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Seismicity acceleration and clustering before the Mw7.9 Gorkha earthquake, Nepal

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1 Seismicity acceleration and clustering before the
2 M_w 7.9 Gorkha earthquake, Nepal

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14 **Abstract**

15 In the last decade, several observations of peculiar seismic and geodetic phases
16 preceding large earthquakes have been documented. Despite being a-posteriori,
17 these observations provide a better understanding of the processes involved in
18 the nucleation of earthquakes. In this study, we investigate the foreshocks and
19 pre-seismic phase of the large M_w 7.9 25 April 2015, Gorkha-Nepal earthquake
20 by applying a matched-filter technique on the nucleation zone of the mainshock.
21 We use the seismic signals of 1800 local earthquakes and the continuous signal
22 recorded at the nearest station for the 6 years preceding the mainshock. The pre-
23 seismic phase depicts a long-term increase of seismicity rate and several bursts
24 of micro-earthquakes. The longest swarm occurs one month before the Gorkha
25 earthquake, lasts one week and consists of 38 repetitive earthquakes located at
26 the north western edge of the rupture zone. It is followed by another increase
27 in seismicity rate which starts six days before the mainshock and includes small
28 foreshocks that develop at less than 10 kilometers from the future earthquake
29 hypocenter. These observations suggest that the Gorkha earthquake was preceded
30 by a pre-seismic phase related to a potential initiation of a slow slip with fluids
31 implicated at the northwestern boundary of the rupture zone.

33 1 Introduction

34 Nepal is located on one of the largest and fastest-slipping continental megathrusts
35 on Earth, the Main Himalayan Thrust (MHT) activated by the continental subduc-
36 tion of the India plate beneath the Tibetan plateau. This tectonic setting results
37 in large devastating earthquakes [3?], the largest of these earthquakes rupture the
38 surface, generating plurimetric seismic scarps. Paleoseismological excavations have
39 gradually revealed what happened at the surface termination of these largest earth-
40 quakes (e.g.[4]) but the mechanisms at work at depth, and in particular along the deep
41 extension of the fault ruptured, suspected locus of the earthquakes nucleation, remain
42 unknown. The M_w 7.9 Gorkha earthquake, on 25 April 2015, is the first Himalayan
43 major event recorded by a permanent and modern network localized above the rupture
44 zone.

45 This earthquake nucleated near the village of Barpak, in the Gorkha district. Its
46 rupture propagated eastward for about 60 seconds over a 50-km-wide by 140-km-
47 long stretch and the maximum coseismic slip has been estimated to be around 7m,
48 located north of Kathmandu [5–9]. The post-seismic slip dominated by afterslip has
49 been located in the downdip part of the mainshock rupture [10, 11]. The analysis
50 of the numerous aftershocks have shedded lights on the structural complexities of
51 this area [11–20]. The correspondence between the 2015 and the 1833 earthquakes
52 (historical magnitude estimated 7.7) in areas, intensity and magnitude indicate that
53 the same section of the MHT was active at that time. Unlike, the 1833 earthquake
54 that was preceded by two foreshocks felt in Kathmandu 5h and 15 minutes before
55 the mainshock [21], no large foreshocks have been felt by the population before the
56 Gorkha earthquake [22].

57 There has been several, made a-posteriori, observations of a pre-seismic phase
58 before large earthquakes using seismicity, either on subduction zones [23–28], or in
59 crustal environment [29, 30], although this pre-seismic phase is not always observed
60 and is highly debated [31]. In this study, we address the question of the existence of a
61 pre-seismic phase to the Gorkha earthquake. We use the nearest station of the National
62 Earthquake Monitoring and Research Center (NEMRC) from the Department of Mines
63 and Geology (DMG) network and apply on its records a matched-filter technique on
64 the nucleation zone of the mainshock. We use about 1800 templates, i.e. signals of
65 local earthquakes that happened within 100 kms from the epicenter (Fig. 1). Using
66 this new catalogue, we describe the pre-seismic phase of the continental subduction
67 Gorkha earthquake and propose different models to explain our observations.

68 **2 Main**

69 The NEMRC network is composed of short period and broadband stations sampling
70 at 50Hz, distributed throughout Nepal. The GKN station lies 25 km south of the
71 epicentre of the Gorkha Earthquake, above the MHT. This station is the closest to
72 the mainshock (red triangle in Fig. 1). We use the records from this short period -
73 vertical component- station to search for micro-earthquakes that remained undetected
74 by analysts, in order to complement the time structure of the seismicity (colored circles
75 in Fig. 1b). By first looking at the continuous recording of the GKN station at the time
76 of the mainshock, we find an earthquake of magnitude estimated at 1.3 (see below)
77 that occurred only 28s before the mainshock (Fig. 2). This event has a S-minus-P travel
78 times of 2.86s suggesting that it happened at 23 km from GKN, assuming a V_p/V_s
79 of 1.75 and a V_p around 6 km/s, consistent with the local velocity models. Note that
80 the station signal saturated during the earthquake and an S-time arrival cannot be
81 determined with accuracy. An event preceding the mainshock is also visible on the
82 seismic signal at KKN, further east, with a P-wave arrival time difference between

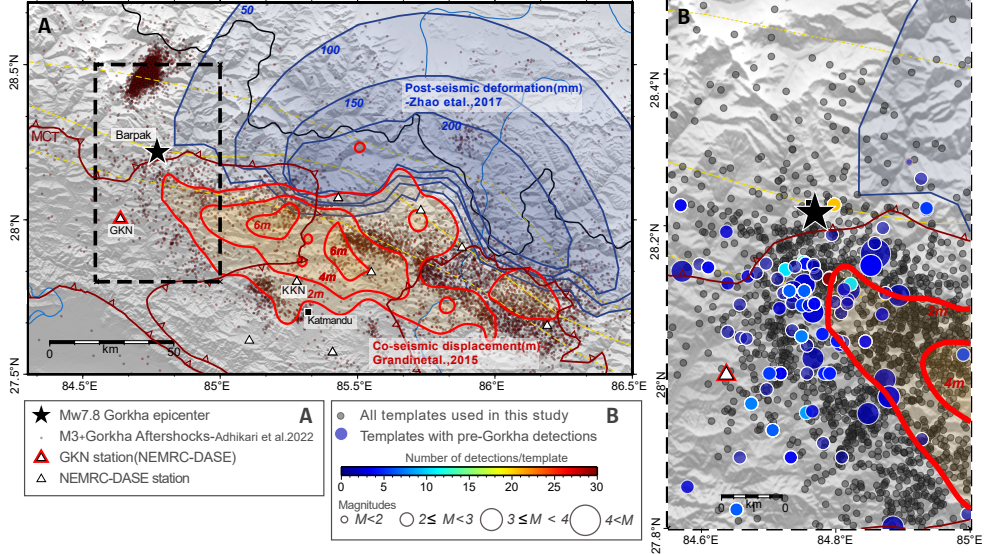


Fig. 1 A: Location of earthquakes and network stations. Red dots show the $M \geq 3$ aftershocks earthquakes [19]. The red contours show the seismic slip with 2m intervals starting at 2m [7]. Contours of afterslip are shown in blue [32]. The black star indicates the Gorkha earthquake epicenter. Black triangles indicate the NSC stations and the red triangle indicates the GKN station used in this study. B: In this study, we focus on the initiation part of the rupture zone taking earthquakes that occur both before and after the Gorkha earthquake as templates (grey dots) at the western edge of the rupture. The colored circles shows the templates that detected during this study, colored with their number of detections.

83 KKN and GKN of 6.8s, identically to the Gorkha earthquake, suggesting that this
 84 foreshock happened at close distance from the epicentre (Fig. S1).

85 We search more systematically for micro-seismic events near the hypocen-
 86 ter of the Gorkha earthquake using the template matching code Obspy
 87 (*obspy.signal.cross_correlation*). We use about 1800 templates, occurring between
 88 December 2013 and May 2016 (grey circles in Fig. 1B). We use the continuous signal
 89 from 2009 to the Gorkha earthquake to compute the correlation between templates
 90 and continuous signals in a frequency band of 2-15Hz, taking an 8-second window
 91 starting 1 second before the P-wave arrival time. We choose a correlation coefficient
 92 threshold of 0.7 and check each detection by eye to avoid false detections. Note that
 93 the signals of station GKN were unusable from December 2010 to November 2013.

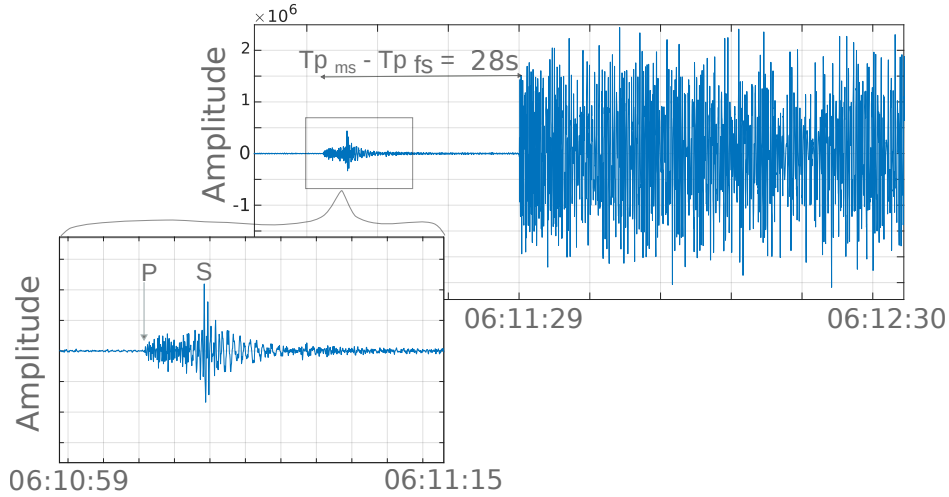


Fig. 2 Record from the GKN station at the time of the Gorkha earthquake. There was an event occurring 28s before the mainshock that has the same difference of P-wave arrival times between GKN and KKN stations than the Gorkha earthquake (see Fig. S1).

94 The magnitude of template events are local and provided by the NSC. The magni-
 95 tudes of the newly detected events are calculated during the correlation computation
 96 based on the maximum amplitude ratio between the detected and template events by
 97 computing a magnitude difference = $4 / 3 * \text{np.log}_{10}(\text{amplitude ratio})$ and adding it
 98 to the template magnitude.

99 Fig. S2a shows an example of detected earthquakes and their stack. Of the 1800
 100 templates used, only 92 are linked with detection of new earthquakes. In this 92, 52
 101 occurred before the mainshock and 40 after it. We obtain a total of 279 detected
 102 earthquakes (including the 52 templates that occurred between November 2013 and
 103 the Gorkha earthquake).

104 The distance between a given template and its detections is necessarily very small
 105 given the waveforms similarity (we chose a coherency thresholds of 0.7). We therefore
 106 consider that the hypocentre of the detections are the same as their corresponding
 107 template. The precise hypocentral location of the template could be enhanced through
 108 the implementation of event specific relocation technique. We use hypo71 (stars on

109 Fig.1) using the Nepalese velocity model [33] and putting a weight of 0.5 on S phases, a
110 weight of 1 below 100 km and a linearly decreasing weight down to 0 at 200 km. While
111 we covered the entire western area of the Gorkha earthquake, these newly detected
112 events are mainly located at the western tip of the rupture zone (Fig. 1).

113 The time series of the cumulative number of earthquakes detected shows different
114 intervals of increased activity (Fig. 3a). Overall, there is an acceleration of the seis-
115 micity with time, especially from September 2014 until the mainshock. We compute
116 the cross-correlation between the detected events (Fig. 3b) and show that there are
117 groups occurring in a short time interval that have higher correlation values than the
118 rest (orange and red colors in Fig. 3b).

119 Period 1 occurs from 02/01/2009 to 19/03/2009, 20 events are detected including
120 a multiplets of seven earthquakes located south to the Gorkha epicenter (light blue
121 dot in Fig. 4a). They are active during a month and also activates later in the analysis
122 (Supplementary Fig.4c and g).

123 Period 2 gathers 21 earthquakes starting at 23:00 on February 21, 2010 and lasting
124 48 hours (yellow dot in Fig. 4b). This period contains a group of 16 earthquakes, that
125 are all detected by the same template in 3.5 hours, 14 of them in only an hour (Fig.
126 S3). The cross-correlation values are particularly high and the relative time delays low
127 for the last ten events in the group. Note that the relative magnitudes are small and
128 similar, suggesting that this group may be a seismic swarm. This group is also active
129 during periods 1 and 3 (Fig. 4a and c, yellow dots).

130 Period 3, from February 23, 2010 to December 12, 2010, contains events with
131 a relatively low inter-correlation, around 0.8-0.85 and a rather stable period with a
132 seismic rate of 0.18 earthquakes per day. The detected earthquakes are clustered south
133 of the Gorkha epicenter, at the western tip of the rupture zone.

134 Period 4 corresponds to a large swarm of 30 earthquakes occurring in just one
135 hour on the 19/03/2014 between 00h35 and 01h39, mainly detected by three templates

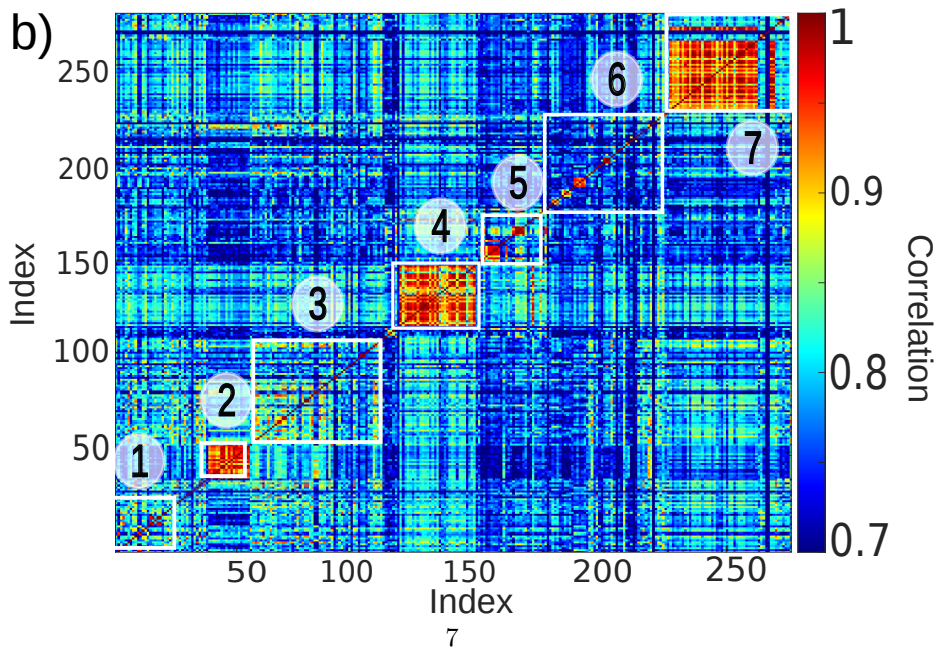
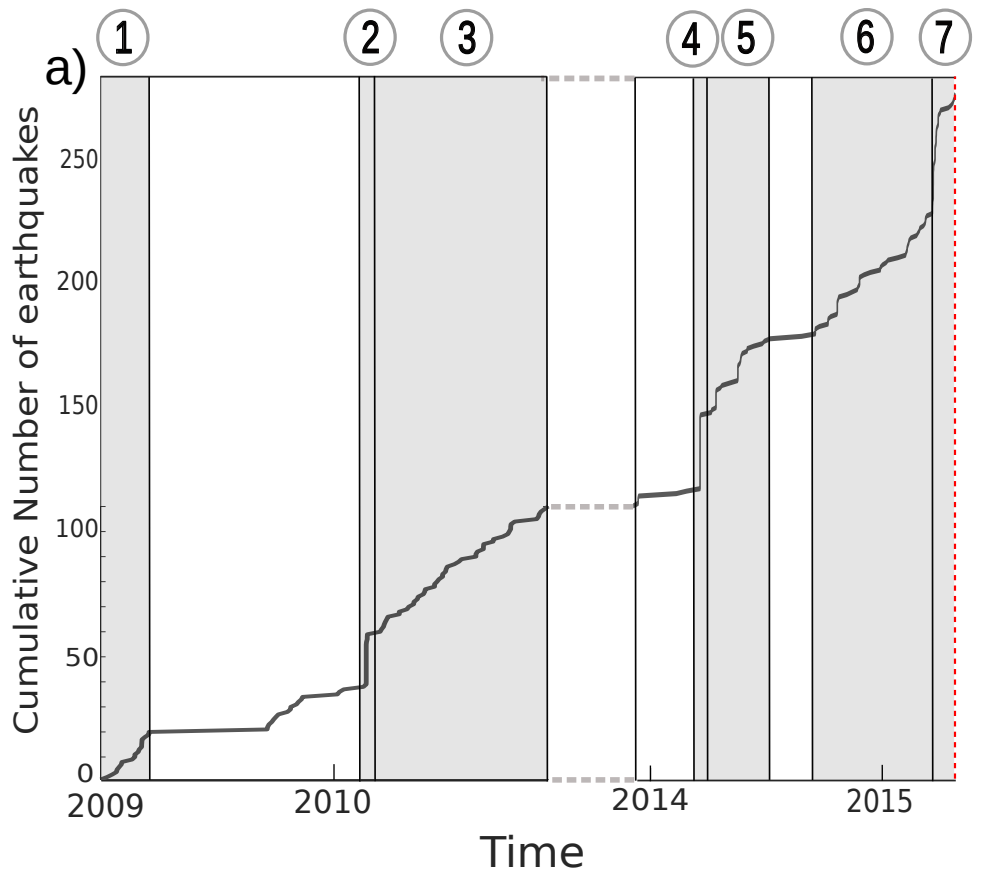


Fig. 3 a) Cumulative number of detected earthquakes with time (gray line) up to the Gorkha earthquake (dashed red line). Note that there was a gap in the seismic data (dashed gray line). Grey periods show significant increases in the seismicity rate. They are numbered at the top and in the correlation matrix (bottom). b) Correlation matrix between all the newly detected earthquakes.

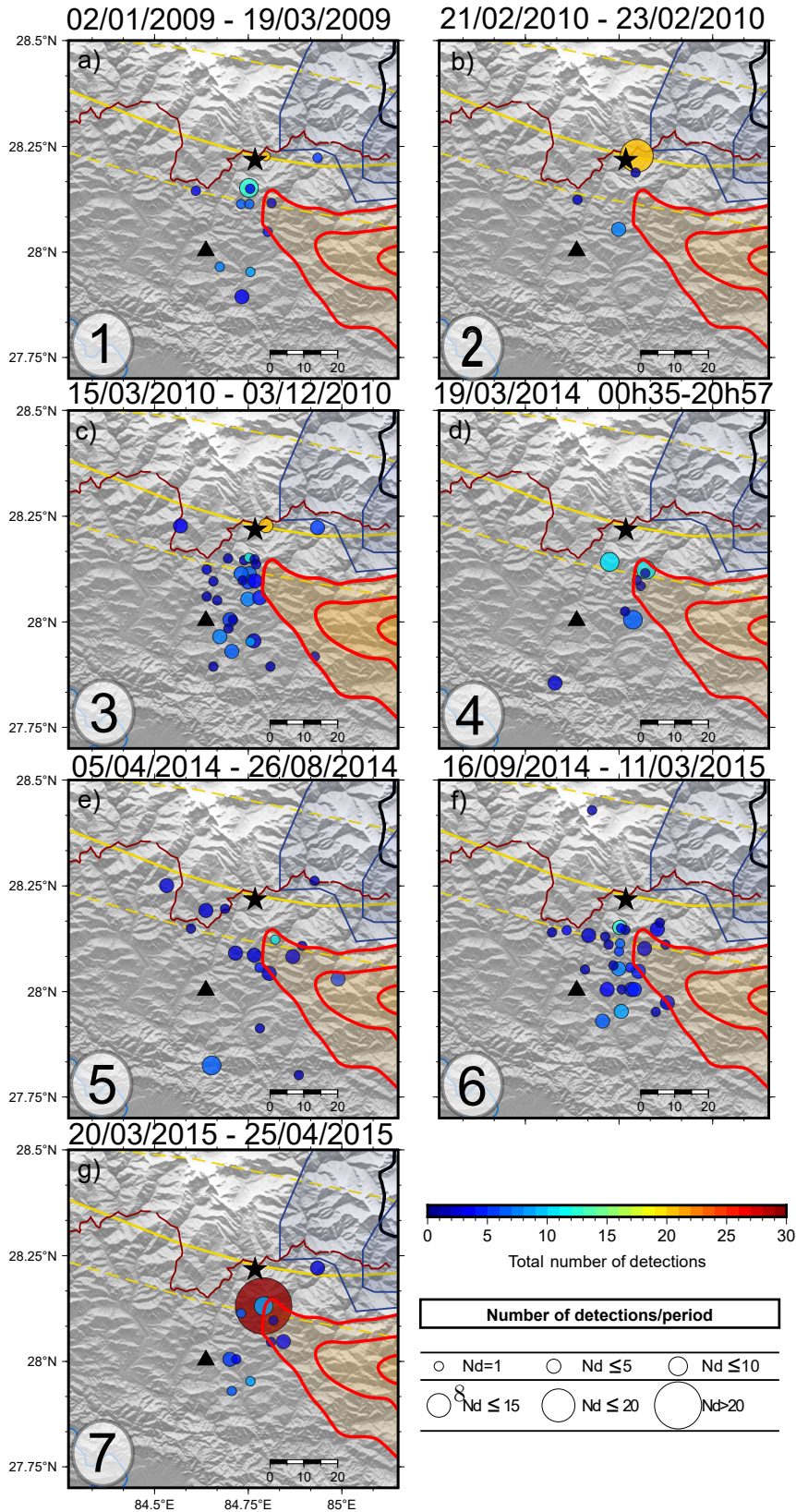


Fig. 4 Snapshots of the seismic activity during the periods of time of Fig. 3. If the template detects during the period, it appears on the snapshot color coded with the total number of detections (over the entire period studied, i.e. 2009-April 2015) and the circle size gives the number of detections during the snapshot only. For example, one template detected a total of 19 earthquakes in periods 1, 2 and 3 (yellow dot in a, b and c), but mainly detected in period 2 (16 earthquakes, b). The black star indicates the epicenter of the Gorkha earthquake, the black triangle locates the GKN station the red contour lines its coseismic slip with a 2m interval starting at 2m.

136 (Fig. 4d). The inter-correlation values of this group range from 0.8 to 1 with a mean
137 of 0.91 (Fig. S4). Some events in the groups have very large cross-correlation values,
138 with a mean of 0.95, possibly indicating that they are repeating earthquakes. Again,
139 there is no dominant magnitude in this very short sequence. One of the templates is
140 also active in period 5 with an additional detection.

141 During period 5 from 05/04/2014 to 26/08/2014, two particular sequences occur
142 with two larger earthquakes at the beginning of each sequence (Fig. S5). The first
143 mainshock has a magnitude of 3.7 and occurs on April 13, 2014, triggering 12 earth-
144 quakes. The second has a magnitude of 3.4 and occurs on May 17, 2014, triggering
145 a sequence of 20 aftershocks. Both mainshocks were already in the catalogue but not
146 their aftershocks.

147 During period 6 there is no clustering in time and the inter-correlation values are
148 low. However, there is a clear increase in the seismic rate of 0.26 earthquakes per
149 day and the seismicity is particularly concentrated at the western tip of the Gorkha
150 earthquake.

151 The last period presents a large swarm with the highest inter-correlation values of
152 the analysis (Fig. 3). This swarm corresponds to 38 earthquakes occurring from the
153 20/03/2015 to the 02/04/2015, detected by two, very close by, templates (red, magni-
154 tude 2.7 and blue, magnitude 3, dots in Fig. 4g) that occur during this sequence. Their
155 magnitudes indicate that their ruptures could have a patch size of about 200-300m.
156 Furthermore, the records of the two templates are very similar when superimposed,
157 and their spectra show the same complexity, suggesting that they are very likely co-
158 located (Fig. 5). The cross-correlation values between the earthquakes of this swarm (ie
159 the two templates and their detections) are high (Fig. S6a). The S-minus-P travelttime
160 is 2.18s (i.e., a distance of 17.5km from GKN) and is very similar for the earthquakes
161 in this swarm. The delay values range from -0.02 to 0.02s (Fig. S6b and c). This swarm

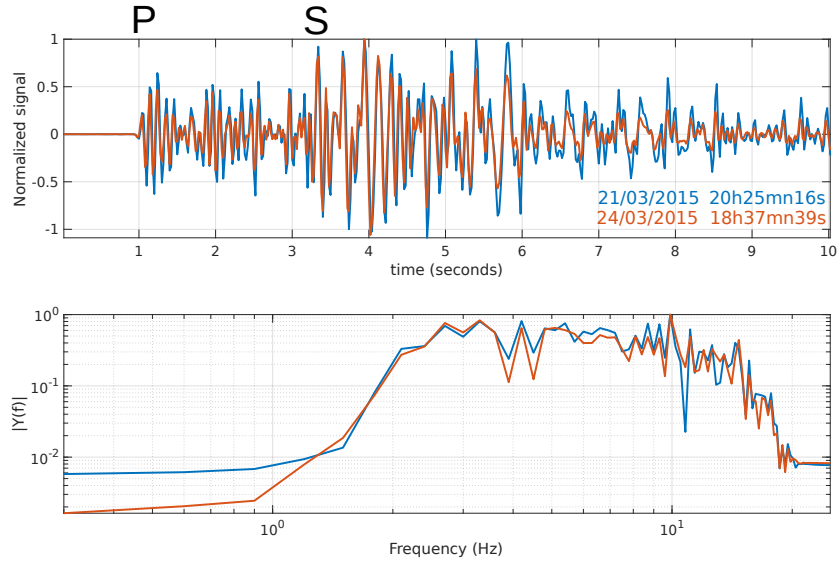


Fig. 5 Top: Superposition of the band-pass filtered (2-20Hz) records of the two largest earthquakes in the sequence of Fig. S6 (magnitude 2.7 and 3, large red circle colocated with a blue one on Fig. 7g) that were already in the NSC catalog, from which 36 new earthquakes were detected. The second waveform has been shifted in time by the time increment that maximizes the cross-correlation of the two signals. Bottom: Comparison of the normalized spectra of the records filtered with a band-pass between 2-20Hz.

162 of earthquakes is located at the western tip of the coseismic slip inversion, where the
 163 rupture initiated [7] (Fig. 4g).

164 There is a final acceleration during period 7 from the April 19, 2015 to the main-
 165 shock with a total of 6 detections, including the small foreshock that occurred only
 166 28s before the mainshock close to the rupture initiation location (Fig. 2).

167 3 Discussion

168 Although they can only be defined after the mainshock has occurred, seismic fore-
 169 shocks are the most relevant observations for understanding the preparation of large
 170 earthquakes. We find several swarms of earthquakes that occurred before the Gorkha
 171 earthquake and that highlight the perimeter of its western coseismic slip, where the
 172 rupture initiated.

173 Depending on the tectonic setting and structural complexity, three main conceptual
174 models have been developed to explain the pre-seismic phase of large earthquakes:
175 progressive localization of the seismicity, cascade-up, and pre-slip [29, 31, 34–36].

176 Interestingly, for many large earthquakes that are preceded by a pre-seismic phase,
177 the strain release is progressive, stepwise [23, 24, 37–39]. This is also noteworthy in
178 this study, where we detect several seismic bursts that can be sudden and last only
179 a few hours (periods 2 and 4). During these periods, the seismic events have similar
180 magnitudes, suggesting a swarm-like behavior. Because of their short duration, fluids
181 may be a good candidate for triggering such events [40]. Intermittent fluid release
182 increases the stress on the fault zones and produces local modification of the frictional
183 behavior as seen in rock experiments.

184 There are multiple indications of fluid presence in the area along the Main
185 Himalayan Thrust (MHT): (a) a seismic low velocity zone (LVZ) coincides with the
186 decollement on that particular section [41], (b) this LVZ is interpreted as a shear zone
187 possibly injected with fluids coming from metamorphic dehydration reactions of sed-
188 iments thrust over by the hot Himalayan hangingwall, (c) analysis of fluid inclusions
189 from quartz exudates taken within the MCT shear zone, which is a former MHT,
190 demonstrate that both aqueous fluids -mainly brines-, and CO_2 -bearing inclusions,
191 originating from metamorphic and meteoric origins, were introduced from mid-crustal
192 to shallower levels [42], (d) the downdip end of the segment of MHT considered corre-
193 sponds with the position of a low-resistivity anomaly [43], possibly attributed to the
194 presence of saline fluids within fractured rocks.

195 This body of evidence suggests that aqueous fluids -or supercritical CO_2 -are
196 present at midcrustal depths in the vicinity of the decollement, with the potential
197 to migrate within the fractured rocks of the shear zone as well as along subsidiary
198 faults in its immediate hangingwall [44]. These fluids migrations could be related with

199 hydrofracturation mechanisms and/or decrease of the friction on the basal decollement,
200 possibly associated to transient decoupling.

201 We also see a long-term increase of seismic rate between 2010 and 2015 (periods
202 3 and 6, although the gap in the data makes it difficult to conclude to a long term
203 acceleration). From March 2015, the seismicity increases even more dramatically with
204 the occurrence of 38 repeating earthquakes from 20 March 2015 to 27 March 2015,
205 probably triggered by a slow slip event that lasts a week [23, 24, 29, 37, 45, 46]. After
206 this slow slip event, there is a last acceleration leading up to the mainshock that
207 includes a smaller event close to the hypocenter, in good agreement with the cascade-
208 up model framework [34, 47]. The strain release with a step-like evolution points to
209 a combination of slow slip and fast failure mode foreshocks that locally increase the
210 loading rate of the MHT as seen in rock experiments [48–50] and numerical modeling
211 [51].

212 The repetitive earthquake activity that preceded the Gorkha mainshock, and the
213 possible transient slow slip associated, could involve various structures at depth. The
214 repeating earthquakes, associated to earthquake templates that happened at mid-
215 crustal depths, occurred necessarily at close distances from the Main Himalayan
216 Thrust, the flat-ramp-flat thrust system which partially ruptured during the main-
217 shock (Fig. 6a-b). In this part of the Himalayas, the geometry of these structures at
218 depth have been inferred from surface exposure of the rocks, [19, 52] and balanced
219 cross section hypothesis, complementing a few geophysical constrains. The position
220 of the upper decollement of the thrust system is associated to the low velocity zone
221 imaged by receiver function analysis [41, 53].

222 A first plausible scenario involves a transient slow slip and repeating earthquakes
223 on the upper decollement, followed by its partial rupture, from the downdip end of the
224 upper decollement, at the upper edge of the ramp (Fig. 6a-b). The average position
225 of the ramp, at geological timescales, is suspected to develop beneath the front of

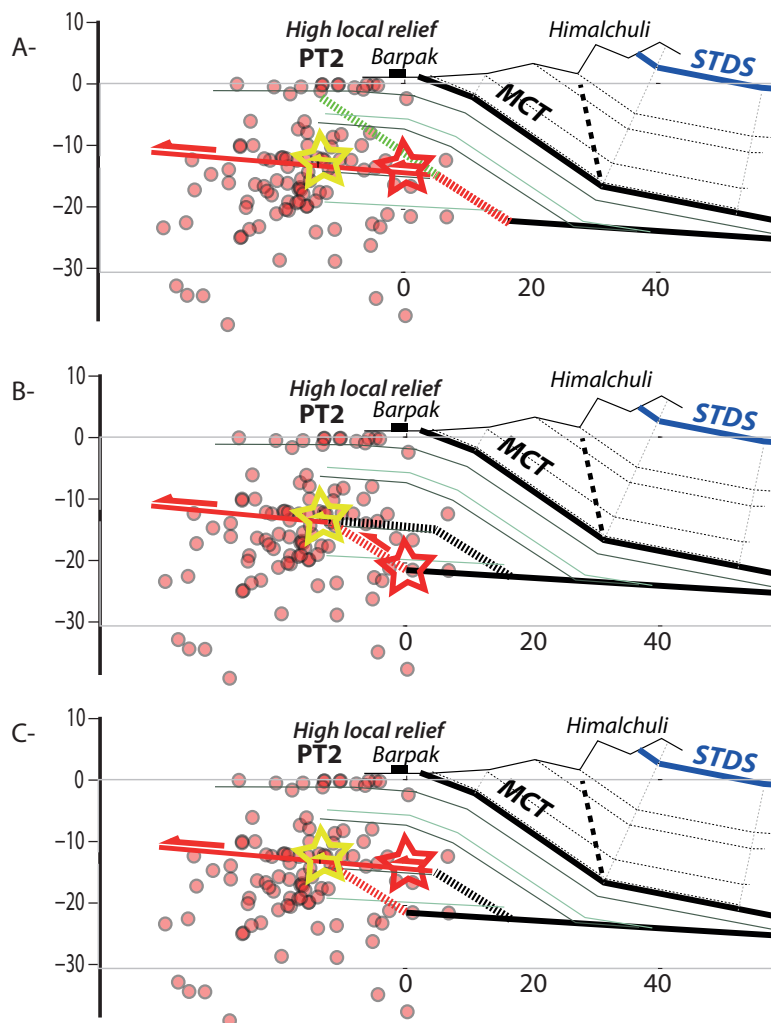


Fig. 6 Interpretative cross sections through the seismicity. The 2015 Gorkha earthquake hypocentre is represented by the red star. The red circles correspond to the location of the earthquakes which were selected as templates. Note that the hypocentral locations of these small earthquakes in the area are associated with very large uncertainties and need to be taken with care: the seismic stations that participate to their location are present to the south of the seismic swarm, leaving large primary azimuthal gaps. The geological structures are constrained by field observations (derived from structural measures of the bedding and schistosity), modified from [19]

226 the high Himalayas. This is consistent with the thermokinematic evolution recorded
227 by the low temperature thermochronometers (e.g. [52]). However, the present day
228 position of the peak of uplift measured by InSAR and the peak of incision estimated
229 along the rivers since the beginning of the Holocene, suggest that the midcrustal ramp
230 recently migrated southward [54] see Fig. 6c. An alternative to the first scenario,
231 could therefore involve the rupture of this active midcrustal ramp, after a focused
232 repetitive activity at the updip end of the ramp, eventually associated with a slow slip
233 event at the edge of the ramp. A third scenario, involves a seismic activity in the
234 midcrustal lesser Himalaya duplex. This scenario may involve a focused precursory
235 activity associated with an eventual slow slip at the updip edge of the active ramp,
236 followed by the rupture of the passive roof thrust of the lesser Himalayan duplex (Fig.
237 6d). These models are difficult to differentiate with the sole seismicity available due
238 to the large uncertainties associated with the earthquake locations. Indeed, the events
239 happen North of Gorkha station and no seismic stations to the North contribute to
240 their location that remain associated to large azimuthal gaps. The seismicity location
241 is therefore associated with significant trade-off between the latitude of the epicenter
242 and the depth of the hypocenter.

243 **4 Conclusion**

244 The application of template matching techniques to the waveforms of the GKN station,
245 the closest station to the epicenter of the Gorkha earthquake, reveals an acceleration
246 of the seismicity rate preceding the earthquake at short distances, within 20 km from
247 its hypocenter. The pre-seismic phase is characterized by the presence of a swarm of
248 earthquakes detected between the 20 March and 27 March 2015, with 38 repeated
249 earthquakes detected by using two very similar templates. This period is followed by
250 the realisation of at least one foreshock that happened 28s before the mainshock.

251 These observations may be associated with the development of a transient event,
252 mostly aseismic, occurring near the brittle-ductile transition zone, with a few repeating
253 microearthquakes happening at the north western edge of the rupture zone. The event
254 was finally followed by the rupture of the mainshock. Our results show that the Gorkha
255 earthquake belongs to the list of large earthquakes with a pre-seismic phase detected
256 a-posteriori using data mining techniques.

257 **Supplementary information.** Figures S1 to S6

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266 BG conceived the study. All authors participated to the writing of the manuscript.

267 **Competing interests:** Authors declare no competing interests. **Data and mate-**
268 **rials availability:** Data available upon request to Blandine Gardonio or Lok Bijaya
269 Adhikari.

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