window from January 2021 to October 2023 ($w = 0.22$ –0.85; Fig. 14). The window ending on 5 January 2024 has $w = 0$, but 190 of its 250 events followed the Mw 7.5; its 60 earlier events give $w = 0.50$. The last 250 events before each large sequence (2021 M 5.1, 2022 M 5.4, 2023 Mj 6.5 and the 2024 M 5.5 that began the Mw 7.5 sequence) had $w = 0.61$ –0.91, within or above the range of the other windows (before the Mw 7.5: $w = 0.67$, 90% bootstrap interval 0.48–0.86); w was not lower before large events than at random times ($p = 0.79$), so it is not a precursor in this catalogue (pre-specified test; only four targets and seven reference windows). In the first 72 h after the Mj 6.5 there was no break although pre-mainshock data of the same size bend in 81% of subsamples: in the first 6 h small events were missing (MAXC 1.7, $D_{\text{small}} +0.53$) and the processing step was absent ($r = 1.02$); from 6 to 72 h both the excess of small events and the steep population were absent. From 72 h to the end of 2023 the break returned in weaker form, with the steep population back (w 0.68). After the Mw 7.5 the catalogue shows strong curvature of the opposite shape ($b_1 < b_2$) in the first 7 days, and from 7 days to 31 March 2024 no Noto-type break although the size control predicts one in every subsample. Whether the break returned later cannot be tested with this catalogue; a physical change (pressure release; Mohanna et al. 2026) and slow recovery of small-event completeness cannot be separated. These comparisons were partly post hoc.

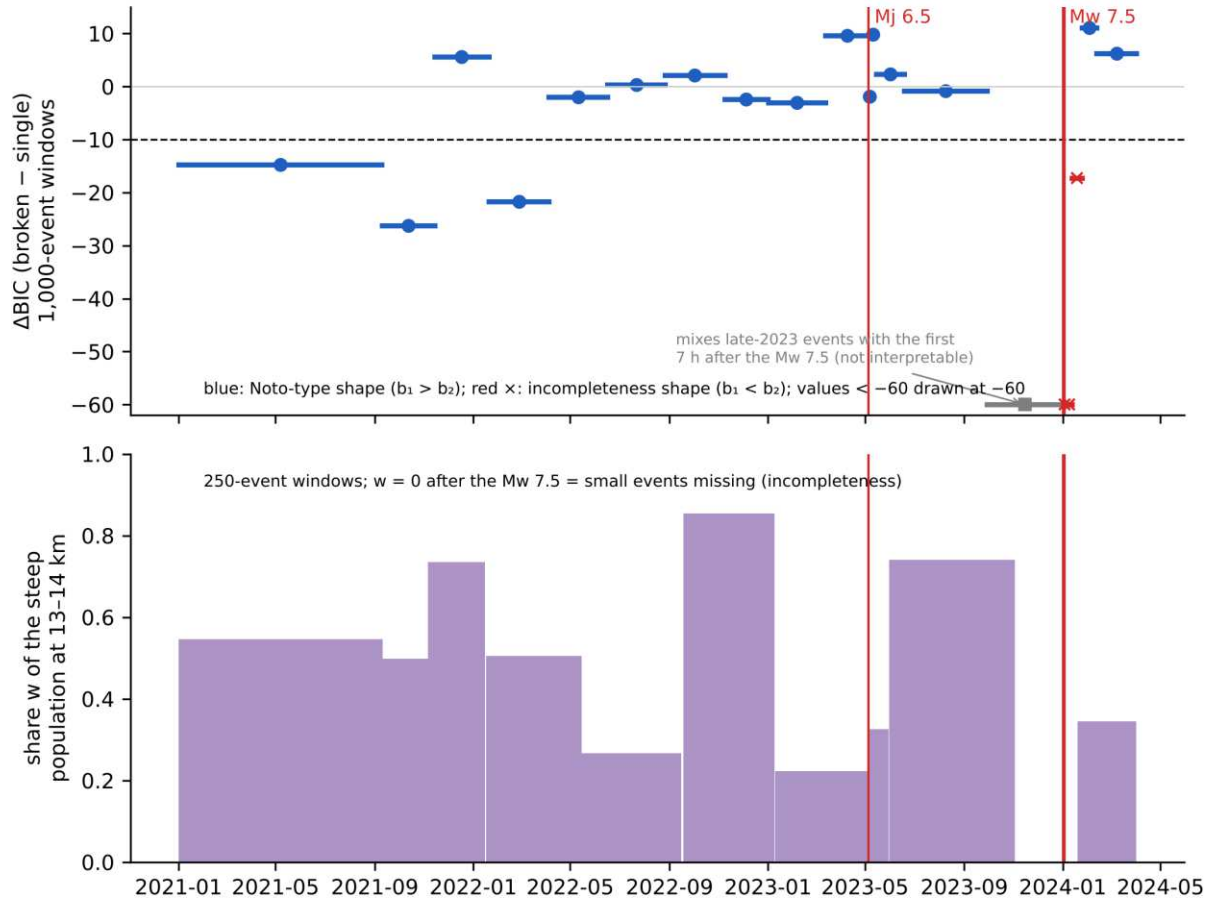


Figure 14. (a) Break strength in consecutive 1,000-event windows (blue: Noto-type shape; red $\times$: incompleteness shape; grey: window mixing late 2023 with the first hours after the Mw 7.5). (b) Weight w of the steep population at 13–14 km in consecutive 250-event windows; the window ending on 5 January 2024 ($w = 0$) consists mainly (190 of 250) of events after the Mw 7.5. Vertical lines: 2023 Mj 6.5 and 2024 Mw 7.5.

4.14 The quiet segment below the busy layer

Between December 2020 and the start of the Mw 7.5 sequence, 65% of events lie at 10–13 km and only 4.0% at 14–16 km (JMA catalogue 4.1%). Counts per kilometre fall from 3,961 at 13–14 km to 616 at 14–15 km and 314 at 15–16 km, then rise to 364 at 16–17 km before decreasing; the JMA catalogue shows the same minimum at 15–16 km (61 against 77 at 16–17 km). The low band, at about 14.5–16.5 km, therefore appears in two independently located catalogues (Fig. 15a). It corresponds to the aseismic zone between the southern cluster and the other clusters described by Takano et al. (2024) from the geodetic sources of Nishimura et al. (2023); here we quantify its geometry, timing and relation to the large events. Its absolute depth depends on the location procedure: in the independent relocation of Nakajima (2022, Fig. 5) the deep early cluster lies at about 13.5–17 km and the gap between it and the later shallow cluster at about 13–14 km, whereas in the JMA catalogue the main peak is about 1 km deeper than in relocated catalogues. The robust feature is the quiet segment between the two clusters, not a fixed depth. It is not a horizontal layer of the whole region: in sections normal to strike the busy layer (median 12.3 km) and the deep cluster where the swarm began (median 16.75 km) are offset by 5.7 km towards the SE, so that the line joining them dips about 38° SE, close to the 43° Suzu blind fault, and the band is the part of this dipping zone with few earthquakes (Fig. 15b, Fig. 16). The same arrangement — an early deep cluster offset to the SE of and below the later shallow cluster, separated by few events — is visible in sections M and N of Nakajima (2022, Fig. 5c). The base of seismicity (90th-percentile depth) deepens from about 13.5 km to 17.3 km towards the SE. The band is empty mainly in the central and south-western parts of the swarm (Fig. 15d), where the GNSS sources of Nishimura et al. (2023) —

aseismic reverse slip at 13.5–13.9 km (dips 35° and 23°) and tensile opening at 16 km — are located. In time, 20–32% of events lay at 14–16 km in December 2020 – March 2021, when activity started at 16–17 km; from mid-2021 the share was 1–6%: the activity crossed the band early and the band then remained quiet. Activity did not expand from the onset point as a single front: during the first year the onset cluster stayed within 3–4 km of it, and from about mid-February 2021 a group about 8 km away dominated (90–97% of events from the fourth month on). In the pre-specified comparison, diffusive ($\sqrt{t}$) and constant-velocity growth of the 95% distance quantile could not be distinguished (cross-validated loss difference -0.66 , favouring constant velocity, but a bootstrap interval of the in-sample difference from -0.035 to $+0.029$; sensitivity cases split both ways), and the earlier one-year fit ($n = 0.41$, $D = 0.50$ m²/s) mainly measured the jump between the two groups. Diffusive migration within clusters (Amezawa et al. 2023) and upward migration (Yoshida, Uno et al. 2023) are therefore taken from published work, not from our fit. The whole swarm moved up by about 3.5 km between December 2020 and September 2021 in both catalogues (post hoc).

All first $M \geq 5$ events of each sequence (M 5.1 in 2021, M 5.4 in 2022, M_j 6.5 in 2023) and the M 5.5 and M 5.9 pre-events of the 2024 M_w 7.5 nucleated at 10.8–12.5 km, 1.2–2.7 km above the local base of seismicity (13.4–14.0 km); the only $M \geq 5$ events at or below the base were aftershocks (M 5.0 in June 2022 at 14.8 km and M 5.4 in May 2023 at 14.4 km) (Fig. 15c). Relative to the mapped transition (Section 4.17) the same first events lie 0.5–2.6 km above z_{50} . This is consistent with nucleation in the brittle layer but is not distinctive: 86% of all events lie above z_{50} , so five events chosen at random would all lie above it with probability ≈ 0.48 (post hoc). The large events did not start in quiet spots: the number of earlier events within 2 km of their hypocentres was typical of all $M \geq 3.5$ events (percentiles 0.48–0.64), except the 2021 M 5.1 in the young swarm (0.13).

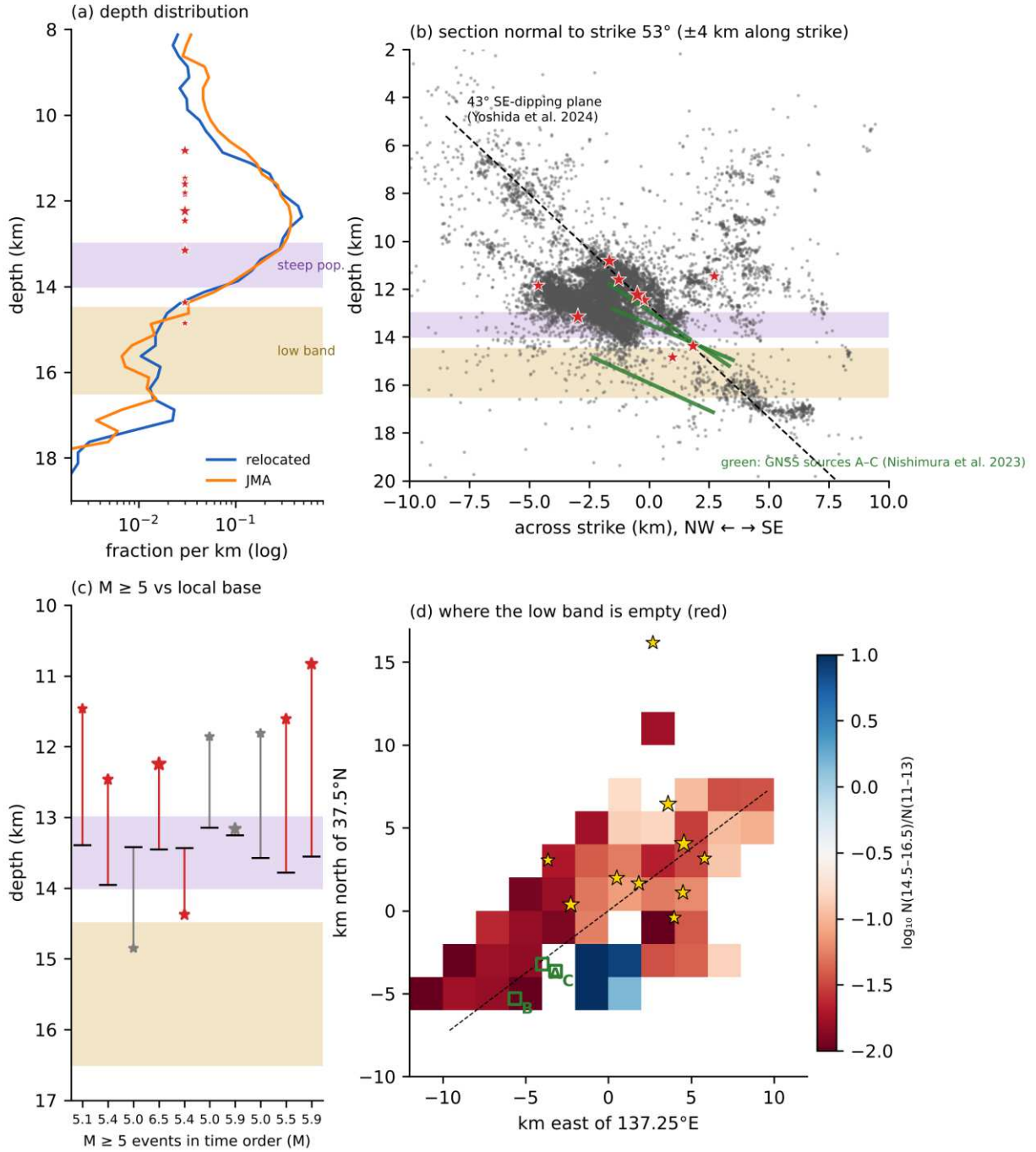


Figure 15. (a) Depth distribution in the relocated and JMA catalogues (Dec 2020 – 1 Jan 2024 16:06); stars: $M \geq 5$. (b) Section normal to strike 53° (± 4 km along strike) with the 43° plane through the 2023 Mj 6.5 and the projected GNSS sources. (c) Depth of each $M \geq 5$ event and the local base of seismicity before it (red: first event of a sequence or Mw 7.5 pre-event). (d) Ratio of events at 14.5–16.5 km to 11–13 km in 2-km cells; stars $M \geq 5$, squares GNSS sources. Purple: steep population (13–14 km); beige: low band.

3-D view (Dec 2020 – 1 Jan 2024): grey plane 43° SE-dipping through the 2023 Mj 6.5;
yellow planes bound the 14.5–16.5 km low band; red stars M ≥ 5

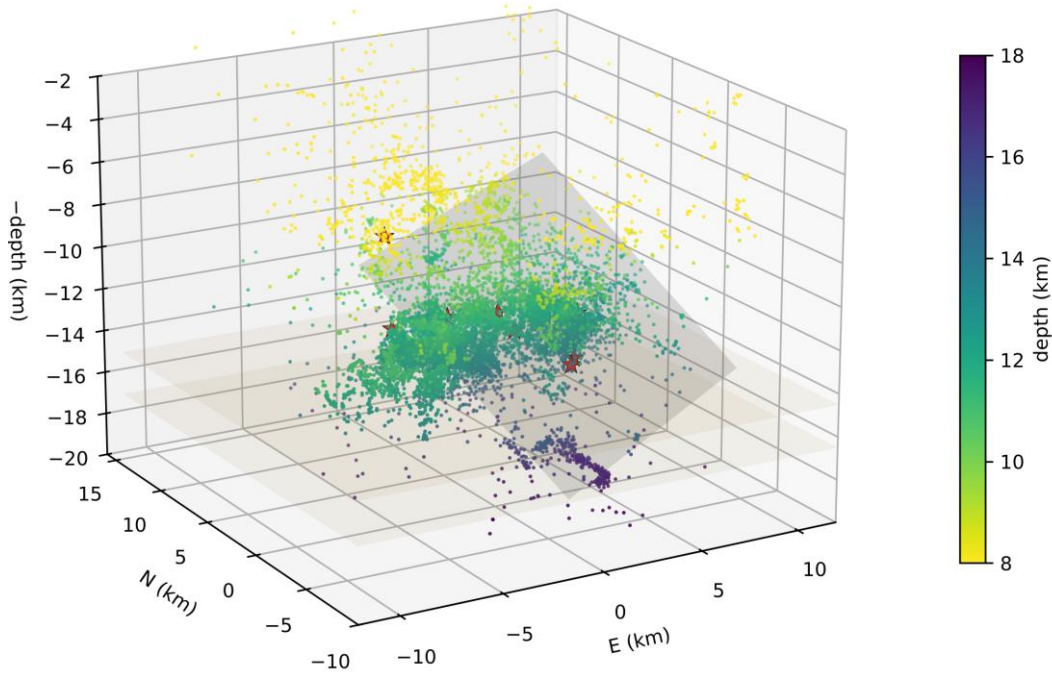


Figure 16. Three-dimensional view of the swarm hypocentres (Dec 2020 – 1 Jan 2024) coloured by depth, with the 43° SE-dipping plane through the 2023 Mj 6.5 and the planes bounding the low band.

4.15 Fault dips and the pore pressure needed to slip

Table 12. Dips of Noto faults and slip planes and the pore-fluid factor needed for reverse slip if differential stress is limited to that of an optimally oriented plane at hydrostatic pressure ($\lambda_v = 0.4$). "locked": beyond the lock-up angle.

Plane	Dip	λ_v needed ($\mu = 0.6$)	λ_v needed ($\mu = 0.75$)	Source
GNSS C, aseismic slip (13.9 km)	23°	0.43	0.41	Nishimura et al. 2023
GNSS A, opening (16 km)	26°	0.41	0.40	Nishimura et al. 2023
GNSS B, aseismic slip (13.5 km)	35°	0.42	0.46	Nishimura et al. 2023
Upper layer → deep cluster	≈ 38°	0.45	0.52	this study
Suzu blind fault	43°	0.53	0.64	Yoshida et al. 2024
2023 Mj 6.5 fault	≈ 45°	0.58	0.70	Kato 2024
2007 Noto Hanto fault	≈ 55°	0.86	locked	Kato 2024
Noroshi-oki fault	60°	locked	locked	AIST database (Kato 2024)

Seismogenic faults of the region dip 43–60°, steeper than the frictional optimum ($\approx 30^\circ$), while the geodetic slip planes at the base of the swarm dip 23–35° (Table 12, Fig. 17). Under the stated assumption, the 43–45° faults need $\lambda_v \approx 0.53$ –0.70, the 2007 fault 0.86 or more, and planes of 60° cannot slip in reverse without near-lithostatic pressure or very low friction, whereas the shallow-dipping GNSS planes need almost no overpressure. Our own estimate of the 2023 plane (37°) is biased low by fitting one plane to two parallel faults and to poorly located offshore events (Section 4.5) and is not used for this argument.

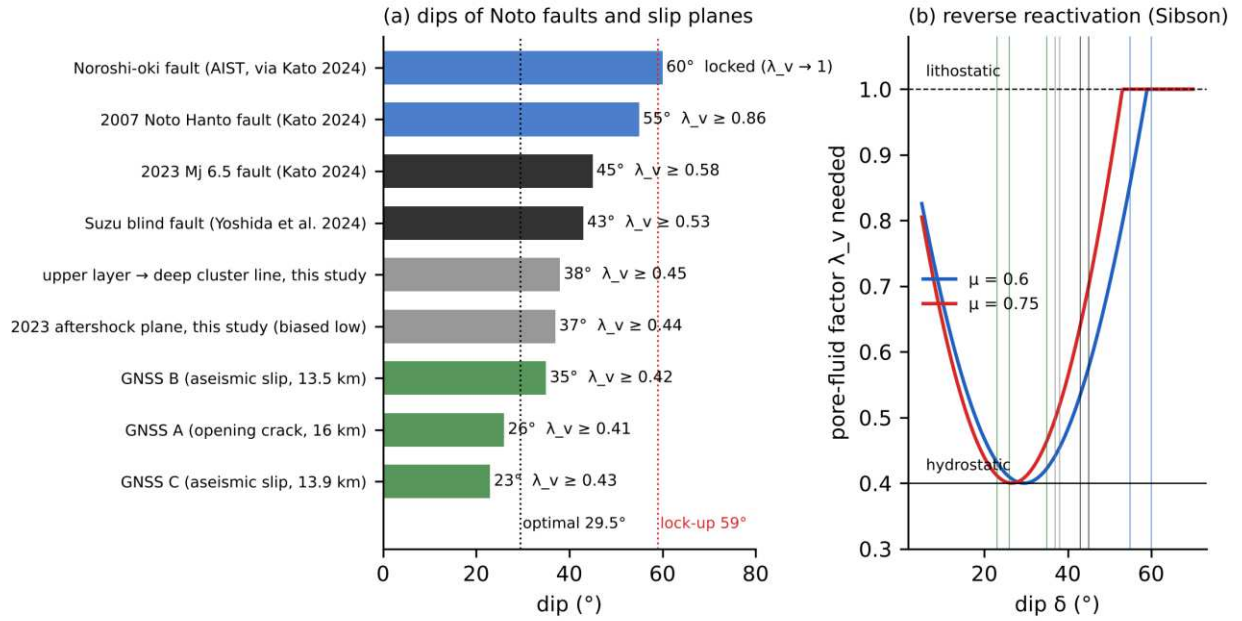


Figure 17. (a) Dips of faults and slip planes in the Noto region with the pore-fluid factor required for reverse slip ($\mu = 0.6$). (b) Required λ_v against dip for $\mu = 0.6$ and 0.75 ; vertical lines mark the planes of (a).

4.16 Shear velocity and helium

Table 13. Shear-velocity anomaly at the hypocentres of each layer (Vs model of Takagi, Yoshida and Okada), compared with depth-matched random points in the swarm area.

Layer (Yoshida et al. depths)	N	mean dVs (km/s)	random points 5–95%	model SD
busy layer 11–13 km	13,673	−0.126 (−3.7%)	−0.091 ... −0.059	0.16
steep population 13–14 km	3,919	−0.096 (−2.8%)	−0.075 ... −0.049	0.17
quiet segment 14.5–16.5 km	654	−0.096 (−2.8%)	−0.060 ... −0.041	0.18
deep cluster 16.5–18 km	400	−0.087 (−2.5%)	−0.048 ... −0.033	0.19

All layers lie in lower Vs than the region and than random points of the swarm area at the same depths (Table 13): the swarm occupies a low-Vs body, consistent with fluid-rich or fractured rock and with the low-velocity lower crust beneath the swarm (Nakajima 2022). The quiet segment, however, has the same anomaly as the steep-population layer and lies within the model uncertainty of the busy layer, so the Vs model does not distinguish it; the model uncertainty at these depths ($\approx 5\%$) and the depth resolution of surface-wave tomography are much coarser than the 1–2 km layers of this study. A high-Vs layer, as expected for a solidified intrusion, is not seen at the swarm depths. Descriptively, the upper part of the SE-dipping seismicity follows the boundary between the low-Vs swarm body and a high-Vs block to its SE at 4–10 km (Fig. 18). The tomography of Nakajima (2022) shows low Vp and low Vs from about 15 km into the lower crust beneath the swarm with Vp/Vs of only about 1.72–1.78, whereas Okada et al. (2024) reported high Vp/Vs at about 18 km beneath the southern cluster; Vp/Vs grid values were not available to us.

Mantle helium is concentrated above the deep onset cluster (Fig. 19a): the three sites within 6 km of the onset point have $^3\text{He}/^4\text{He}$ of 2.9–4.6 R_A (36–58% mantle helium; the Sakamoto value has a large error), whereas Rokko, above the northern busy cluster and the 2023 fault, shows crustal helium (0.04 R_A) and two distant sites 0.5–0.6 R_A (Spearman $\rho = -0.60$ with distance, $n = 6$). At the two monitored sites the ratios do not follow the local event rate or depth ($\rho \approx 0$); the Ashiyu ratio was lowest around the 2023 Mj 6.5 (2.3–2.5 R_A) and recovered by October 2023 (Fig. 19b). These comparisons are descriptive.

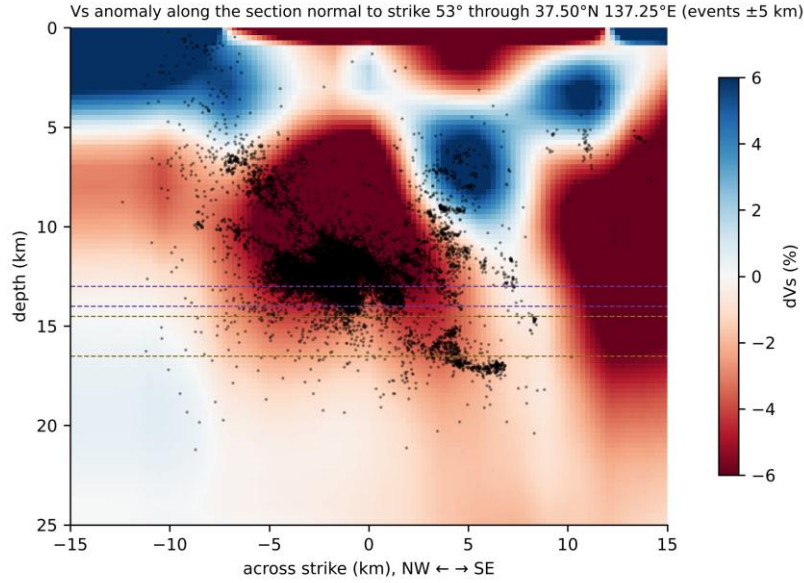


Figure 18. Shear-velocity anomaly along the section normal to strike 53° through 37.50°N 137.25°E (Vs model of Takagi, Yoshida and Okada) with events within ± 5 km; dashed lines bound the steep-population layer (purple) and the quiet segment (brown).

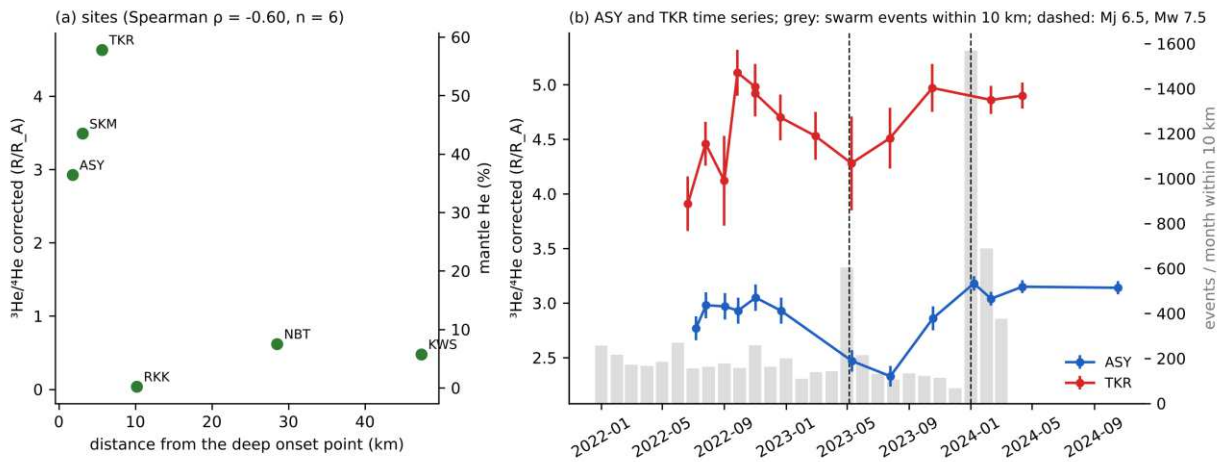


Figure 19. (a) Corrected $^3\text{He}/^4\text{He}$ of six sites (Kagoshima et al. 2025) against distance from the deep onset point; right axis: mantle helium fraction. (b) Time series at Ashiyu (ASY) and Takarayyu (TKR) with the monthly number of swarm events within 10 km; dashed lines: 2023 Mj 6.5 and 2024 Mw 7.5.

4.17 A three-dimensional map of the transition

Of 236 nodes with enough events, 126 have a located z_{50} and 110 lie above the base of the steep population ("below seismicity"); 90 of the located nodes are well constrained by the post hoc quality rule. At these nodes z_{50} ranges from 12.1 to 13.85 km (10–90%: 12.45–13.5 km; median 13.15 km). The transition depth differs between tiles more than in any of 200 permutations ($G = 14.55$; null 95th percentile 5.93; $p < 0.005$; with well-constrained tiles only $G = 9.9$ against 3.9, post hoc). The synthetic tests show that the method neither creates nor removes lateral variation: a flat surface is recovered with a median absolute error of 0.15 km and no false detection ($p = 0.985$; without the processing step 0.10 km, $p = 0.90$), and the dipping surface is recovered with the same error and detected ($p < 0.005$). Single nodes scatter by about ± 0.5 km (10–90% error -0.50 to $+0.32$ km; 14% of nodes err by more than 0.5 km), so only patterns spanning several nodes are interpreted (Figs. 20, S8, S9).

Table 14. Three-dimensional transition proxy $z50$ in two independently located catalogues. The JMA tests J1–J4 were specified before the run. G: likelihood gain of tile-wise $z50$ against the permutation null (95th percentile).

Quantity	Relocated catalogue (Yoshida et al.)	JMA catalogue	Status
Events used; M_c	9,576; 1.2	4,084; 1.5	
b_{low} / b_{high} ; width s	0.88 / 1.72; 0.25 km	1.06 / 1.81; 0.05 km	
Well-constrained nodes	90 of 236	88 of 170	post hoc QC
$z50$ median (10–90%)	13.15 km (12.45–13.5)	13.95 km (13.54–14.15)	offset 0.9 km
Lateral variation (tile test)	G 14.55 vs 5.93; $p < 0.005$	G 2.95 vs 2.39; $p = 0.01$	replicated (J1)
Same pattern at common nodes	—	$\rho = 0.67$, $n = 63$, $p = 1 \times 10^{-9}$	replicated (J2)
East deeper than centre	≈ 13.9 vs 13.1 km (tiles)	difference -0.07 km (90% CI $-0.20 \dots 0.05$)	not replicated (J3)
SE deepening of $z50$	0.075 ± 0.012 km/km (4.3°), $p = 5 \times 10^{-9}$	0.058 ± 0.011 km/km, $p = 5 \times 10^{-7}$	replicated (J4)
Constant-depth control	$p = 0.985$ (synthetic)	$p = 0.985$	no false detection

The most robust feature is a gentle deepening of the transition to the SE, across strike: 0.075 ± 0.012 km per km (4.3° ; $p = 5 \times 10^{-9}$, $n = 90$). The deepening is absent in the SW part of the swarm (-0.047 ± 0.024 km/km at -3 km along strike), moderate in the centre ($+0.063 \pm 0.013$ at $+1$ km) and twice as steep near the 2023 Mj 6.5 ($+0.155 \pm 0.017$ km/km, $\approx 9^\circ$, at $+5$ km). The transition rises towards the NW end of the sections; the flat synthetic surface does not shallow at the section ends (error 0 to $+0.55$ km, i.e. deeper), so this is not an edge artefact. The base of seismicity at each node (90% depth) lies a median 0.4 km below $z50$, with a weak correlation ($\rho = 0.27$, $p = 0.01$).

The JMA catalogue, with independent locations and a higher completeness, reproduces the lateral variation (J1, $p = 0.01$, with three tiles), the pattern of the map (J2, $\rho = 0.67$ at 63 common nodes; $\rho = 0.75$ at 70 nodes with $N \geq 200$) and the SE deepening (J4, 0.058 km/km, $p = 5 \times 10^{-7}$), whereas the constant-depth control shows no variation ($p = 0.985$). Its transition lies 0.9 km deeper, consistent with the known depth offset between the two location procedures (Section 5.8). The deeper transition beneath the eastern cluster seen in the relocated catalogue (≈ 13.9 km in the tile near the 2023 Mj 6.5) is not reproduced (J3: -0.07 km), and we do not interpret it (Fig. 20).

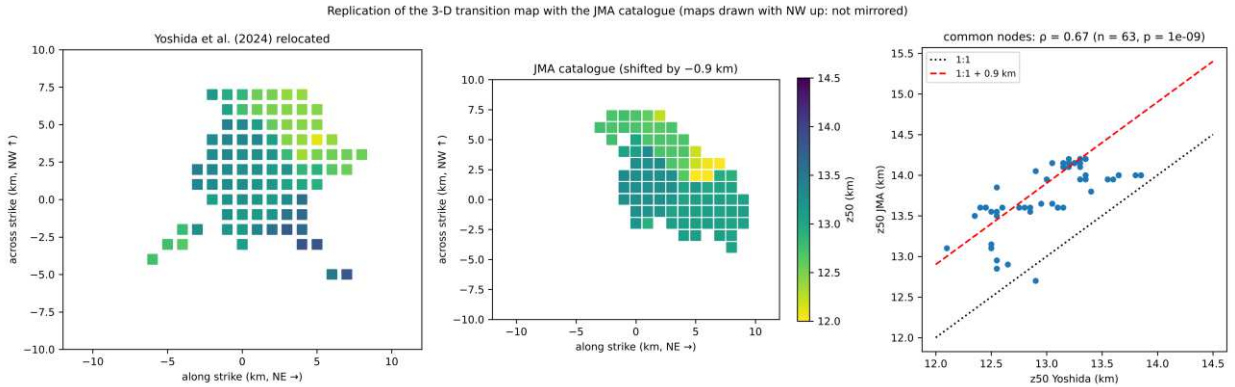


Figure 20. Maps of the transition proxy $z50$ at nodes of a 1-km grid in rotated coordinates (along strike 53° , NE to the right; across strike, NW up, so that the maps are not mirrored): (left) relocated catalogue, well-constrained nodes; (centre) JMA catalogue, shifted by -0.9 km; (right) $z50$ at common nodes with the 1:1 line and the 1:1 line plus the median offset.

The transition is sharp. When each event is referred to the local $z50$, the steep share w is 0.00–0.05 more than 1 km above it, 0.02 at 0.5–1 km above, 0.19 at 0–0.5 km above, 0.89 at 0–0.5 km below and 0.96 at 0.5–1 km below; b of all events changes from 0.88 at 0.5–1 km above to 1.67 at 0.5–1 km below (Fig. 21). Because $z50$ is fitted to the same events, the sharpness could be partly built in; we therefore mapped $z50$ from one random half of the events and measured w with the other half (post hoc). w still rises from 0 to 0.11, 0.40, 0.84 and 1.0 between 1.5 km above and 1 km below the surface. The width of the JMA transition ($s = 0.05$ km) is even smaller, but this value is at the lower edge of the search grid and is not interpreted.

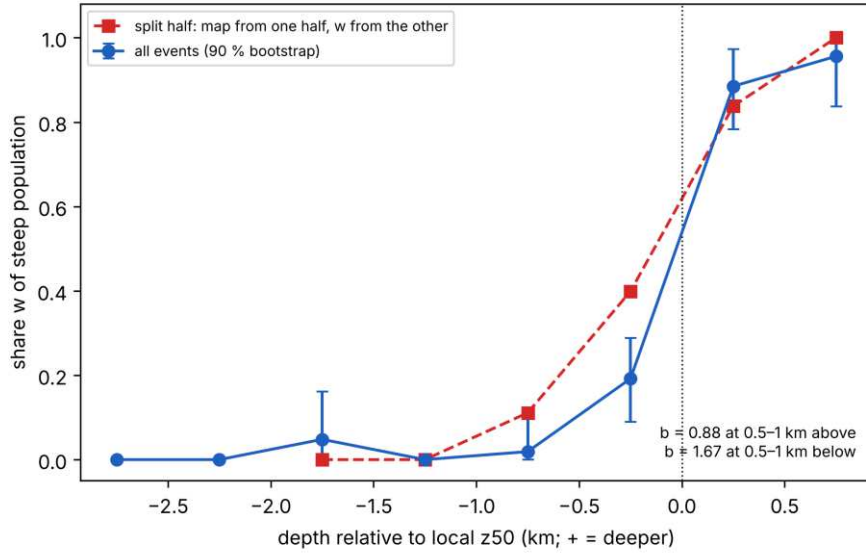


Figure 21. Share w of the steep population against depth relative to the local $z50$ (90% bootstrap intervals) for all events (blue) and in a split-half test in which $z50$ was mapped from one half of the events and w measured on the other half (red, post hoc). Inset: b of all events above and below the surface.

4.18 The transition and the seismicity-poor zone

In sections across strike (seen from the SW, NW to the left) the transition is a gently SE-dipping surface at the base of the busy layer, and the seismicity-poor zone of Section 4.14 lies below it (Fig. 22). At all 62 nodes above the zone, $z50$ is 1.4–3.2 km (10–90%; median 2.5 km) above the top of the zone; this separation is partly built in, because the zone is defined to start below 13.5 km. At fixed depth the steep share does not increase towards the zone (12.5–13.25 km: $w = 0.06$ at 1.5–3 km and 0.11 at more than 3 km from it), so the steep population is controlled by depth relative to the transition, not by proximity to the zone (post hoc).

Seen along strike, the zone is a shallow bowl. Its centre is deepest (≈ 16.2 km) about 2 km NW of the section origin (curvature -0.032 km^{-2}), it is widest at 15.5–16.5 km (10.5 km against 8 km at 13.5–14.5 km), and its SE rim reaches higher (13.75 km) than the NW rim (14.75 km). The same shape is found for all threshold variants and for a wider depth window, but the shape is partly set by the definition of the zone as the space between the busy layer and the deep cluster, and we describe it without a physical interpretation of its curvature (post hoc). The deep cluster consists of a main SE component ($\approx 28 \text{ km}^3$ at 15.75–18.25 km, ≈ 4.6 km SE of the origin) and a smaller central component ($\approx 5 \text{ km}^3$ at ≈ 15.8 km). The line from the busy layer to the main deep component dips about 38° to the SE (4.4 km deeper over 5.7 km), close to the published $43\text{--}45^\circ$ dips of the swarm faults.

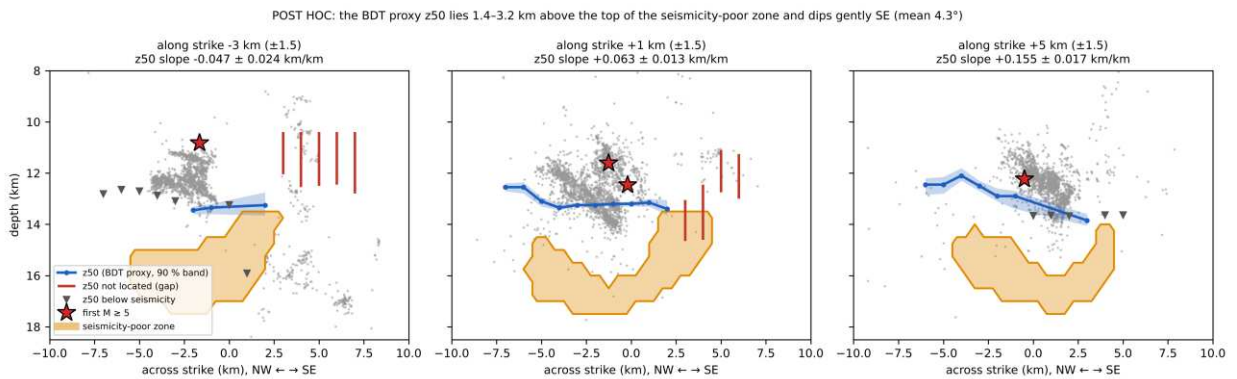


Figure 22. Sections across strike at -3 , $+1$ and $+5$ km along strike (± 1.5 km), seen from the SW (NW left, SE right): hypocentres (grey), $z50$ with its 90% band (blue), nodes where $z50$ is not located (red bars: gap; triangles: below

seismicity), the seismicity-poor zone (orange) and first $M \geq 5$ events (stars). The z50 slope of each strip is given in the title.

The migration of the swarm is consistent with this geometry but does not test it. Between late 2020 and late 2023 the centroid moved 5–6 km across strike to the NW (up-dip) and 4–5 km upward, the direction in which the fault dip, the buoyancy of fluids and the rise of the transition all point, so the three cannot be separated. An earlier statement that the net path follows the up-slope direction of z50 within 1.4° is withdrawn: the angle ranges from 19° to 53° with reasonable choices of start and end windows and centroid definition, the up-slope direction itself is uncertain (21° , 95% interval -3° to 43°), and the quarterly steps after 2021 show no consistent steering (post hoc). A thicker brittle layer is not associated with larger events once the event count is controlled (partial $\rho = 0.13$, $p = 0.22$).

4.19 Is there a b-value precursor?

With the published approach (S1) the last 90-day block before the Mw 7.5 has a higher b than the preceding block (1.21 against 1.05, $N = 444$ and 471; $\Delta\text{AIC} = 2.61$, $P = 0.04$), as reported. The same threshold, however, is passed by 5 of 9 ordinary blocks (56%) of the same series, and by 71% of the ordinary blocks before the Mj 6.5, whose own last block is not significant ($\Delta\text{AIC} = -0.5$). Compared with all earlier blocks pooled, the Mw 7.5 block is not significant ($\Delta\text{AIC} = -0.47$). Above the processing threshold (S2: $\Delta\text{AIC} = -1.05$), with the step-corrected counts (S3: -0.5) and in the 10–13 km layer alone (S4: b 1.07 against 0.91, $N = 90$ each; $\Delta\text{AIC} = -0.76$, with no ordinary block significant) the rise is not significant (Table 15, Fig. 23). In the JMA catalogue the last block lies within the range of earlier blocks for S1 (b = 0.98; 5–95%: 0.77–1.00) and S4 (1.00; 0.90–1.04) and slightly above it only for S2 (1.00 against 0.79–0.98). The pre-specified decision is that a precursor is not supported. The b-values of S1 follow the share of deep events in each block ($r = 0.84$; 0.52, $p = 0.13$, without the first block), so at low completeness the b of a block measures mainly how many steep-population events it contains.

Table 15. Utsu test of the last 90-day block before each mainshock against the preceding block (relocated catalogue). N of S3 are step-weighted counts. The false-alarm column gives the share of ordinary blocks passing $\Delta\text{AIC} > 2$.

Setting	M_c	Depths	b last block (N)	b previous (N)	ΔAIC	ordinary blocks $\Delta\text{AIC} > 2$
S1 published approach	1.4	all	1.21 (444)	1.05 (471)	+2.61	5/9 (56%)
S2 above M th	1.8	all	1.01 (133)	0.90 (163)	-1.05	—
S3 step-corrected	1.2	all	0.94 (475)	0.87 (530)	-0.50	—
S4 one layer	1.8	10–13 km	1.07 (90)	0.91 (90)	-0.76	0/7 (0%)
Before Mj 6.5, S1	1.4	all	1.17 (625)	1.25 (888)	-0.50	5/7 (71%)
Before Mj 6.5, S4	1.8	10–13 km	0.87 (174)	0.93 (174)	-1.54	2/6 (33%)

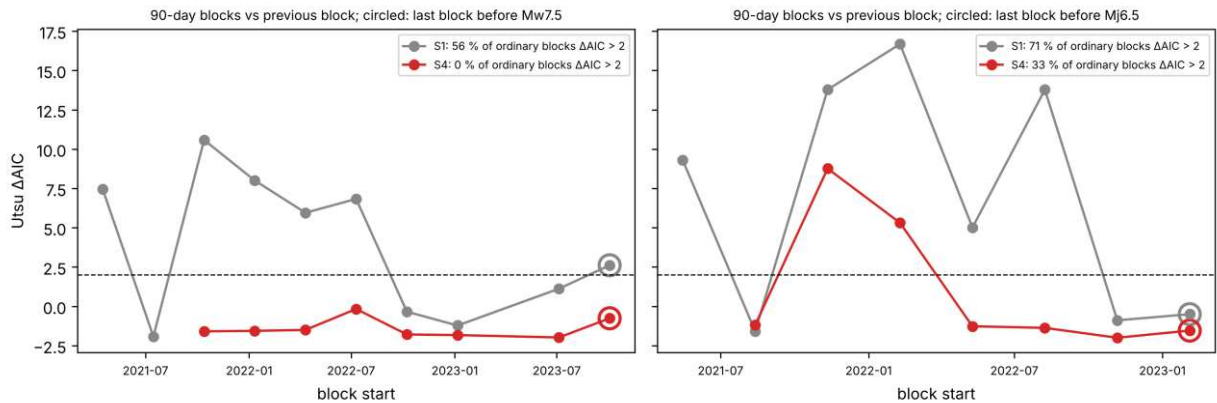


Figure 23. Utsu ΔAIC of each 90-day block against the preceding block before the 2024 Mw 7.5 (left) and the 2023 Mj 6.5 (right) for setting S1 (grey; $M_c = 1.4$, all depths) and S4 (red; $M_c = 1.8$, 10–13 km). Circles: last block before the mainshock; dashed line: $\Delta\text{AIC} = 2$.

5. Discussion

5.1 What is established

The FMD of the relocated catalogue at $M \geq 1.2$ is inconsistent with a single GR law at middle and deep levels. This is not a chance result of searching for a break (bootstrap and null calibration), and it is not produced by depth errors, the choice of depth boundaries, aftershock sequences, the magnitude type or a single year. It predates the 2023 earthquake and is concentrated in the northern cluster at 12–14 km. These are properties of the catalogue that any user of these data should know. The new mapping shows, in addition, that the depth at which the steep population takes over can be located node by node, that it varies laterally and deepens gently to the SE, and that these features are reproduced by an independently located catalogue.

5.2 Catalogue processing

Four observations tie most of the break to the JMA processing threshold. The steep branch lies largely below $M_{th} = 1.7$, where three-quarters of the events are automatic; the count ratio across M_{th} is far below its GR expectation in every band, year and period; the same drop appeared in 2016 in distant regions; and an unrestricted search places the break at 1.7. A synthetic excess of events below 1.7 reproduces the location and most of the strength of the break. Above M_{th} the shallow and middle bands follow single laws. The mechanism is not known; possibilities include re-processing of events whose provisional magnitude reaches M_{th} , with automatic magnitudes about 0.1 larger than reviewed ones (Tamaribuchi 2018), and the selection of automatic events below M_{th} . A uniform shift of automatic magnitudes does not reproduce the shape, so the effect is more likely in event counts than in magnitudes.

The processing step alone does not explain why the break depends on depth and cluster. Within 10–13 km the step has the same size in slices that bend and in slices that do not, and the automatic share and station coverage do not change down to 14 km (Section 4.11); the larger raw deficit at depth in Table 5 is partly expected from the steep population present there. A distortion of the deep size applied equally at all depths would have been detected in groups of the shallow size (in 100% and 92% of simulations for 1,787 and 1,073 events). The processing step therefore explains the steep branch common to all middle-depth slices, but the extra steepening at depth requires something that changes at about 13 km. A depth-dependent processing effect is not excluded, but it would have to change at 13 km without changing the processing class or the number of stations.

5.3 A layered explanation of the depth dependence

The depth-slice tests support a layered picture. (1) Above the brittle–ductile transition (10–13 km), one brittle population with $b \approx 0.85\text{--}0.95$ above M_{th} occupies the swarm faults. The processing step steepens its FMD below 1.7 by the same amount in every slice, and whether a slice is significantly bent then depends mainly on its size and on how many large events it contains; at these depths the break is chiefly a catalogue feature. (2) Across the transition (13–14 km), a second population of small events with $b \approx 1.7\text{--}1.9$ — the slope of the deep southern cluster — mixes with the brittle population, and its share rises from about 5% to 40–65% within 1 km. The steep population dominates the small magnitudes and the brittle population the large ones, which gives $b_1 > b_2$ and the rapid increase of b_1 with depth (0.23 per km). (3) Below 14 km only the steep population remains, with small maximum magnitudes (≤ 1.7 in cluster N and ≤ 2.6 in Sd), and the FMD is a single steep law without a break.

The 2023 fault gives this picture a location. The large events that keep b_2 low are concentrated on the fault, and below 14 km the events away from it form the pure steep population ($b \approx 1.9$, no event of $M \geq 3$). The two populations therefore meet where the base of the fault reaches the steep population, at 13–14 km, which is where Kato (2024) placed the initiation of the 2023 rupture and the 2022 Mj 5.4 aftershocks, and just above the 14–16 km zone of fluid-driven opening and aseismic slip (Nishimura et

al. 2023). The evidence for this localisation is suggestive rather than conclusive (Fisher $p \approx 0.06$; the on/off ΔBIC contrast is within sample-size variability).

Each layer agrees with independent observations. A rise of b below the brittle–ductile transition is a general property of continental crust (Spada et al. 2013; inflection near 15 km in most regions and about 25 km in Switzerland), and the transition beneath Noto is at about 13 km (Omuralieva et al. 2012). Kumazawa and Ogata (2024) also found b increasing with depth within the swarm. Near the transition, seismic slip is expected on small brittle patches embedded in rock that deforms partly aseismically; at Noto, aseismic slip and fluid-driven opening occur at 14–16 km (Nishimura et al. 2023), and Hirose et al. (2024) attributed the high b of S_d to high pore pressure. Small patches limit rupture size, which explains the small maximum magnitudes of the steep population, while larger events nucleate on continuous faults of the brittle layer, where swarms with migrating ruptures on single faults have lower b than diffuse networks (Shelly et al. 2016). The lower stress drops in the medial parts of the northern-cluster faults (Fukuoka et al. 2024) show that fluid-related heterogeneity exists at the same depths. Classical rupture-width saturation (Pacheco et al. 1992) acts at much larger magnitudes and produces the opposite curvature, so it cannot explain the break itself.

Three cautions remain. The steep population consists mainly of events below M 1.9, most of which have automatic hypocentres, so its magnitudes are JMA automatic magnitudes; the argument rests on the fact that the processing indicators are the same at 11–13 km, where this population is absent. The tidal test of the break volume did not find tidal sensitivity, but that group (12–14 km) is dominated by 12–13 km events, where the steep population is only about 5%, so it mainly constrains the brittle population. Finally, the weak deep feature above M_{th} (Section 4.7) is not explained by the steep population, whose events are small.

The new results extend this picture downward and in time. Below the steep-population layer the dipping fault zone continues to the deep cluster where the swarm began, but the segment between them (≈ 14.5 – 16.5 km in this catalogue) produced few earthquakes after the first months, at the depths where geodesy requires aseismic reverse slip and opening and where Takano et al. (2024) placed an aseismic zone. The simplest reading is that this segment slipped largely aseismically — because it lies below the brittle–ductile transition, because fluid pressure there was high, or both — and loaded the base of the brittle faults above it, where every large event nucleated (Fig. 24). The steep small-event population at 13–14 km is the seismic expression of the transition between the two regimes. This reading agrees with Kato (2024) and Nishimura et al. (2023), who proposed that fluid-lubricated aseismic slip at depth triggered the swarm up-dip, and with the general tendency of large earthquakes to nucleate near the base of the seismogenic layer. Three alternatives cannot be excluded: the band may partly reflect a velocity-model boundary in the location procedures; it may be a gap between two separate structures rather than a segment of one fault; and the GNSS source geometry is only approximately known.

The three-dimensional map adds a surface to this picture (Fig. 24). The brittle layer ends at a transition that is sharp (b changes from 0.88 to 1.67 within about 1 km), lies at about 13.2 km in the relocated catalogue (about 14 km in the JMA catalogue) and deepens gently to the SE, most steeply near the 2023 M_j 6.5. A depth of the brittle–ductile transition near 13 km beneath Noto agrees with the regional cutoff depth (Omuralieva et al. 2012), and an increase of b below the transition is expected for crust whose deeper part deforms by distributed rather than localised failure (Spada et al. 2013). That the transition can be mapped from magnitudes alone, with a node scatter of about ± 0.5 km, suggests that the mixture approach could map transition depths in other dense swarms, provided processing steps are corrected first. We do not claim that z_{50} is the brittle–ductile transition itself: it is the depth at which a population of small, steep-FMD events becomes dominant, and a temperature, fluid-pressure or rock-type boundary could produce the same change. The SE deepening of the transition, the 38° line from the busy layer to the deep cluster and the 43 – 45° dip of the faults all point the same way; the swarm migrated up this structure, but its geometry cannot tell whether the transition guided the migration or merely records the same fault zone.

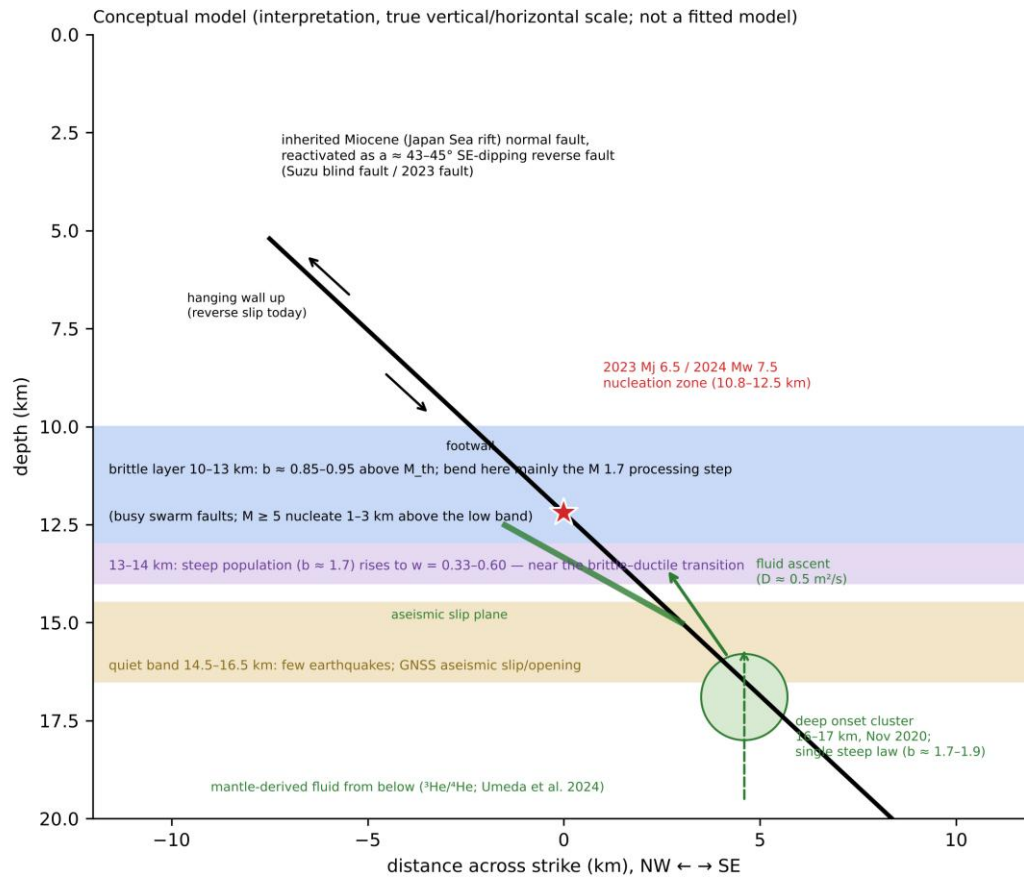


Figure 24. Conceptual cross-section (interpretation, true scale): inherited SE-dipping fault reactivated in reverse; brittle layer with the processing-dominated break; steep small-event population at 13–14 km near the brittle–ductile transition; quiet band with aseismic slip; deep onset cluster and fluid ascent; nucleation of the large earthquakes at the base of the brittle layer.

5.4 Inherited faults, fluids and the 2007 earthquake

The fault geometry links the Noto swarm to the regional pattern of inversion. The 2007 Noto Hanto fault ($\approx 55^\circ$), the Noroshi-oki fault (60°) and the Suzu blind fault ($43\text{--}45^\circ$) all dip SE and steeper than the frictional optimum. Faults this steep are poorly oriented for reverse slip and are expected to be reactivated old normal faults rather than new reverse faults; their reactivation requires either very low friction or pore pressure well above hydrostatic (Table 12; Sibson 1985, 2009). Sibson (2009) made this argument for inversion structures in NE Honshu, and Kato (2024) adopted it for the 2023 rupture. Our results add three observations consistent with it: the swarm began at 16–17 km and spread upward and outward, by a jump between clusters rather than a single front, with diffusive migration within clusters (Amezawa et al. 2023); the segment between the deep cluster and the brittle faults slipped largely without earthquakes; and the large events nucleated at the base of the brittle faults. We have no relocated data for the 2007 sequence, which lies outside the catalogue region, so the comparison with 2007 rests on its published geometry only.

5.5 Magmatic and mantle fluids

A layer of intermediate strength formed when the Japan Sea opened — for example solidified intrusions along the rift faults — could focus fluids and deformation, and Yoshida, Uno et al. (2023) discussed fluid leakage from a hidden magma system. The helium data support fluids with a mantle component ($^3\text{He}/^4\text{He} \approx 3.9 R_A$; Umeda et al. 2024; Kagoshima et al. 2025), but mantle volatiles can reach the crust without a magma body, and hypocentres cannot distinguish the two. The quiet band and the steep population are compatible with a fluid-rich, partly aseismic zone near the brittle–ductile transition whatever the source

of the fluid. A magmatic origin would require independent evidence, such as a high-velocity or magnetic intrusive body at the right place or isotopic signatures of degassing magma. The Vs model shows no high-velocity layer at the swarm depths, only a high-Vs block beside the upper part of the fault zone; Okada et al. (2024) related high Vp/Vs at about 18 km to a Tertiary magma reservoir, and a recent study proposed that rupture of solidified ancient magma that had impeded the swarm migration led to the 2024 earthquake (Sci. Adv. 2025). Our data are compatible with fluids of mantle origin rising beneath the southern cluster — where the helium signal is strongest — but they cannot distinguish whether the fluids passed through or were released by an old magmatic body; we therefore do not claim a magmatic origin.

5.6 Why JMA depths give a decreasing b with depth

Hirose et al. (2024) found b decreasing from 10 to 14 km and increasing below. The same events give this profile with JMA depths but an increasing profile with relocated depths (Section 4.10), because automatic hypocentres are placed about 0.4 km shallower, relative to their relocated positions, than reviewed hypocentres of the same magnitude. Since small events are mostly automatic and large ones reviewed, small events are moved upward relative to large ones, which inflates b in the upper part of the swarm and deflates it near its base. The high b below 14 km and its interpretation by Hirose et al. (2024) are not affected; the decrease above 14 km is.

5.7 Implications

- b -values of the post-2016 JMA catalogue that span M_{th} mix processing classes. In this swarm the deep b -value is 1.45 at $M_c = 1.2$ but 0.92 at $M_c = 1.7$. Studies of depth or time changes of b should use $M \geq M_{th}$, fit processing classes separately, or check the count ratio across M_{th} .
- Depth- b profiles from catalogues with mixed processing classes can be biased by class-dependent location offsets; in the Noto swarm automatic hypocentres are about 0.4 km shallower than reviewed ones relative to relocated positions, enough to reverse the sign of the b -depth trend at 10–14 km. Relocated depths should be used for depth profiles of small events.
- Depth comparisons in a swarm can be confounded with time; in Noto, shallow events are mostly 2023 aftershocks. Results should be shown by depth and period together.
- In intense swarms the Schuster test can be inflated several-fold by clustering even after declustering; a clustering-preserving null such as a time-shift test should be used before tidal triggering is claimed.
- Pre-specified protocols, replication on other sequences and complete reproducibility packages made it possible to identify and report the processing effect rather than a spurious physical signal.
- b -value changes in time in a swarm with a depth-dependent FMD can be produced by changes in the depth mix of events. Claims of a b -value precursor should report the false-alarm rate of ordinary windows and repeat the test above the processing threshold and within a single depth layer.
- An event-level mixture with processing weights can map the depth of an FMD transition laterally; such maps should be checked with synthetic flat and dipping surfaces and with an independently located catalogue.

5.8 Limitations

- The break was found by exploring the data; the processing audit, the depth-slice tests and several sensitivity checks were post hoc (labelled).
- All magnitudes are amplitude-based JMA magnitudes; no independent moment magnitudes exist for $M < 3$ events (Fukuoka et al. 2024 assumed $M_w = M_j$ for many events).
- Cluster boxes were read from a published figure. The fault-plane classification is approximate (RMS 0.9 km); its dip (37°) is lower than that of Kato (2024; $\sim 45^\circ$) because one plane was fitted to two parallel faults and to offshore events (39° before the M_j 5.9 aftershock).
- The upper part of the deep FMD rests on 37 events of $M \geq 3$; the tidal test uses one fault orientation per group.

- The time-evolution comparisons, the quiet-band analysis and the big-event positions were post hoc; only four independent large-event sequences are available. The band could be influenced by velocity-model boundaries; no focal mechanisms or Vp/Vs data were used; the GNSS source sizes were not available to us.
- Four other sequences were compared; this does not show that no other region has such a break. The catalogue ends on 31 March 2024.
- Absolute depths differ between location procedures by about 1–2 km (Nakajima 2022; JMA); the depths of the layers should be read relative to the clusters. The Vs model cannot resolve 1–2 km layers, Vp/Vs grids were not available, and the helium analysis rests on six sites and two short time series.
- The transition map: single nodes scatter by about ± 0.5 km; the quality rule for well-constrained nodes, the split-half test, the relation to the seismicity-poor zone, the bowl shape, the migration geometry and the position of the large events relative to z50 were post hoc; the JMA transition is 0.9 km deeper; and the eastern deepening was not replicated. An error in the sign of the synthetic processing step in the specification was corrected before use. Three-dimensional views in earlier unpublished material were mirrored because of a left-handed coordinate triple; all figures here are drawn correctly.
- The b-value precursor test uses 90-day blocks, so only 6–9 ordinary blocks per series are available for the false-alarm rate; other window lengths were not tested.

6. Conclusions

The relocated catalogue of the 2020–2024 Noto swarm contains a statistically robust break in the FMD that predates the 2023 Mj 6.5 earthquake. Removing the JMA processing step with factors measured in other regions eliminates the break at 10–13 km, so there it is a catalogue feature; below 13 km the break survives because a steep population of small events ($b \approx 1.7$) rises from a few per cent to 33–60% of events within 1 km, consistent with mixing near the brittle–ductile transition. This population persisted from 2021 to late 2023; it was absent in the first days after the 2023 mainshock and after the 2024 mainshock (to March 2024), mainly because small events are missing. Below it, a quiet segment — the previously recognised aseismic zone, at about 14.5–16.5 km in this catalogue and seen also in an independent relocation — lies on the SE-dipping continuation of the swarm faults towards the deep cluster where the swarm began, at the depth of geodetically inferred aseismic slip; all large earthquakes nucleated 1–3 km above it. The steep inherited reverse faults of the region (43–60°, including the 2007 Noto Hanto and Noroshi-oki faults) can slip only with supra-hydrostatic pore pressure, which links fault inversion to the deep fluids indicated by mantle helium, strongest directly above the deep onset cluster. The swarm lies in low shear velocity, but the quiet segment has no resolvable Vs signature of its own. The depth z50 at which the steep population takes over can be mapped in three dimensions: it lies at 12.45–13.5 km, varies laterally, deepens gently to the SE (4.3°, about 9° near the 2023 Mj 6.5), separates $b \approx 0.88$ from $b \approx 1.67$ within about 1 km, and is reproduced in pattern and dip by the JMA catalogue with a 0.9 km offset; the large earthquakes started above it, as most events did. The b-value rise reported before the 2024 Mw 7.5 is matched by half or more of ordinary 90-day blocks and disappears above the processing threshold and within one layer; it is not a precursor. Depth–b profiles based on JMA depths are biased by a class-dependent location offset. Four other pre-mainshock sequences show no comparable break. Moment magnitudes of small events, focal mechanisms, Vp/Vs structure and template-matching catalogues (Mohanna et al. 2026) are needed to test this layered interpretation; the magmatic origin of the fluids remains untested.

Abbreviations

BDT: brittle–ductile transition; BIC: Bayesian information criterion; CFF: Coulomb failure function; FMD: magnitude–frequency distribution; GR: Gutenberg–Richter; JMA: Japan Meteorological Agency; M_c:

completeness magnitude; M_k : break magnitude; M_{th} : JMA processing threshold magnitude; PREM: Preliminary Reference Earth Model.

Declarations

Availability of data and materials

The relocated catalogue is available from Zenodo (<https://doi.org/10.5281/zenodo.12799165>; CC BY 4.0). The JMA unified hypocentre catalogue is available from the Japan Meteorological Agency. The other catalogues are available from https://github.com/sadeghkarimpouli/Family_based_features (commit 5e67f5a) and GFZ Data Services (doi 10.5880/GFZ.4.1.2023.004). TidalStrain.2 is distributed by the Meteorological Research Institute. The analysed event tables, all scripts, protocols with SHA-256 fingerprints, Excel workbooks with live calculations and all figures are provided in the reproducibility packages (Noto_four_tests, Noto_Kato_tests, Noto_Hirose_cluster_test, Noto_tidal_test, Replication_kink, Noto_depth_logic_tests, Noto_population_tests, Noto_time_bend_tests, Noto_H1_H4_tests, Noto_gap_test, Noto_Vs_Helium, Noto_diffusion_vs_velocity, Noto_w_precursor_test, Noto_Gap1_Gap2, Noto_BDT3D_Gap1 (three-dimensional transition map, synthetic tests, b-value precursor test and an interactive three-dimensional view), Noto_BDT3D_JMA (replication with the JMA catalogue) and the processing analysis of version 2), to be deposited in a public repository on acceptance.

Competing interests

The author declares no competing interests.

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Authors' contributions

R.P. designed the study, performed all analyses and wrote the manuscript.

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Supplementary figures

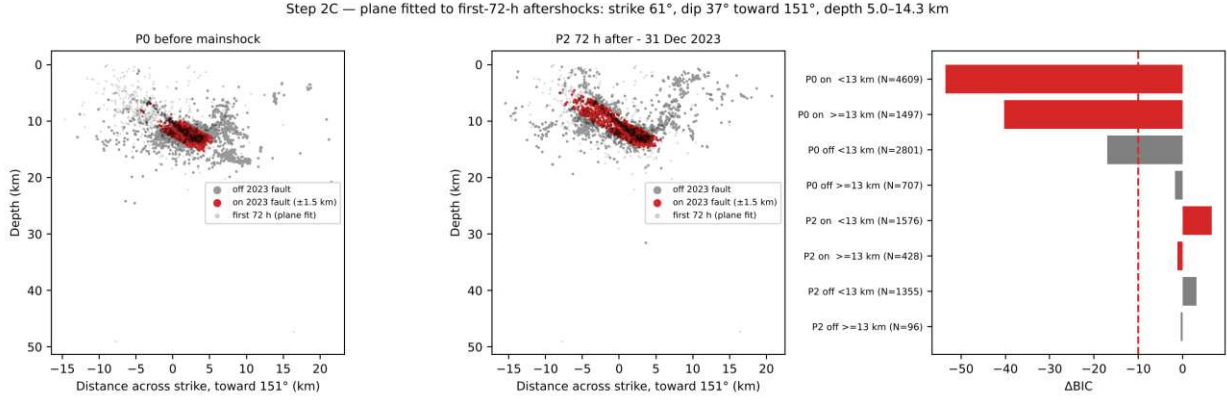


Figure S1. Cross-sections perpendicular to the plane fitted to the first-72-h aftershocks of the 2023 Mj 6.5 earthquake, before (left) and after (centre) the mainshock; red: events within 1.5 km of the plane. Right: ΔBIC of on- and off-plane groups.

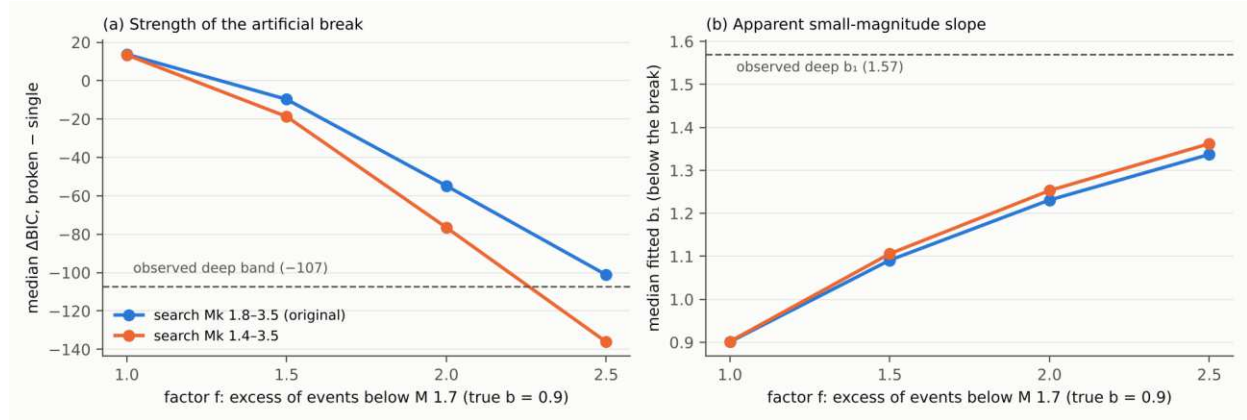


Figure S2. Synthetic processing step: median ΔBIC and fitted small-magnitude slope b_1 as functions of the excess factor f of events below $M 1.7$, for the original and the extended break search.

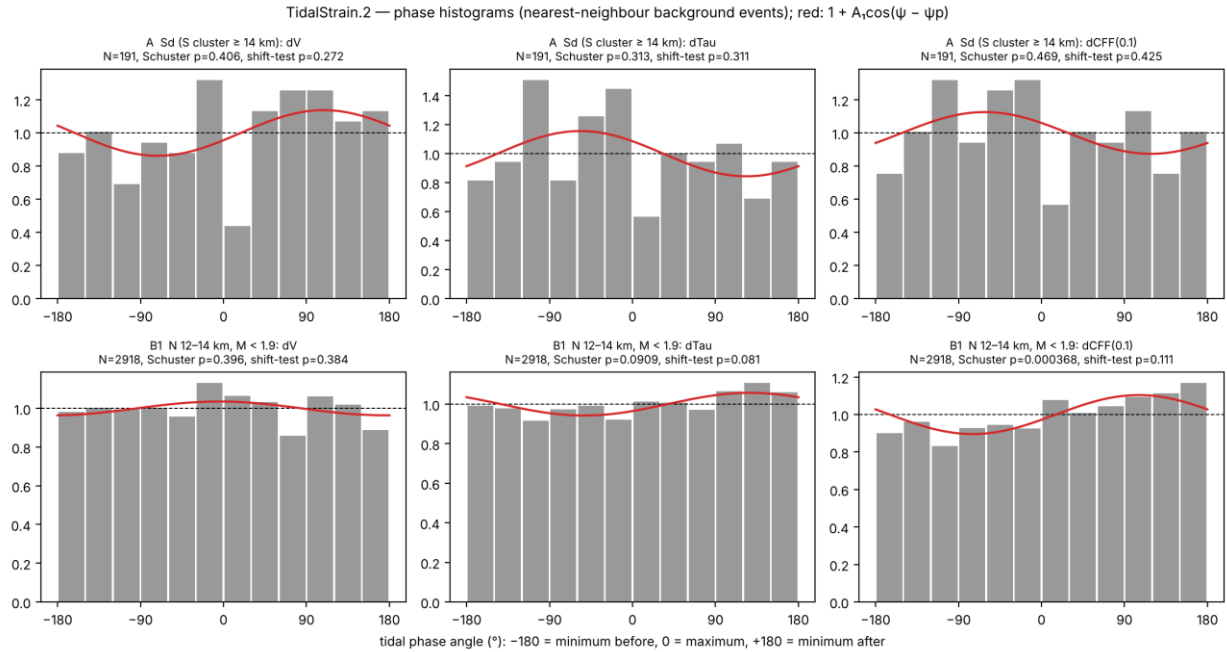


Figure S3. TidalStrain.2 phase histograms for S_d (top) and the small events of the break volume (bottom) for ΔV , $\Delta \tau$ and $\Delta CFF(0.1)$, with Schuster and time-shift p -values.

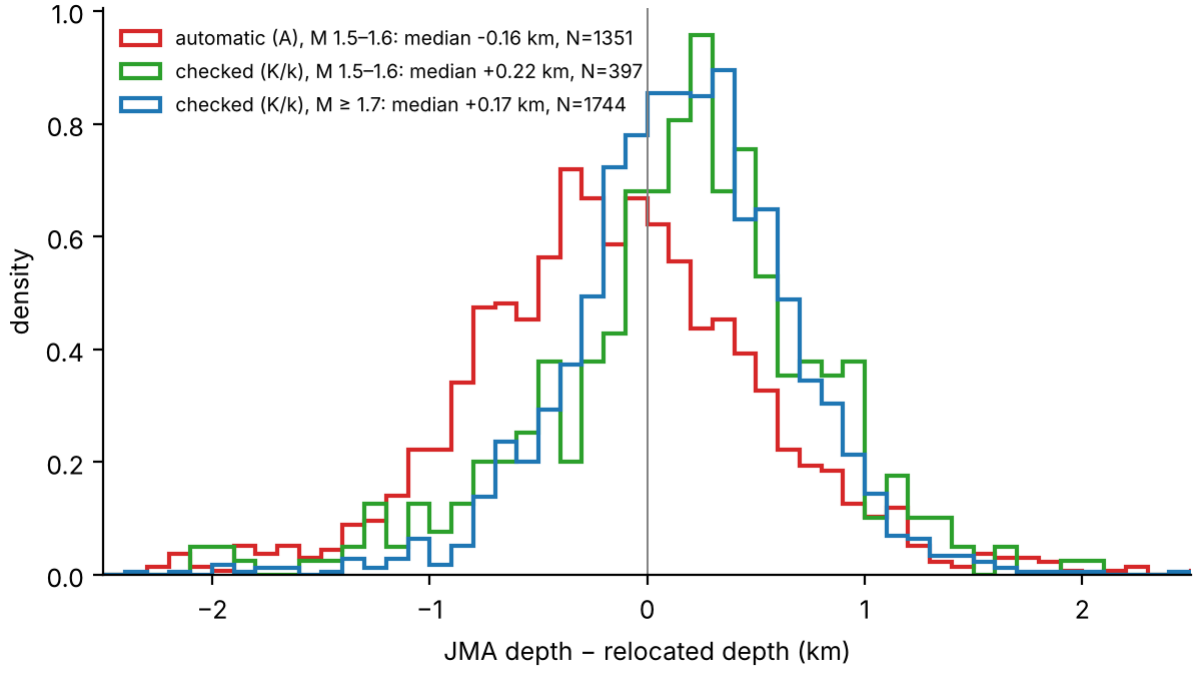


Figure S4. Distribution of JMA – relocated depth by JMA processing class for the Hirose et al. (2024) selection ($M \geq 1.5$).

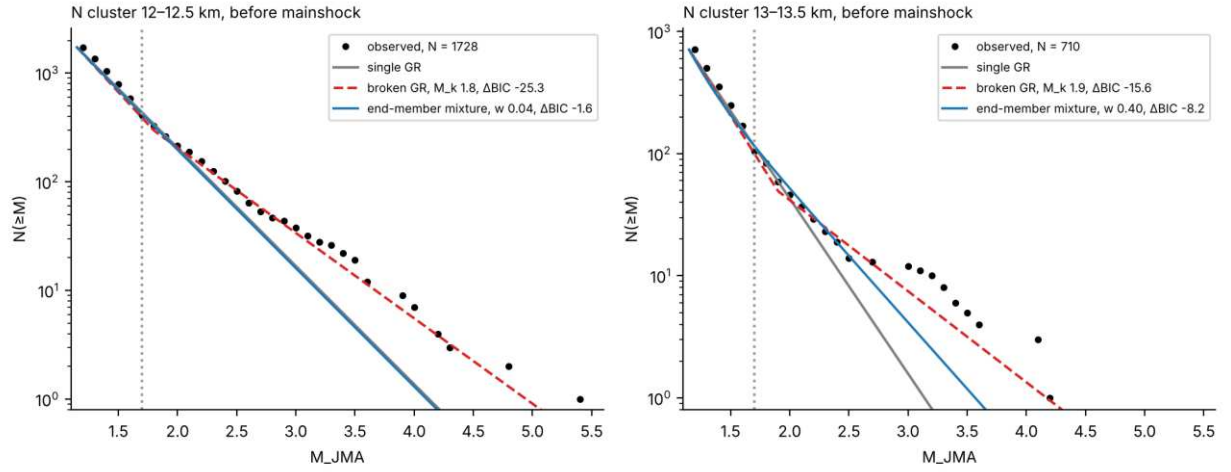


Figure S5. FMDs of the 12–12.5 km and 13–13.5 km slices of cluster N before the 2023 mainshock with single, broken and end-member mixture fits; dotted line $M_{th} = 1.7$.

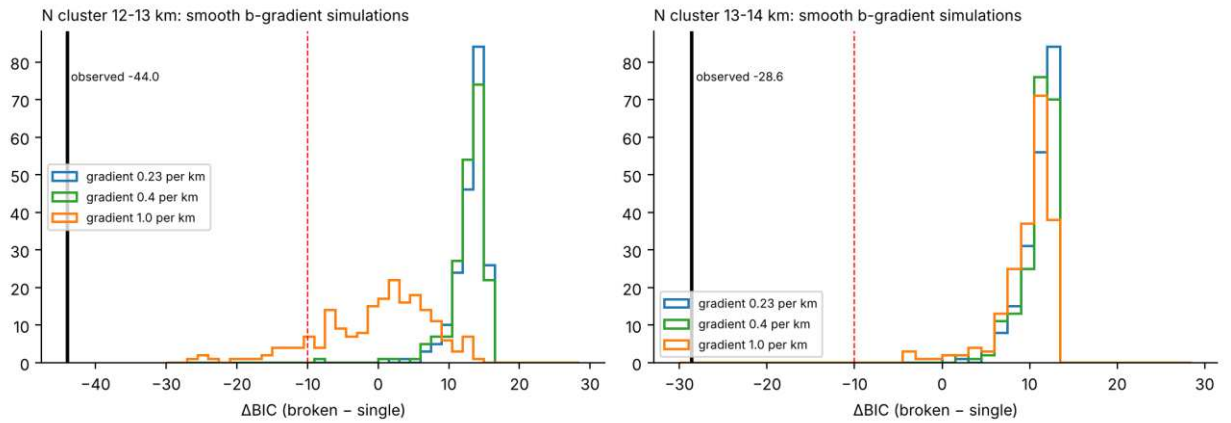


Figure S6. Δ BIC of simulated slices whose b changes smoothly with depth (0.23, 0.40 and 1.00 per km) compared with the observed values of the 12–13 and 13–14 km slices of cluster N (black).

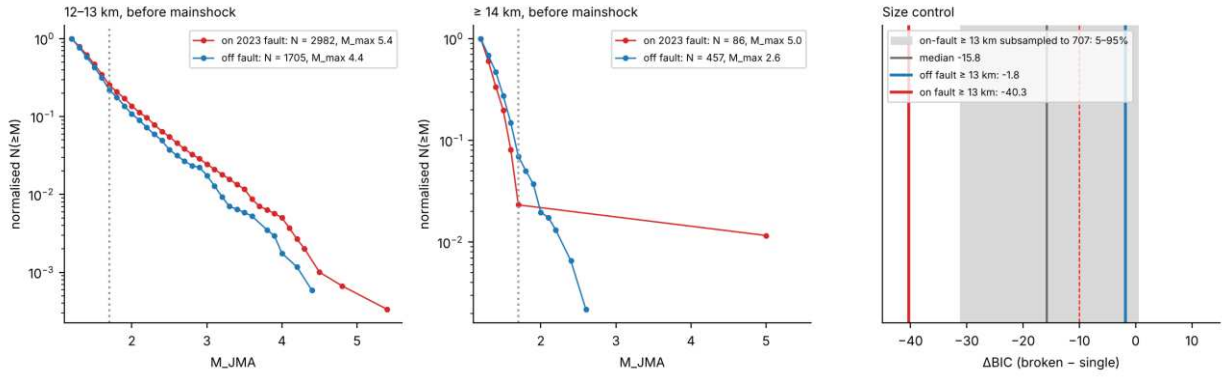


Figure S7. Pre-mainshock FMDs on and off the 2023 plane at 12–13 km and below 14 km (normalised), and the size control for the on/off contrast at ≥ 13 km (on-plane events subsampled 200 times to the off-plane size).

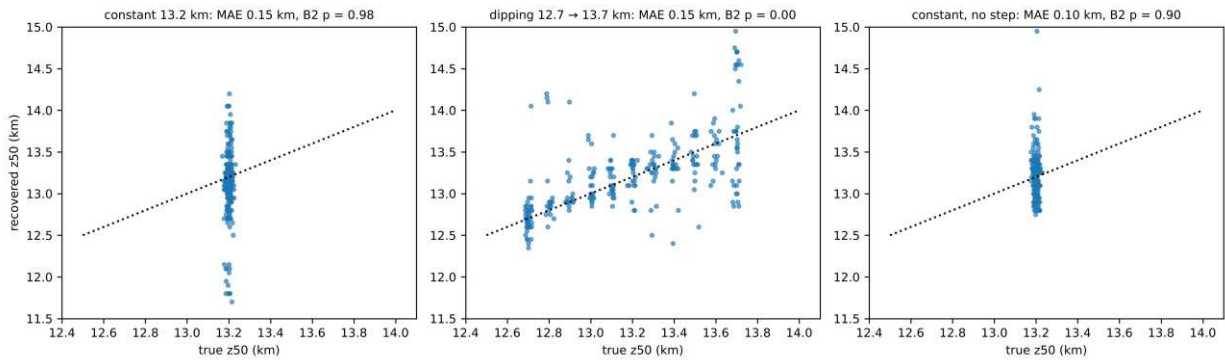


Figure S8. Synthetic tests of the transition map: recovered against true z_{50} for a flat surface at 13.2 km with the processing step, the same without the step, and a surface dipping from 12.7 to 13.7 km; titles give the median absolute error and the p -value of the tile test.

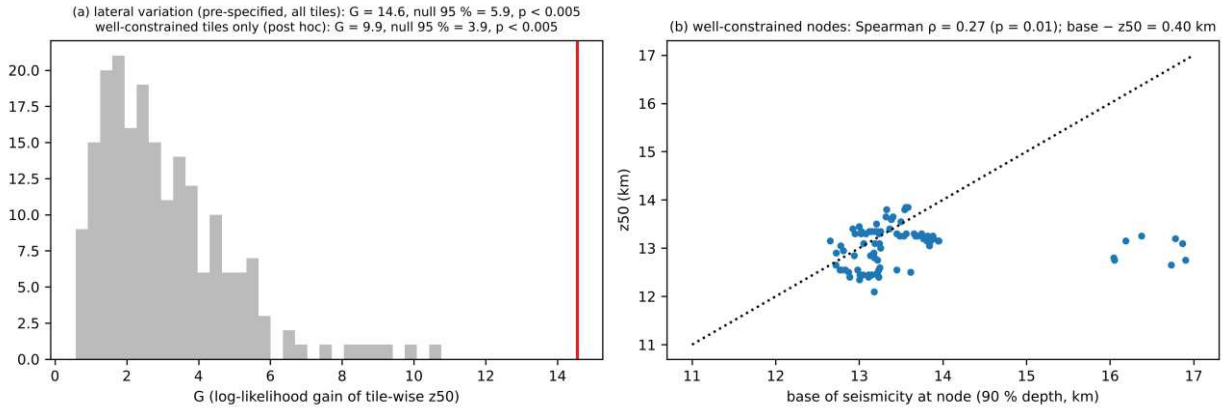


Figure S9. (a) Tile statistic G of the relocated catalogue (red) against its permutation null (grey), for all tiles (pre-specified) and for well-constrained tiles (post hoc). (b) z_{50} against the base of seismicity (90% depth) at each node.

Supplementary Files

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