



OPEN Precursory seismicity unveiled before the M_w 7.1 Dingri earthquake in Tibet

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On 7 January 2025, an M_w 7.1 normal-faulting earthquake struck the Dingri region in southwestern Xizang (Tibet), located within the extensional domain of the plateau - one of the most seismically active intraplate regions on Earth. Investigating the preparatory phase of such events in remote areas is particularly challenging due to limited station coverage. We analysed continuous records from IO.EVN, the only permanent seismic station within approximately 90 km of the epicentre that freely provides available data. Using an AI-based approach that integrates phase detection, polarisation analysis and template matching, we reconstructed an earthquake catalogue for the two years preceding the mainshock. Our results reveal a marked increase in event rate and clustering beginning about 45 days before the mainshock, coinciding temporally with an M_L 2.4 event at the Himalayan front. We interpret this evolution as a slow, progressive increase in seismicity, consistent with a late-stage nucleation process modulated by regional tectonics. Our results are therefore compatible with tectonic loading, and suggest that single-station seismic monitoring, when enhanced by AI techniques, can help identify retrospective seismicity patterns prior to rupture, even in data-sparse and tectonically complex regions.

On 7 January 2025 an M_w 7.1 normal-faulting earthquake (hereinafter referred to as the Dingri earthquake) occurred in southern Xizang (Tibet), Dingri County (Yao et al. 2025)¹ (Fig. 1). The epicentre (28.57° N; 87.45° E) as reported by the China Earthquake Networks Centre (CENC)¹, was located 80 km northeast of Mount Everest (Fig. 1). Six km south of the world's highest mountain, there is an Italian Observatory (Pyramid), where a seismic station with a Güralp CMG-3ESPC (60 s) seismometer is also installed (IO.EVN)². The IO.EVN seismic station was established eleven months before the M_w 7.9 Gorkha earthquake in 2015 (orange triangle in Fig. 1) to improve seismic monitoring in a critical and poorly instrumented region near the border between Nepal and Tibet. IO.EVN is the only station in the epicentre region that provides free data to the scientific community for detecting and studying environmental vibrations (such as icequakes, avalanches, landslides) and natural seismicity². Aware of limitations due to the use of a single seismic station, we apply a combination of AI-driven workflow seismic detection and the cross-correlation matching filter (see Methods section and Supplementary Material) to the continuous three-component seismic recordings from the IO.EVN station data. This enables the reconstruction of a detailed foreshock catalogue and the retrospective identification of long-term precursory signals leading to the mainshock. Previous studies on single-station analyses have shown that deep-learning approaches integrated with a supervised template matching can effectively reveal hidden or transient seismic signals³.

The Tibetan Plateau is one of the most complex intracontinental regions with an active fault^{4,5} due to the ongoing process of north-south convergence between India and Eurasia⁶. This ongoing convergence⁷ at a rate of about 19 ± 1.4 mm per year leads to compressive stresses, especially in the Himalayan region and along the border with Tibet. However, the simultaneous presence of normal and strike-slip fault systems indicates significant east-west extension within a complex structural configuration in the southern and central parts of Tibet⁵⁻⁸. GPS observations⁹ show that the total extension rate of all rifts is about 18.4 ± 1.7 mm per year⁻¹. This tectonic extensional regime generates large normal-fault earthquakes such as the M_w 7.1 Dingri earthquake.

Despite this complex configuration of faults, most crustal deformation is currently concentrated along the Himalayan arc and is driven by the high rate of convergence between the Indian and Eurasian plates. The rapid uplift of the plateau in the last 40 Ma (middle Palaeogene)¹⁰ must also be considered for a clear overview of the

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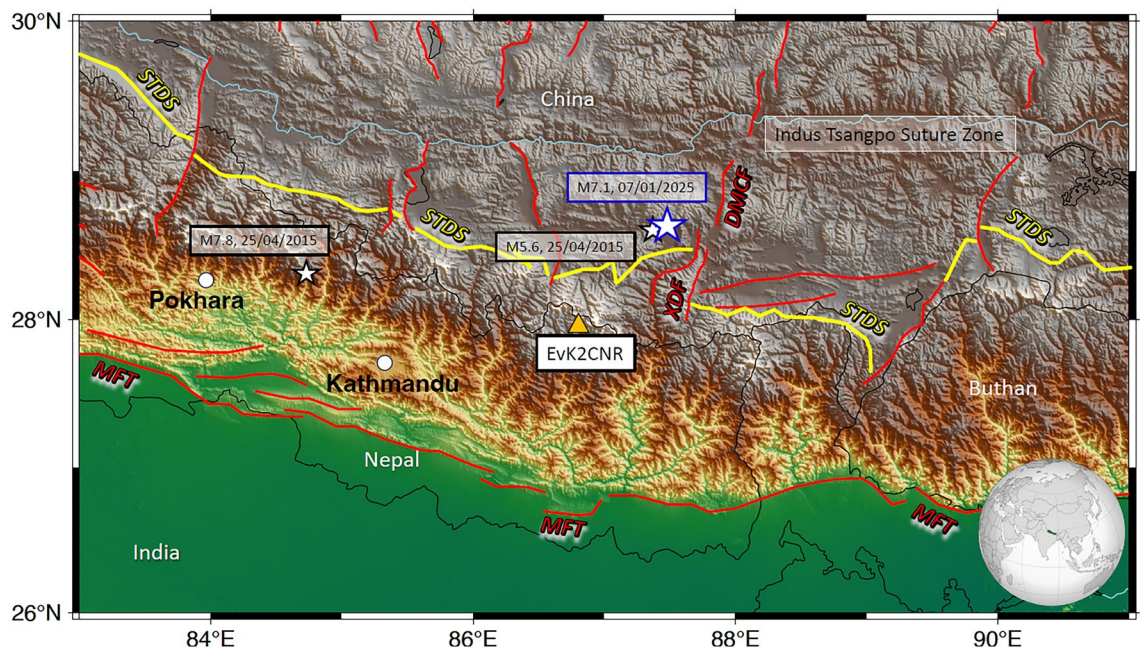


Fig. 1. Simplified tectonic map of eastern Nepal and the southern part of the Tibetan plateau, with the most important tectonic features. The largest star marks the epicentre of 7 January 2025 a M_w 7.1 Dingri earthquake southeastern Xizang (Tibet), the orange triangle indicates the location of the Pyramid Laboratory/Observatory, which is about 6 km from Mount Everest. The small star near the Dingri earthquake is the M_L 5.6 of 25 April 2015 (epicentre EMSC-CSEM - <https://www.emsc-csem.org/>), aftershock of the Gorkha M_w 7.9 earthquake, whose epicentre is the small star to the west of the other two.

deformation in this region. The Indo-Eurasian convergence is a puzzling geodynamic process that gives rise to several interpretative models⁶. All models propose that the Tibetan lithosphere is tectonically pushed eastward by the N-S convergence of the highly rigid Indian lithosphere, with eastern Tibet rotating clockwise¹¹. Competing models of the Indo-Eurasian convergence, including gravitational collapse¹² and channel flow^{13,14}, instead emphasize the complex mechanical coupling and partial melting beneath southern Tibet. Recent geophysical studies^{15,16}, suggest a correlation between the locations of these channel flows and the Tibetan grabens.

Before examining the seismicity preceding the M_w 7.1 Dingri earthquake, we refer to data from the temporary seismic network installed by Yao et al. (2025)¹ and CENC in the epicentre area the day after the mainshock. Aftershocks indeed provide key constraints on the seismogenic source (see the black cloud in Fig. 2a) which can help us to retrospectively decipher the preparatory phase of the main Dingri earthquake. The spatial distribution of the aftershocks with 31,038 events from 8 to 19 January reveals a north-south structure divided by three main fault segments with different strike and dip directions. This fault belongs to one of the normal fault systems (Rift Systems^{1,4}) that traverse the Tibetan plateau from south to north in a N-S direction on the northern edge of the Himalayas. Specifically, the fault is the Deng Me Cuo fault (hereafter DMCF)^{1,5} part of the Shenzha-Dingjie rift system within the Xainza-Dingjie fault XDF (Fig. 1). The inversion of the InSAR data shows an average strike of 188° , a dip of 50° with a maximum displacement of 4–5 m and an average displacement angle of 83° at a depth of 5 km^{9,17}. Another source inversion technique with multi-data integration¹⁸, identified a three-fault system, coherent with¹, and estimated the centroid at a depth of 4.8 km, well constrained by seismic and geodetic data. This normal fault system with a length of ~15–50 km, coexists with a system of major strike-slip lines in the east-west direction. The processing of the InSAR data has shown that an east-dipping secondary fault is coseismically connected to the main fault¹⁹.

The Dingri earthquake occurred in the region known as the Tethys Himalaya (Fig. 1), which borders the Yarlung Tsangbo Suture Zone (YSZ) to the north and the Great Himalayan Region to the south. The rift system, which includes the Dingri earthquake fault, intersects the South Tibetan Detachment System (STDS)²⁰, potentially limiting coseismic propagation. These observations support a tectonic setting where normal faulting in the Tibetan extensional domain interacts with inherited Himalayan structures (Fig. 1). The STDS is a series of low-angle faults with top-to-the-north shear zones that run parallel along the entire strike length (about 2000 km) of the Himalayan orogen and form the lower boundary of the Tethyan Himalayan sequence. Previous large normal-faulting earthquakes in Tibet, such as the M_w 7.1 Yutian event in 2008²¹, demonstrate the potential for high-magnitude extensional ruptures in this intraplate region. The M_w 7.9 Gorkha thrust earthquake in 2015 also triggered aftershocks as far as southern Xizang²². These events highlight the need to assess possible stress interactions between the Himalayan front and normal faults within the plateau interior. One of them, occurred on 25 April 2015 at 09:17:03 UTC, with M_w 5.6 (M_s 5.9)²² (see Fig. 1), in the epicentre zone of the 2025 Dingri earthquake, and with a fault mechanism very similar to it (see the Fig. 1 in²²). Figure 2b shows the distribution of fault mechanisms in the GCMT catalogue (<https://www.globalcmt.org/>)²³, with predominantly normal faults

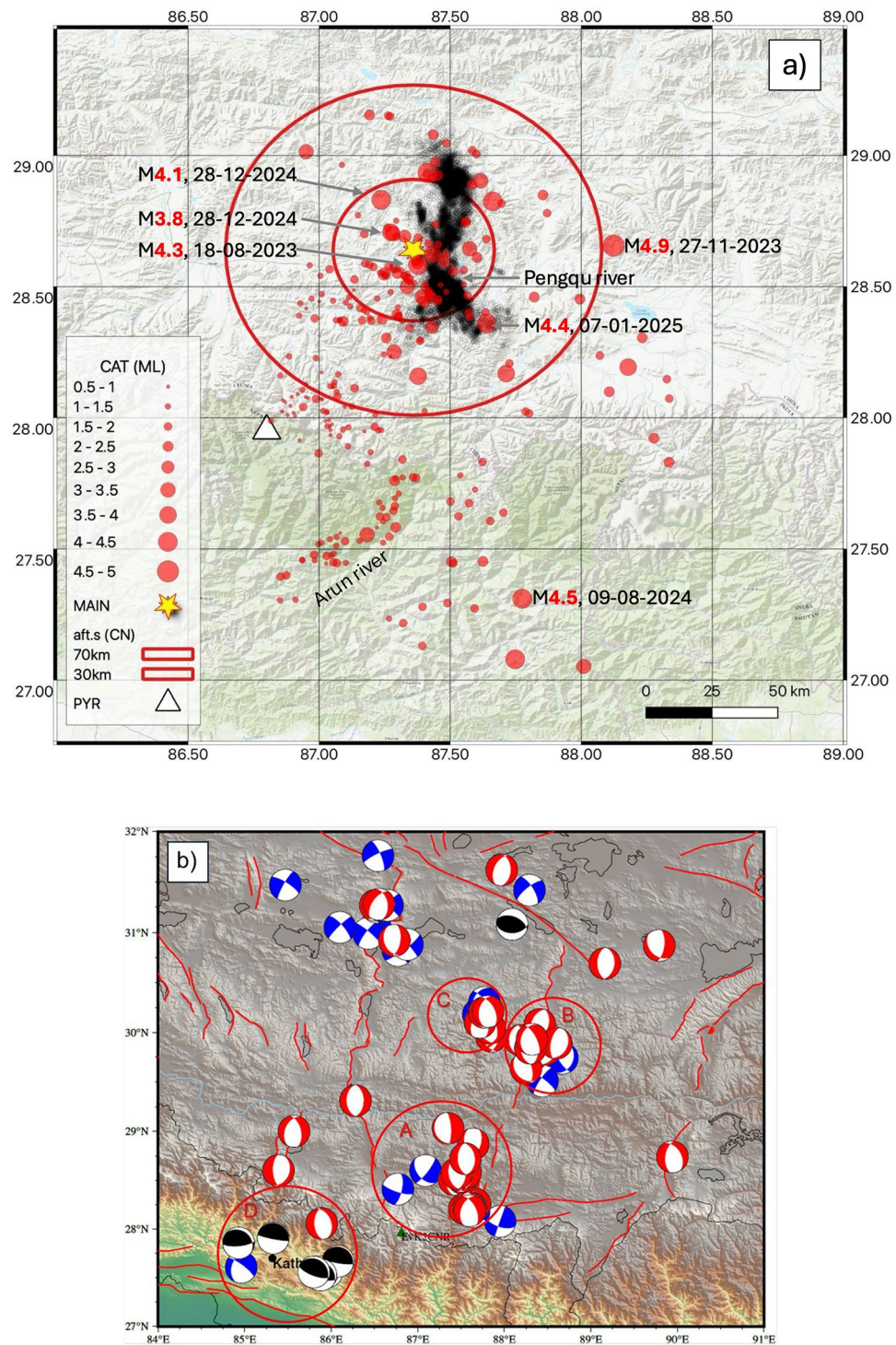


Fig. 2. (a) Map of the 289 events (*template catalogue*) identified by PhaseNet. The white triangle marks the location of the EvK2cnr pyramid, where the IO.EVN (OGS) seismic station is installed. The yellow star indicates the epicentre (CENC catalogue) of 7 January 2025 a M_w 7.1 Dingri earthquake, and the black dotted cloud shows the distribution of aftershock from their catalogue. The larger red circle encompasses events within 70 km of the epicentre, while the smaller circle includes those within 30 km. (b) Distribution of fault mechanisms of the GCMT catalogue (<https://www.globalcmt.org/>) (1980–2025): normal faults (red), strike-slip (blue) and reverse mechanisms (black) in the Himalayan zone. We distinguish three zone in which normal faults predominant. Zone A is the area of the Dingri earthquake epicentre and the events that are more directly related to the Dingri earthquake and are the subject of the analyses proposed in this study. Zone A corresponds to the area within the large red circle of (a). B and C Zones where normal mechanisms prevail, but north of the epicentre. Zone D is the area of M_w 7.8 Gorkha earthquake of 25 April 2015.

(red), followed by strike-slip (blue) and reverse mechanisms (black) predominating in the Himalayan zone. The area A includes the circle of 70 km from epicentre visible in Fig. 2a. The most recent fault mechanism before the Dingri event occurred in 2021 (Fig. 2b).

The combination of AI-based detection, established single-station methods, and template matching enabled the reconstruction of a long-term record of the preparatory phase of a large intraplate earthquake in Tibet²⁴. The observed pattern may be interpreted as consistent with a late-stage nucleation phase, potentially influenced by regional tectonics²⁵.

Methods and data analysis

From the perspective of a “single station”, we selected and localised the events using PhaseNet²⁶, a method based on a deep neural network (Supplementary Fig. S1). The description of the entire procedure can be found in the Supplementary material. We analysed the data from the IO.EVN station from 1 January 2023 to the time of the main earthquake 01:05:16.824 on 7 January 2025, and filtering between 2 and 8 Hz. All events clearly show that P arrivals and S-P travel times are within 14 s, indicating that these events are within approximately 120 km of the IO.EVN station. To calculate the distance, we checked the time synchronisation with the origin time from the high-resolution aftershock catalog¹ which provides P and S waves travel times (Supplementary Fig. S2). Finally, we used a polarisation analysis method²⁷ to calculate the azimuth. Thus, we obtained an initial catalogue of 289 events detected with PhaseNet²⁶ (hereinafter referred to as the “*template catalogue*”). For the detection of the complete catalogue of 1,138 events, we employed a supervised template matching (TM)^{28,29}, and used the 289 events as input templates. We refer to this catalogue as the “*augmented catalogue*”. Because the analysis is based on a single seismic station, events detected through TM cannot be independently relocated. Therefore, all *augmented catalogue* events are assigned the location of the reference *template catalogue*. Figures 2, 3a–c, 4, 5, 6, 7 and 8, and S2, S3 show only *template catalogue* events to highlight waveform families, while Figs. 3d and e, 6, 7, 9 and 10, and S7a–c use the full machine learning *augmented catalogue*. A full description of the procedures can be found in the Supplementary material.

Results

Spatial distribution of the aftershocks

Our backward analysis of the preparatory phase of the M_w 7.1 Dingri earthquake begins with the intriguing observation that the spatial distribution of the aftershocks from the Chinese dataset¹ suggests an excessive size relative to the moment magnitude, extending over nearly 100 km (see the black cloud in Fig. 2a). For a typical intraplate normal-faulting event with M_w 7.1, empirical scaling relations (e.g., Wells & Coppersmith, 1994³⁰) predict a surface rupture length of ~40–50 km, with a maximum of about 60 km for the most recent relation of Thingbaijam et al. (2017)³¹. Although the actual source parameters are incomplete (e.g. stress drop), the aftershock cloud reflects a combination of rupture complexity^{18,19}, distributed slip, immature graben or stress transfer onto neighbouring structures, also in the light of studies on the seismic potential of crustal faults in Tibet⁴. Further studies are required to constrain the slip distribution and stress drop for this event, especially given the low density of seismological stations in the epicentral area.

Spatiotemporal distribution of the precursors

We show the location of the 289 events (*template catalogue*), detected exclusively by the IO.EVN station in Fig. 2a. The dataset covers the period from 1 January 2023 to the mainshock. These events were recognised by applying PhaseNet²⁶ and subsequently located through visual inspection on P and S phases and single station methods (see Methods section and the Supplementary). A significant number are concentrated within 70 km (red circle) around the mainshock¹ epicentre (yellow star). Two additional groups are observed: one to the south, in the Himalayan region, north-east of the Pyramid (white triangle), and the second forming a more scattered distribution towards the southeast, roughly following the Arun River valley. North of the epicentre, there is a gap in the data that probably coincides with the segment of the fault that underwent the main coseismic slip, as also suggested by InSAR data and modelling results shown in^{18,19,32}.

The 289 events are then used as templates identify smaller sibling earthquakes buried in the seismic noise by a template matching (TM) approach^{33,34}, (see Method and Supplement). Using TM, in the 2–8 Hz frequency band, we obtain a catalogue of 1,138 earthquakes (*augmented catalogue*), ranging from M -0.82 to M 4.9, with a cross-correlation value ≥ 0.60 for all three available channels (Fig. 3d). All *augmented catalogue* events are plotted at the location of the reference *template catalogue* (see Methods).

The spatiotemporal evolution of foreshocks is often used to identify different stages of the preparatory phase and to investigate the potential effects of distant and delayed triggering in space and time²⁴. We performed a non-parametric cumulative, interevent analysis in time (hours) and distance (km) of the *template catalogue* (Fig. 3a, b). The temporal evolution of seismicity (bins in Fig. 3a) shows a sudden increase in the event rate about 40 days (990 h, see the red arrow) This corresponds to a decrease in interevent time before the mainshock (triangles in Fig. 3a). The first detectable event within this phase is an M_L 0.9 event of 27 November 2024 at 18:59:47, located about 74 km from the epicentre along the Himalayan margin 20 km east from Pyramid. This event may mark a transition in the seismicity pattern, although its physical role remains uncertain. In Fig. 3b, we observe two characteristic distances: the first discontinuity appears at ~30 km, while the second is at around 70 km from the mainshock. The temporal and spatial distributions shown in Fig. 3a and b highlight two characteristic distance scales, approximately 30 km and 70 km from the epicentre. These distances seem to represent distinct physical processes occurring at different spatial scales. The 70 km radius encompasses most of the foreshocks recorded by the IO.EVN station and corresponds to the spatial extent of the extensional fault within the Shenzha-Dingjie rift system, as confirmed by the focal mechanisms in Fig. 2b. This greater distance

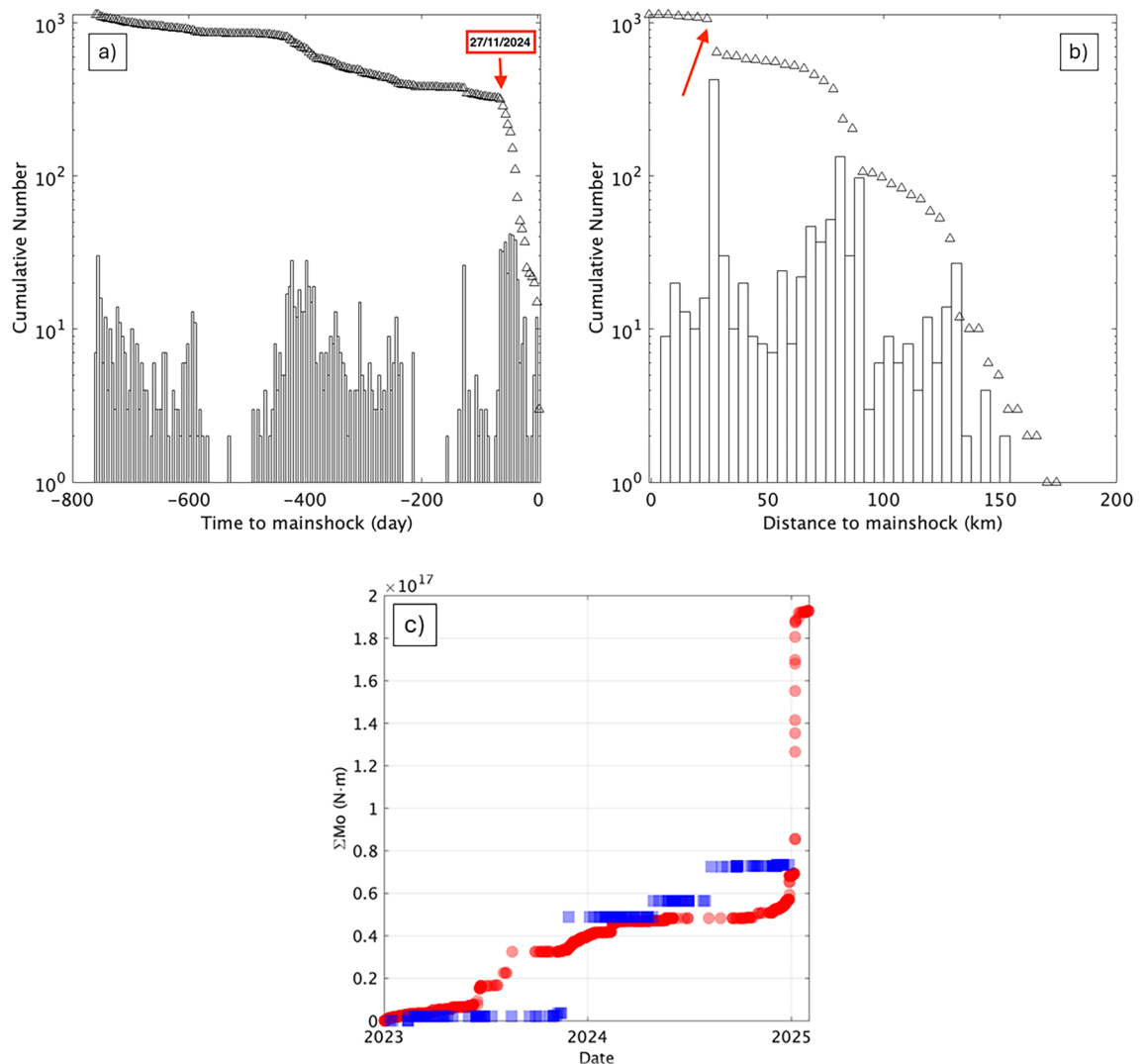


Fig. 3. (a) Non-parametric cumulative analysis in time of the zone A (Figs. 2) of *template catalogue* events; (b) non-parametric cumulative interevent analysis in distance of the zone A (*template catalogue*); (c) development of the cumulative moment release (*template catalogue*) with a radius of 70 km around the epicentre of the Dingri earthquake (within 70 km red dots, beyond 70 km blue dots); (d) histograms comparing the magnitude of 289 (*template catalogue*) events (brown) with the complete data set of 1,138 (*augmented catalogue*) events (blue); (e) M_w distribution of all 1,138 events over time: (within 70 km red dots, beyond 70 km blue dots). The red arrow in (a) indicates the temporal position of M_L 0.9 event of 27 November 2024 at 18:59:47. The red arrow in (b) indicates the start of the final acceleration beginning with the epicentral cluster at the end of December.

likely defines a regional stress interaction zone, where long-range static stress changes or tectonic loading may influence seismicity. By contrast, the radius of approximately 30 km marks the internal nucleation zone, where a sharp increase in event frequency and momentum release is observed in the days preceding the mainshock (see Figs. 2a and 3c). At this stage, these distances do not indicate a specific physical mechanism, but they provide a useful framework for organising subsequent analyses. First, we focus on the larger spatial domain, and we analyse the cumulative magnitude-moment release for the two main seismic zones (Fig. 3c): (i) within 70 km (red dots) from the epicentre, and (ii) considering events beyond 70 km (blue dots). To convert the M_L of our catalogue in M_w , we used the relationship calibrated for the region³⁵. In the Supplementary, we also provide Supplementary Fig. S3, where the analysis is repeated considering events within 30 km (red dots) and beyond (blue dots). The results for the two spatial scales do not appear to differ significantly, except for the density of the events in specific periods. The first increase in cumulative moment occurs within 70 km of the epicentre (red), due to the four events from 6 to 10 April 2023 with a magnitude of 3.0 to 3.4, followed by three events in August with $M_L > 4.0$ (see 18 August 2023 M_L 4.3 in Fig. 2a). The sharp increase in the cumulative moment, beyond the 70 km (blue), is due to the event of 27 November 2023 M_L 4.9 (Fig. 2a and Fig. S4a), which occurred 85 km east of the epicentre. This was followed by a period of low release and low event density within 70 km until the third decade of December, when on 28 December 2024 two M_L 4.1 and 3.8 events occurred near the epicentre (Fig. 2a,

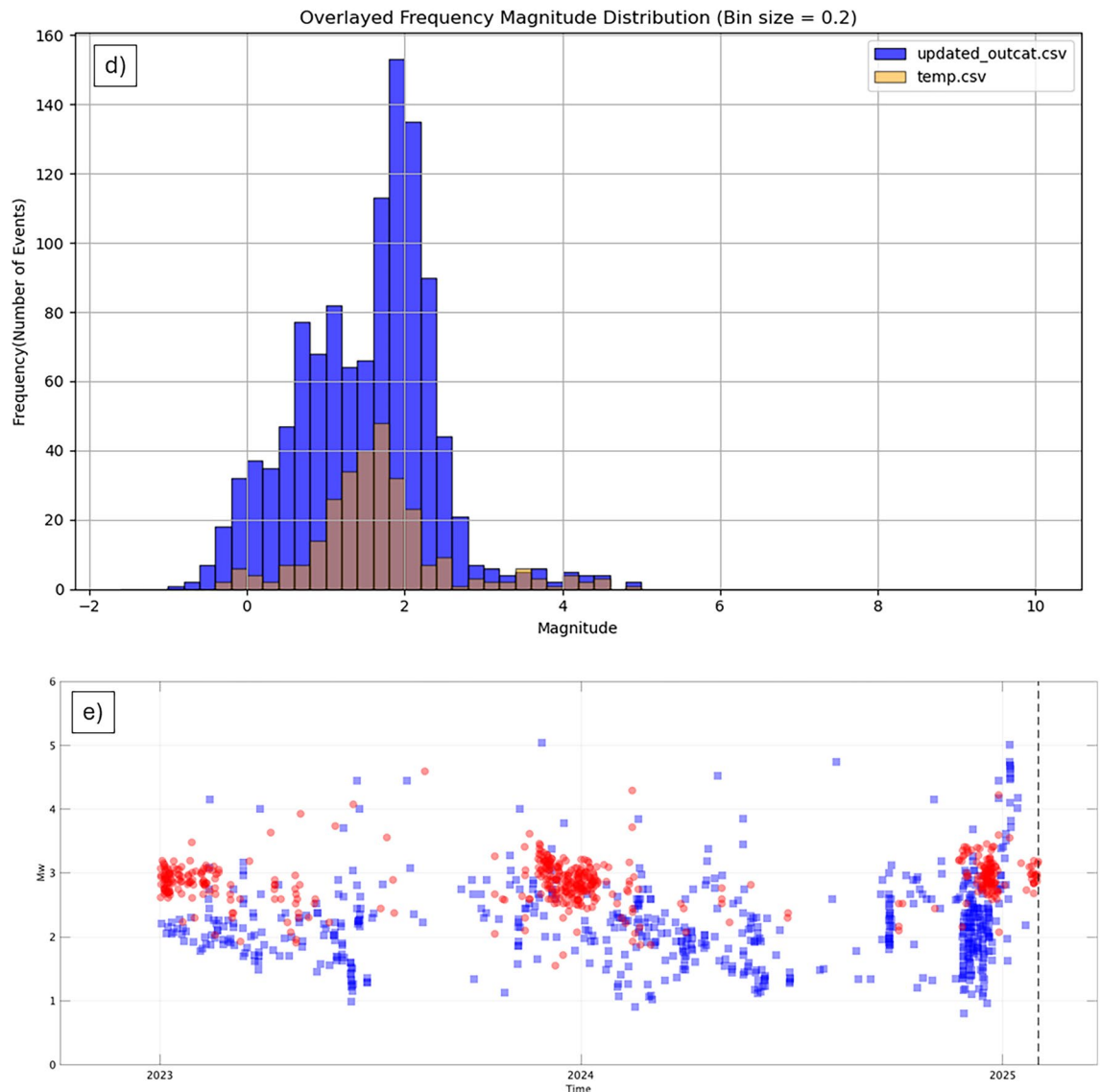


Fig. 3. (continued)

and Fig. S4b), followed by the last foreshock of M_w 4.4 one hour before the mainshock. These latter could explain the rapid upsurge of the cumulative moment shown in Fig. 3c. The gap period between 1 July and 1 October 2024 occurred mainly in the epicentral region, while only one significant M_L 4.5 event occurred on 9 August 2024 in the Himalayan region east of the Pyramid (Fig. 2a). Figure 3e shows the distribution over time of all *augmented catalogue* events in function of M_w . The events within 70 km appear to be organized into three clusters (red), with the last one preceding the mainshock by a few months. Events beyond 70 km (blue) show a concentration of low magnitude earthquakes during the months before the main event. Among them is the M_L 0.9 event of 27 November 2024 belongs to this Himalayan cluster. As this event has a very low magnitude, it is not considered individually significant, but simply marks the early phase of the observed rate increase.

The first cluster began in the epicentral region during January–February 2023 (Fig. 3e) and developed roughly in an east–west direction. This is visible in Fig. 4a, the first snapshot of the spatiotemporal evolution of the precursors for the first dataset (*template catalogue*). It follows the course of the Pengqu River (Bumqu in Tibetan; see also Fig. 2a), which roughly corresponds to the position of the event cluster extending ESE–WNW in Fig. 2a south of the epicentre. Figure 4b shows the evolution from the April 2023 cluster to the end of 2023, with the second cluster consistently along the Pengqu River valley, a set of events around the epicentral valley, within the 30 km and some $M_w > 4$ including the M_w 4.9 event of 27 November 2023. See also the cluster along the Arun River (see Fig. 2a). This was followed by the period of relative stasis in 2024 (01/01/2024–30/11/2024, Fig. 4c), and finally, in Fig. 4d, the final phase in December/January 2025 with the acceleration of foreshocks and the $M_w > 3.8$ events.

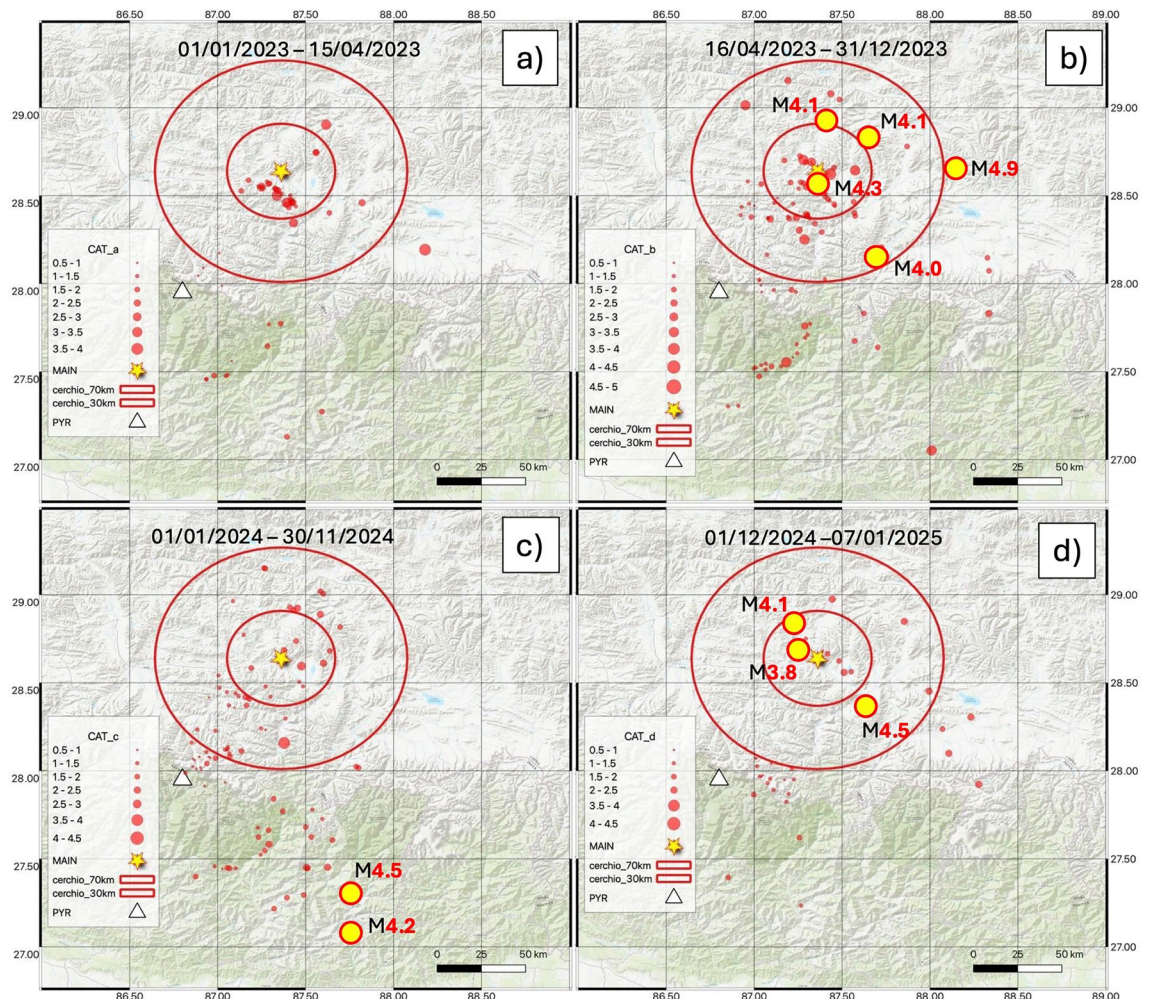


Fig. 4. Four different periods in the evolution of (*template catalogue*) events before the Dingri earthquake; (a) snapshot of period 01/01/2023–15/04/2023; (b) period 16/04/2023–31/12/2023; (c) period 01/01/2024–30/11/2024; (d) period 01/12/2024–07/01/2025. The yellow star marks the epicentre of Dingri earthquake, the triangle indicates the location of the Pyramid Laboratory/Observatory and the IO.EVN station. The figures report the relevant events with $M_w > 4$.

Analyses of seismicity for the complete catalogue

The b -value (i.e., the slope of the Gutenberg–Richter frequency–magnitude relationship, Gutenberg and Richter, 1942)³⁶ describes the relative ratio of small to large earthquakes. The interest in using this parameter to infer the preparatory phase is related to the observation that it is inversely related to the differential stress in the crust^{37,38}. Therefore, temporal or spatial variations in the b -value have been interpreted as indicators of evolving stress regimes and are increasingly used to track preparatory processes that precede large earthquakes^{33,39}. We opted for the b -positive ($b+$ hereafter) version⁴⁰, which is more robust than b -value that extrapolates magnitude completeness. As done before, we calculate $b+$ considering the two spatial scales identified (i.e., threshold distances) from the Dingri epicentre, applied to all detected events: earthquakes within 30 km (Fig. 5a, b), using 526 events and beyond 30 km; (Fig. 5c, d) events within 70 km (Fig. 5e, f), with 993 events and beyond 70 km (Figs. 5g, h). Both datasets allow robust estimates of the $b+$ (see e.g., Marzocchi et al. 2019)⁴¹. For instance, in a recent article⁴², the authors used a number equal to 150. The threshold value of 30 km has proven in this case to be more reliable as the $b+$ value remains stable as a function of ΔMc (differences in the order of magnitude of completeness). Furthermore, the $b+$ value for earthquakes within 30 km is quite high ~ equal to 1.2, while above this threshold it is stable at 0.7. The $b+$ value within the 70 km threshold is initially around 0.7 but less stable for different ΔMc (i.e., a clear drift appears for $\Delta Mc > 0.3$). This instability in $b+$ for the events within this wider range, which extends beyond the main fault, may indicate that the event population is heterogeneous. As shown in Fig. 2a, this region includes seismicity from the Himalayan front, potentially reducing reliability of the $b+$ estimate. Outside this area, the events are mainly distributed in the Himalaya and Nepal regions.

Threshold 30 km

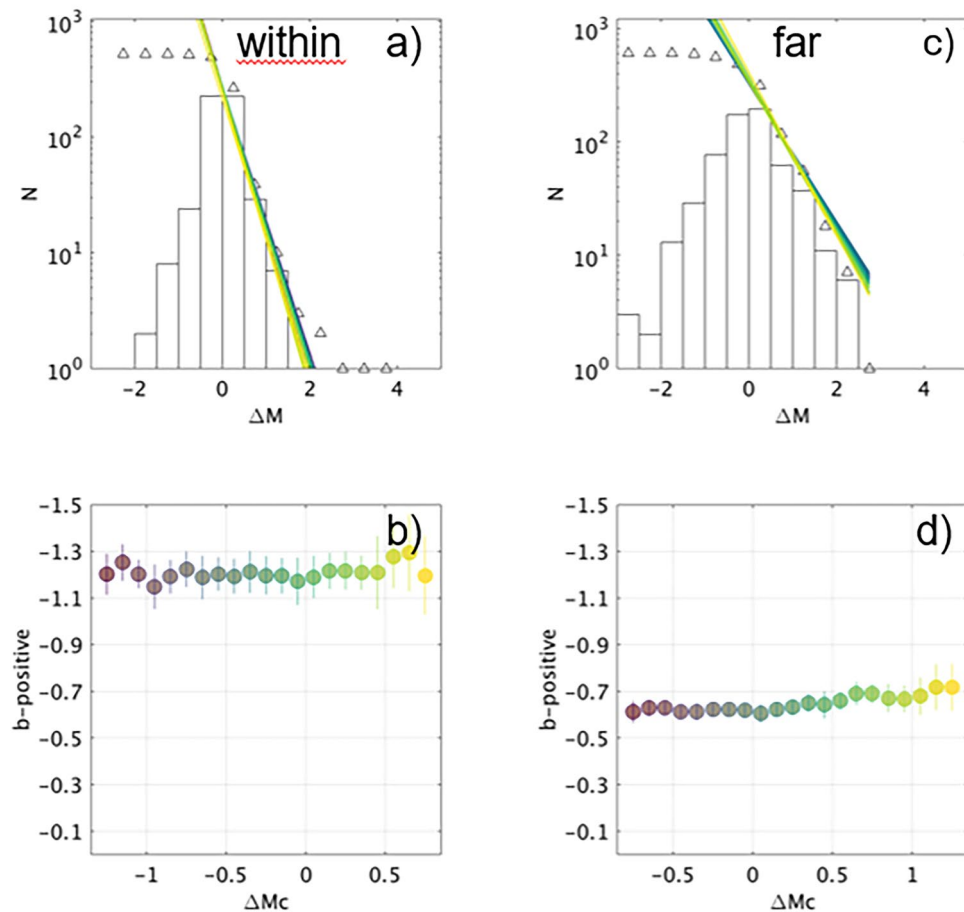


Fig. 5. Seismicity analyses (*template catalogue*) according to b-positive in two window thresholds: (a,b) within 30 km; (c,d) outside 30 km; (e,f) within 70 km; (g,h) outside 70 km. Above the Gutenberg–Richter analysis with the histograms of ΔM ; below the analyses of the stability of the b-positive in function of ΔM magnitude of completeness.

Discussion

Figure 4 shows that in 2023, the seismicity was concentrated in the DMCF, with a spread of earthquakes, including those with $M_L > 4$. The Fig. 3e confirms this distribution, showing two clusters within 30 km at the beginning and end of the year. In 2024, after a period of relative calm and events distributed across the region, a cluster formed approximately 30 km southwest of the epicentre. In percentage terms, the cluster in Fig. 3e comprises: the first cluster, 8%; the second cluster of 2023, 16%; and the final cluster, 12% of the 1,138 events. Figure 4d shows the final acceleration phase, with three events of $M_L > 4$; the largest occurring 50 min before the mainshock.

In addition to the b-value analysis, the 30-km threshold is also useful for examining the evolution of seismicity. The cumulative seismic moment (Fig. 3c) shows a marked acceleration during the final phase preceding the mainshock, coinciding with a decrease in the b_+ value outside the 30-km threshold. This temporal correspondence suggests that changes in the magnitude distribution accompany the accelerating phase of seismic release. However, we emphasise that the evolution of the b-value alone does not independently demonstrate a precursory activation process; rather, it must be interpreted alongside the cumulative moment release and clustering analyses. The temporal distribution of magnitudes (Fig. 3e) for events occurring ‘within’ and ‘beyond’ the epicentral area, shows that the events within 70 km are temporally clustered - specifically at the beginning of 2023, at the end of 2023, and again between late 2024 and early 2025, when the mainshock occurred - whereas events occurring between these clusters appear more scattered over time. The lower b_+ outside the 30 km threshold (~ 0.7 - Fig. 5c, d) is consistent with seismicity occurring in regions of higher crustal strength. Conversely, we observe higher b_+ in the epicentral area (~ 1.2 - Fig. 5a, b) indicating a relative enrichment in small-magnitude events. At first glance, this result may appear counterintuitive, as it is often assumed that crustal stress is higher in the nucleation area than elsewhere. Such behaviour observed in the epicentral area may reflect enhanced crustal fracturing, either pre-existing or induced by a progressive weakening process, and/or the presence of crustal fluids (i.e. both conditions would lead to an increase in small earthquakes due to a progressive decrease in the shear resistance of the crust). Independent geophysical observations in the Dingri area indicate

Threshold 70 km

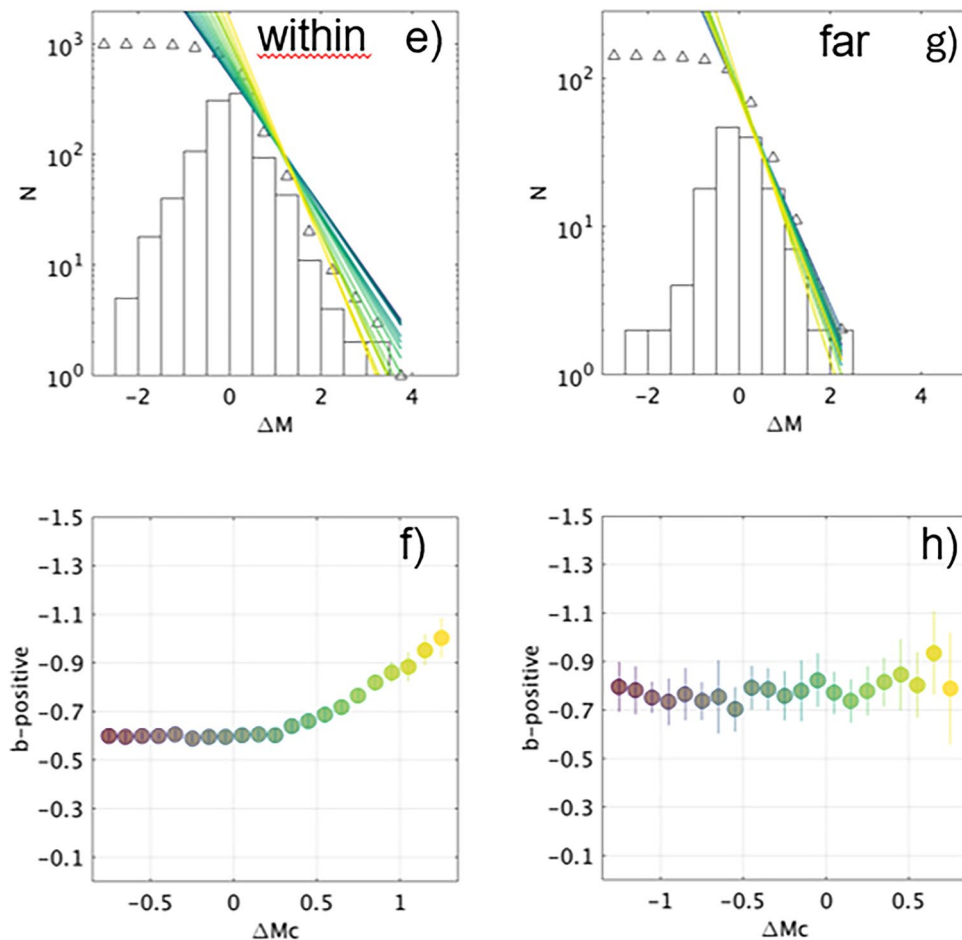


Fig. 5. (continued)

a mechanically weak crustal domain and complex stress perturbations during the earthquake cycle⁴³, providing a plausible physical framework for this weakening. Given that our analysis relies on data from only one seismic station operating in the area before the earthquake, we are currently unable to advance our interpretations further. However, future studies, facilitated by the recent deployment of additional seismic stations, are expected to yield deeper insights into the preparatory processes of large earthquakes in the Himalayan and Tibetan region.

Anyway, elevated b in epicentral area is consistent with models of Accelerating Moment Release (AMR) process⁴⁴. As a precursor analysis, in Fig. 6a we show the fitting of a simple exponential model (1) as described by Mignan (2014)⁴⁵, as a simplified representation of the accelerating release of moment. This follows the formulation often used in precursor studies⁴⁶ although the author shows that this model has lost validity over time and discussed it critically in^{44,47}. We used the formula, with the complete catalogue, for the last 3000 h of the sequence, of *augmented catalogue*, long before the temporal variation of seismicity shown in Fig. 6a

$$N(t) = N_0 + Ae^{\beta t} \quad (1)$$

The positive β with a value of $9.1 \cdot 10^{-4}$ and the good fit suggest that the final phase in the last 1000 h (see the rise in the curve) clearly follows an exponential acceleration overall, which is consistent with a late-stage nucleation phase.

For the analysis with distance r , we used an inverse spatial Omori-law⁴⁷ (Fig. 6b)

$$N(r) = a r^{-\gamma} \quad (2)$$

The best-fitting exponent is $|\gamma| = 1.43 \pm 0.12$. The absolute value, being less than 2, indicates that the seismicity is not homogeneously distributed over a two-dimensional area but is instead organised along a restricted, fault-controlled domain. While $|\gamma| = 1.43$ mainly reflects a spatial organisation controlled by faults (dimension $D < 2$), the combination of this non-uniform scale with the marked temporal acceleration (Fig. 3c) indicates that seismicity becomes increasingly confined within a narrow epicentral domain prior to failure.

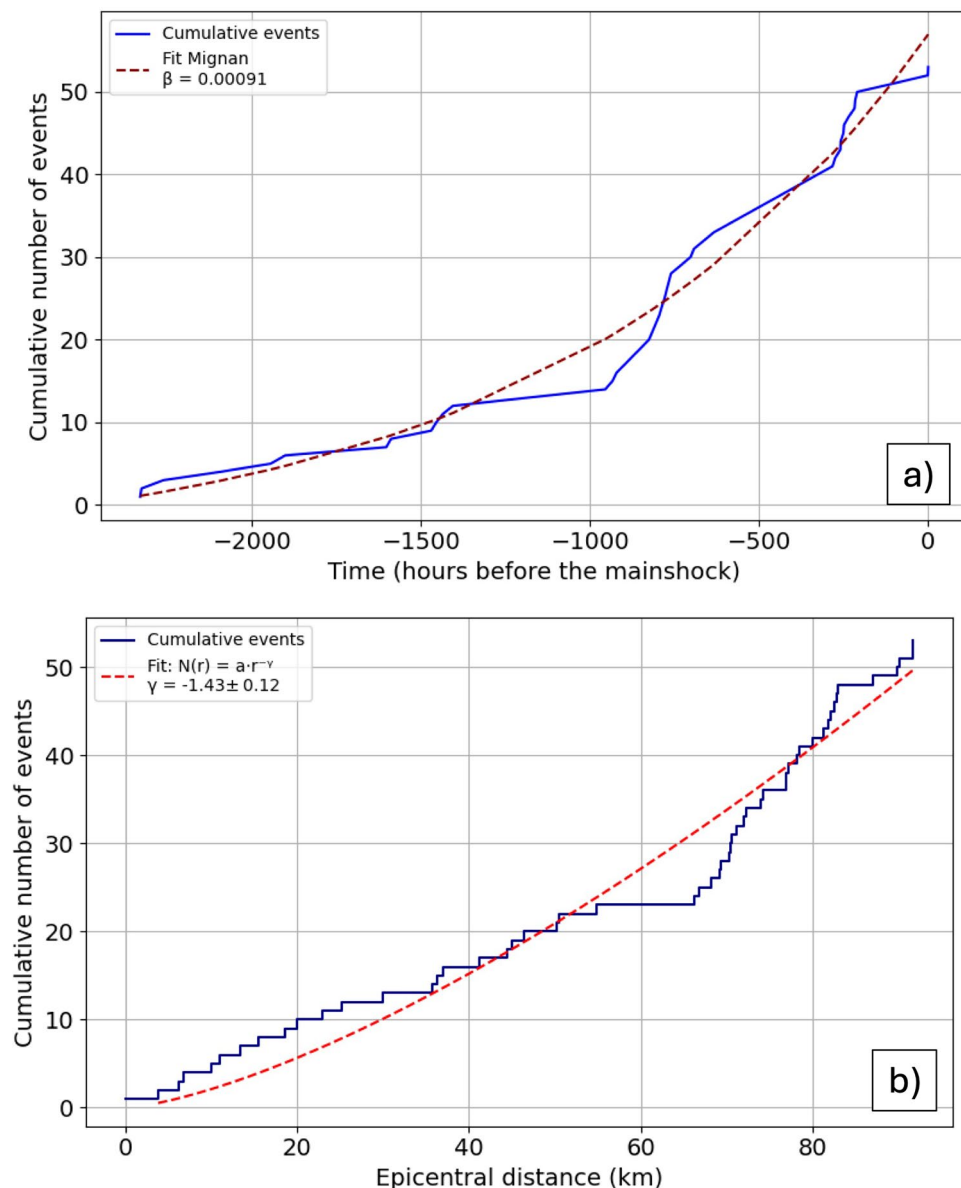


Fig. 6. *augmented catalogue* data: (a) Fitness of the Accelerating Moment Release (AMR) model⁴⁴, formula (1) of the last 3000 h of the complete dataset of events within zone A of Fig. 2. Blue is the cumulative number of events, and the red dashed curve is the fitted model; (b) Fitness of the model of inverse spatial Omori⁴⁷, formula (2) of the last 3000 h the complete dataset of events within zone A. Blue is the cumulative number of events, and the red dashed curve is the fitted model.

Always with the *augmented catalogue* data, Fig. 7a show the closer clustering near the epicentre over time, according to the inverse Omori analysis of shock distances, while Fig. 7b presents the clustering in terms of azimuth (relative to the epicentre). Both figures display an increase in the number of events that began around 1,100 h before the mainshock. Thus, we have ascertained that it belongs to a cluster in the Himalayan region starting about 45 days before the mainshock (Fig. 3e). Again, using the *augmented catalogue*, a cluster at 26 km from the mainshock, is noteworthy, starting with the event of 23 November 2024, 21:05:52 $M_L 2.4$ –90 h before the $M_L 0.9$, southwest of the epicentre and repeating until about 200 h earlier. It could be that this small event did not lead to a more important one, but it indicates the transition to an unstable acceleration phase and an emerging of foreshocks (as long as the events are clustered both in space and time). The green and yellow dots in Fig. 7c show their evolution together with the concentration of events around the epicentre in the last 500 h. This evolution, although based on a limited number of events, is consistent with a localised acceleration that may indicate the onset of a nucleation phase⁴⁸. However, full coalescence of clusters cannot be conclusively established from the available data and remains a working hypothesis consistent with the observed patterns.

In line with the analysis of Figs. 3c and 7, we refine the inter-event analyses for all combinations, by first generating the matrix for each pair (i, j) for Δt and Δr (Fig. 8a), and also compare it with a version in which

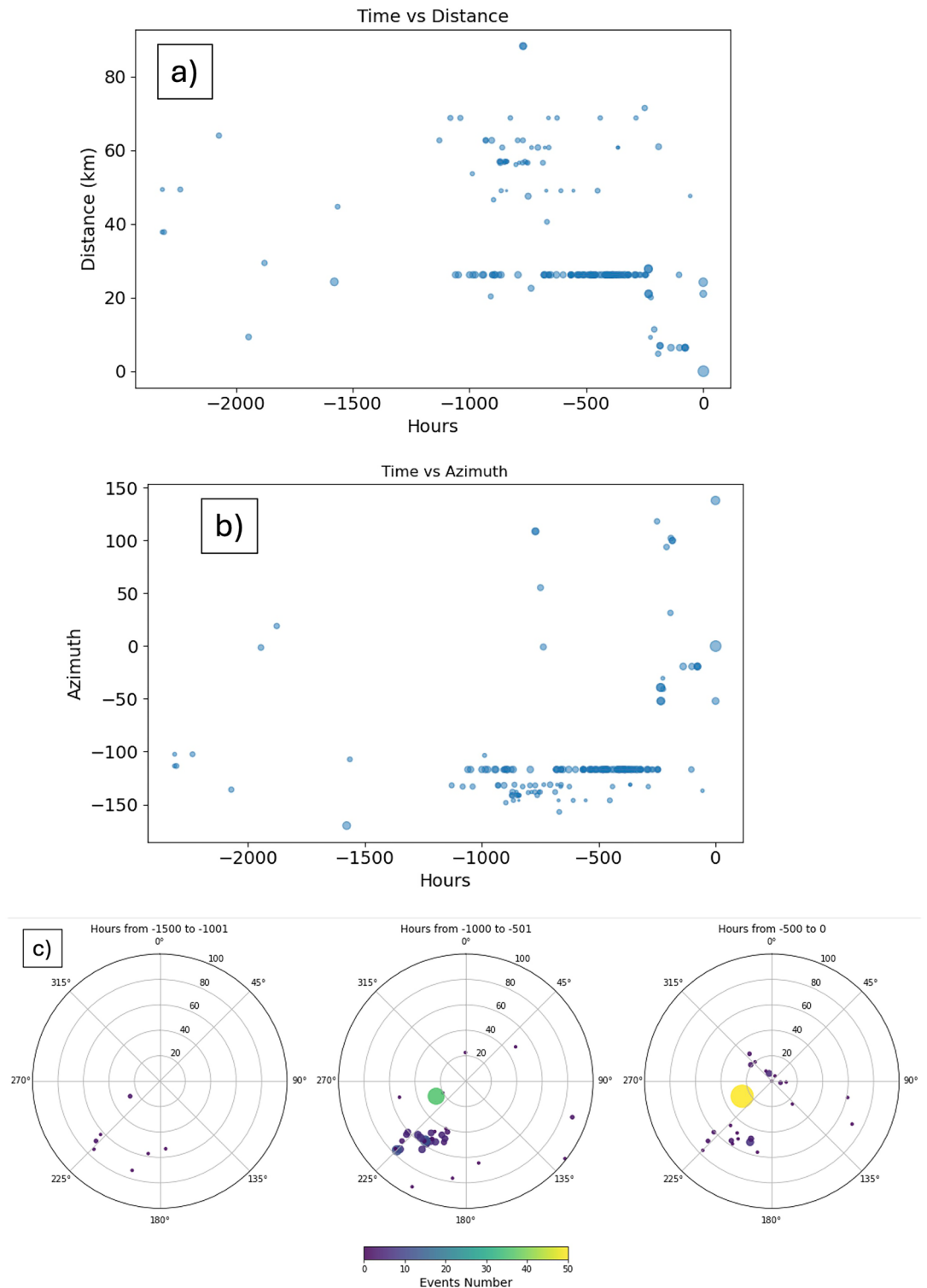


Fig. 7. (a) Temporal evolution in distance with respect to the epicentre; (b) temporal evolution in azimuth with respect to the epicentre. You can see the increase in the number of events in the last 1000 h before the main earthquake. (c) polar diagrams in the development of the last 1500 h before the main earthquake. The colours in the legend represent the cumulative number of events in the same position.

positions are randomly swapped to test the non-randomness of the phenomenon (Fig. 8b). The result highlights a net concentration of pairs with small Δt (closely spaced time points) and Δr (short distances), characterising the overall spatio-temporal clustering of the sequence, rather than a mainshock-centred convergence. In Fig. 8b, the density in Δr , is much more evenly distributed even for the short times, so that the spatial clustering disappears,

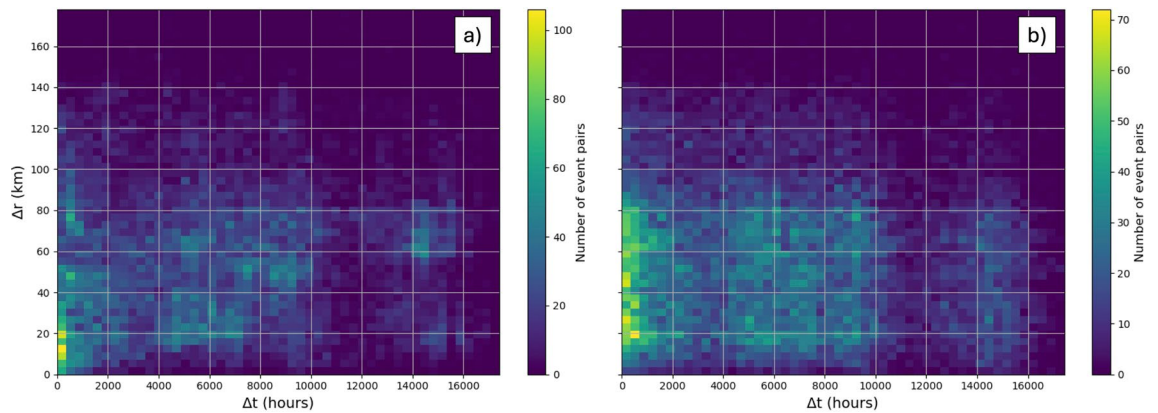


Fig. 8. (a) matrix of the inter-event analysis based of all combinations for each pair (i, j) for Δt and Δr of the entire dataset; (b) matrix of the randomly swapped positions version pairs (i, j) for Δt and Δr , for comparison with empirical matrix a).

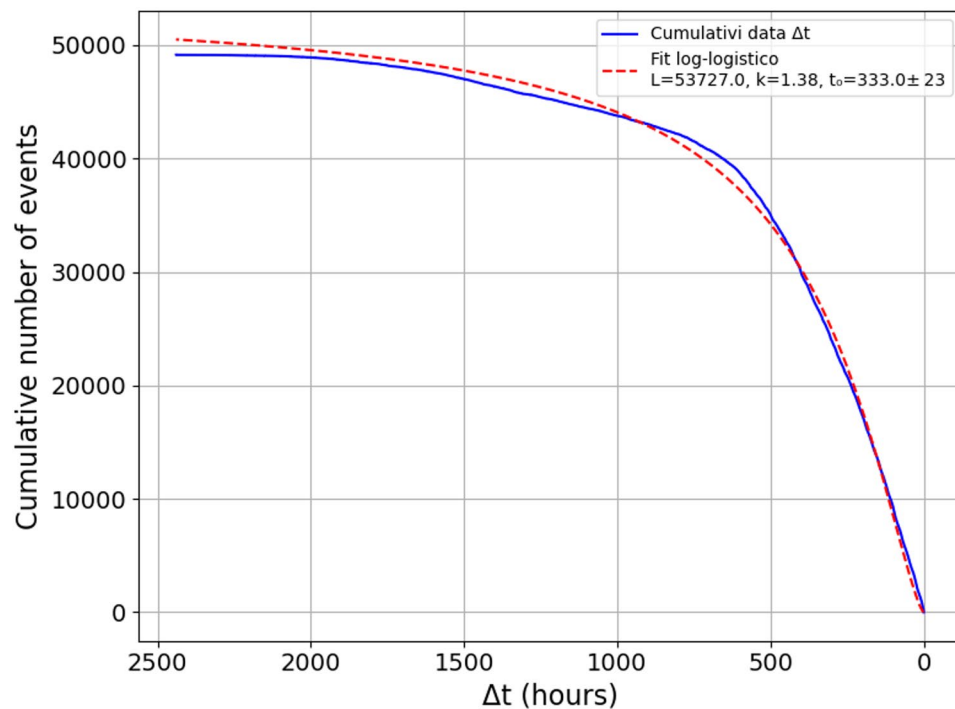


Fig. 9. Fitness of the log-logistic⁴⁹ for the inter-event pairs (i, j) (*augmented catalogue*) of Δt over the last 3000 h, using the model (3). t_0 indicates the inflection time of the curve when the final critical phase begins.

suggesting that there is organisation in the data and that it is not a random process. The specific concentration towards the mainshock epicentre is assessed independently using the distance-to-mainshock evolution (Fig. 7a) and the cumulative moment acceleration (Fig. 3c). To support this hypothesis, a log-logistic⁴⁹ was constructed for the inter-event pairs (i, j) of Δt in the last 3000 h (Fig. 9), whereby the model

$$N(\Delta t) = \frac{L}{1 + \left(\frac{\Delta t}{t_0}\right)^{-k}} \quad (3)$$

L is a normalisation parameter which indicates the total number of inter-event pairs, $k=1.38$ is the slope, which indicates rapid and sigmoidal growth, while $t_0=333$ h, is the inflection time of the curve, which corresponds approximately to the time of the final acceleration, beginning a few days before the two $M \sim 4$ events of 28 December 2024 (see Fig. 2a). The log-logistic model fits well and shows that the temporal accumulation exhibits a scalar behaviour typical of models with balanced critical phases - neither explosive nor pure cascade^{50,51}, - although there is no clear boundary between foreshock styles.

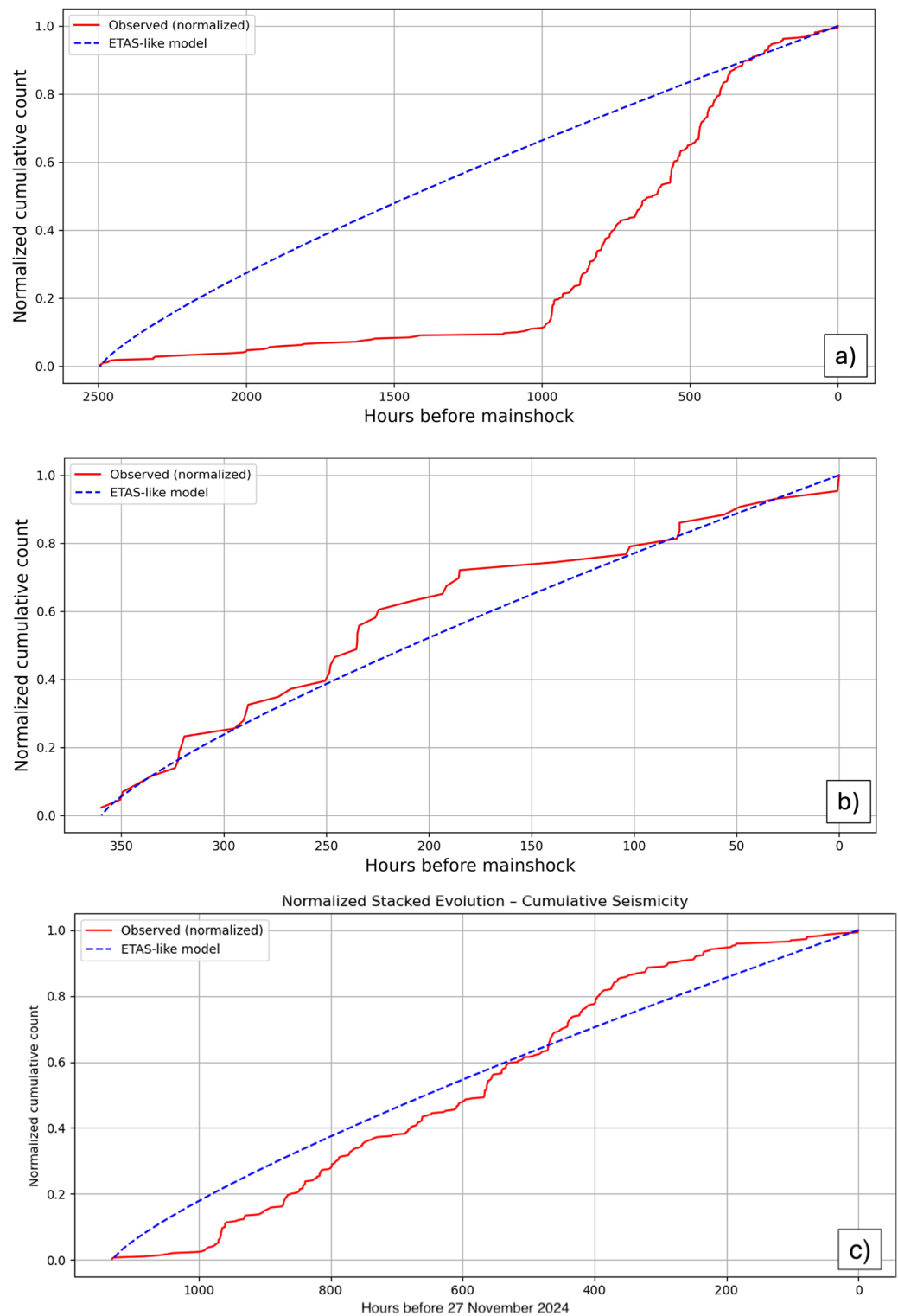


Fig. 10. Normalized cumulative evolution of the events using the *augmented catalogue* data (red), before the intraplate Dingri earthquake of 7 January 2025, M_w 7.1. The blue curves show the corresponding ETAS sequence simulation. (a) the normalized evolution starting from 2500 h (104 day) before the main shock; (b) the normalized evolution in the last 15 days; (c) normalized evolution of our sequence for the Himalayan region only (27.25–28.25 N, 86.50–87.60 E), from the 104th day to the M_L 0.9 27 November 2014 (18:59:47) event.

Our results are consistent with a critical nucleation pattern^{25,45}, in which part of the fault (the northern segment of the DMCF) has slowly accumulated stress to an unstable state, leading to the transition to the final unstable acceleration phase. A similar increase in seismicity, triggered by an $M \sim 4$ event a few days before the mainshock, was also observed prior to the 2015 Gorkha earthquake ($M_w 7.9$)⁵². In that case, an $M 5.2$ earthquake occurred ~ 240 km northwest of the Gorkha epicentre and marked the onset of a significant foreshock sequence. Although the tectonic contexts differ - the older is a low-angle Himalayan thrust, while Dingri is an intraplate normal fault event - both cases show that small-to-moderate magnitude events can act as temporal markers of a transition to unstable faulting.

The three identified clusters are broadly consistent with the northeastern displacement of the Himalayan-Tibetan system, as shown by the rotation of the strain rate and GNSS velocity field⁶, supporting the interpretation of an active extensional regime in this sector. The Tibetan Plateau is a region of diffuse intraplate deformation⁵⁻⁷. Our results suggest that even in such intraplate contexts - often considered less predictable - high-resolution monitoring of individual stations, combined with AI-assisted detection, can help identify retrospective signatures of fault weakening and nucleation.

Finally, it remains to be verified whether the proposed sequence of precursors is consistent with an intraplate earthquake such as the one in Dingri. Bouchon et al. (2013)²⁴ compare 31 sequences in both interplate and intraplate cases (their figures S15). This authors, normalised the cumulative number of events to the total number of events to emphasise temporal evolution regardless of the absolute seismicity rate. In the interplate case, the acceleration phase preceding the mainshock is remarkably robust, but less so in the intraplate case. In Dingri case (Fig. 3c), the development of the cumulative moment shows a strong acceleration in the last 15 days. In this case, Fig. 10a shows the normalised cumulative evolution of our sequence starting from 2,500 h (104 days) before the mainshock, for comparison with Figs. 4 and S15 of reference²⁴ where the authors use 150 days. We used less than 150 days because the events in the days between August and September are sparse, making the first phase of about 50 days less relevant (see Supplementary Fig. S7a). Figure 10b shows the evolution over the past 15 days. This is very similar to Supplementary Fig. S7b when using only the data from the range 28.25–29.50 N, 86.50–87.75 E (about 30 km from the epicentre) for the last 15 days. These last two cumulative graphs closely resemble the intraplate stacks from the past few days, as shown in figure S15b²⁴. This indicates that the intraplate seismic activity (foreshocks) has been concentrated in the epicentral area over the past 15 days. As our catalogue includes part of the Himalayan region (interplate) and part of the southern Tibetan plateau (intraplate), Fig. 10c also presents the normalised cumulative evolution of our sequence for the Himalayan region only (27.25–28.25 N, 86.50–87.60 E), from day 104th (before the mainshock) to 27 November 2024 (18:59:47), the time of the $M_L = 0.9$ event is used here solely as a temporal reference marking the beginning of the detectable rate increase. The evolution is entirely different from Fig. 10b and S7b and highlights the Himalayan cluster. Figure S7c, considering the data in coordinates (27.25–28.25 N, 86.50–87.60 E) also confirms the scarcity of events in the Himalayan area after the event of 27 November.

Anyway, there are some partial inconsistencies between our sequence and that of Bouchon et al. 2013²⁴. In this article, the stacked cumulative number of foreshocks curves is compared with ETAS curves⁵³. The aim of this analysis is to assess whether the observed sequence prior to the mainshock is compatible with a purely cascading random triggering model (ETAS) or whether it exhibits more structured behaviour. While the ETAS simulations reproduce final acceleration, it remains systematically weaker than that observed in the stacked cumulative curves. In contrast, no acceleration is seen in Figs. 10a, b close to the mainshock. These results suggest that a simple cascading triggering model alone may not fully account for the observed acceleration. Instead, the data appear more consistent with a progressively organised phase of seismicity, although alternative explanations cannot be fully excluded. Furthermore, in²⁴ is reported that only 16% of the 31 intraplate sequences show the highest magnitude foreshock in the last eight hours, compared to 42% for interplate sequences. In our case, the highest magnitude foreshock of the final acceleration occurred 1 h before the mainshock. This observation also agrees with that of Núñez-Jara et al. (2025)⁵⁴ during the preparatory phase of large earthquakes in Turkey, supporting the broader relevance of precursor clustering, regardless of faulting style. However, to compare the intraplate sequence in the epicentral area with the sequence confined to the Himalayas, further analysis is required.

Conclusions

In this study, we analyse the long-term preparatory phase of the Dingri earthquake using a single-station AI-enhanced workflow. The resulting high-resolution catalogue in the two years before the mainshock reveals three clusters and highlights the capability of single station monitoring to detect seismic rate changes in complex intraplate settings such as Tibet. 45 days before the $M_{7.1}$, the observed slow and progressive increase in seismicity rate, along with clustering within a ~ 30 km radius, is consistent with a late-stage nucleation process. Distance analysis also indicates a progressive acceleration, corresponding to the onset of a seismic cluster mainly in the third decade of December 2024, followed by two major $M 4.0$ events on 28 December, suggesting a possible organisation of foreshocks along a restricted, fault-controlled domain.

This acceleration in the cumulative seismic moment (Fig. 3c) and in the normalised stacking analysis (Fig. 10a) is spatially confined within 30 km of the epicentre. In the same region, we observe elevated b_+ values (~ 1.2), indicating a relative increase of small-magnitude events. Although the evolution of the b -value alone does not independently demonstrate nucleation, this spatial and temporal correspondence is consistent with progressive microfracturing or heating in the middle-to-lower crust^{14,43}, that may have preceded instability. The b_+ analysis therefore provides complementary support for the precursory activation rather than constituting standalone evidence.

The consistency between our results and the tectonic setting of the Tibetan Plateau – an intraplate region characterised by distributed deformation and high stress concentration due to India–Asia convergence supports the interpretation of an intraplate sequence in the epicentral area.

Further studies are needed to better understand the complex interaction between an interplate region (Himalayas) and an intraplate region (Tibet Plateau). Integrating additional seismic stations would provide more accurate data on the processes preceding large earthquakes in this transition zone.

Data availability

Data within the manuscript and its Supplementary Information are available from the corresponding author upon reasonable request.

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Author contributions

F.P., A.V. D.S. and M.P. provided research idea. F.P. analysed all events detected by PhaseNet, performed the models of interevent analysis and wrote the paper. A.V. performed the PhaseNet analyses and filter matching detections and wrote the test of methods in the Supplement. D.S. contributed with the calculation and compilation of the catalogue. M.P. contributed with seismicity analyses. G.P. involved in data acquisition and maintaining the IO.EVN broadband station. All authors took part in finalizing the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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