Investigation of ground-motion to damage relationship in the Kathmandu Valley from aftershock and microtremor observations

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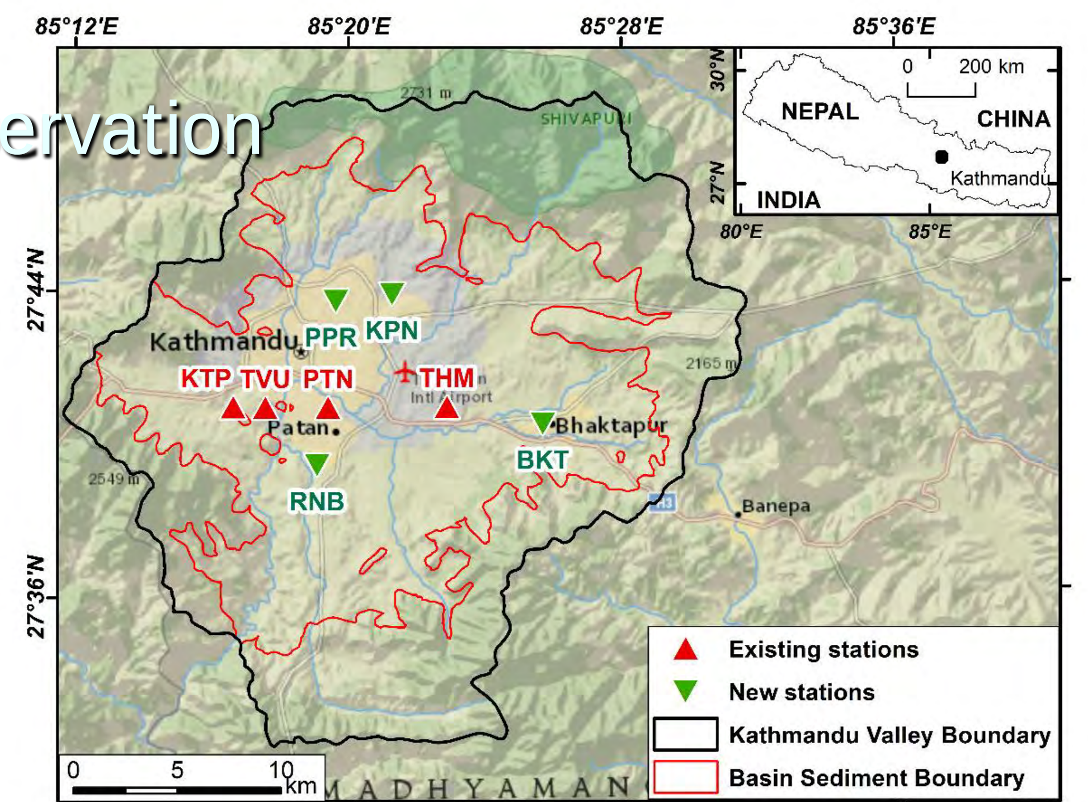
Activity 1:
Strong motion observation

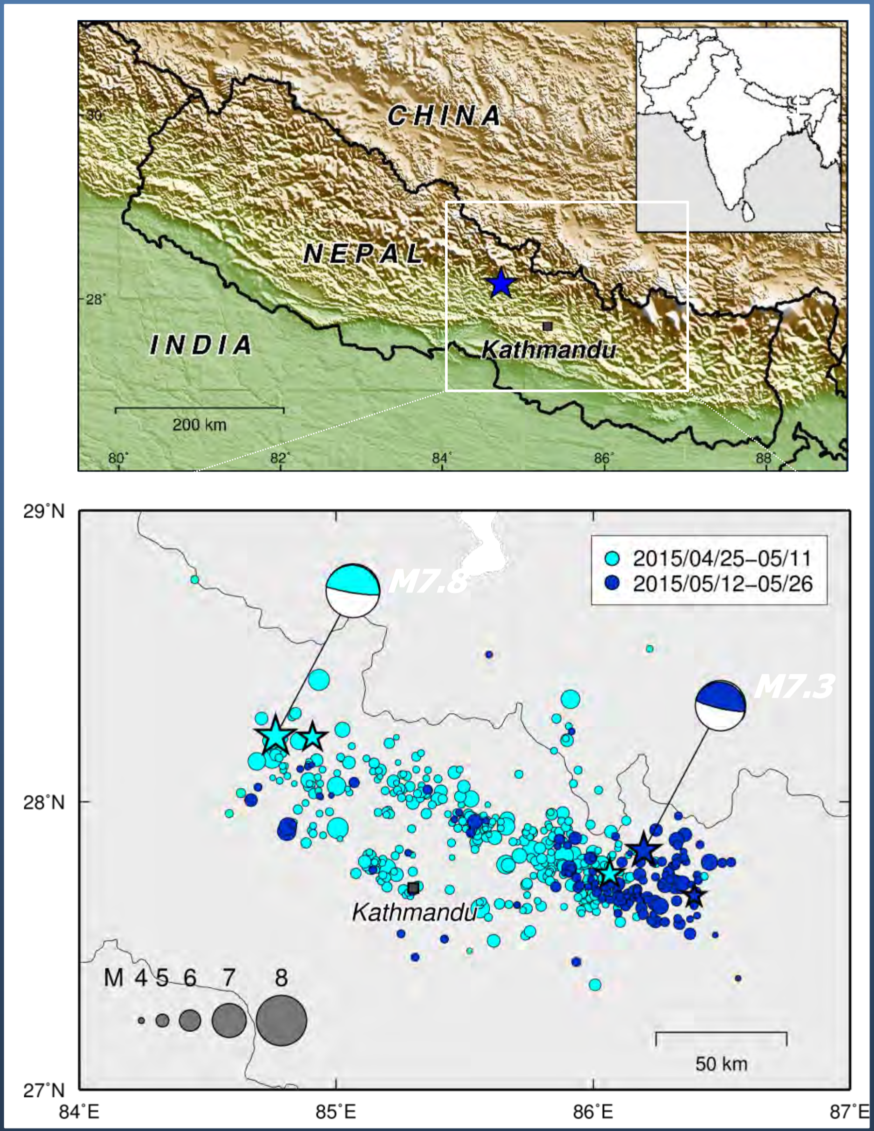
- **Existing stations**
  - From 20 September 2011
  - 4 stations along a west-east profile
- **New stations**
  - From 5 May 2015 (by J-RAPID)
  - 3 stations along a north-south profile
  + Bhaktapur



2015 Gorkha Earthquake Sequence

- **Mainshock**
  - Continental megathrust
  - 2015-04-25 11:56 (UTC)
  - M_w 7.8, Hypocenter: 8.2 km deep
  - 77km NW of Kathmandu

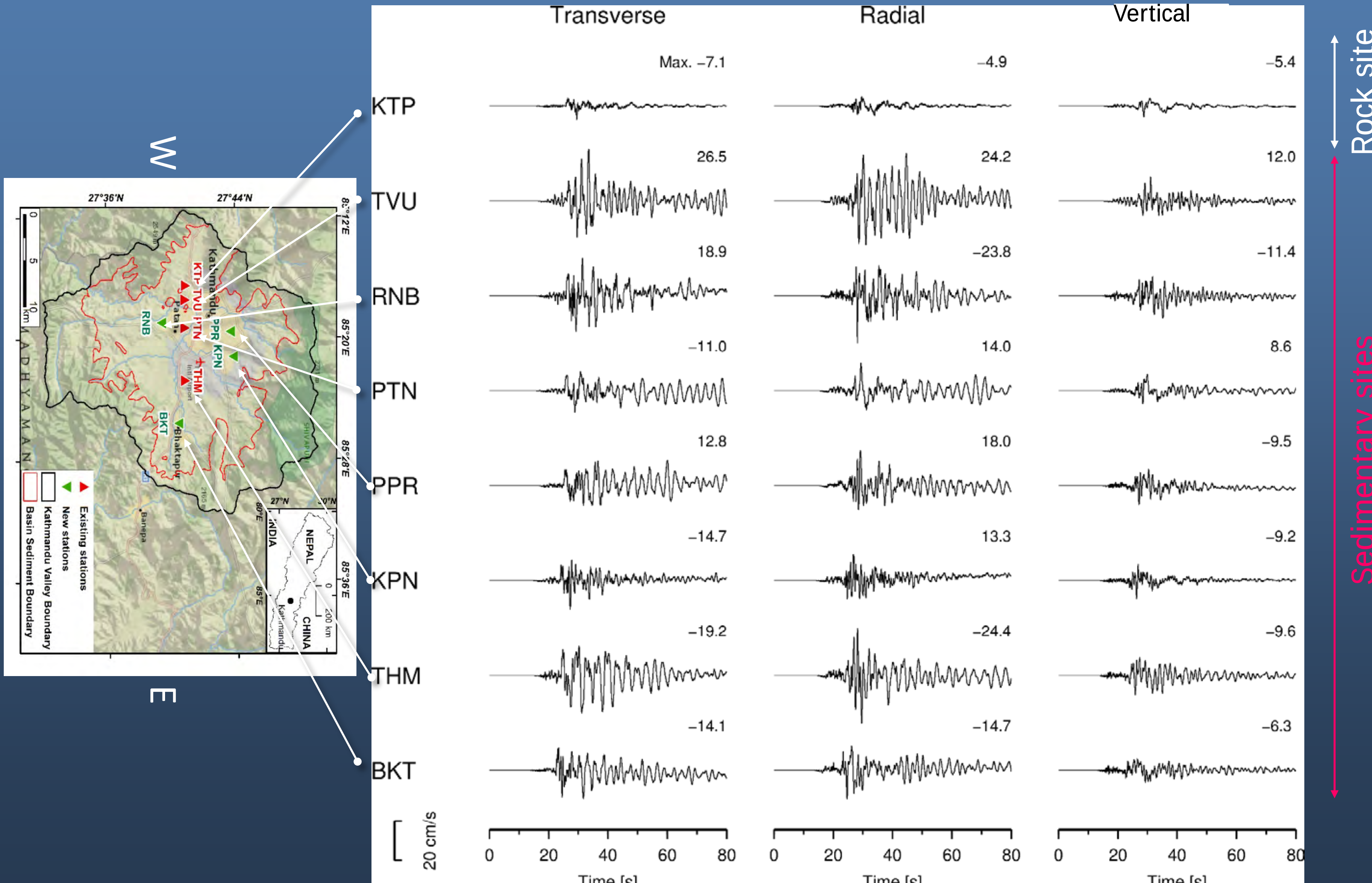
- **Aftershocks M>6: 4 events**
  - Largest aftershock
  - 2015-05-12 07:11
  - M_w 7.3, Hypocenter 15.0 km deep
  - 74 km E of Kathmandu



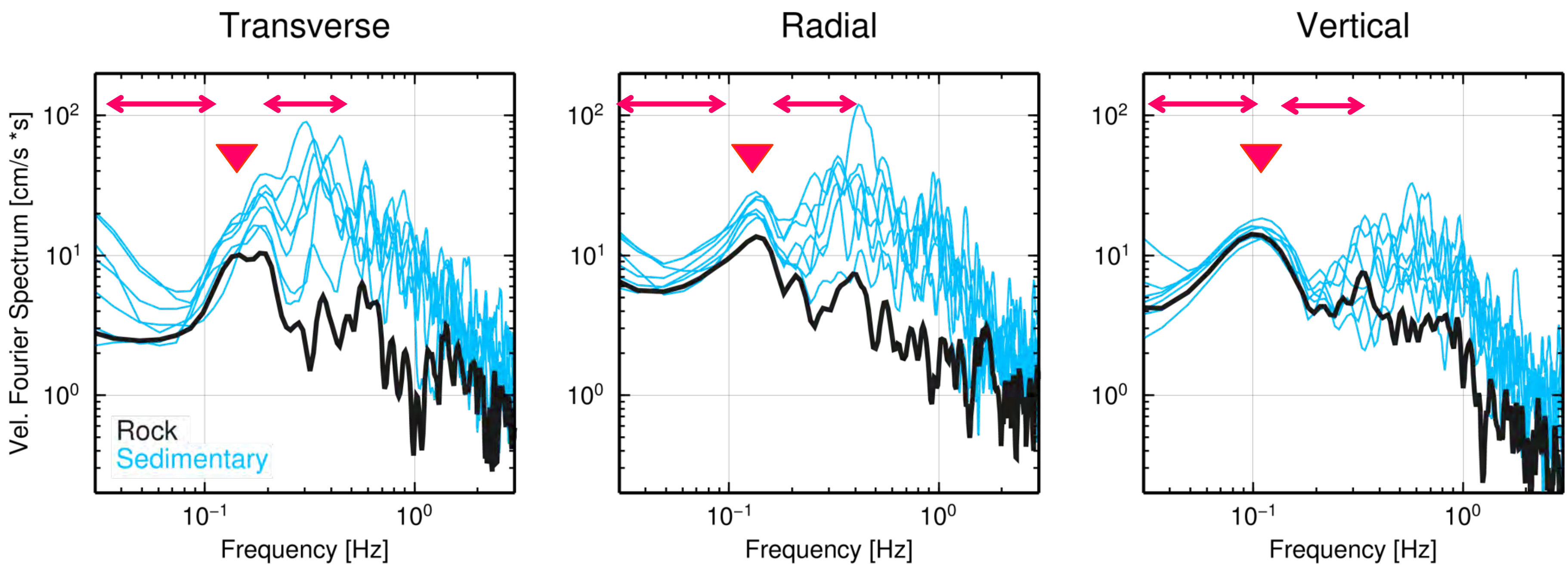
Mechanism USGS, Epicenter NSC 2015/04/25-5/26

Largest Aftershock: 2015-05-12 M7.3

Velocity waveforms



Velocity Fourier spectrum

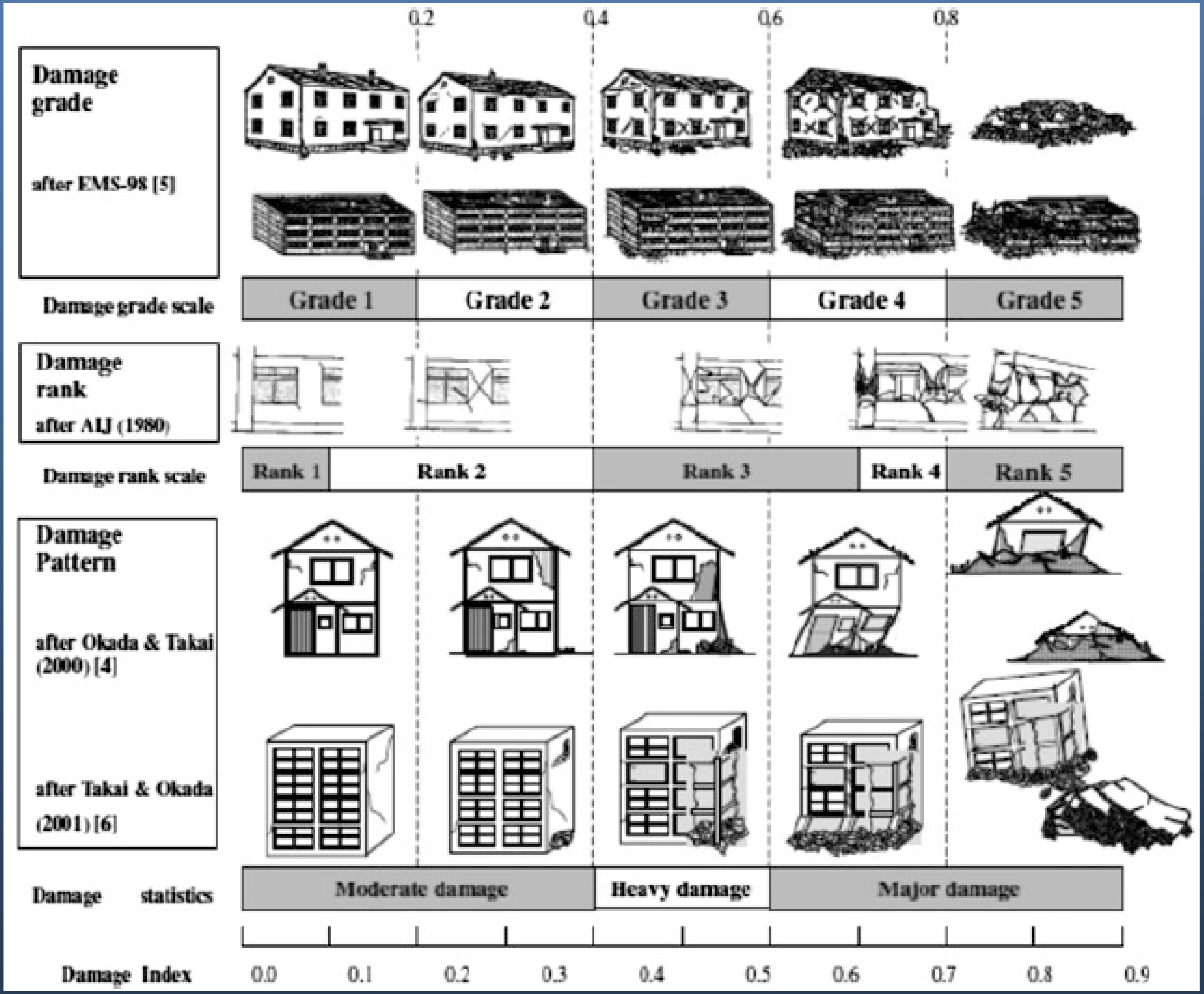


- < 0.1 Hz Small contribution
- 0.1-0.2 Hz Similar peak frequency
- 0.2-0.4 Hz Large amplification and different peak frequency

3rd is the main feature of various sedimentary effects on strong ground motion.

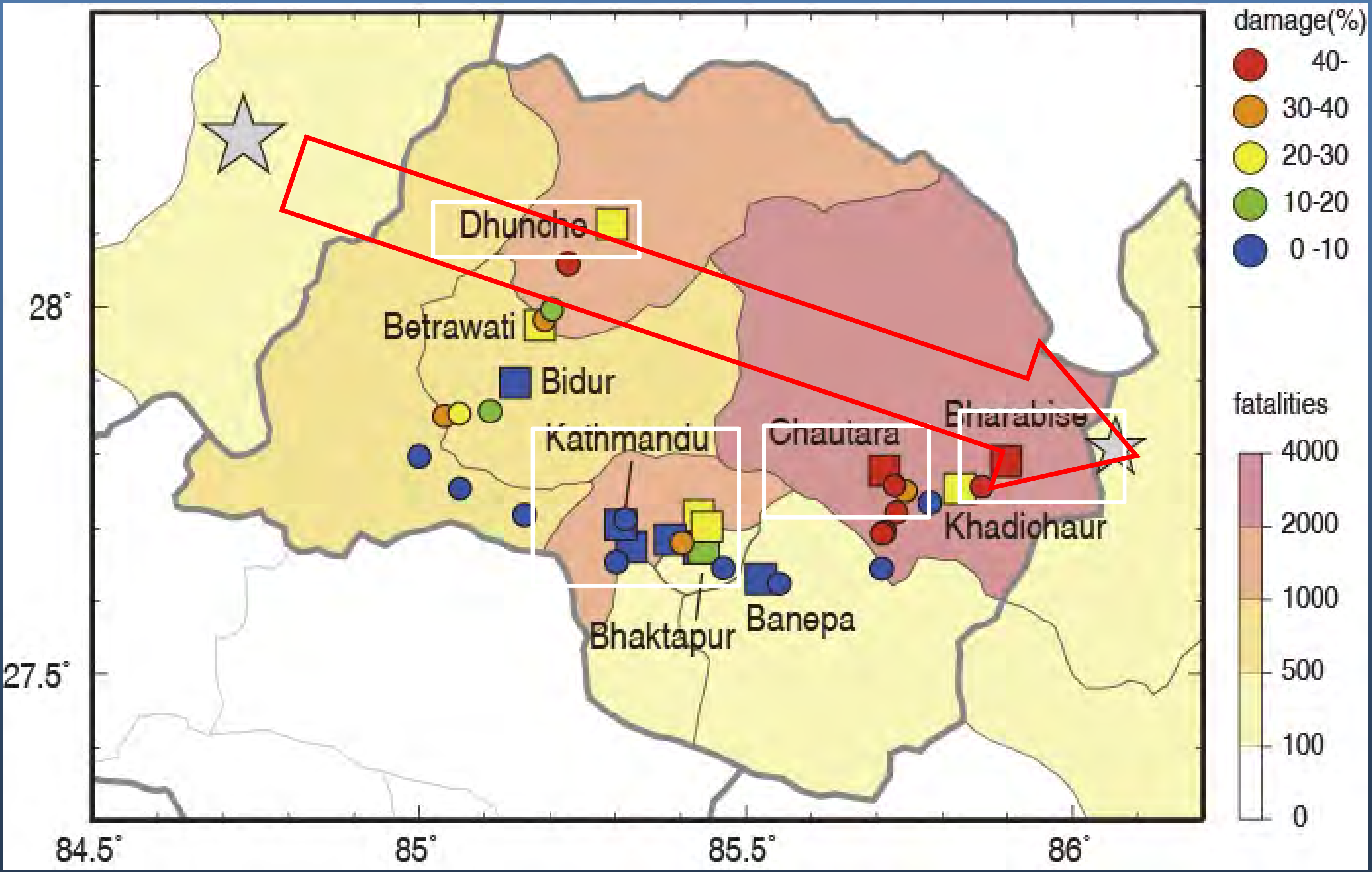
Activity 2:
Damage survey & microtremor observation

Okada (2004)



Results of the damage survey & microtremor observation areas

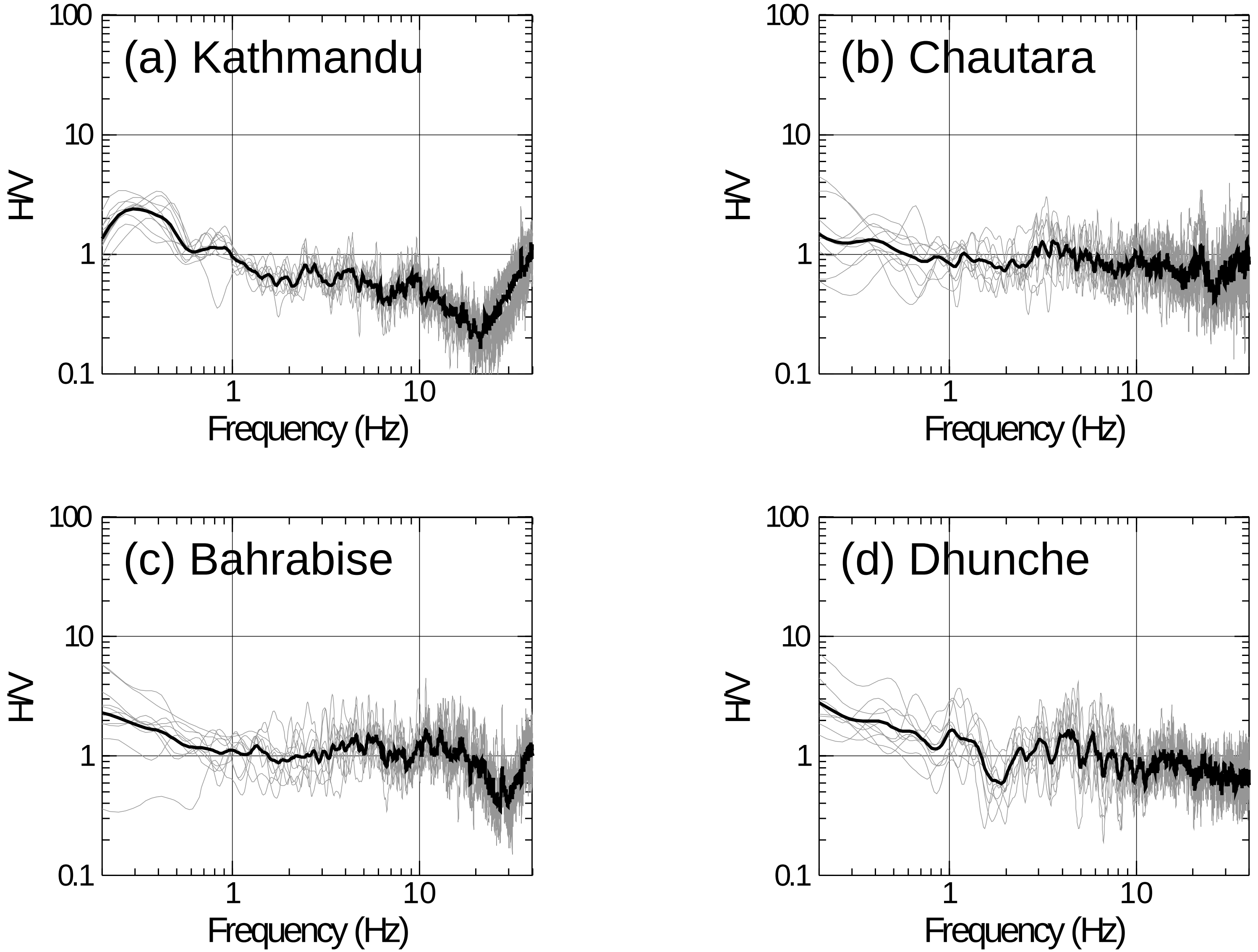
damage grade ≥ 4



Heavy damage sites are distributed from the hypocenter to the east.

Microtremor observations:
H/V ratio at (a) is high only for low frequencies.

H/V spectral ratio of microtremor is a popular index of ground motion amplification.



High-rise structures with low natural frequencies such as Bhimsen Tower were affected the most.

http://www.firstpost.com/world/before-and-after-devastating-earthquake-wipes-off-important-monuments-in-nepal-2214488.html

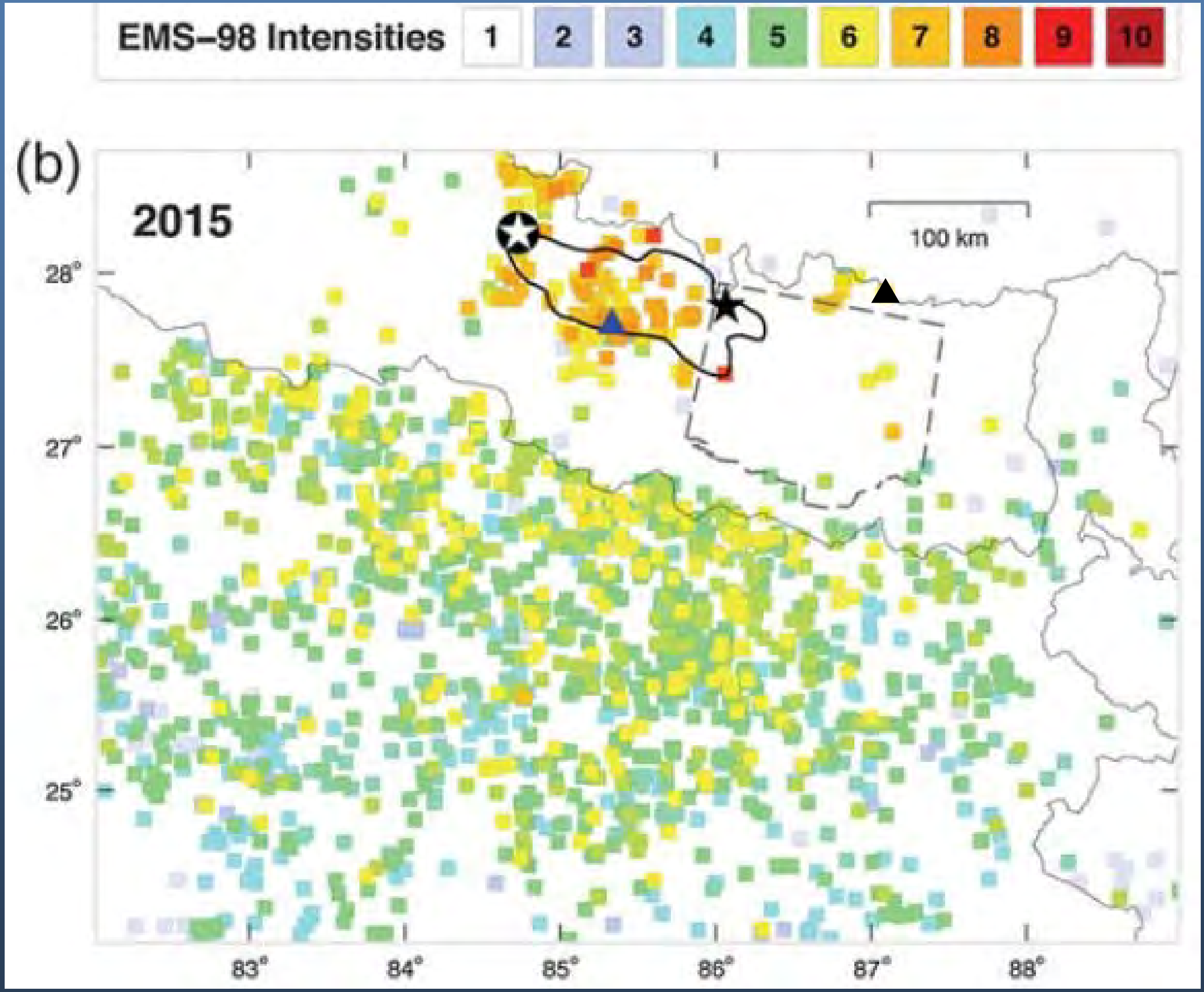
Significant damage extended far eastwards, from central Nepal to the district of Mount Everest.

From jiji.com

This extension can be seen in seismic intensity distribution.

▲ Kathmandu
▲ Mt. Everest

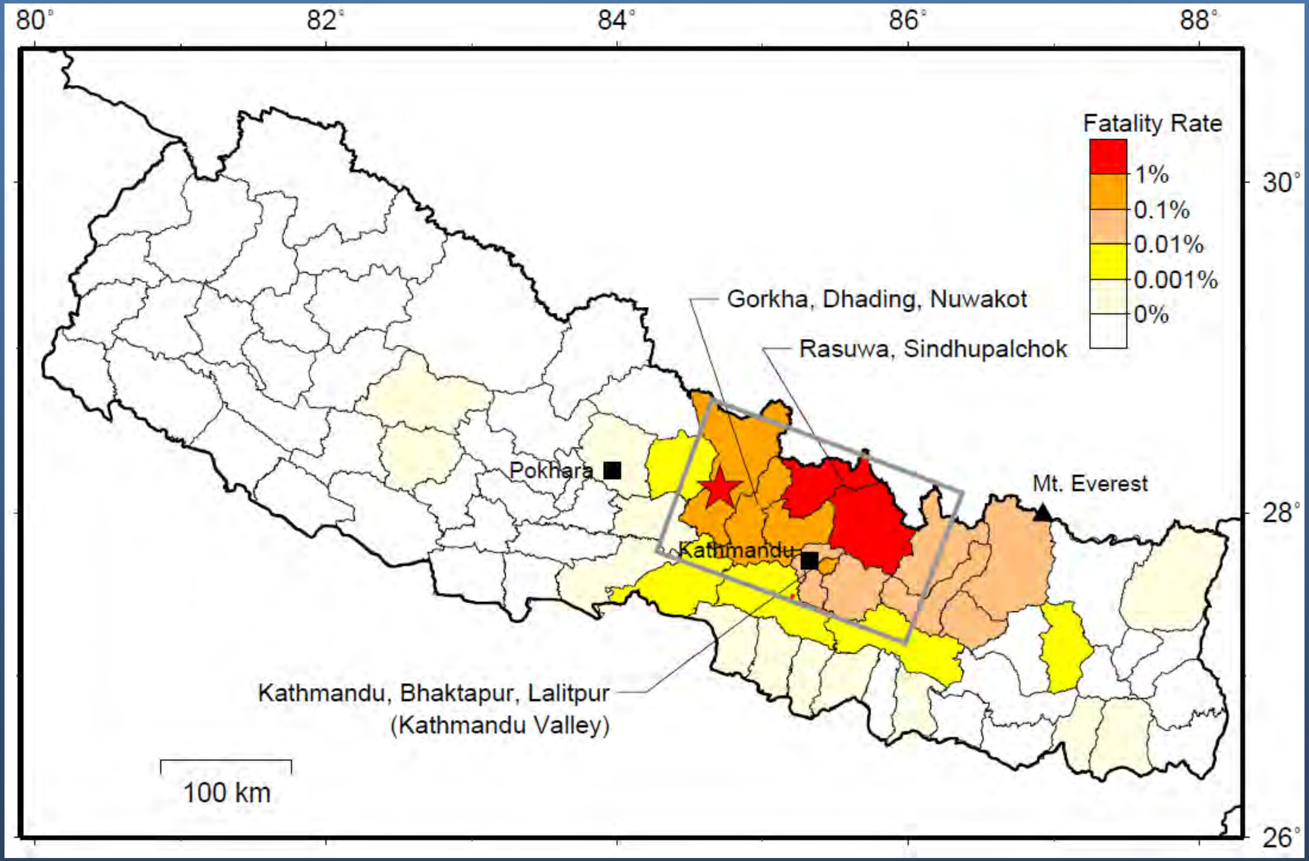
However, there is a part of missing intensity data between longitudes of 86 and 87°.



Martin et al. (2015)

The missing part should be filled with large intensities as can be imagined from

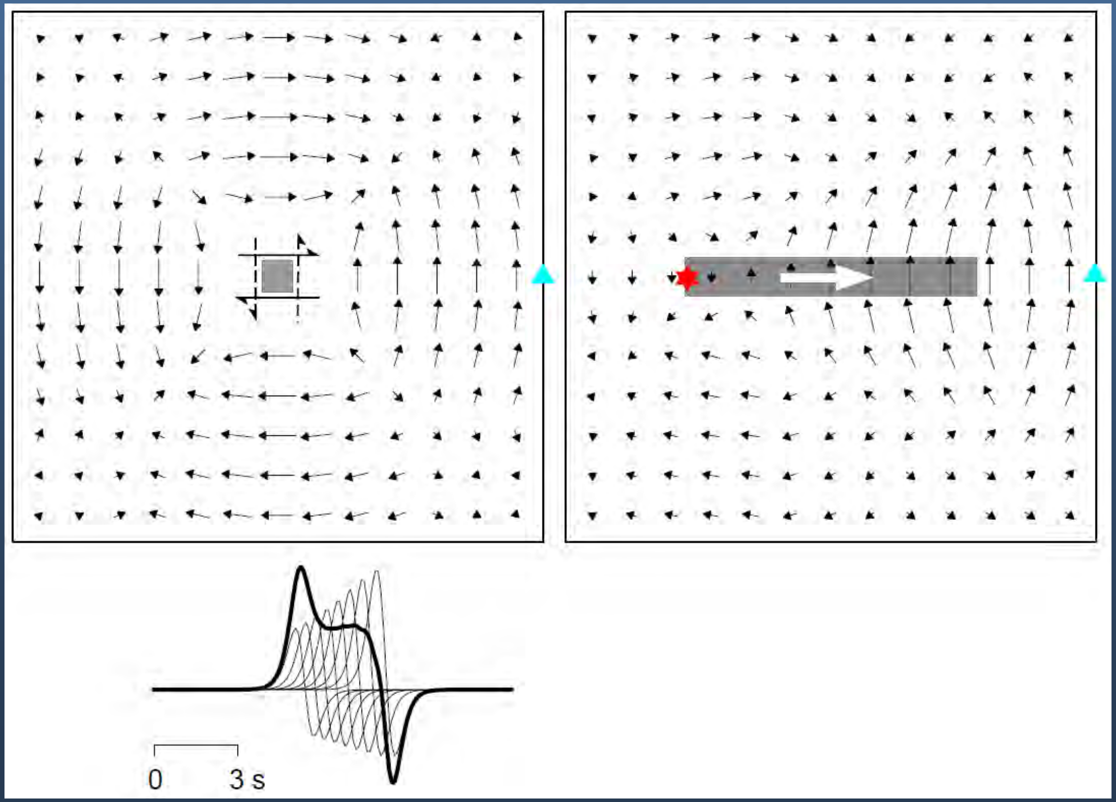
the fatality rate distribution, referring to Sapkota et al. (2016).



The fatality rates were calculated from the numbers of fatalities announced by Nepal Police and district populations of the latest National Census.

Such extension is an obvious evidence of "rupture directivity."

Rupture directivity is a combined effect of rupture propagation, the earthquake source radiation pattern, and particle motion polarization on seismic ground motions (Spudich and Chiou, 2008). This effect is known to cause directional variations in seismic ground motion and damage, and to occur if a strike-slip or dip-slip rupture propagates to a site in the along-strike or updip direction, respectively (Somerville et al., 1997). Large ground motion pulses are generated in the forward propagation direction due to constructive interference.



Other evidence (1): Pulses in Kathmandu Valley

Although Gorkha earthquake was dip-slip faulting and Kathmandu Valley is located in the nearly along-strike direction, large velocity pulses were observed as firm evidence of rupture directivity. Nevertheless, later parts were contaminated by basin reverberation.

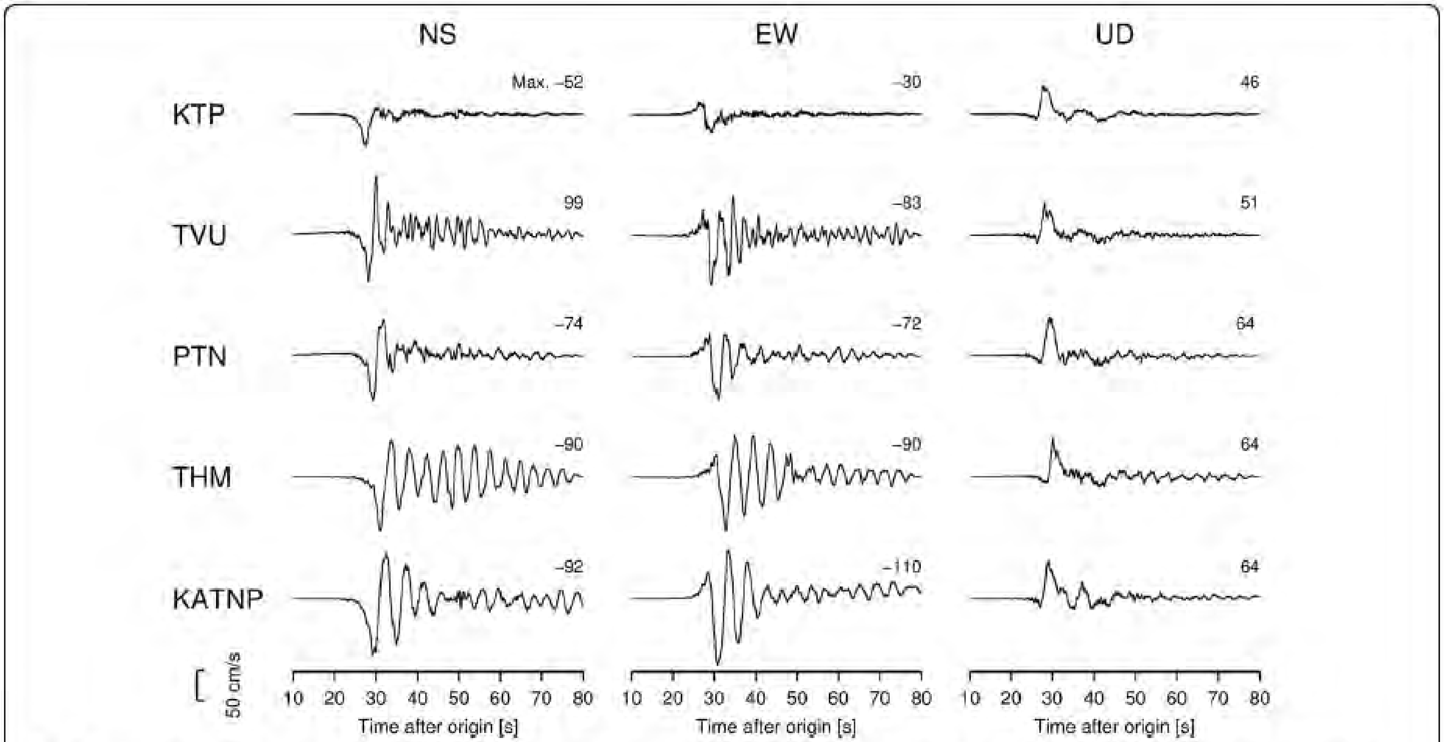
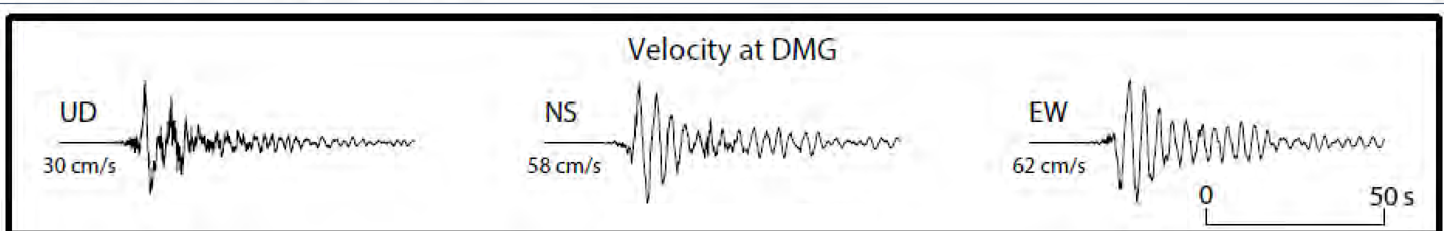


Fig. 3 Ground velocities at five stations. These velocity waveforms were derived by integrating the accelerograms, shown in Fig. 2, by using a linear acceleration method in the time domain

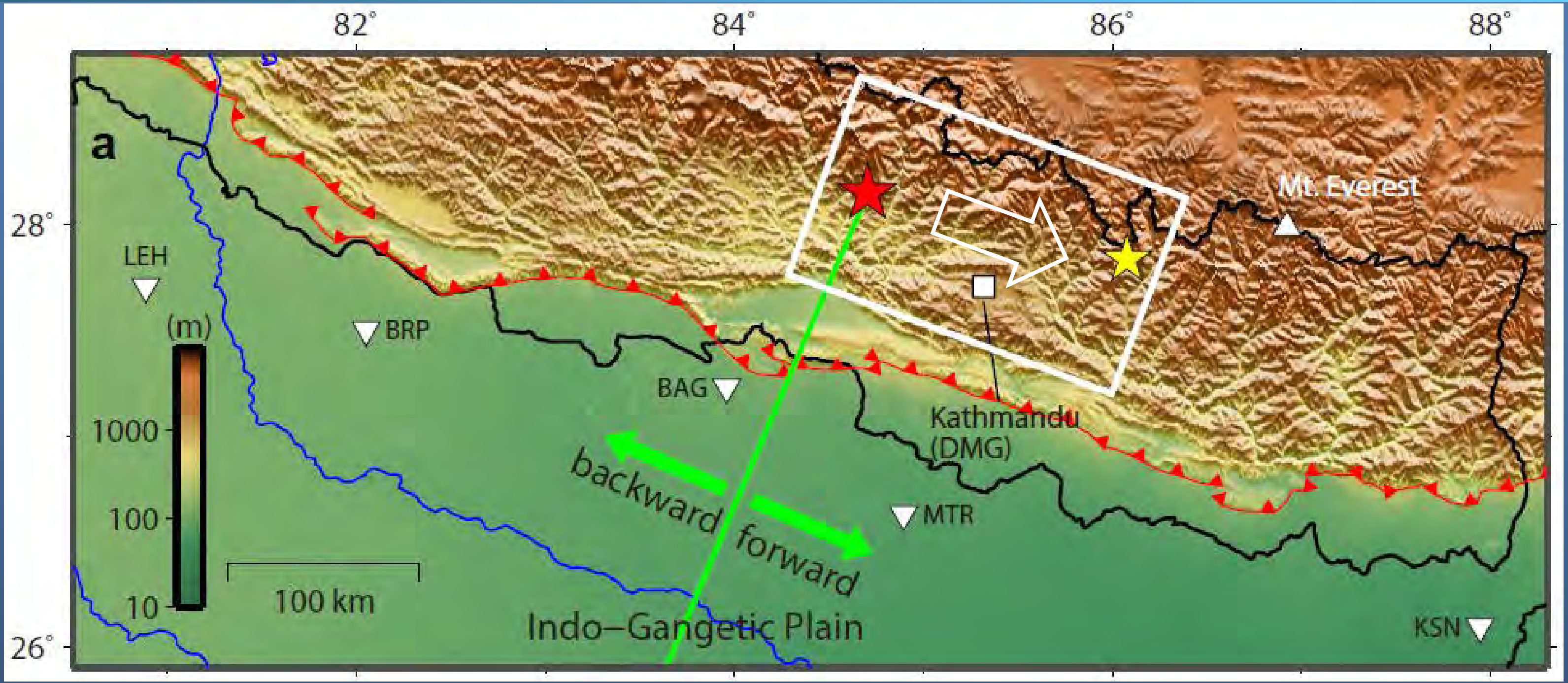
Takai et al. (2016)



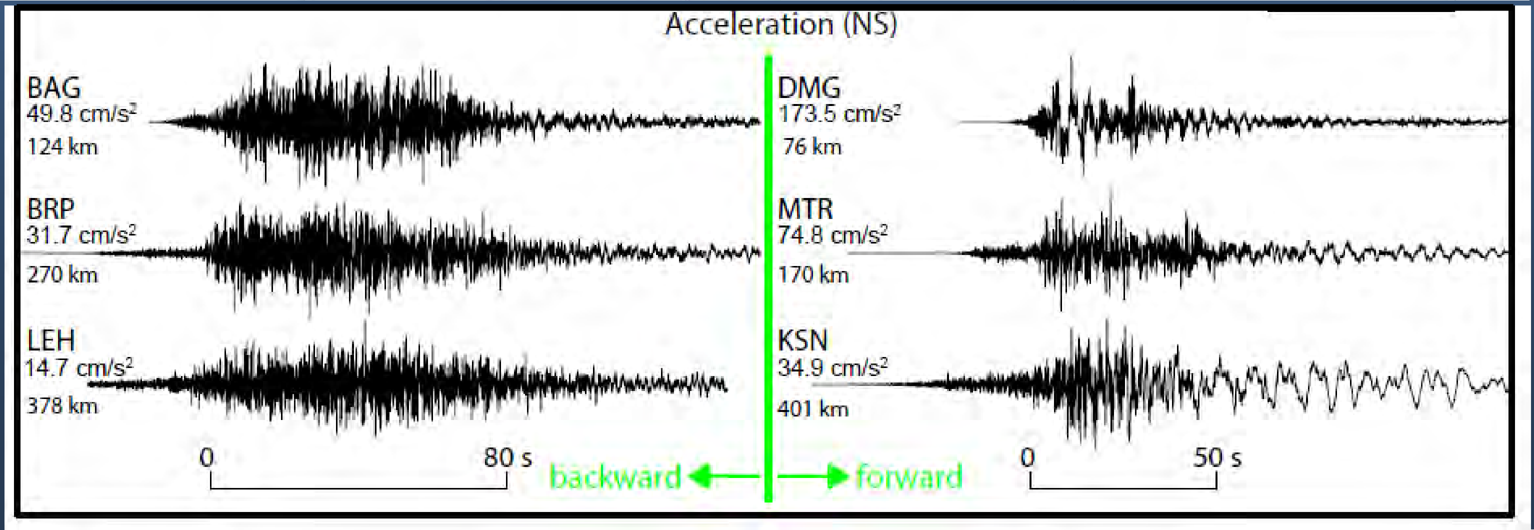
Bhattarai et al. (2015)

Other evidence (2): regional acceleration duration

Considering the location of the hypocenter in the assumed source fault, the rupture should have propagated eastwards.

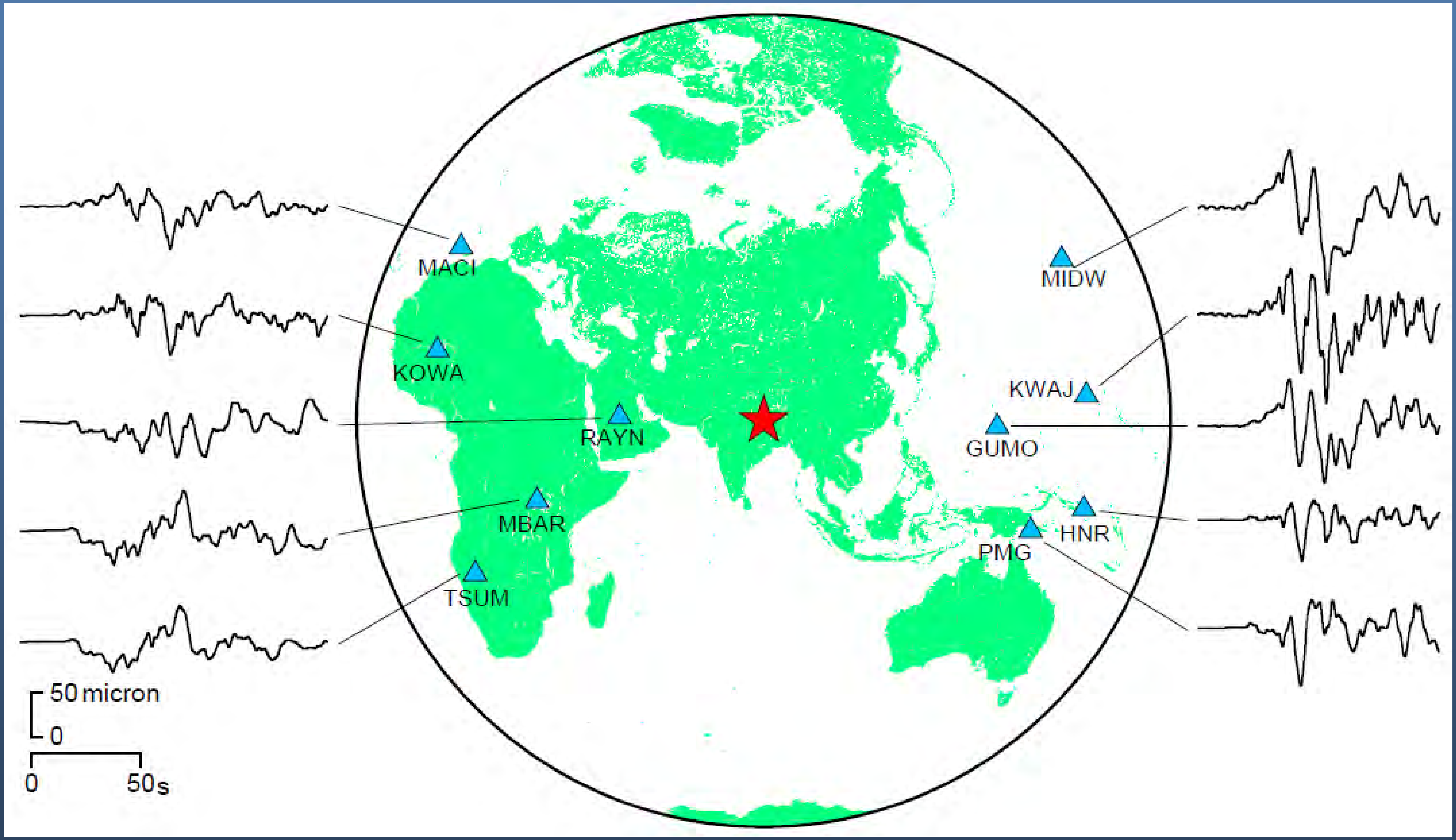


Regional acceleration duration in the forward direction is shorter than in the backward direction.



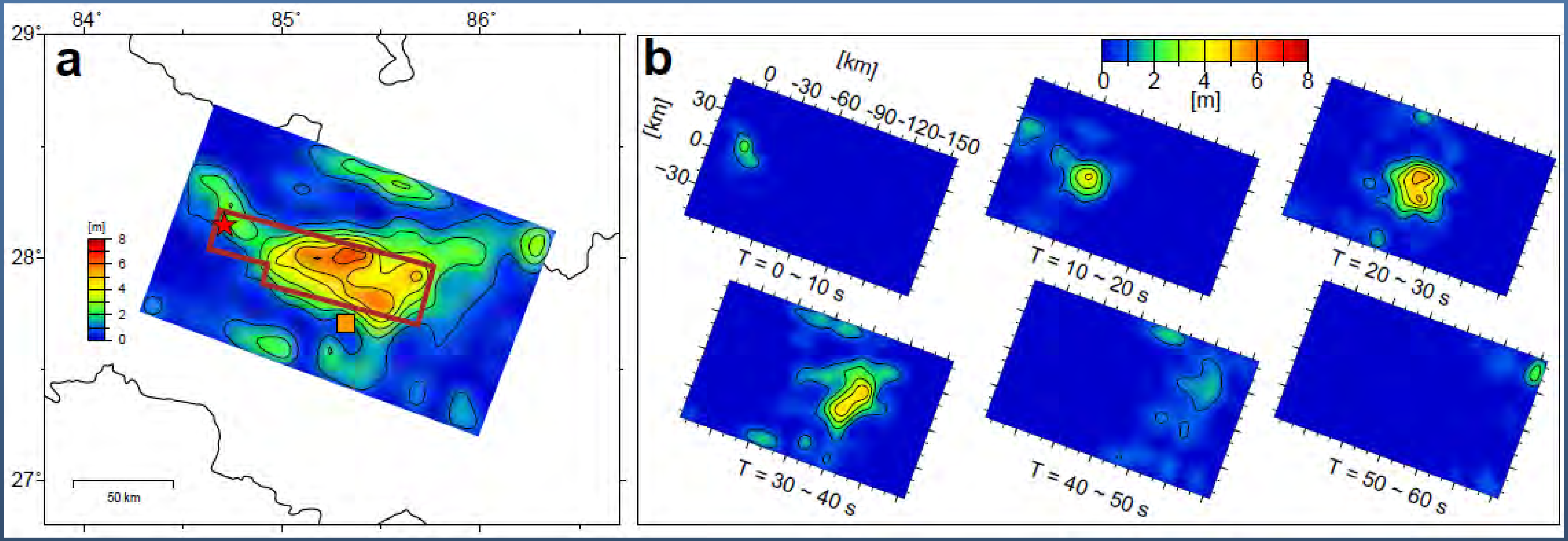
Chadha et al. (2015)

Other evidence (3): teleseismic waveforms



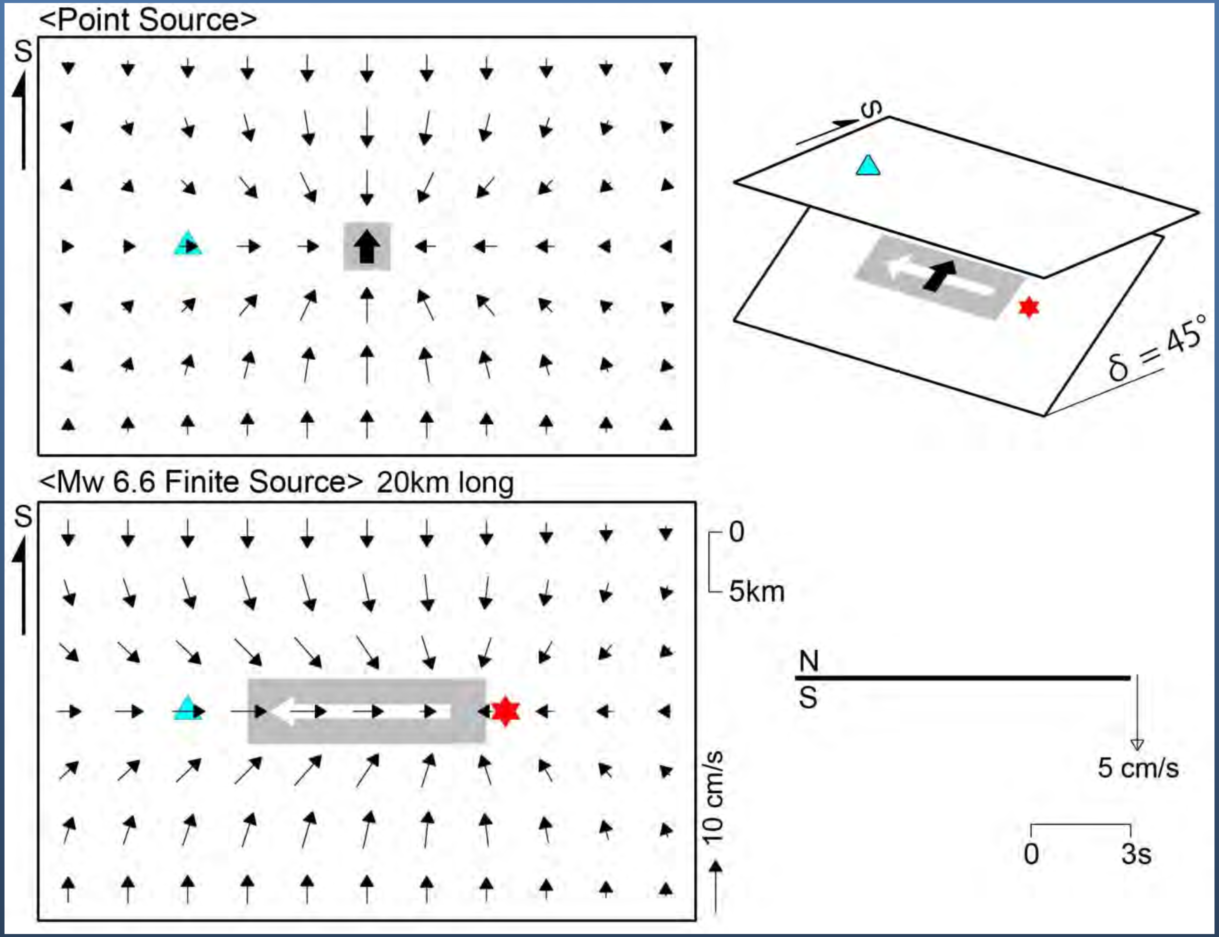
The teleseismic displacement seismograms show both the large pulse-like waveforms and shorter ground motion duration in the forward direction.

Results of source inversion



The source inversion confirmed that the rupture propagated along the fault strike forming a narrow large-slip area in the north of Kathmandu. The rupture velocity is as fast as 3.1 km/s, about 90% of S-wave velocity.

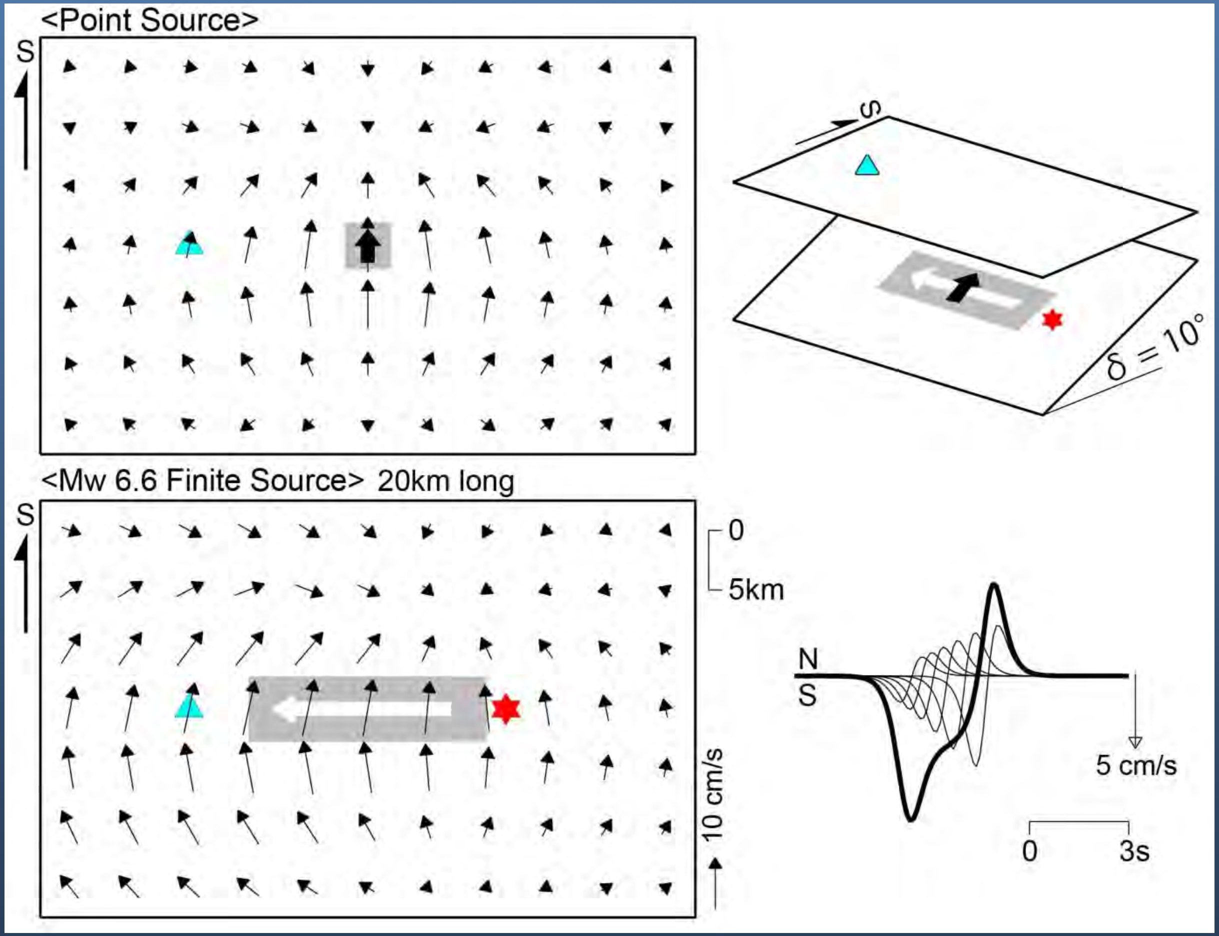
Why along-strike rupture directivity for dip-slip faulting?



A typical dip-slip earthquake with a dip angle of 45° has a nodal plane extending to the immediately above ground, so rupture directivity cannot be found.

The Gorkha case is

a dip-slip earthquake with a dip angle of as low as 10°

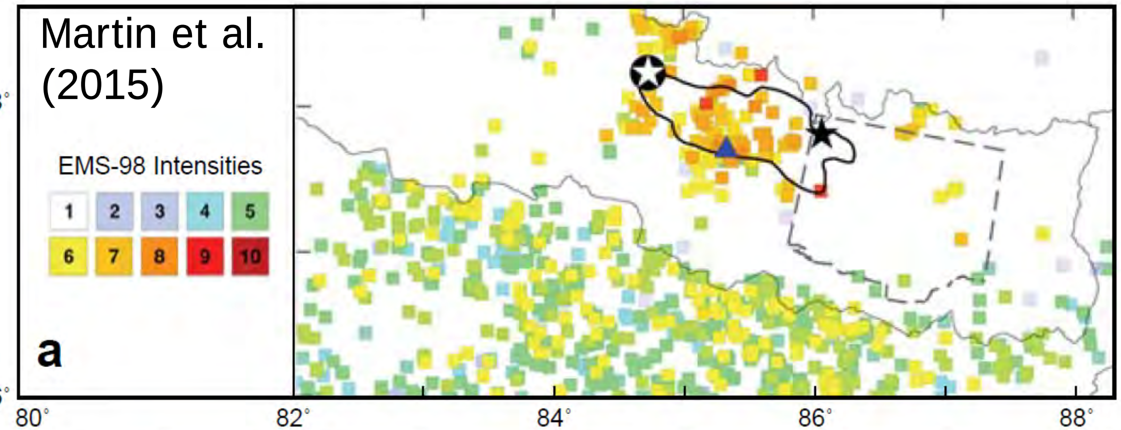


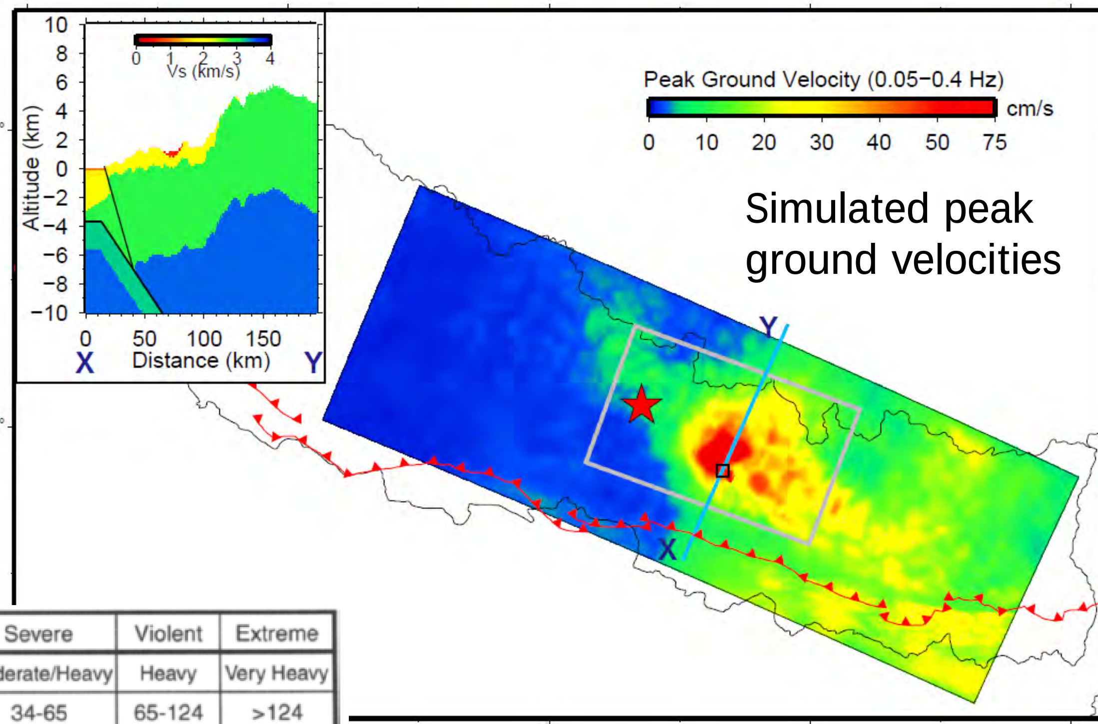
In this case rupture directivity can be identified, because the immediately above ground is located in a lobe of large S-wave.

To confirm the previous slides, we conducted ground motion simulations.

We modeled the 3-D velocity structure based on a geological profile in central Nepal, global relief data, a global model of Earth's crust, and a geological model of the Kathmandu Valley. Using this model and the source inversion result, we conducted ground motion simulations by Voxel FEM.

It was found that the resultant distribution of peak ground velocities simulates the intensity distribution augmented by the fatality rate distribution fairly well, if we refer to the relationship of intensities and peak ground velocities (Wald et al., 1999).



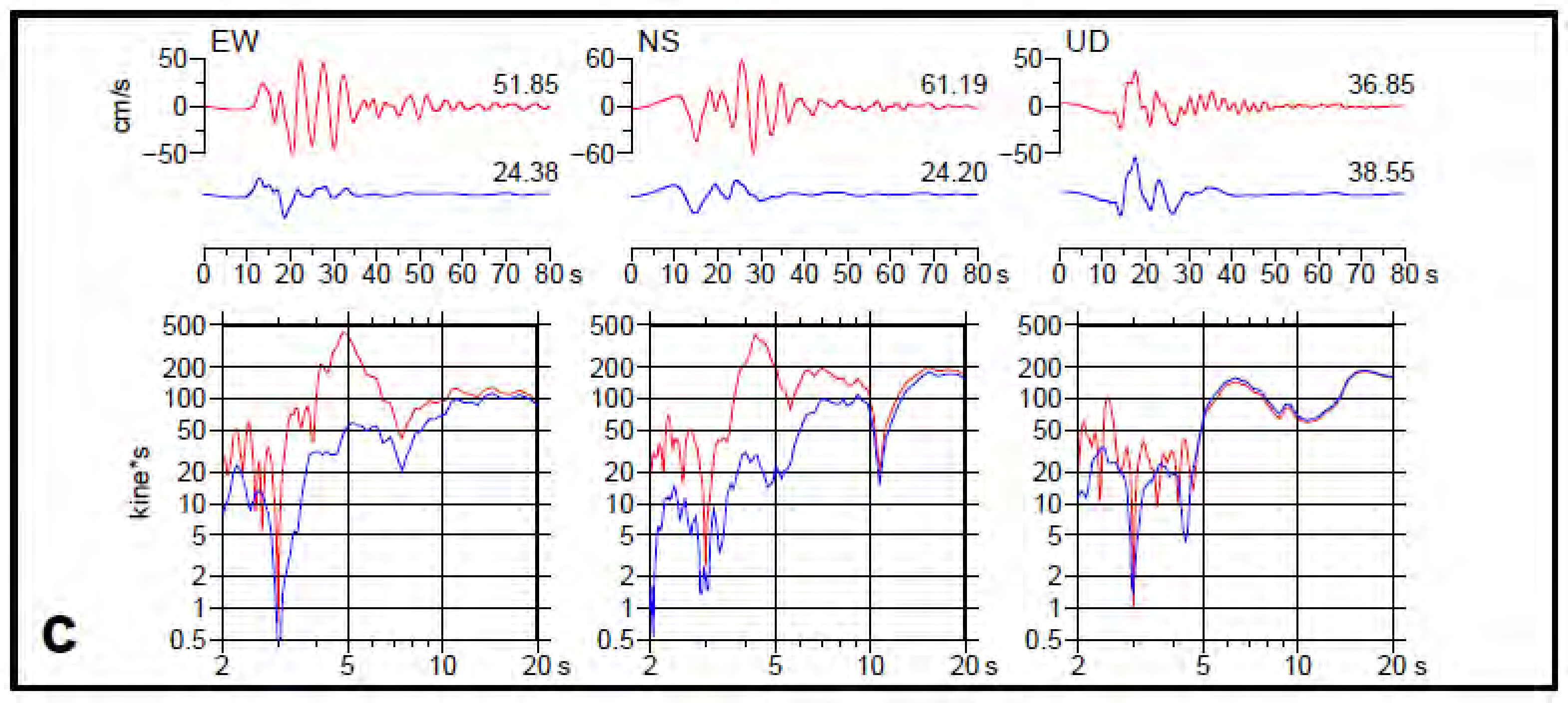


Wald et al. (1999)

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL. (cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Velocity structures with or without Kathmandu Valley

Ground velocities simulated with the velocity structure with Kathmandu Valley (upper red traces) or that without Kathmandu Valley (upper blue traces). Their Fourier spectra are also shown in the lower half.



The comparison indicates that the horizontal ground velocities were amplified twice or more by the sediments, while no amplification was found in the vertical component. In particular, at resonant frequencies of 4 to 5 s, the horizontal velocity spectra were amplified by as much as ten times.

Conclusions

- The damage survey suggested that strong ground motions from the Gorkha earthquake extended along the strike of the source fault.
- Aftershock and microtremor observations suggested that horizontal ground velocities were amplified at frequencies of 0.2 – 0.4 Hz by the sediments in Kathmandu Valley.
- The extended ground motion distribution implied that along-strike rupture directivity for dip-slip faulting was found for the first time during the Gorkha earthquake with a low dip angle.
- The rupture directivity was confirmed by observational evidences such as ground motion pulses, regional acceleration duration, and teleseismic waveforms.
- It was then firmly confirmed by the comparison of observed and simulated ground motion distributions.
- We showed that the radiation pattern of low-angle dip-slip faulting could lead the along-strike rupture propagation to the rupture directivity effects.
- Ground motion simulations also confirmed the amplification by the sediments in Kathmandu Valley.

Publications

- Takai, N., M. Shigefuji, S. Rajaure, S. Bijukchhen, M. Ichiyanagi, M. R. Dhital and T. Sasatani, Strong ground motion in the Kathmandu Valley during the 2015 Gorkha, Nepal, earthquake, *Earth, Planets and Space*, **68**(10), doi:10.1186/s40623-016-0383-7, 2016.
- Yamada, M., T. Hayashida, J. Mori and W. D. Mooney, Building damage survey and microtremor measurements for the source region of the 2015 Gorkha, Nepal earthquake, *Earth, Planets and Space*, in press.
- Koketsu, K., H. Miyake, Y. Guo, H. Kobayashi, T. Masuda, S. Davuluri, M. Bhattarai, L. B. Adhikari and S. N. Sapkota, Widespread ground motion distribution caused by rupture directivity during the 2015 Gorkha, Nepal earthquake, *Scientific Reports*, **6**(28536), doi: 10.1038/srep28536, 2016.

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Widespread ground motion distribution caused by rupture directivity during the 2015 Gorkha, Nepal earthquake

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The ground motion and damage caused by the 2015 Gorkha, Nepal earthquake can be characterized by their widespread distributions to the east. Evidence from strong ground motions, regional acceleration duration, and teleseismic waveforms indicate that rupture directivity contributed significantly to these distributions. This phenomenon has been thought to occur only if a strike-slip or dip-slip rupture propagates to a site in the along-strike or updip direction, respectively. However, even though the earthquake was a dip-slip faulting event and its source fault strike was nearly eastward, evidence for rupture directivity is found in the eastward direction. Here, we explore the reasons for this apparent inconsistency by performing a joint source inversion of seismic and geodetic datasets, and conducting ground motion simulations. The results indicate that the earthquake occurred on the underthrusting Indian lithosphere, with a low dip angle, and that the fault rupture propagated in the along-strike direction at a velocity just slightly below the *S*-wave velocity. This low dip angle and fast rupture velocity produced rupture directivity in the along-strike direction, which caused widespread ground motion distribution and significant damage extending far eastwards, from central Nepal to Mount Everest.

The Gorkha earthquake occurred on 25 April 2015 (UT) in the north part of central Nepal, causing widespread damage with more than 8,000 fatalities. In the Himalayan region, including Nepal, the Indian plate is colliding with the southern margin of the Eurasian plate, and the Indian lithosphere underthrusts beneath the Himalayas[1] along the Main Himalayan Thrust (MHT), which reaches the ground surface at the Main Frontal Thrust (MFT; Fig. 1a). This underthrusting generates large Himalayan earthquakes, the hazards of which have been noted for decades, together with the seismic vulnerability of the countries around the Himalayas[2,3]. According to the tectonics described above and the result of the Global CMT Project (GCMT)[4], the focal mechanism of the Gorkha earthquake was dip-slip rupture with a strike of west-northwest (WNW).

Rupture directivity is a combined effect of rupture propagation, the earthquake source radiation pattern, and particle motion polarization on seismic ground motions[5]. This effect is known to cause directional variations in seismic ground motion and damage[6–9], and to occur if a strike-slip or dip-slip rupture propagates to a site in the along-strike or updip direction, respectively[10]. However, although the focal mechanism of the 2015 Gorkha earthquake was dip-slip faulting, as mentioned above, rupture directivity was found in the Kathmandu Valley, which is located in the nearly along-strike direction.

The ground motions observed by the Department of Mines and Geology (DMG) of Nepal in Kathmandu during the earthquake (upper traces in Fig. 1b)[11] show large pulse-like waveforms, especially in the vertical component, although the later parts of the horizontal components were complicated by the basin effects of the Kathmandu Valley. Such ground motion pulses are considered to be firm evidence of rupture directivity[6–9]. The occurrence of rupture directivity was also confirmed by the regional acceleration seismograms[12] in the lower traces in Fig. 1b, where the strong-motion duration in the forward direction is shorter than in the backward

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