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## **Slip pulse and resonance of the Kathmandu basin during the 2015 Gorkha earthquake, Nepal**

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1 **Slip pulse and resonance of Kathmandu basin during the 2015 Gorkha earthquake,**  
 2 **Nepal**

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30  
 31 **Detailed geodetic imaging of earthquake rupture enhances our understanding of**  
 32 **earthquake physics and induced ground shaking. The April 25, 2015 Mw 7.8 Gorkha,**  
 33 **Nepal earthquake is the first example of a large continental megathrust rupture**  
 34 **beneath a high-rate (5 Hz) GPS network. We use GPS and InSAR data to model the**  
 35 **earthquake rupture as a slip pulse of ~20 km width, ~6 s duration, and with peak**  
 36 **sliding velocity of 1.1 m/s that propagated toward Kathmandu basin at ~3.3 km/s**  
 37 **over ~140 km. The smooth slip onset, indicating a large ~5 m slip-weakening**  
 38 **distance, caused moderate ground shaking at high >1Hz frequencies (~16% g) and**  
 39 **limited damage to regular dwellings. Whole basin resonance at 4-5 s period caused**  
 40 **collapse of tall structures, including cultural artifacts.**

41  
 42 **One sentence summary:** High-rate GPS records reveal that the Gorkha earthquake  
 43 resulted from eastward propagation of a ~6s long slip pulse, with smooth onset which  
 44 generated mild ground shaking but excited resonance of Kathmandu basin at ~4-5 s.  
 45

46 The shape of the slip-rate time function (STF) during seismic rupture provides critical  
47 insight into constitutive fault properties. The abruptness of slip onset determines the high  
48 frequency content and hence the intensity of the near-field ground motion (1), whereas the  
49 tail, which discriminates pulse-like and crack-like ruptures (2), has a low frequency  
50 signature. Therefore, resolving the STF with band-limited strong motion records is difficult.  
51 The combination of high-rate GPS waveforms (3, 4), which capture both dynamic and  
52 permanent deformation, overcomes this limitation.

53 The April 25<sup>th</sup> 2015  $M_w$  7.8 Gorkha, Nepal earthquake resulted from unzipping of the  
54 lower edge of the locked portion of the Main Himalayan Thrust (MHT) thrust fault, along  
55 which the Himalayan wedge is thrust over India (5). The earthquake nucleated ~80 km  
56 northwest of Kathmandu and ruptured a 140 km long segment of the fault (Figure 1A) with  
57 a hypocentral depth of ~15 km and a dip angle of 7-12°(5, 6). The MHT accommodates the  
58 majority of the convergence between India and southern Tibet with a rate between 17 and  
59 21 mm/yr (7). For the 2015 event, which resulted in over 8,000 deaths, mostly in the  
60 Kathmandu and adjacent districts, Mercalli shaking intensities (MMI) reported by the  
61 National Society for Earthquake Technology (8) reached up to IX (violent) and exceeded VI  
62 (strong) over a 170x40 km<sup>2</sup> area. Kathmandu has been struck by repeated earthquakes in  
63 the past, with major destruction (MMI>X, extreme) in 1255, 1344, 1408, 1681, 1833 and  
64 1934 (9-11). These earthquakes all occurred close to Kathmandu and have been assigned  
65 magnitudes between  $M_w$  7.5 and 8.4. Damages in the Kathmandu basin were probably  
66 amplified by site effects during the Gorkha earthquake as happened with past events (12,  
67 13). The basin is filled with 500-600 m of fluviolacustrine sediments resting on  
68 metamorphic basement (14).

69 The damage to the most vulnerable vernacular dwellings in Kathmandu, which rarely  
70 exceed 4 stories, was in fact much less than expected in view of the 2015 earthquake's  
71 magnitude and its proximity to Kathmandu. By contrast, some taller structures were more  
72 severely affected, such as the 60 m tall Dharahara tower which collapsed, but had partially  
73 survived the  $M_w$  8.1-8.4 1934 earthquake.. The 1934 event induced much more extensive  
74 destruction to vernacular dwellings in Kathmandu than in 2015 (20% of the buildings in  
75 Kathmandu were destroyed in 1934, less than 1% in 2015) (15). These observations reflect  
76 the combined effects of the source characteristics and local geological conditions, in  
77 addition to evolution of building practices.

78 The 2015 Gorkha earthquake ruptured a subhorizontal portion of the MHT lying  
79 directly beneath a network (16) of continuous GPS (cGPS) stations recording at a high rate  
80 of 5 samples per second, and one accelerometer station (17) (Fig. 1A). In addition, surface  
81 displacements were measured with interferometric synthetic aperture radar, InSAR,(18,  
82 19) (fig. S1). While a number of recent earthquakes were documented with similar  
83 techniques (20, 21), the Gorkha event is the first occurrence of a large continental thrust  
84 earthquake to be observed by high-rate cGPS stations at very close distances to and  
85 completely encompassing the rupture area. The combination of these measurements  
86 provide the opportunity to image the kinematics of the source process and the strong  
87 ground motion that led to the particular pattern of structural damage observed during this  
88 earthquake.

89 The records of seismic displacements and accelerations (Figs. 2 and S2) show  
90 southward motion of up to 2 m, with a rise time on the order of 6 seconds. The pulse is  
91 particularly clear at cGPS station KKN4 located on bedrock just north of Kathmandu and

92 only ~13 km above the fault. The displacement at this station started at about 25 s after the  
93 onset of rupture, corresponding to 15 seconds after P-waves arrival time (Fig.2), and  
94 reached its final static value by about 32 s, using the USGS origin time of radiated direct P  
95 waves at 06:11:26.270 UTC (6). The records clearly indicate a pulse-like rupture (22) with  
96 slip on any given portion of the fault occurring over a short fraction of the total ~70 s  
97 duration of the earthquake source (5). Given the ~78 km distance of KKN4 to the epicenter,  
98 the pulse must have propagated at ~3 km/s, a value consistent with waveform modeling  
99 and back projection of high frequency seismic waves recorded at teleseismic distances (5).  
100 Surface velocities reached values of ~0.7 m/s. The cGPS station NAST within Kathmandu  
101 basin shows, in addition to the pulse seen at KKN4, strong oscillations of period of about 3-  
102 4 seconds lasting for ~20 s (Figs. 2 and 3A). The Gorkha earthquake must have excited a  
103 resonance of the Kathmandu basin as a whole. The resonance is clearly shown in the  
104 response spectra from these stations as well as from the accelerometer station KATNP (Fig  
105 3G-I).

106 To retrieve the kinematics of the seismic rupture, we carried out a formal inversion of  
107 time-dependent slip on the fault (23, 24) and compared the recorded waveforms with  
108 forward predictions assuming a propagating slip pulse with varied characteristics. We  
109 assumed a planar fault geometry with a strike of 295° and a dip of 11° in accordance with  
110 the teleseismic W-phase moment tensor solution from the USGS (6). We tested shallower  
111 dips up to 7° but found that 11° provided a better fit to the data. The fault was discretized  
112 into 10x10 km subfault segments. We jointly inverted the three-component, 5 Hz GPS  
113 derived velocity waveforms, the GPS static offsets, and the InSAR line of sight (LOS) static  
114 displacements measured between February 22 and May 3 (fig. S1). The GPS displacement  
115 time series shows large postseismic motion at only one station (CHLM) with less than 2 cm  
116 magnitude on both the horizontal and vertical over the week following the earthquake.  
117 Therefore, for our purposes, we neglect the contribution of postseismic deformation to the  
118 LOS displacements.. The model fits both data sets closely (Figs. 1A), with 86% variance  
119 reduction for the InSAR and GPS coseismic displacements and 74% variance reduction for  
120 the GPS velocity waveforms (Figs. S2, S4). The model indicates predominantly unilateral  
121 rupture to the southeast with peak slip of ~6.5 m on a large asperity to the north of  
122 Kathmandu. The event duration is 65 s (fig. S4) with peak moment release at 23 s when the  
123 slip pulse is less than 10 km north of Kathmandu (movie S1), and peak slip-rate is 1.1 m/s.  
124 Most of the slip is concentrated within a narrow region between the 10 and 20 km fault  
125 depth contours. We find a large asperity with 3.0 m of slip due east of the main asperity and  
126 between 20 and 23 km depth. The rupture velocity of the propagating slip pulse indicated  
127 by the onset of slip in our best-fitting model is ~3.2 km/s and has a maximum allowed  
128 velocity of 3.3 km/s (fig. S4). This velocity corresponds to ~95% of the shear wave speed at  
129 the depth of the majority of slip (15 km) according to the local velocity model used to  
130 calculate the Green's functions (Table S2), indicating a very fast rupture propagation. Slip  
131 tapers at 17-20 km depth along the edge of the locked zone of the MHT. The inversion has a  
132 large number of parameters, which allows for a relatively complex rupture history.  
133 However, the resulting model is remarkably simple with essentially a single propagating  
134 slip pulse. The spatio-temporal evolution of the slip pulse matches well the location of the  
135 sources of high frequency (0.5-2Hz) seismic waves derived from the back projection of the  
136 teleseismic waveforms (5) (Movie S1).

137 We calculated the static stress change on the fault plane due to the earthquake (Fig. 1B).  
138 It shows loading of the fault around the main asperity where most of the aftershocks  
139 occurred, including the Mw 7.3 aftershock of May 12, as expected from triggering by  
140 coseismic stress transfer (25). The model predicts a pattern of uplift of the Kathmandu  
141 basin and subsidence at the front of the high range (fig. S4), approximately opposite to the  
142 pattern observed in the interseismic period as expected from simple models of the seismic  
143 cycle on the MHT (26, 27).

144 The record at station KKN4 should be a close representation of the slip-rate time  
145 function as it lies only about 13 km above the propagating slip pulse and is not affected by  
146 the site effects seen at the stations in Kathmandu basin. We conducted synthetic tests with  
147 the same Earth structure model used in the inversion (Table S1) to assess the distortion  
148 and smoothing introduced by the elastic half space response (fig. S5). We found a vertical  
149 velocity amplitude of about 70% of the peak slip rate on the fault directly beneath it along  
150 with a well-preserved temporal shape. Furthermore, the tests demonstrate that the smooth  
151 onset of slip is not an artifact resulting from the transfer through the elastic medium  
152 represented by the elastodynamic Green's functions. The shape of the slip pulse can also be  
153 retrieved from the GPS records at NAST and strong motion vertical records at KATNP  
154 which are less affected by site effects than the horizontal records (Fig. 1). All three records  
155 indicate a  $\sim 6$  s duration pulse. The shape of the pulse fits the regularized Yoffe function  
156 (28) yielding a rather smooth rise, with an acceleration time to peak slip rate of  $\tau_s=1.7$  s, a  
157 rise time of  $\tau_R=3.3$  s and a total effective duration of  $\tau_{eff}=6.7$  s. The slip-rate pulse derived  
158 from the inversion is also well fit using the same values of  $\tau_s$  and  $\tau_R$  s and peak slip-rate of  
159  $\sim 0.9$  m/s (Fig. 4). We compared the recorded waveforms with predictions from a suite of  
160 forward models to test the robustness of our results. We used the static slip model in these  
161 tests deduced from the inversion of the GPS static and InSAR measurements (Fig. S7). We  
162 assumed a propagating slip pulse with varying characteristics using the regularized Yoffe  
163 STF. We varied the rupture velocity between 2.8 and 3.6 km/s, and the rise time between 2  
164 and 10s (fig. S8). We also tested the resolution power of the inversion and the limited bias  
165 introduced by the regularization applied to the inversions by inverting synthetics  
166 calculated from forward modeling (24, fig. S10, fig. S11). Together, these tests demonstrate  
167 the duration of the slip pulse is probably less than 10 s and the time to the peak-slip rate  
168 cannot be shorter than 1 s ( we would otherwise observe a much larger amplitude at high  
169 frequencies) and the average propagation rate of the slip pulse is not less than  $\sim 3.0$  km/s  
170 over the first 30 s (until KKN4, NAST and KATNP records a pulse signal).

171 Tinti et al (28) analyzed how the shape of the STF relate to the characteristics of the  
172 friction law governing the dynamics of the rupture. Based on this rationale (their equations  
173 6 and 11), we estimate the slip-weakening distance to be  $\sim 5$  m (for a peak-slip of 6.5 m).  
174 The distance is a large value compared to those estimated from kinematic and dynamic  
175 modeling of seismic ruptures (29, 30), which tend to be overestimated (1) and are typically  
176 on the order of 0.5 to 1 m. The large value we obtained is possibly related to the earthquake  
177 occurring close to the brittle-ductile transition at the lower edge of the locked portion of  
178 the MHT. The modeled smooth onset of the STF and the related large slip-weakening  
179 distance provide an explanation of the relatively low amplitude of shaking at frequencies  
180 above 1 Hz. The observed slip-weakening behavior does not require the friction law to be  
181 actually slip-weakening. A fault obeying rate and state friction can show an effective slip-

182 weakening behavior with an effective critical distance several orders of magnitude larger  
183 that the critical distance entering the friction law (31). Aspects of the rupture kinematics  
184 and ground strong motion observed during the Gorkha event may also be due to hanging  
185 wall effects, the importance of which could be assessed through dynamic modeling of the  
186 rupture (32, 33).

187 Our study provides insight into the main factors that determined damage sustained  
188 during the Gorkha earthquake. While the hypocenter was ~80 km away from the city, the  
189 main asperity that radiated most of the energy was much closer, just north of the basin and  
190 at relatively shallow depth. Comparison of the waveforms recorded within the sedimentary  
191 basin at NAST and KATNP (fig. 3) with the bedrock records at KKN4 shows prominent  
192 differences even though the stations are less than 13 km apart. The waveforms at the  
193 bedrock station KKN4 are simple, mostly dominated by the single pulse, while within the  
194 basin peak horizontal ground velocities of 0.5 to 0.8 m/s (considered severe to violent,  
195 (34)) are sustained for 20 s at KATNP and 40 s at NAST. The ratio of the amplitude spectra  
196 of the basin waveforms to those at the hill station (Fig. 2D-F) shows amplification of long  
197 period energy between 1 and 9 s with the basin amplitudes being 6-7 times larger in the  
198 horizontal direction than at the bedrock station. The response spectra (Fig. 2G-I) show that,  
199 within this amplified period band, it was the 4 s period shaking that was the strongest at  
200 the basin stations.

201 The 4 s peak in the response spectra coincides with the observation that the source  
202 time function beneath Kathmandu likely had a duration of ~6-7 s. The net effect of this long  
203 source duration with slow onset time is to produce radiation that is depleted of high  
204 frequency energy (fig. S11). This explains why vernacular dwellings with only a few stories  
205 were not severely affected despite the anticipated short period site effects from  
206 microzoning (13). Furthermore, high frequency intensity measurements such as peak  
207 ground accelerations were modest (Fig 2, ~1.6 m/s<sup>2</sup>, MMI VI), while longer period intensity  
208 measures such as peak ground velocity (Fig 3) were very large (80 cm/s, MMI IX).  
209 Kathmandu was faced with a combination of source and site effects. Rupture directivity  
210 focused radiated seismic energy towards the city; the smooth onset and 6-7 second  
211 duration of the pulse excited a resonance of the Kathmandu basin, producing protracted  
212 duration of violent shaking at a period around 4s.

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245

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## 247 **References and Notes**

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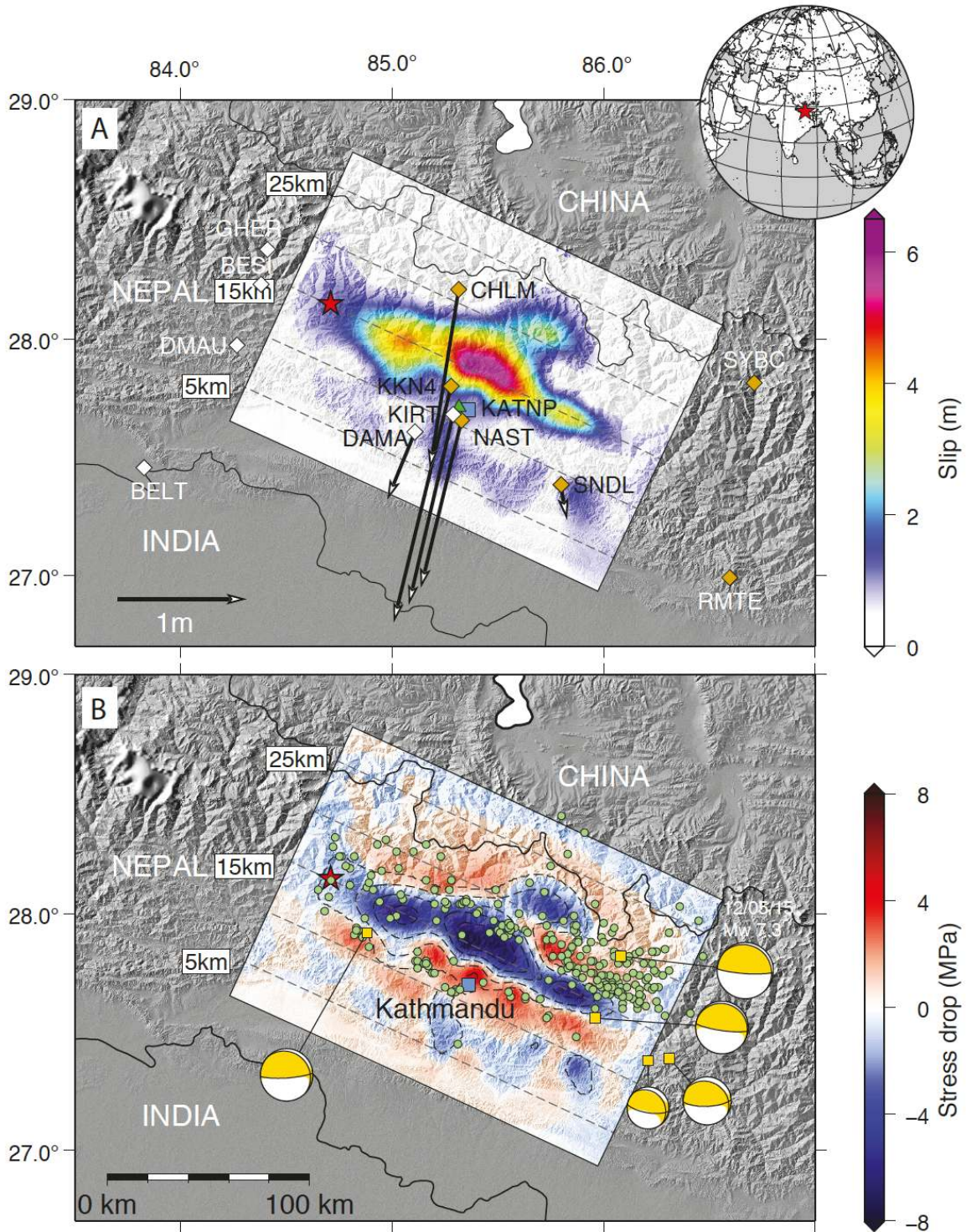
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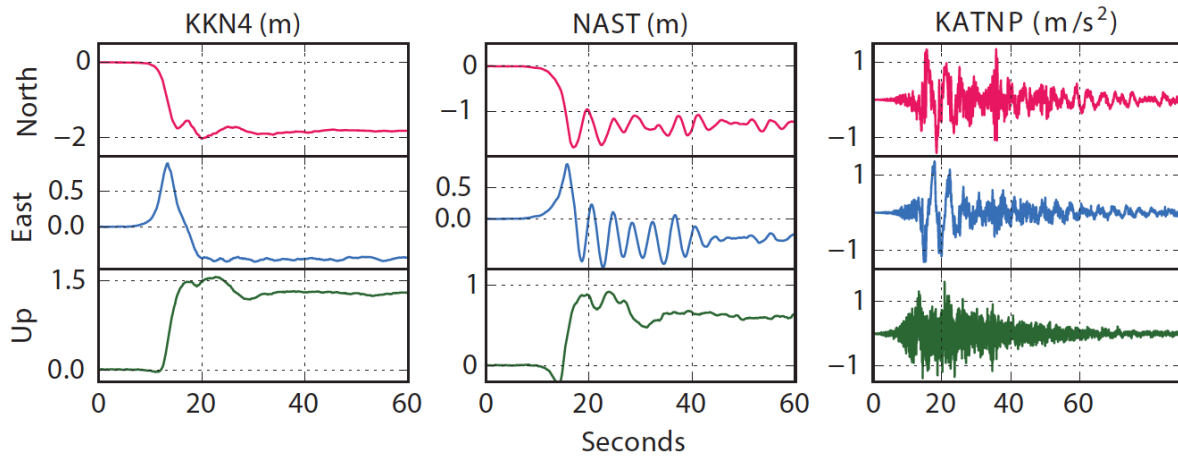


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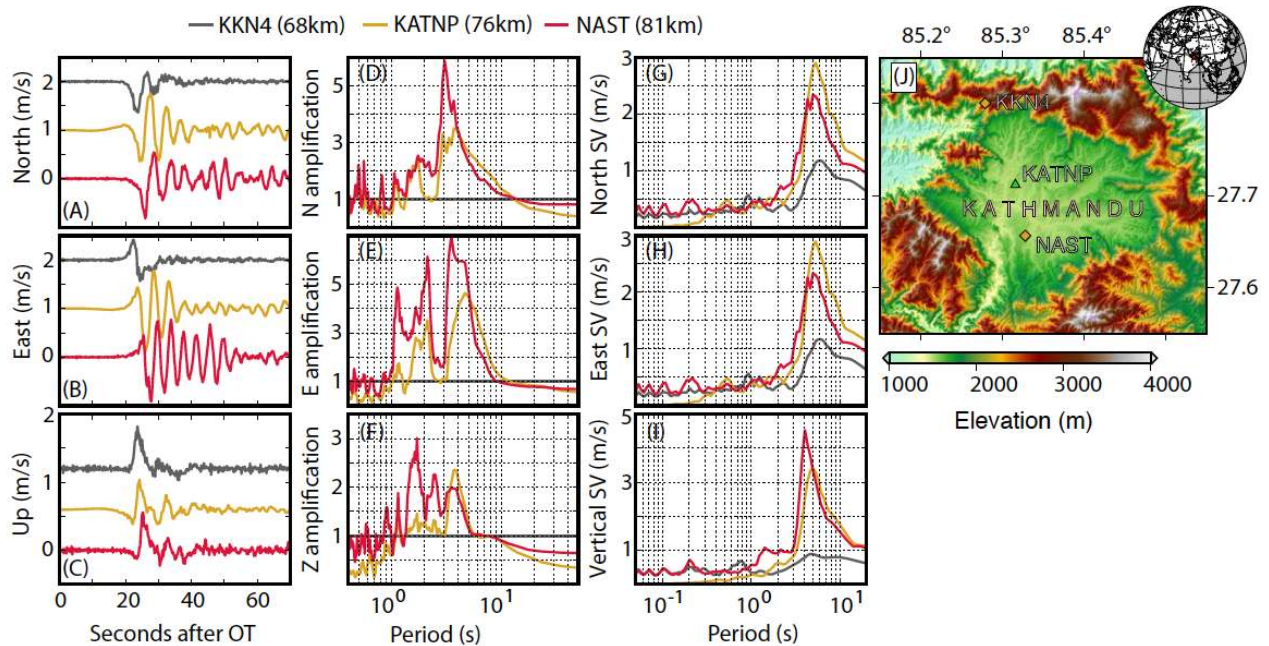


356  
 357 **Figure 1: Cumulative slip distribution and static stress drop due to the Gorkha**  
 358 **earthquake.** (A) Slip inversion results for the Mw7.8 Gorkha event. The red star is the  
 359 hypocenter. Dashed contours are depths to the fault. Orange diamonds are 5 Hz cGPS  
 360 stations and white diamonds are low rate (1/30 Hz) stations. The green triangle is the  
 361 strong motion station. Kathmandu is represented by the blue square. The black arrows

362 indicate the coseismic offsets measured at the sites (the values and uncertainties are given  
 363 in Table S1). Vectors with less than 10cm displacement are not shown (B) Static stress  
 364 drop predicted by the model of figure 1A. Green circles are aftershocks with local  
 365 magnitude >4 recorded and located by the Nepal National Seismic Center. Focal  
 366 mechanisms represent the GCMT moment tensors for aftershocks with magnitude larger  
 367 than 6.  
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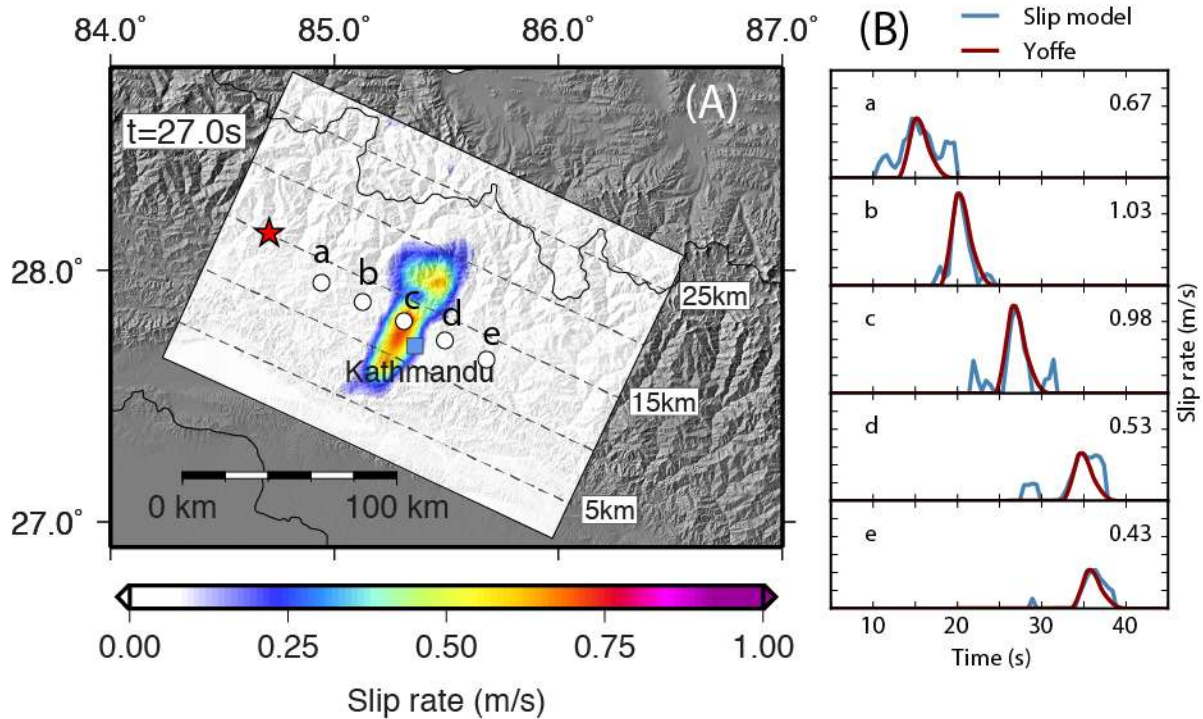


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 371 **Figure 2: Records of ground displacements and accelerations during the Gorkha**  
 372 **earthquake.** Displacement waveforms at cGPS stations KKN4 and NAST (5 samples per  
 373 second) and acceleration waveforms at strong motion station KATNP (figure 1).  
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 377 **Figure 3: Evidence for resonance of Kathmandu basin.** (A)-(C) three components of  
 378 ground velocity observed at two high-rate GPS stations (KKN4 and NAST) and one strong  
 379 motion station (KATNP) in the Kathmandu region. KKN4 is located on hard rock northwest

380 of Kathmandu while the other 2 stations are on soft sediment in the basin. The GPS is  
381 differentiated to velocity and the strong motion integrated after high-pass filtering at 0.02  
382 Hz. (D)-(F) Ground motion amplification observed at the two basin stations. Plotted is the  
383 ratio of the amplitude spectra of the basin stations to the amplitude spectra of the  
384 reference bedrock station KKN4. (G)-(I) 5% damped velocity response spectra for all 3  
385 stations. (J) Close up map showing the location of the basin and bedrock stations.  
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**Figure 4: Slip pulse kinematics during the Gorkha earthquake** (A) Snapshot of slip rate on Main Himalayan Thrust at 27 s after origin time during propagation of the seismic rupture from the model in figure 1. The red star is the hypocenter and dashed lines represent the depth to the fault. The white circles are the centers of 5 subfaults used to compare against theoretical regularized Yoffe source time functions(28). (B) STFs at the 5 locations from (A). Plotted are the inverted slip rates and the regularized Yoffe functions measured from the vertical velocity at KKN4 scaled to the maximum observed slip rate at each point which is indicated numerically. Time is relative to the hypocentral origin ( $28.147^\circ\text{N } 84.708^\circ\text{E}$ ; 2015-04-25 06:11:26.270 UTC).

399	<b>Supplementary Materials:</b>
400	Materials and Methods
401	Figs. S1 to S11
402	Tab. S1 to S2
403	Movie S1
404	References (35-45)
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