EARTHQUAKE HAZARD IN THE HIMALAYA

Lessons learnt from recent earthquakes

Outline

- Broad Context
- Himalayan Seismicity (recent examples)
- What have we learnt?

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India is surrounded by Active Plate Boundaries

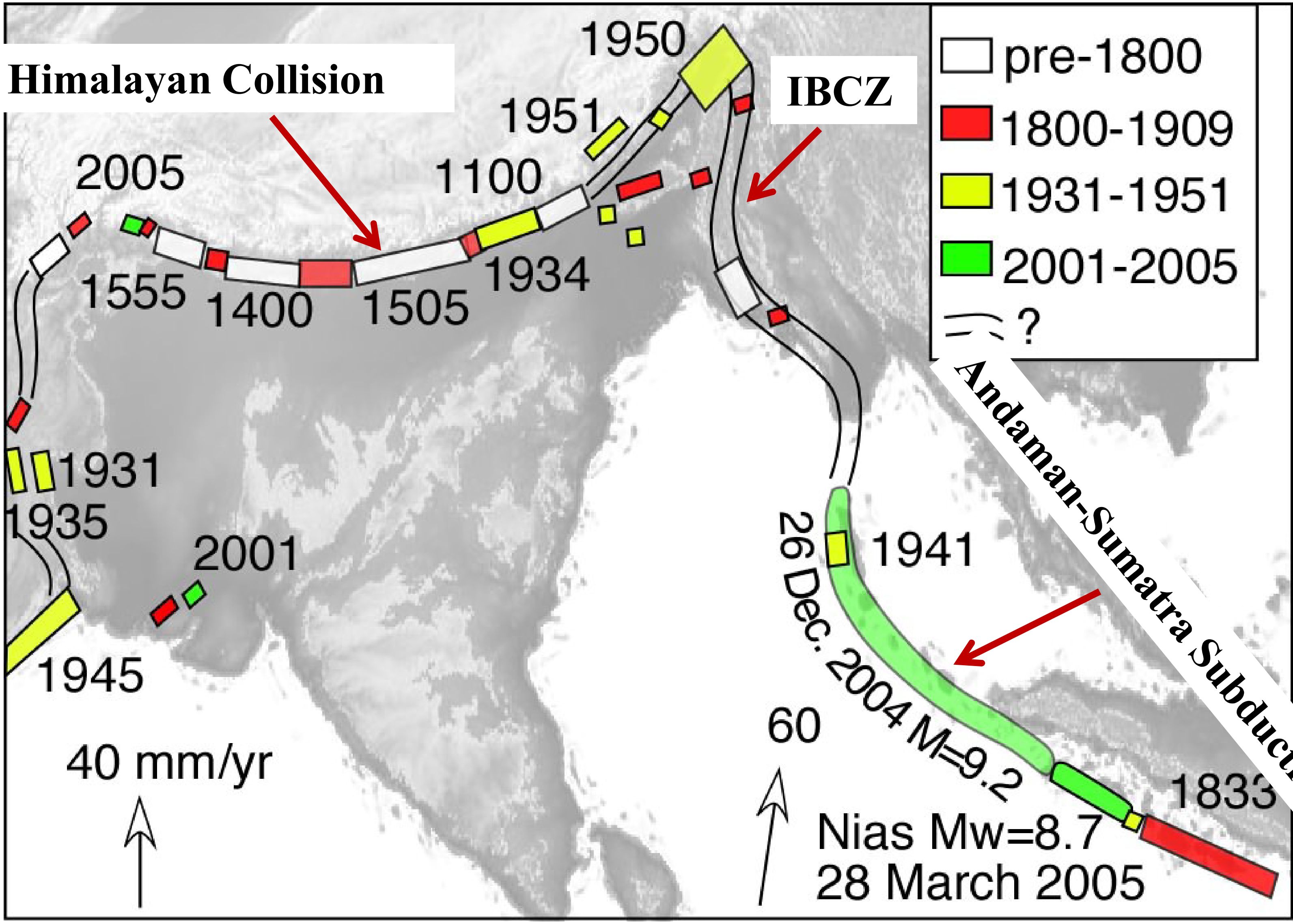
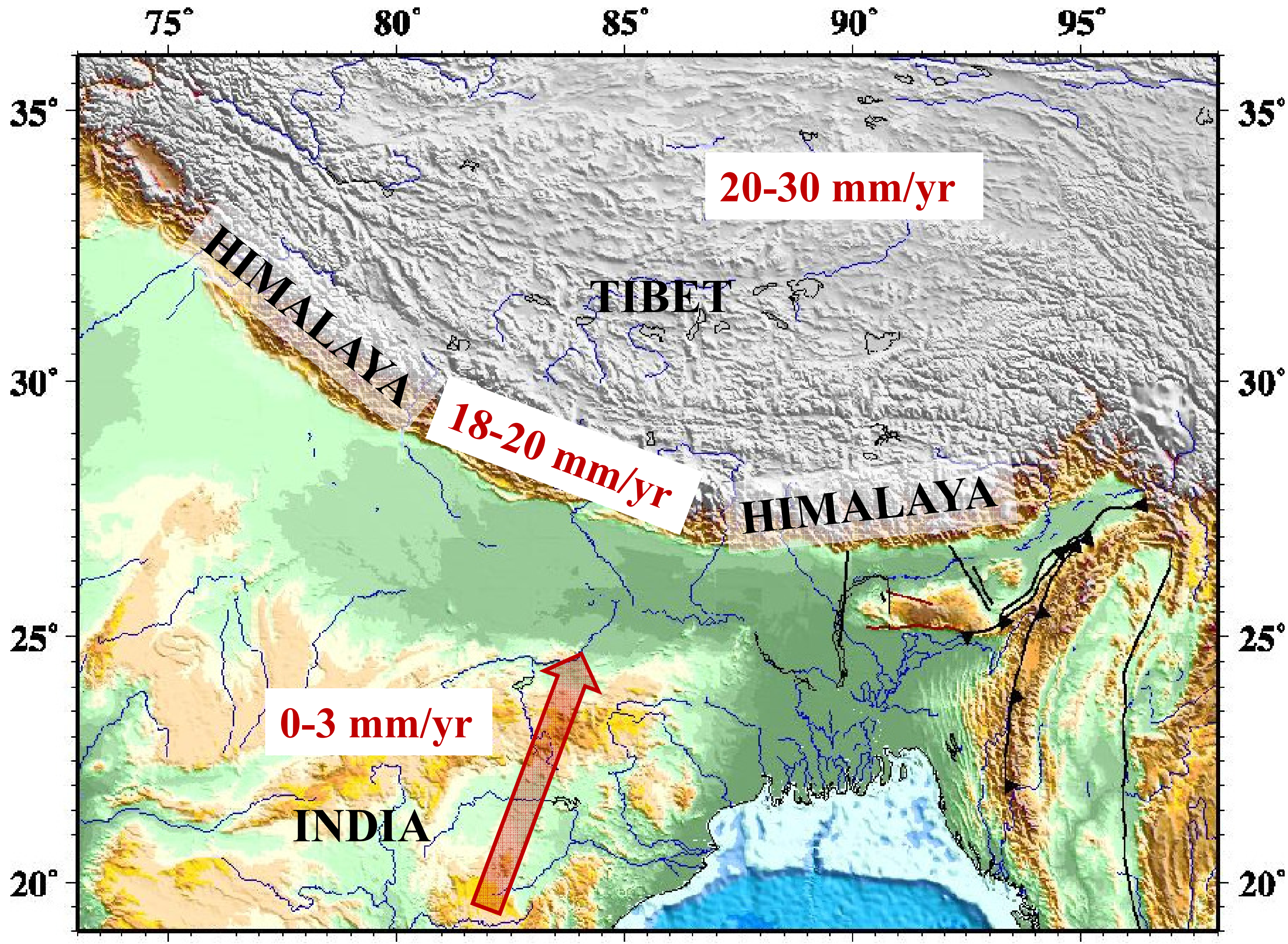
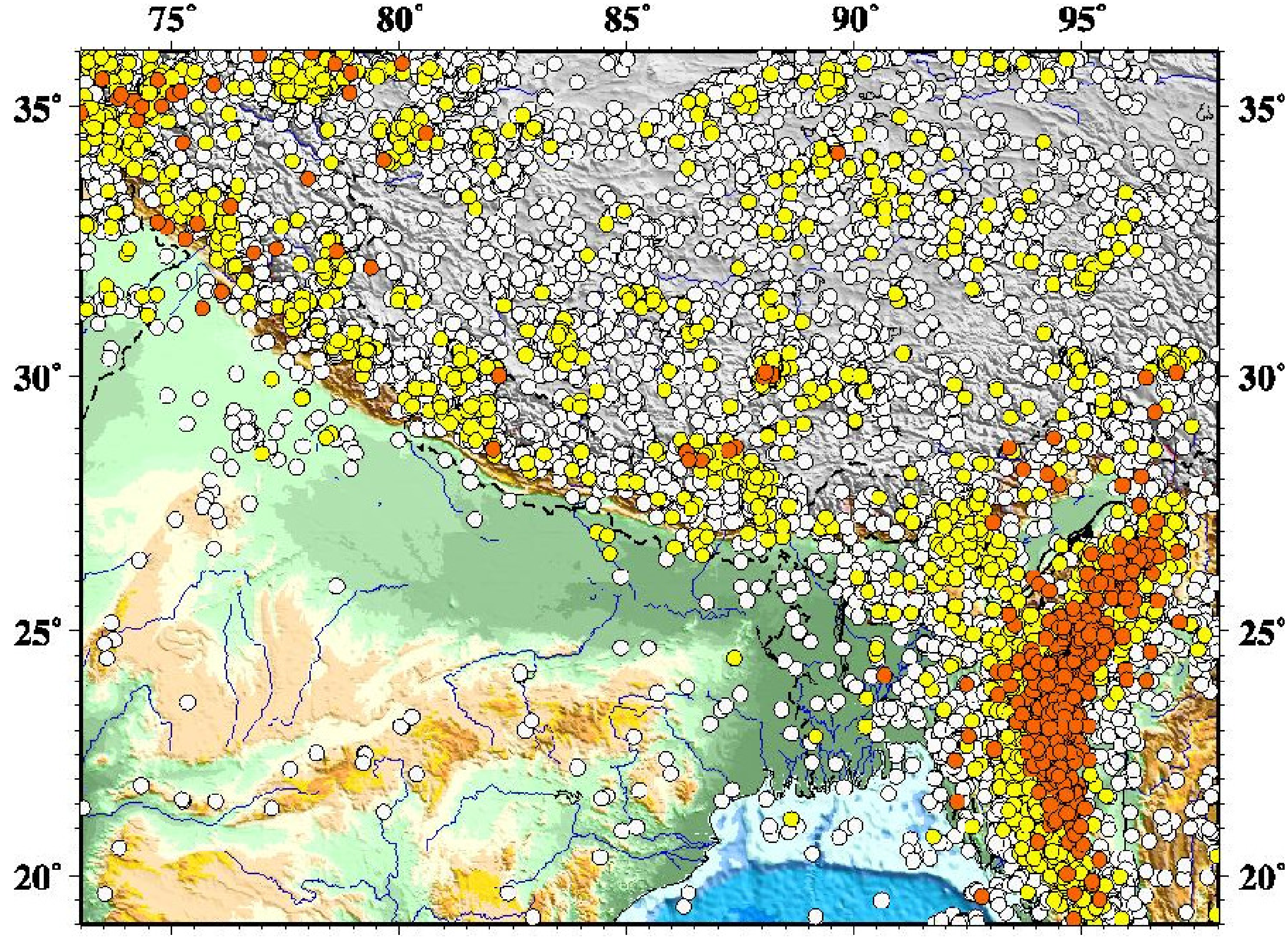


Figure courtesy Roger Bilham

Continent-Continent Collision: 40-50 mm/yr shortening



<u>Continent-Continent Collision</u>: 40-50 mm/yr shortening



Major Plate Boundary Earthquakes and 'Seismic Gaps'

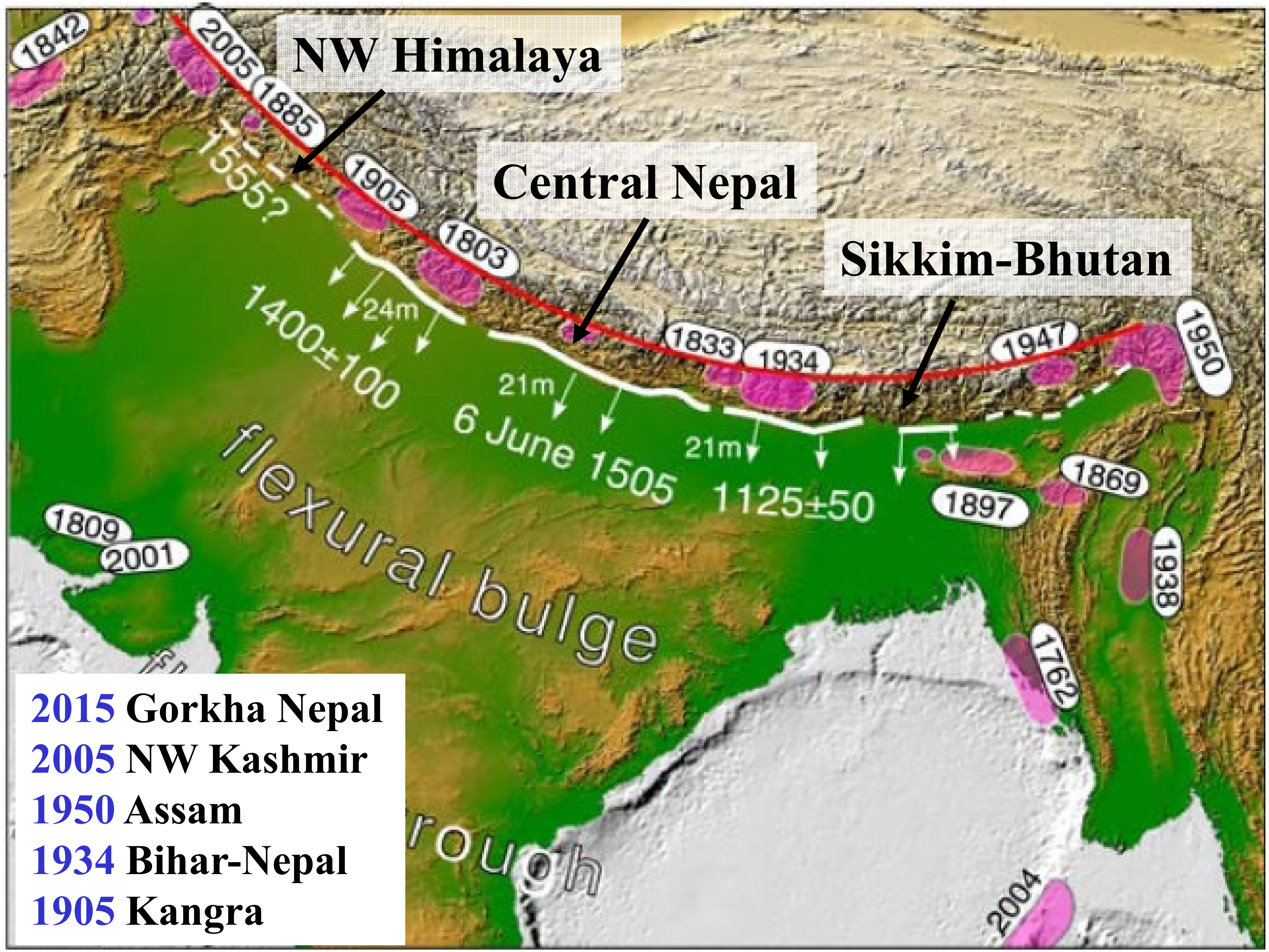
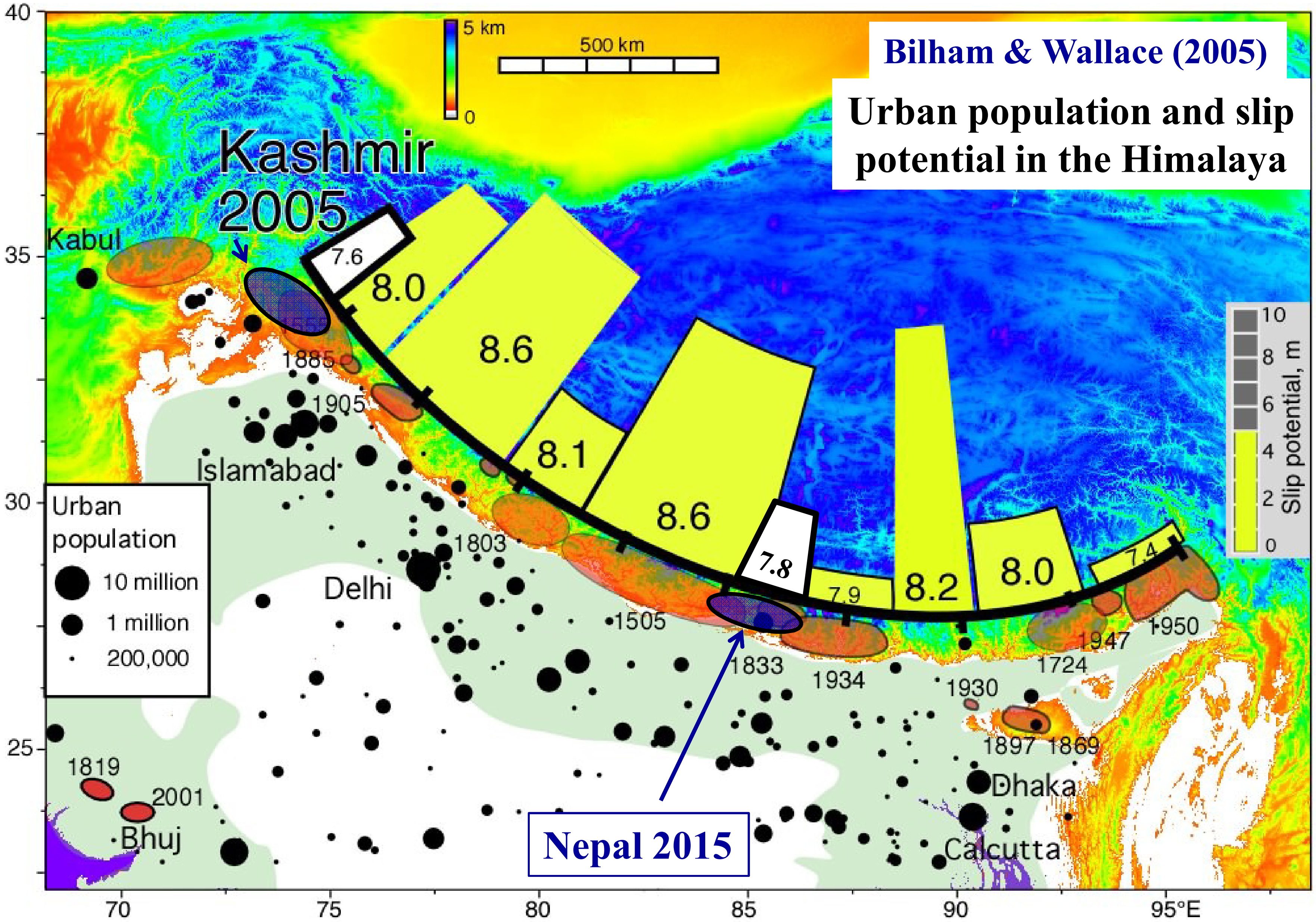
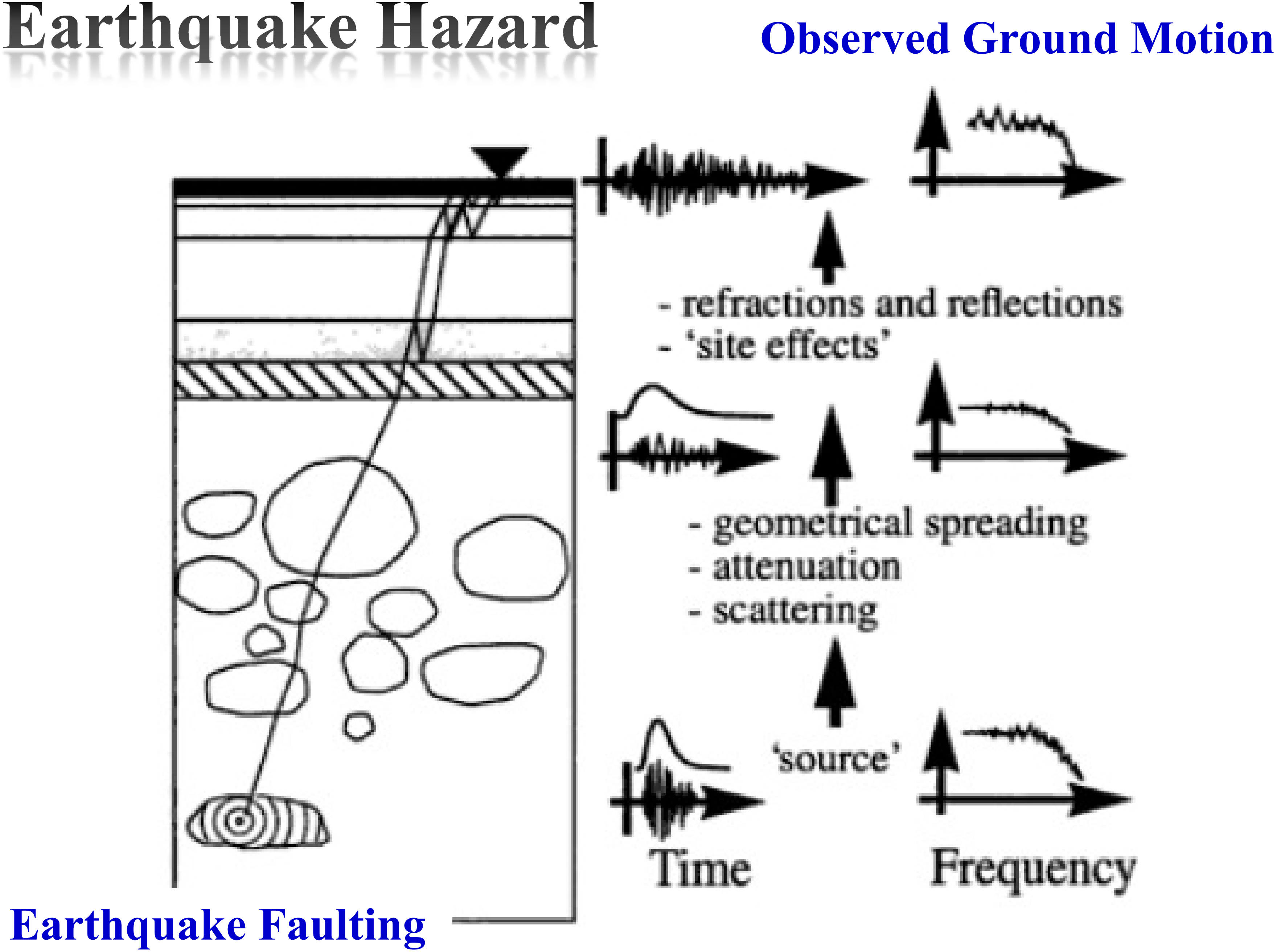


Figure courtesy Roger Bilham

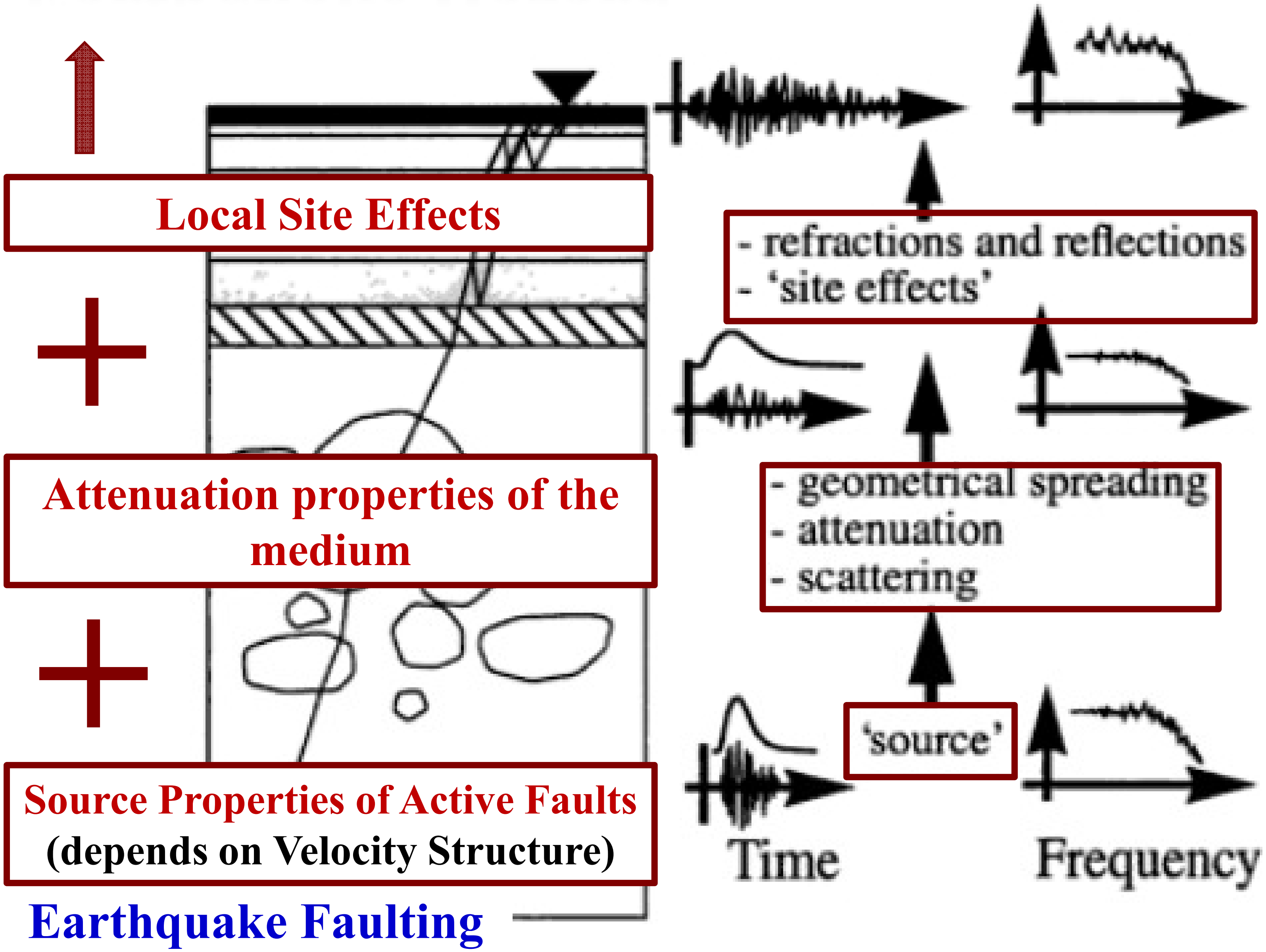
Maximum Credible Earthquake



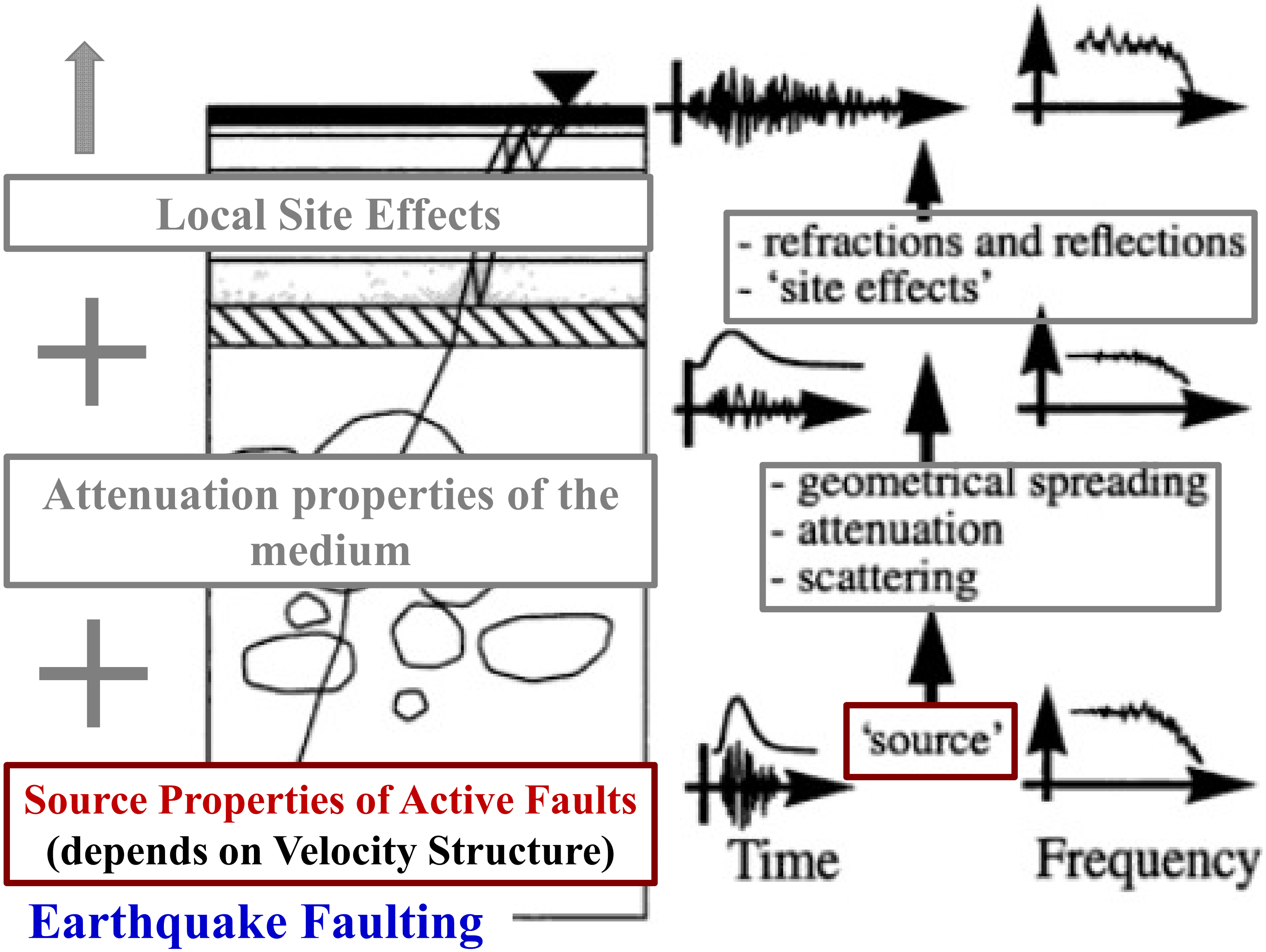
Earthquake Hazard



Predict Future Ground Motion ⇔ Observed Ground Motion

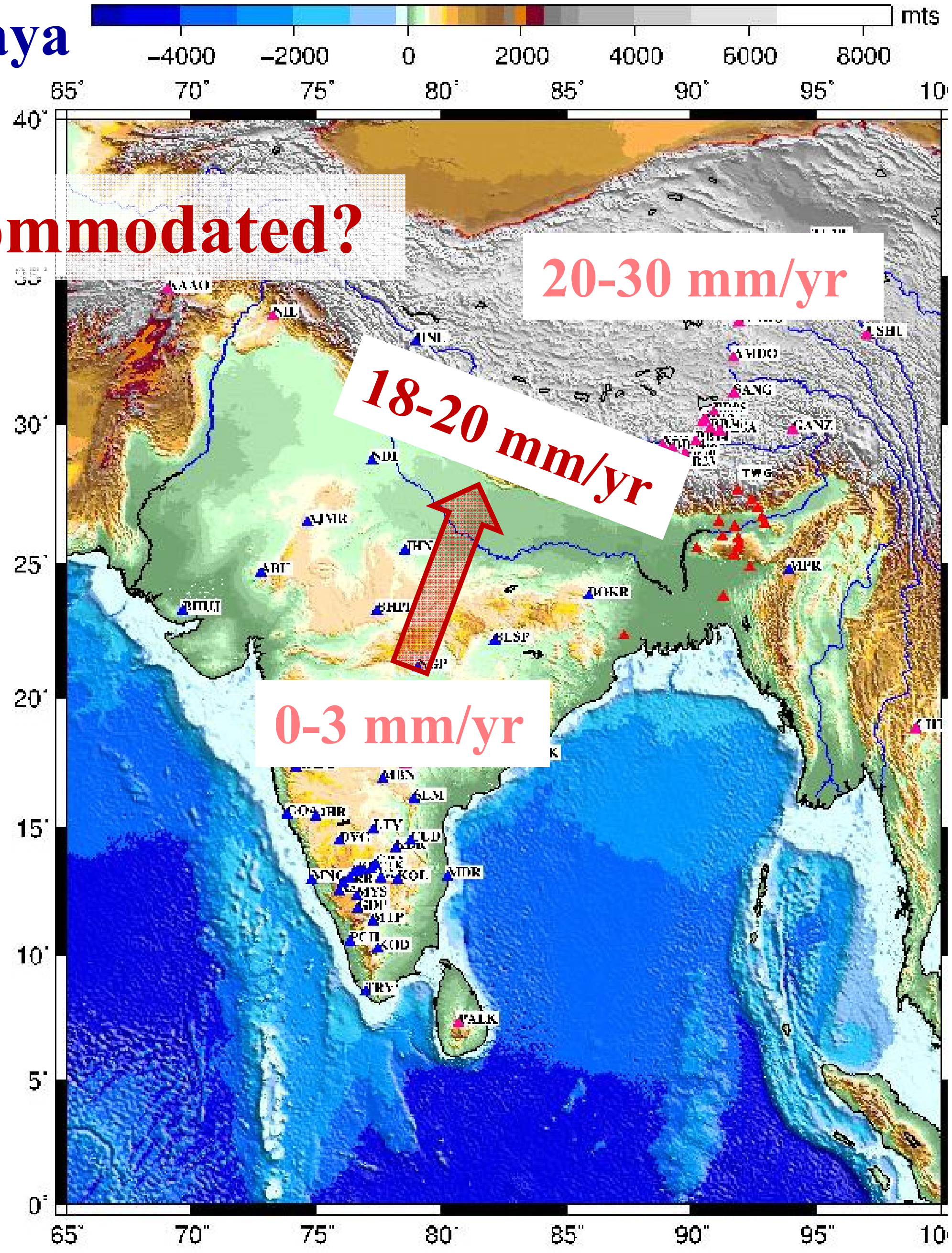


Predict Future Ground Motion ⇔ Observed Ground Motion

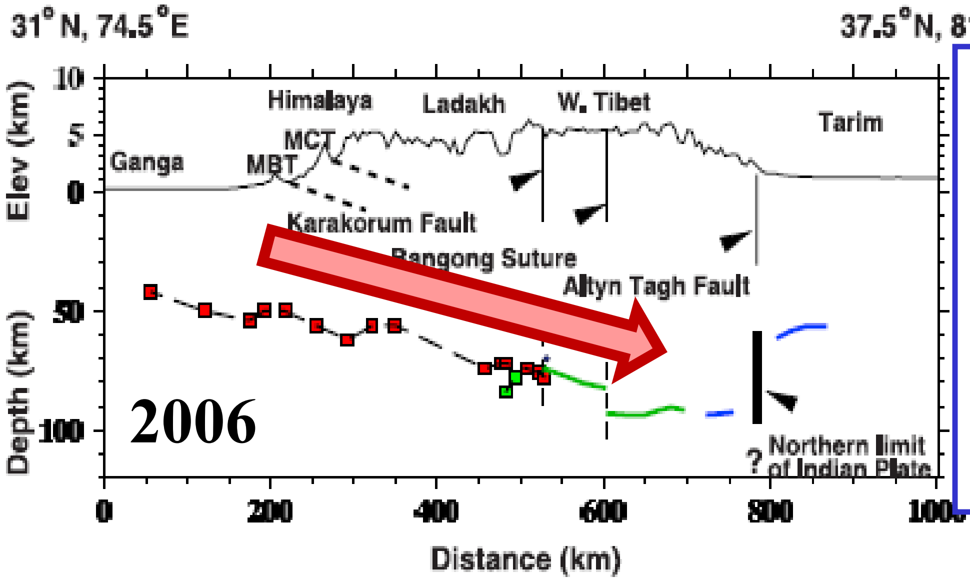


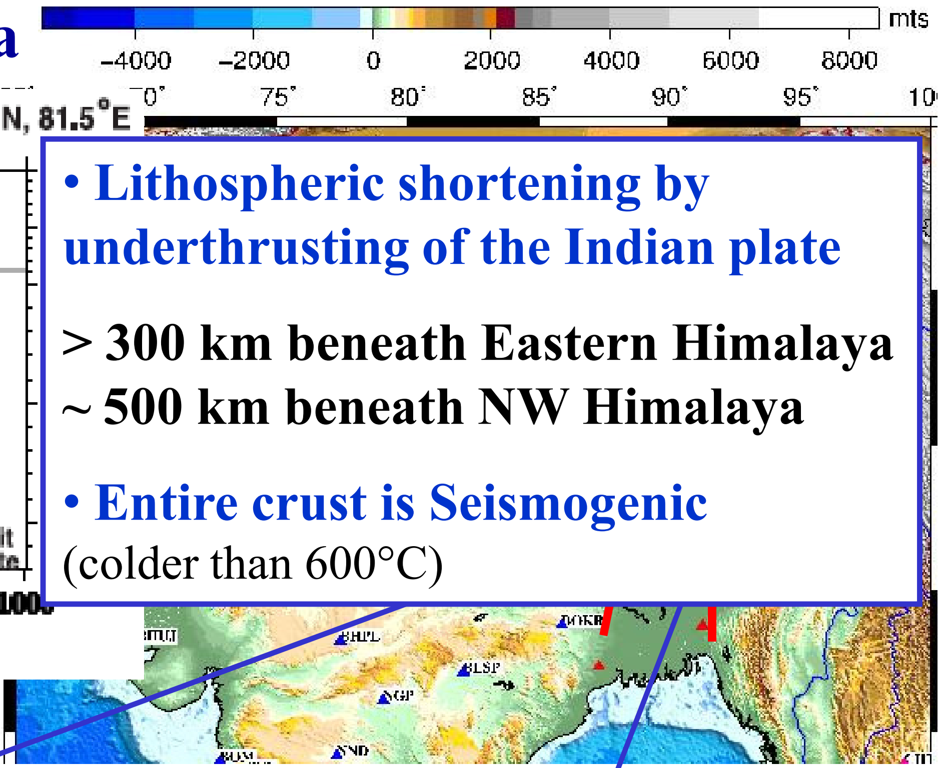
Velocity Structure of The Himalaya

How is the shortening accommodated?



Velocity Structure of The Himalaya



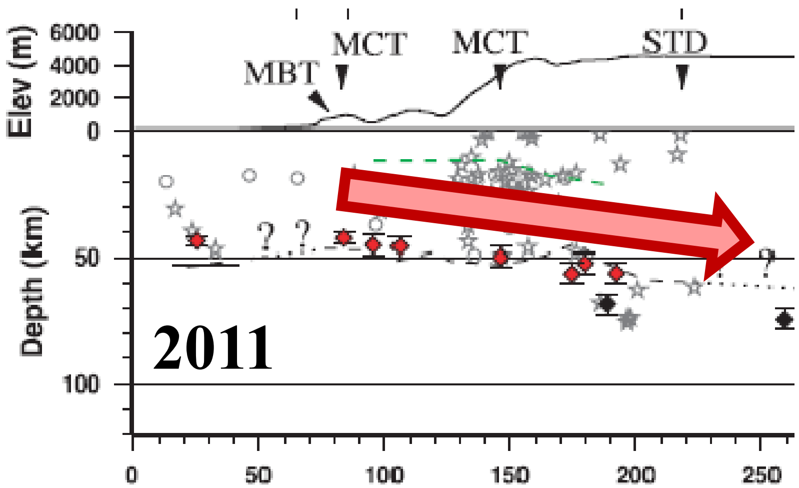


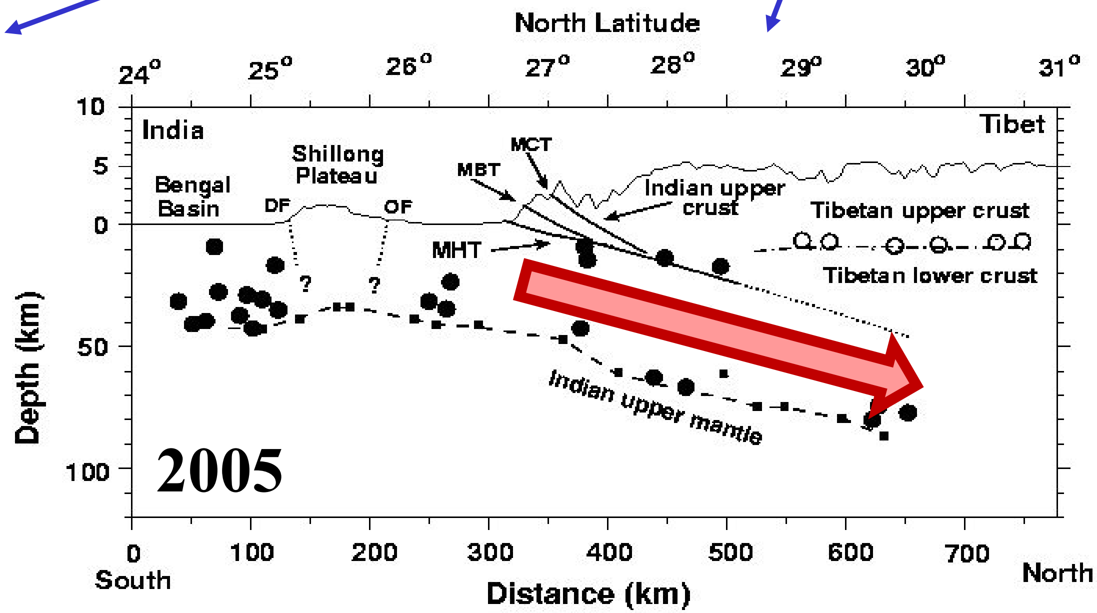
- **Lithospheric shortening by underthrusting of the Indian plate**

> 300 km beneath Eastern Himalaya
~ 500 km beneath NW Himalaya

- **Entire crust is Seismogenic**

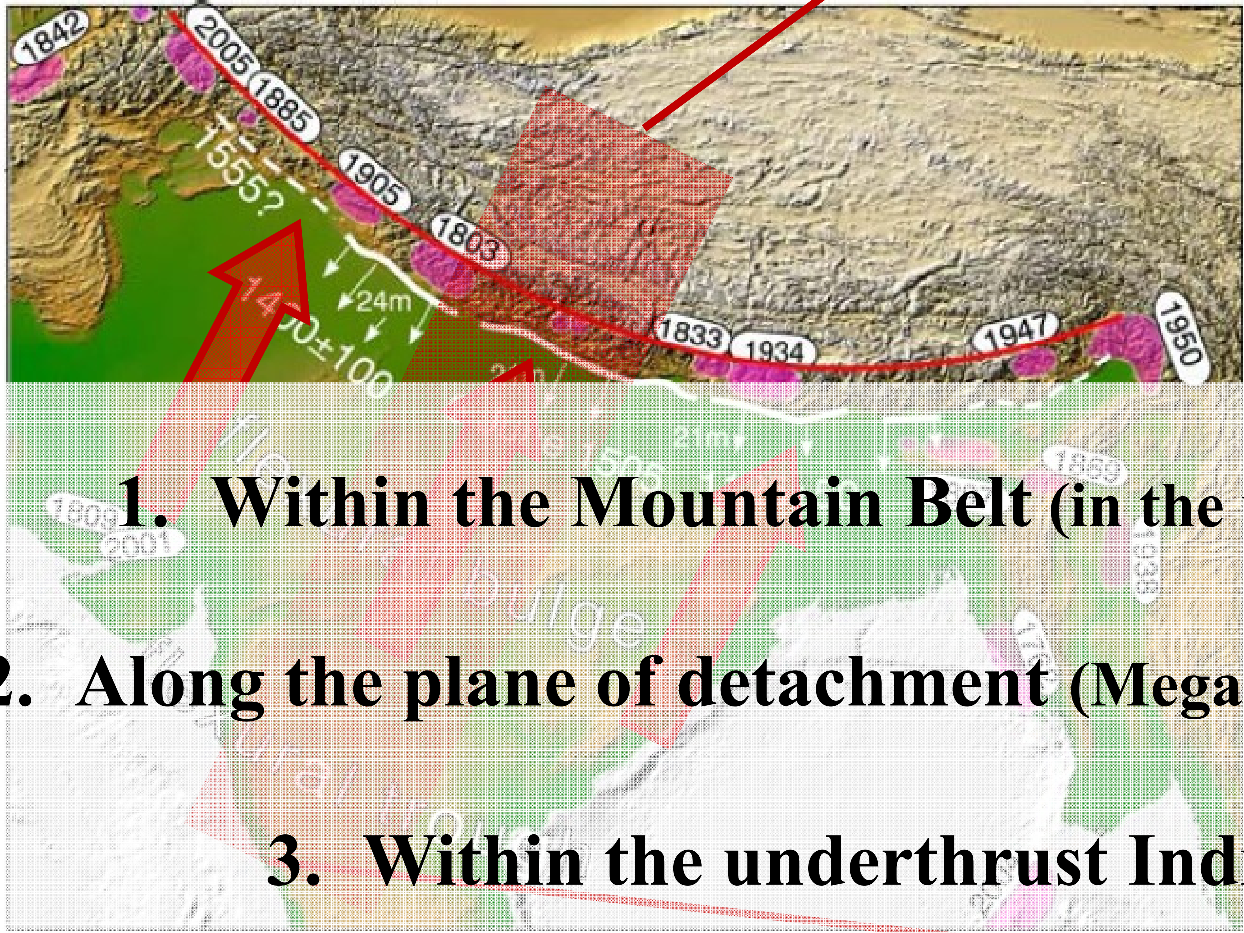
(colder than 600°C)

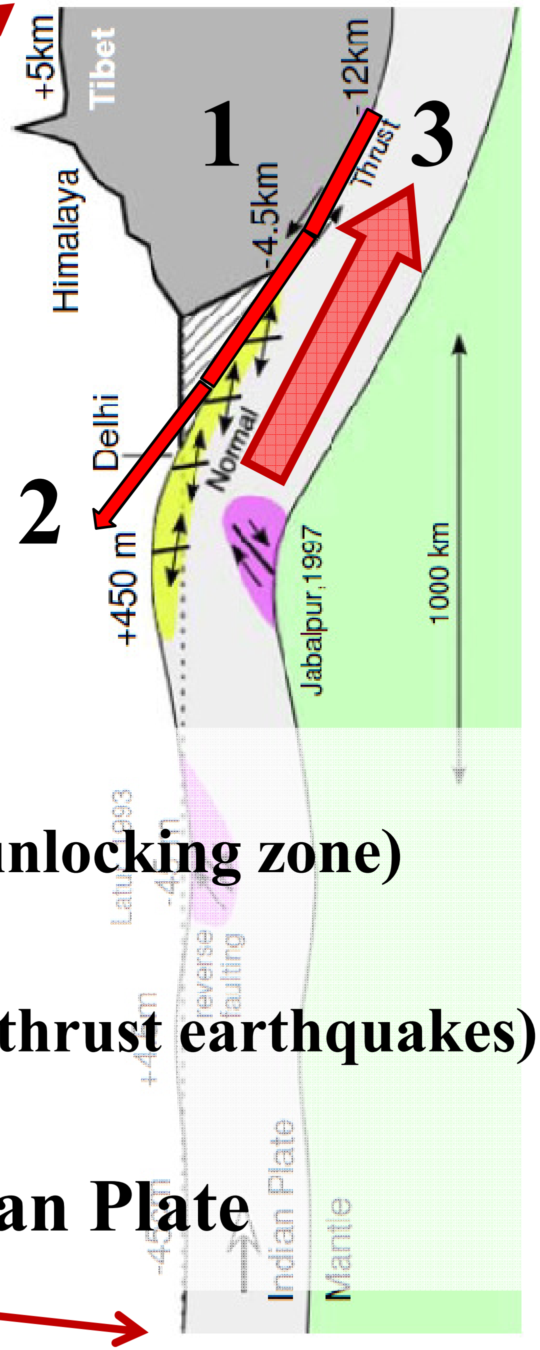




Himalayan Seismicity

Three Distinct Regions

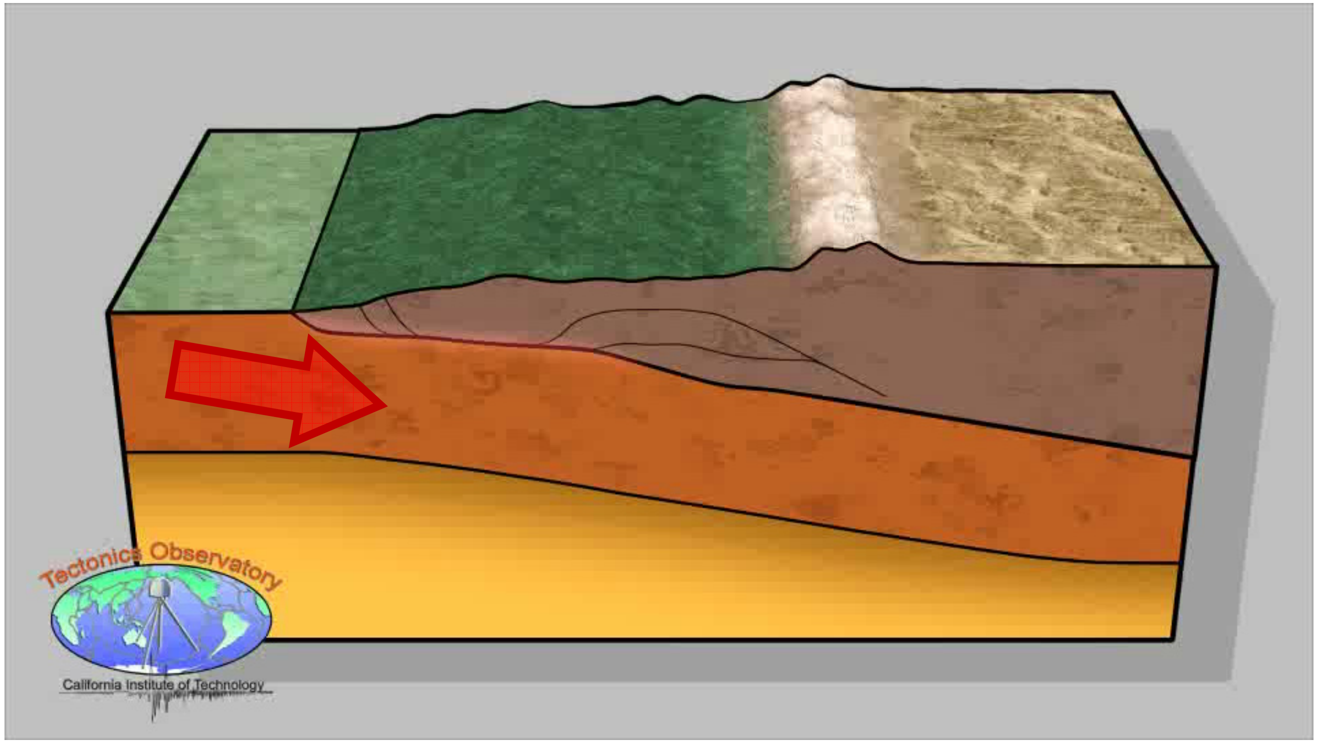


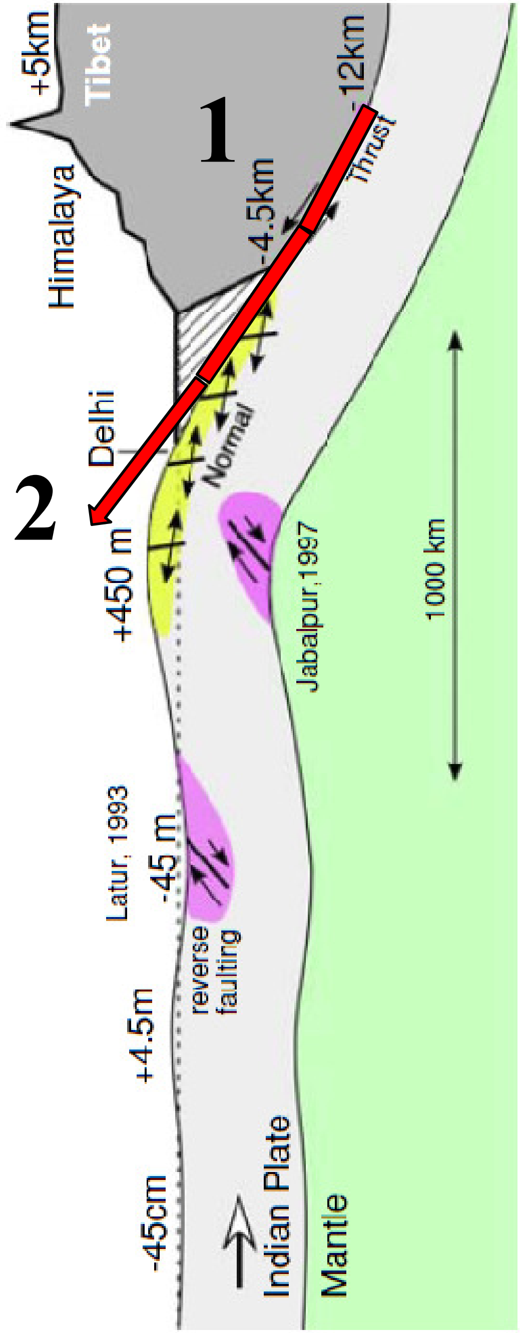


1. **Within the Mountain Belt (in the unlocking zone)**
2. **Along the plane of detachment (Mega-thrust earthquakes)**
3. **Within the underthrust Indian Plate**

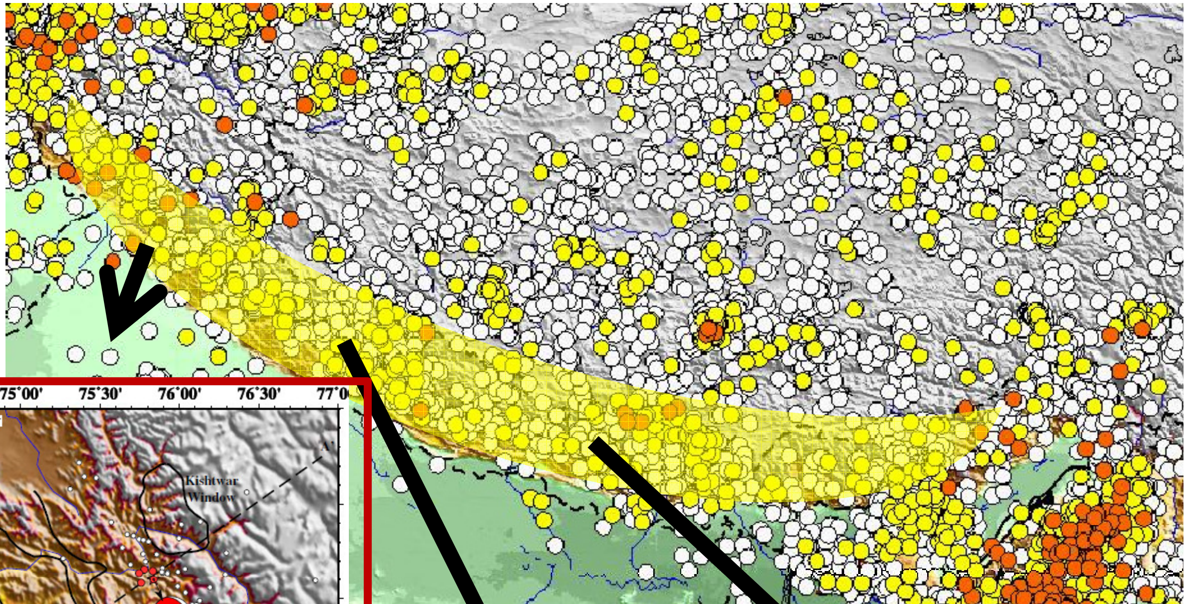
Himalayan Seismicity

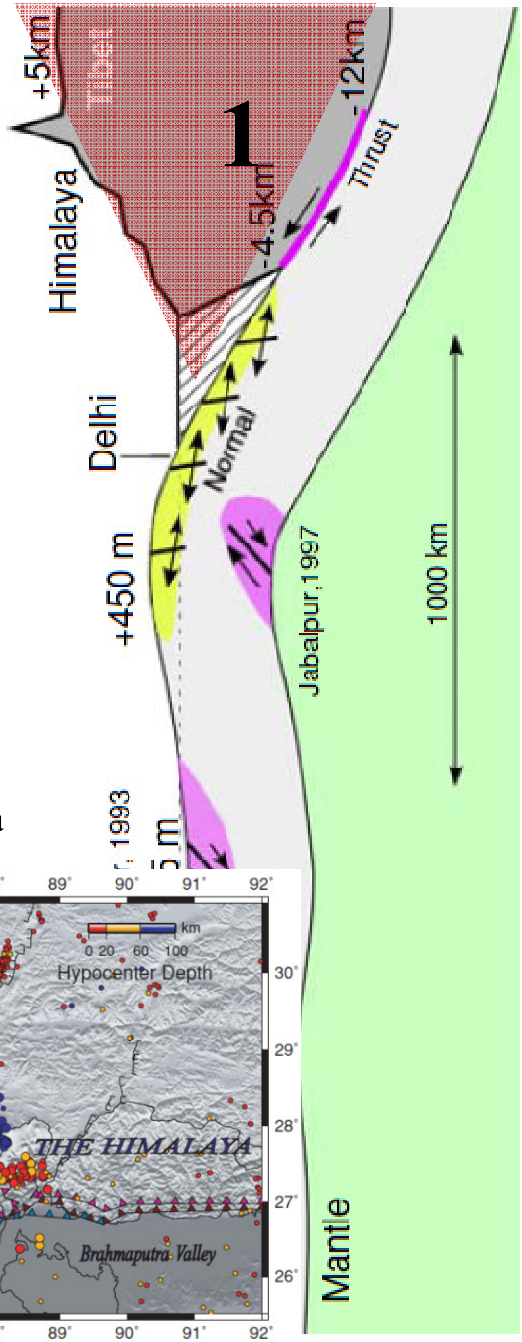
1. **Within the Mountain Belt**
2. **Along the plane of detachment**

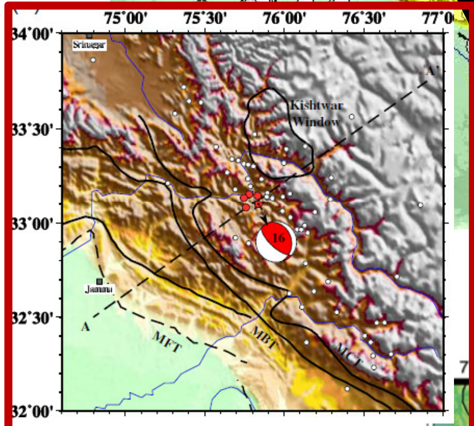




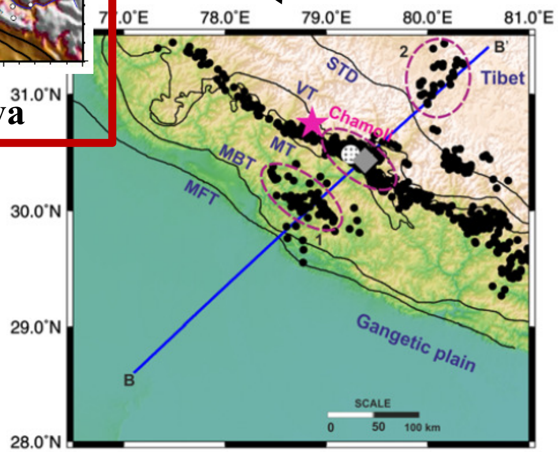
1. Within the Mountain Belt





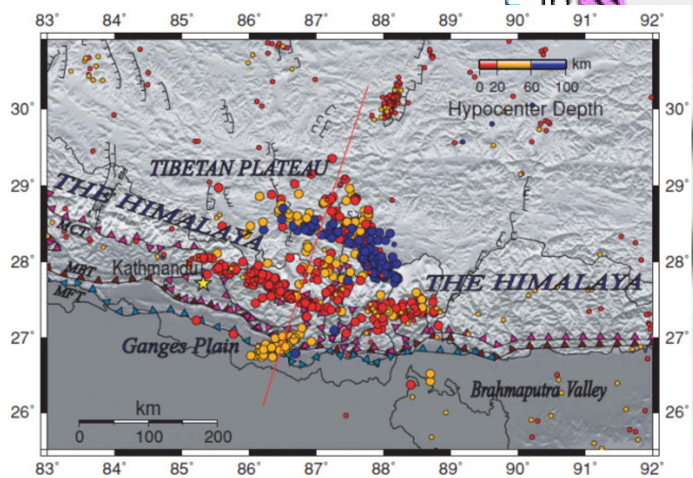


NW (J&K) Himalaya

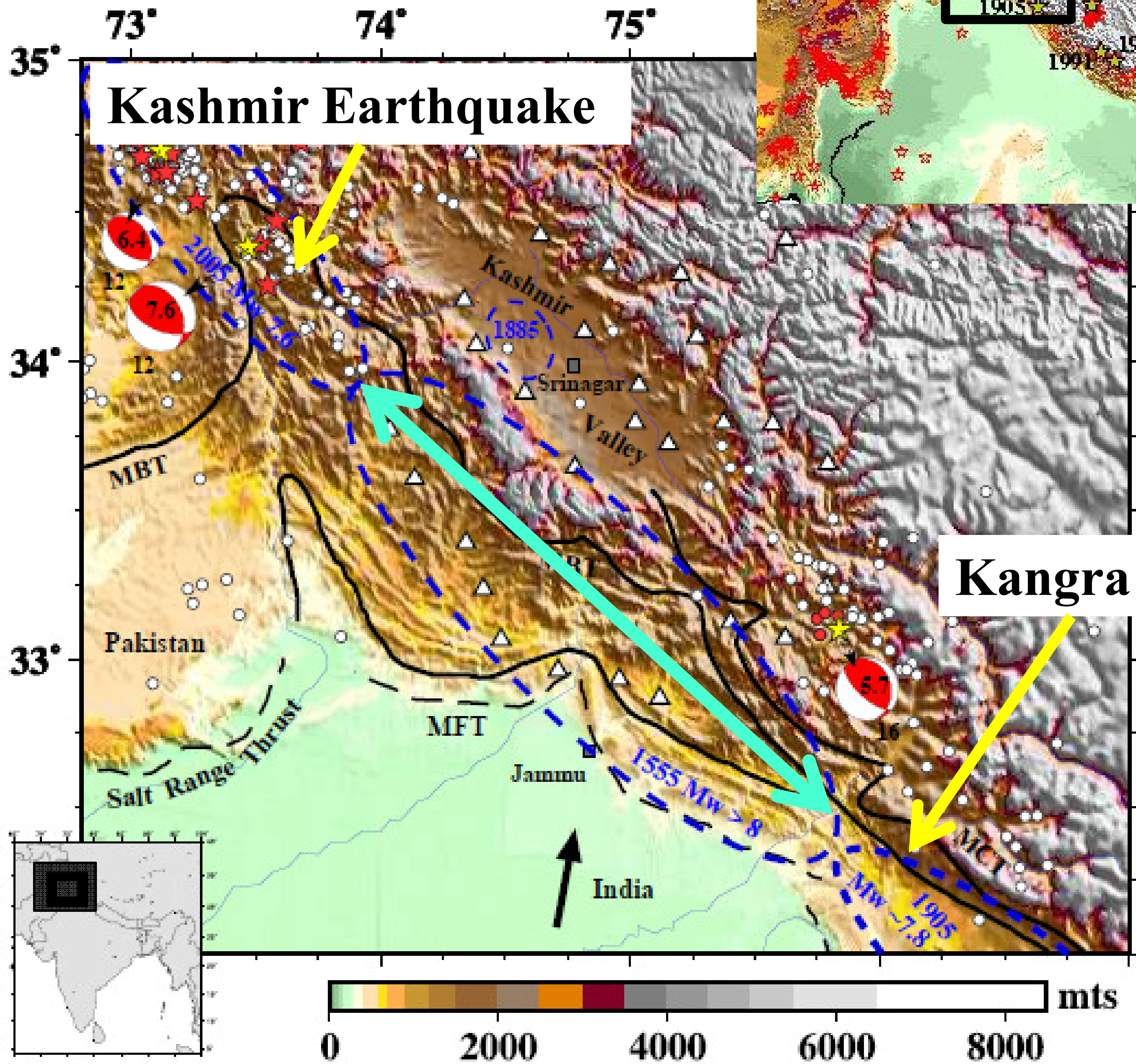


Uttaranchal Himalaya

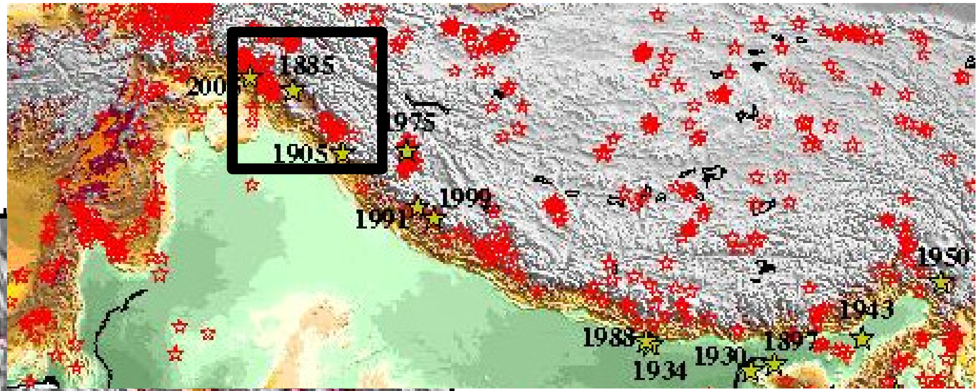
Nepal Himalaya



NW Himalaya

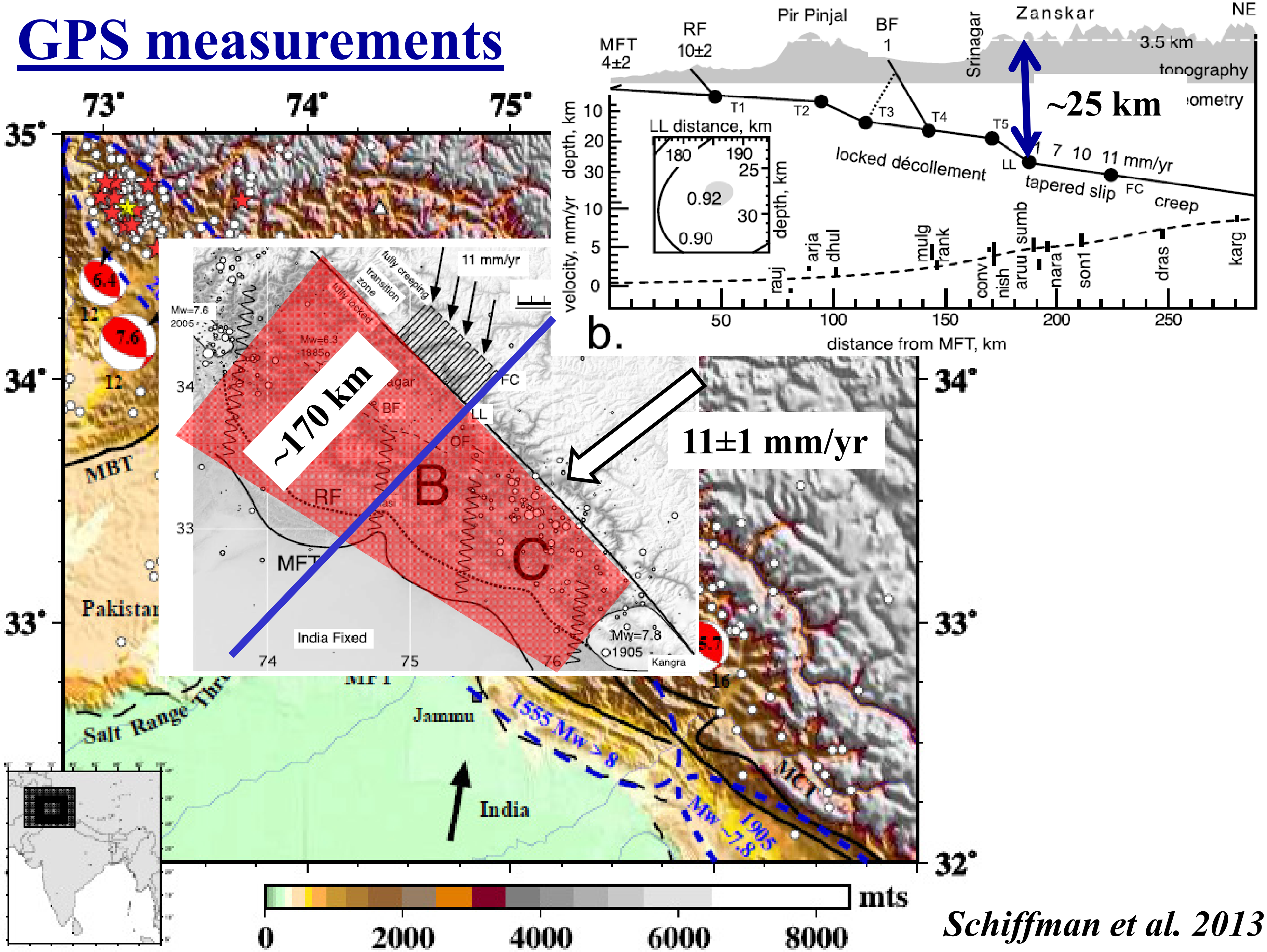


Kashmir Earthquake
Kangra Earthquake
73°
74°
75°
35°
34°
33°
32°
6.4
12
7.6
12
2005 Mw 7.6
Kashmir
1885
Srinagar
Valley
MBT
Pakistan
Salt Range Thrust
MFT
Jammu
1555 Mw > 8
India
1905 Mw ~7.8
MCT
5.7
16
0
2000
4000
6000
8000
mts



1885
1905
1975
1991
1999
1950
1943
1988
1934
1930
1897

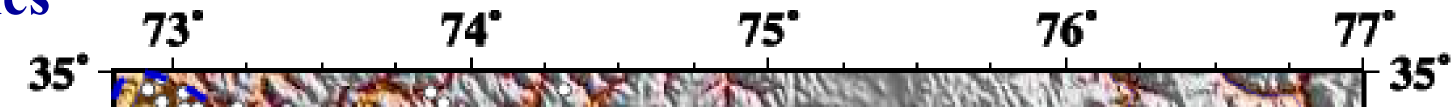
GPS measurements



Schiffman et al. 2013

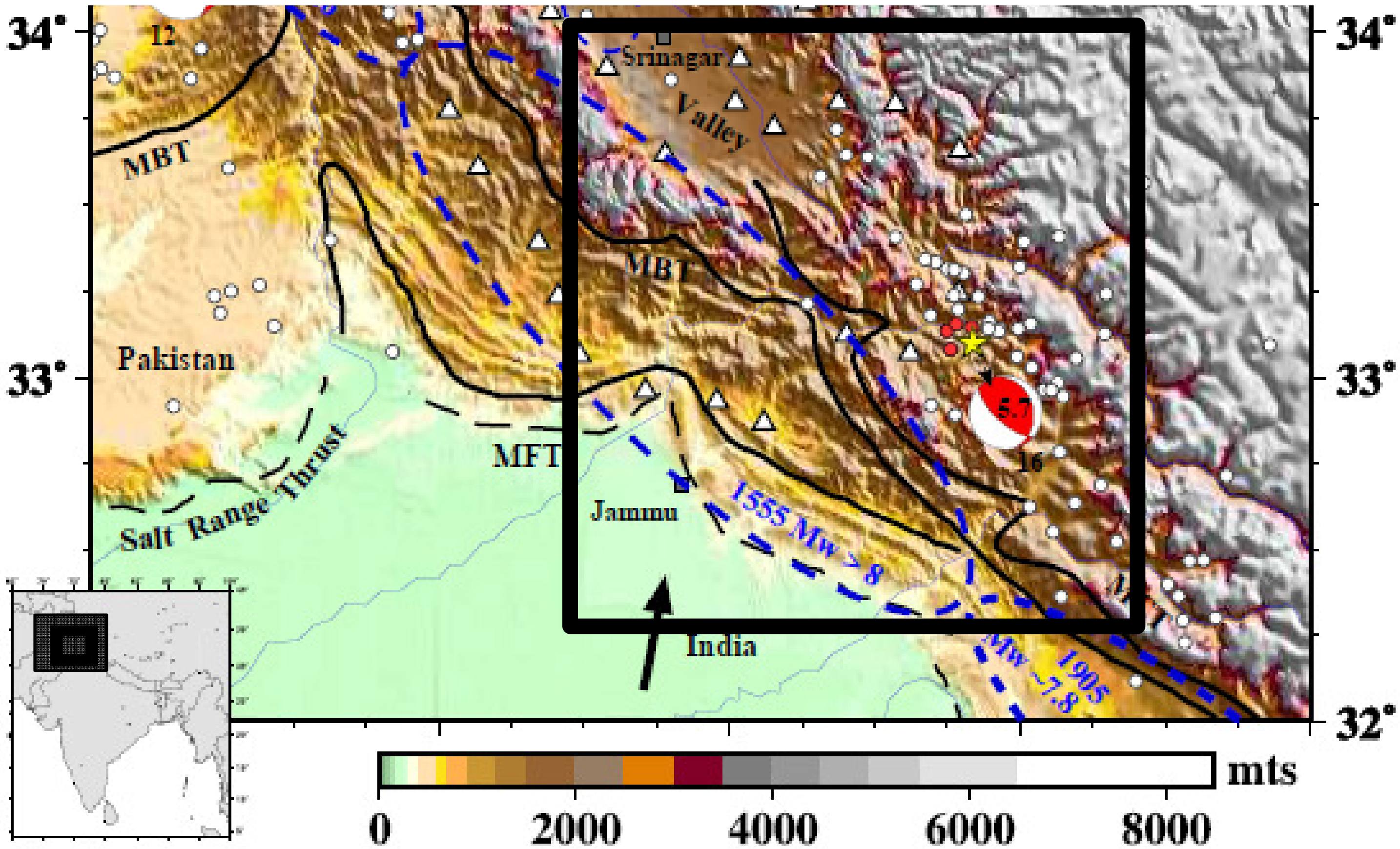
NW Himalaya
Source Studies

1 May 2013 Kishtwar Earthquake



- Magnitude (m_b) 5.7 - in the Kashmir seismic gap

- Focus beneath the Greater Himalaya (close to SE edge of the meisoseismal zone of the 1555 Kashmir earthquake - Mag ~7.6)

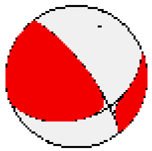


Methodology (Source)

Earthquake (Re)Location: Phase travel times

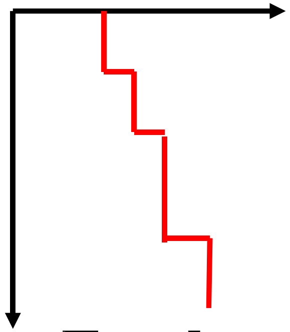
Earthquake Mechanism: Waveform Fitting

Earthquake Source



Assume Source (Moment Tensor)

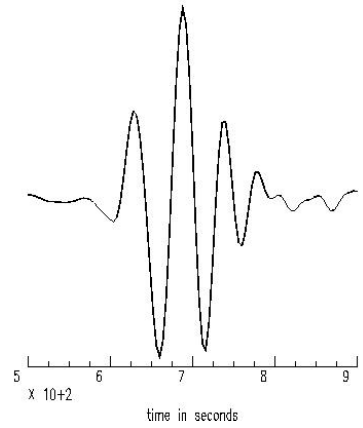
*



Earth Structure

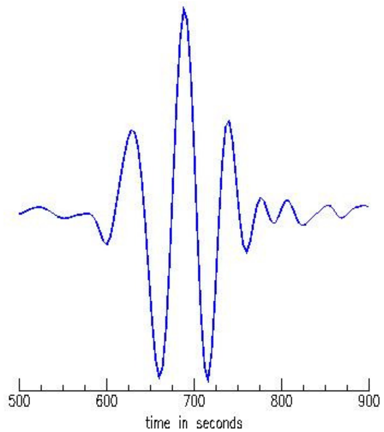
=

Recorded Waveform



Minimum Misfit

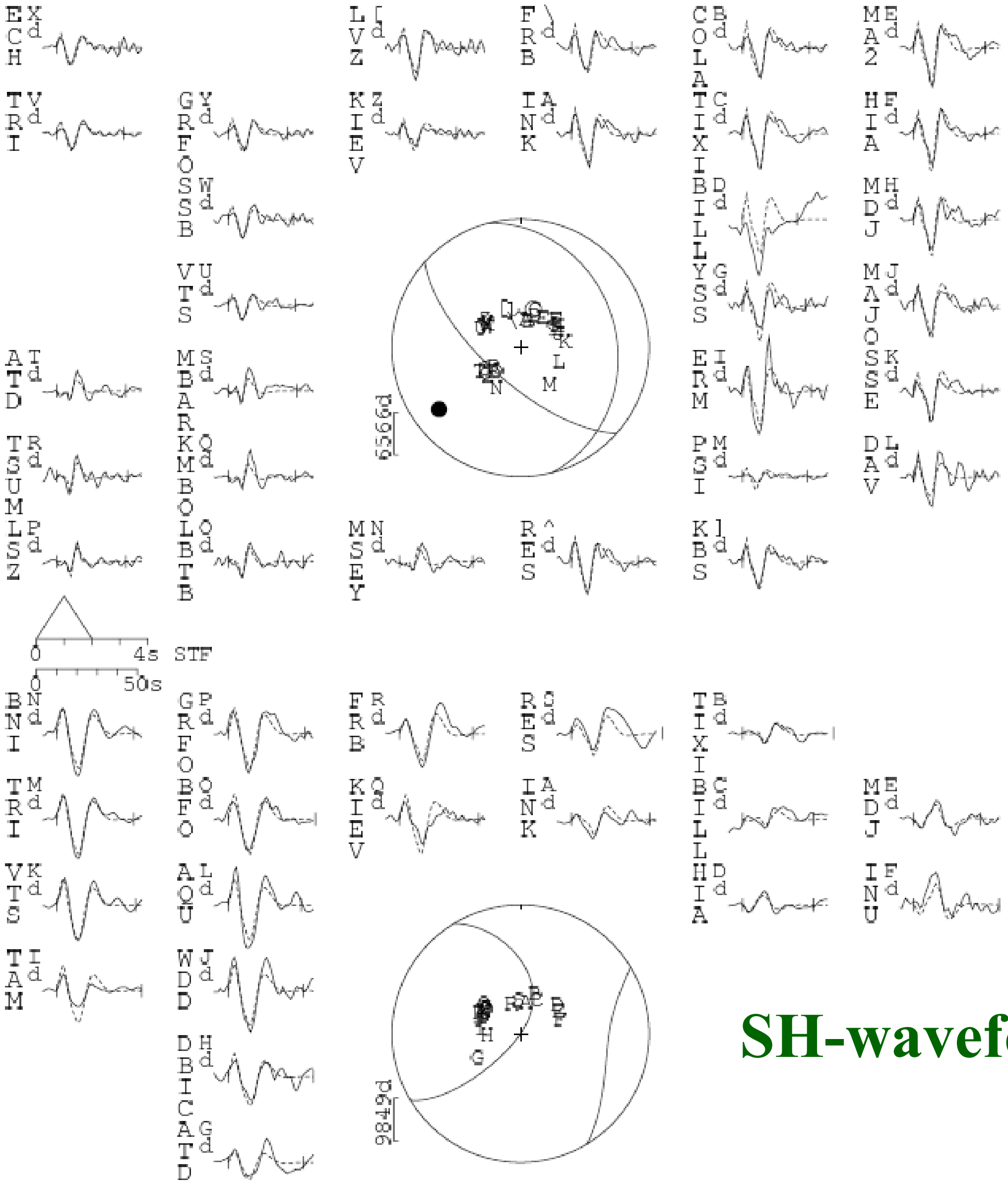
Computed Waveform



Source Mechanism (Global P and SH-waveform Inversion)

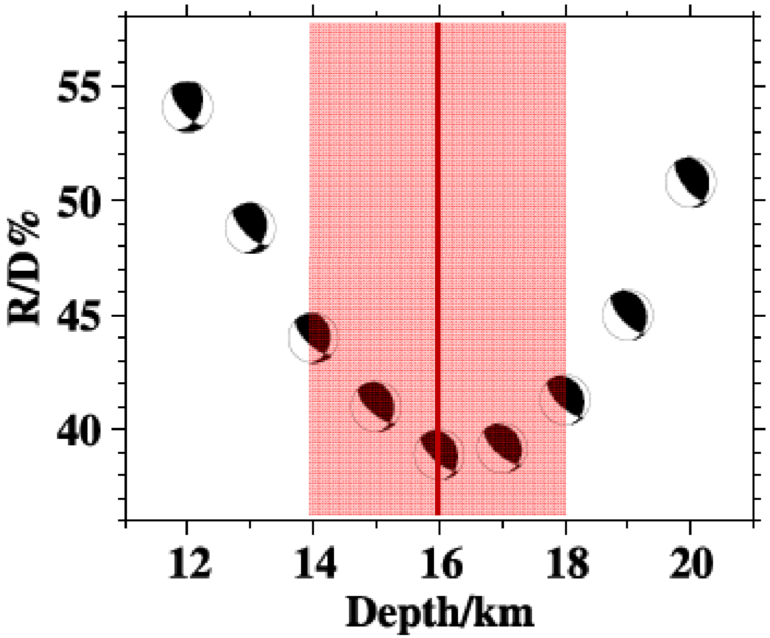
01 May 2013, Mw=5.7 Kashmir, India

Strike=346, Dip=26, Rake=121, Depth=16 km, M0=2.072+E17



P-waveforms

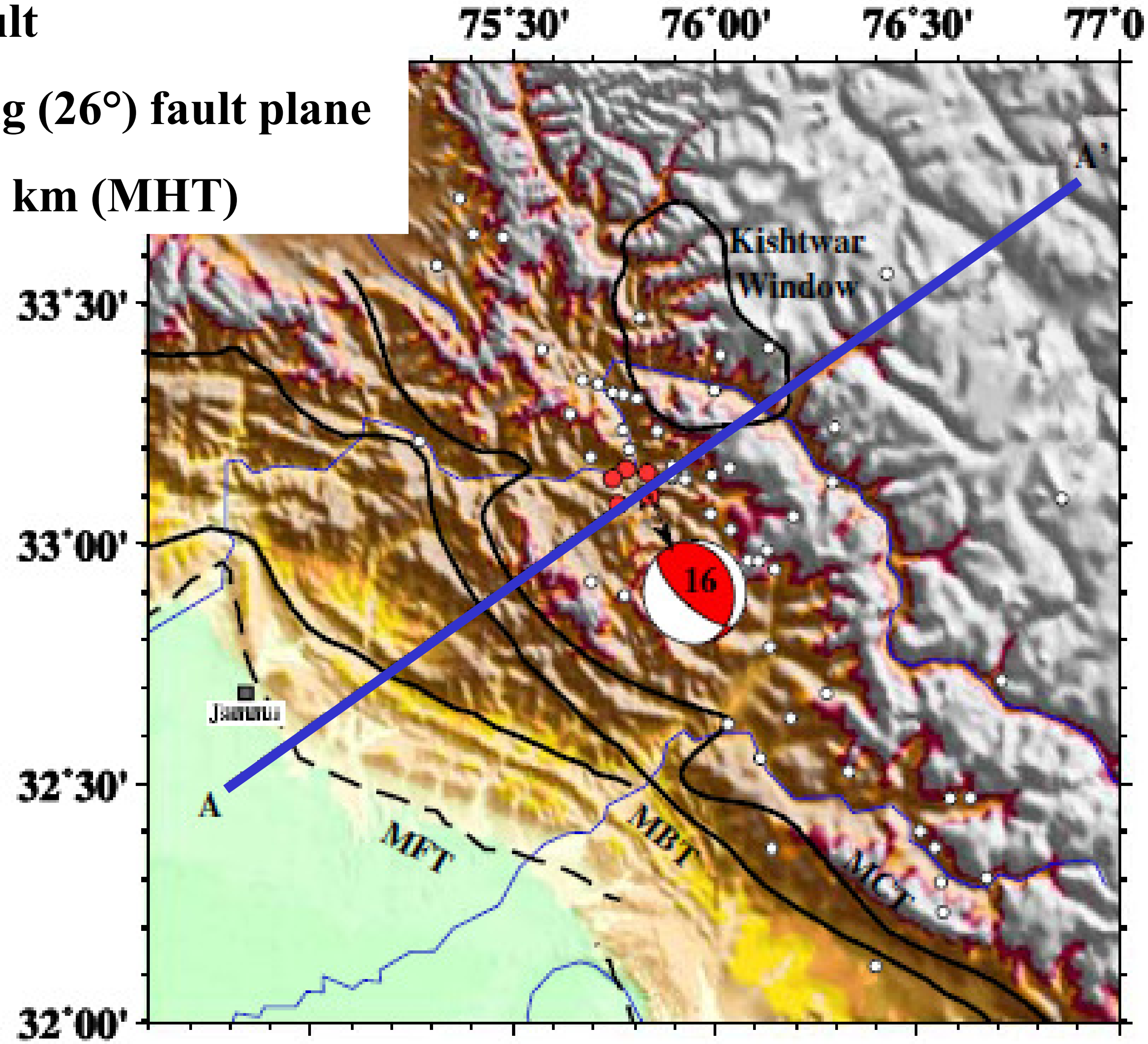
SH-waveforms



Depth
16±2 km

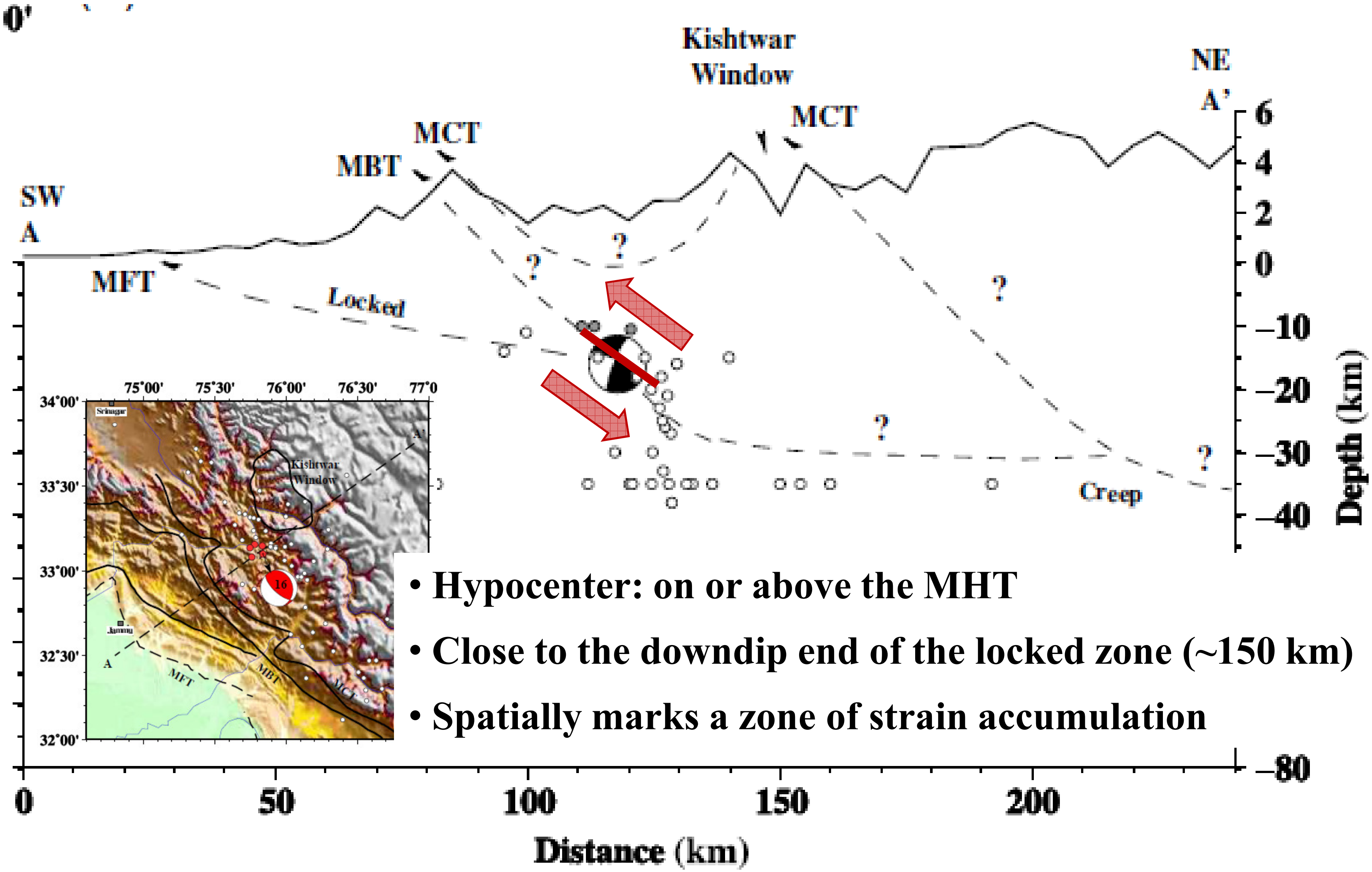
2013 Kishtwar Earthquake

- Thrust fault
- NE dipping (26°) fault plane
- Depth ~16 km (MHT)



S. Mitra, Sunil Wanchoo and Priestley, K. (2014) *Bull. Seismo. Soc. America, 104 (2), pp 1013-1019.*

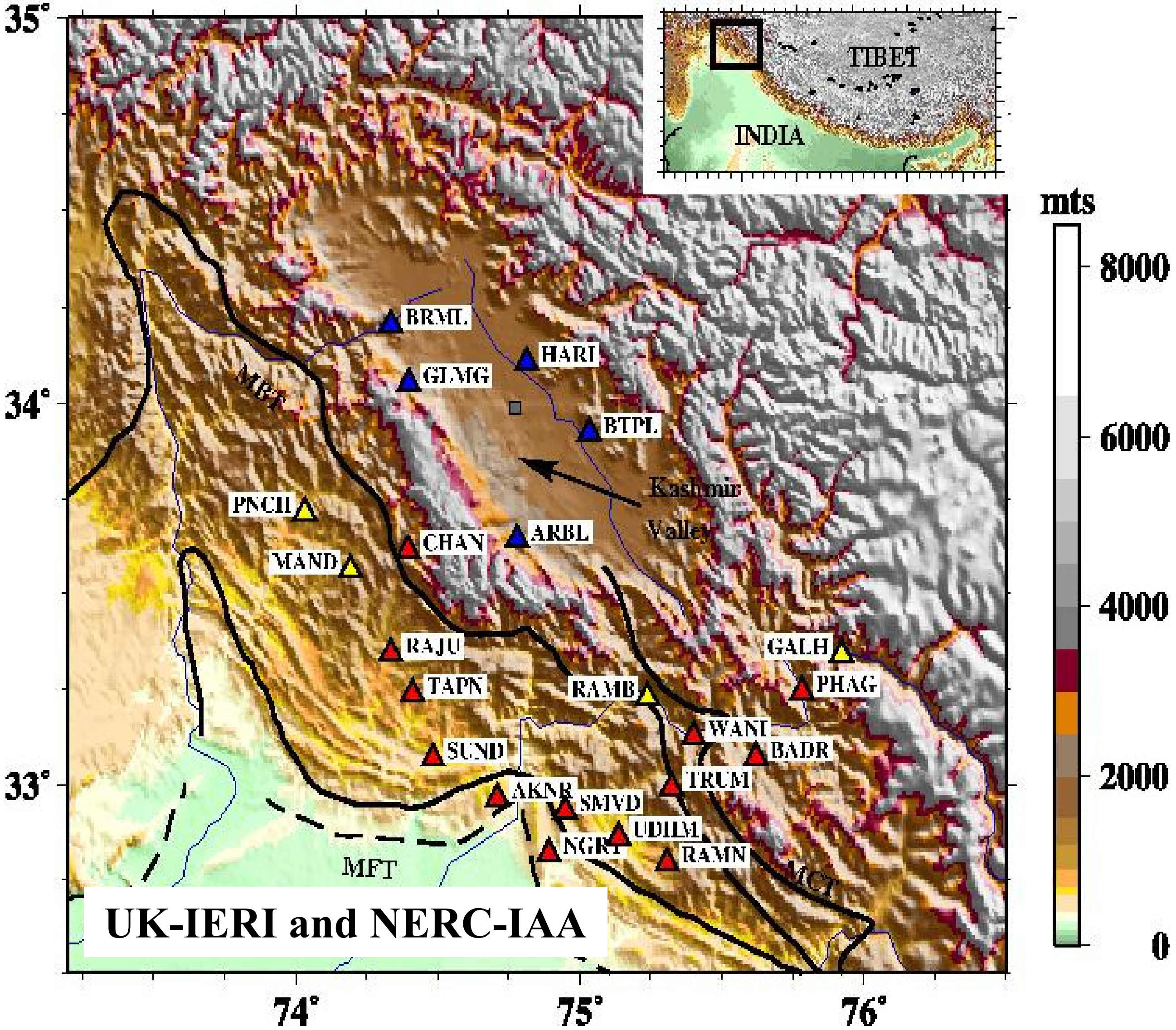
2013 Kishtwar Earthquake



- Hypocenter: on or above the MHT
- Close to the downdip end of the locked zone (~150 km)
- Spatially marks a zone of strain accumulation

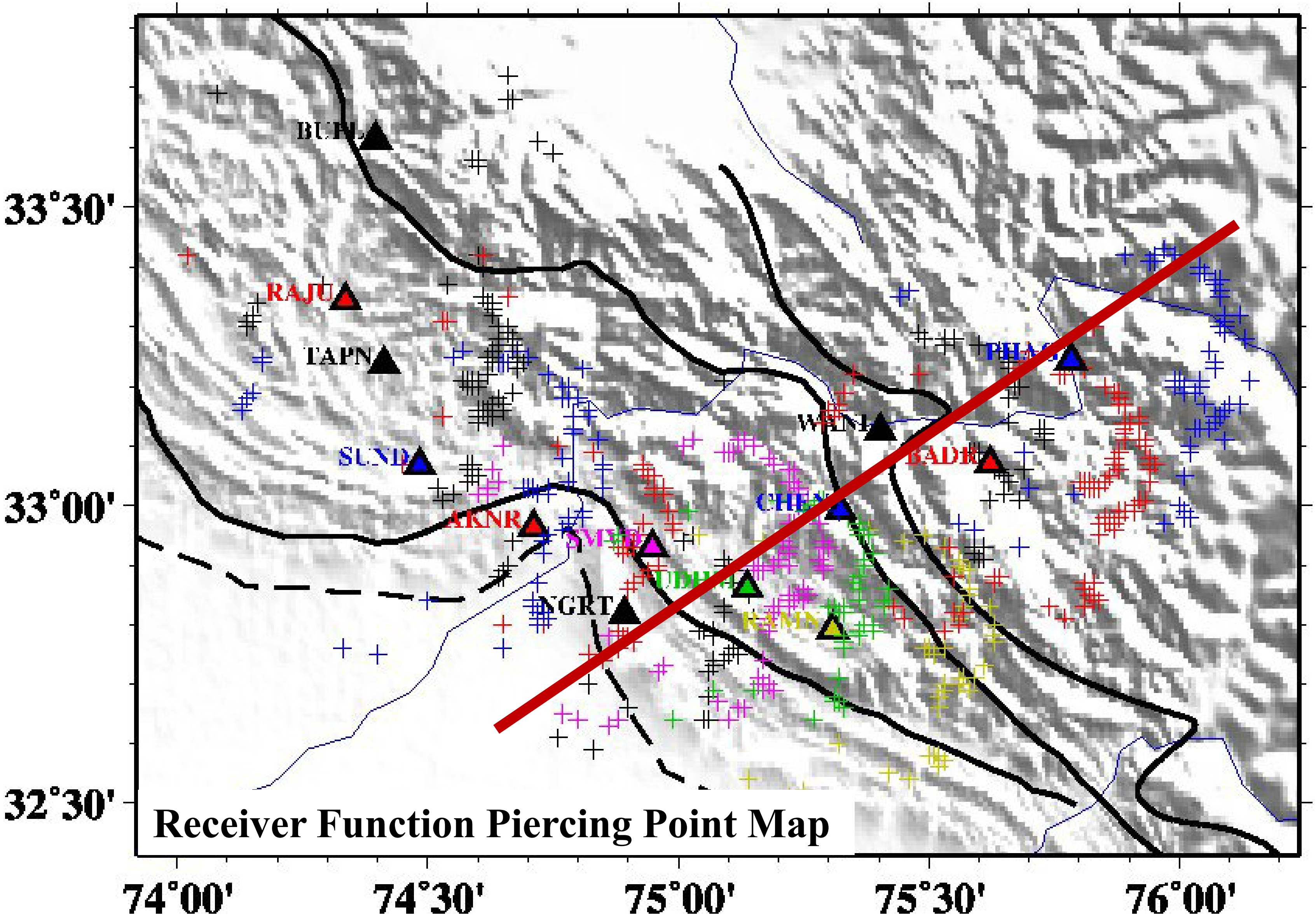
S. Mitra, Sunil Wanchoo and Priestley, K. (2014) *Bull. Seismo. Soc. America, 104 (2), pp 1013-1019.*

Kashmir Himalaya: Lithospheric Structure and Earthquakes



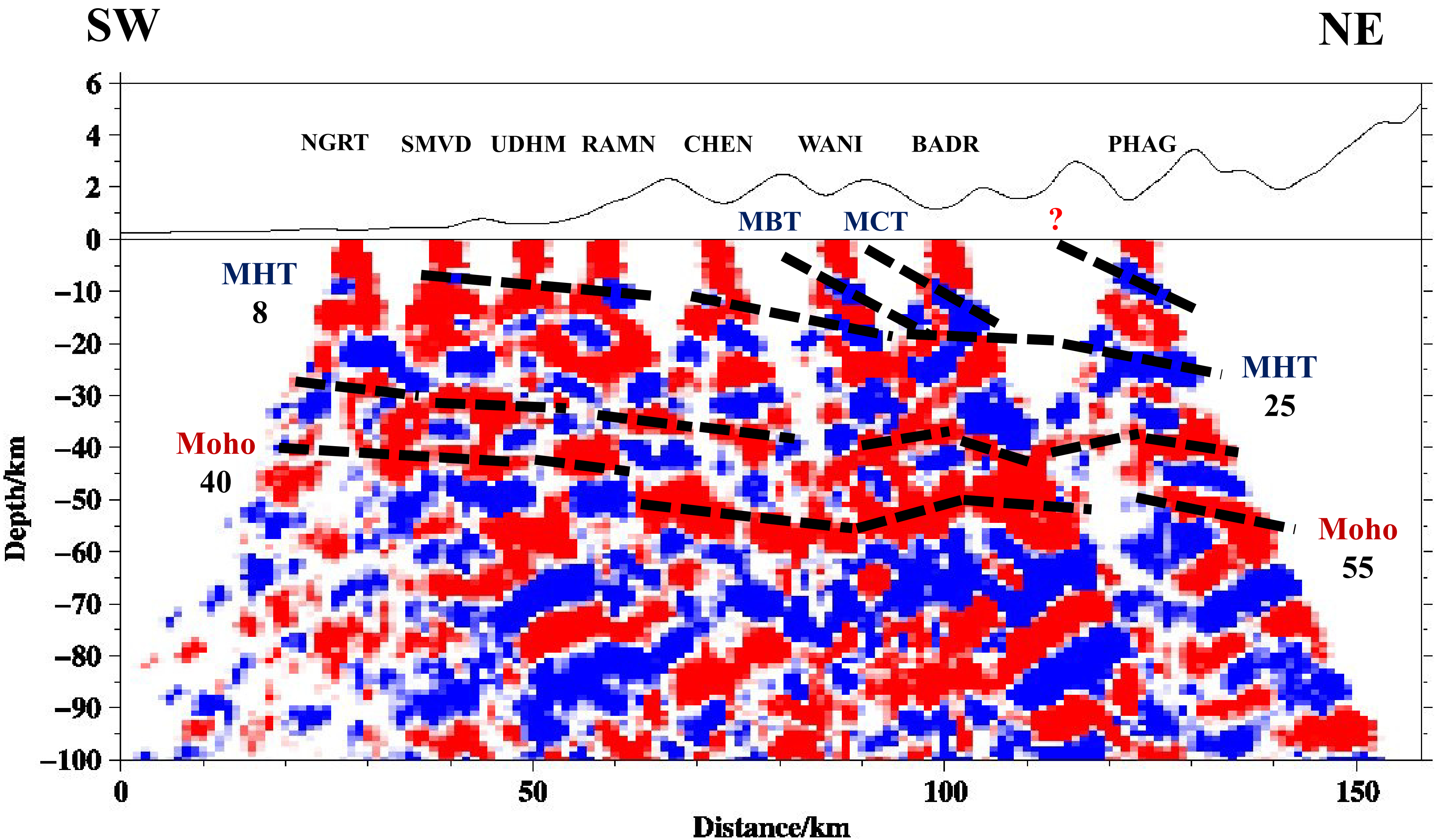
Debarchan Powali, Sharma, Swati, Mitra, S., Wanchoo, S.K., Priestley, K.F. and Gaur, V.K. Lithospheric Structure and Earthquakes beneath Kashmir Himalaya. ***Abstract (T21B-4587) AGU Fall Meeting 2014.***

Kashmir Himalaya: Lithospheric Structure and Earthquakes



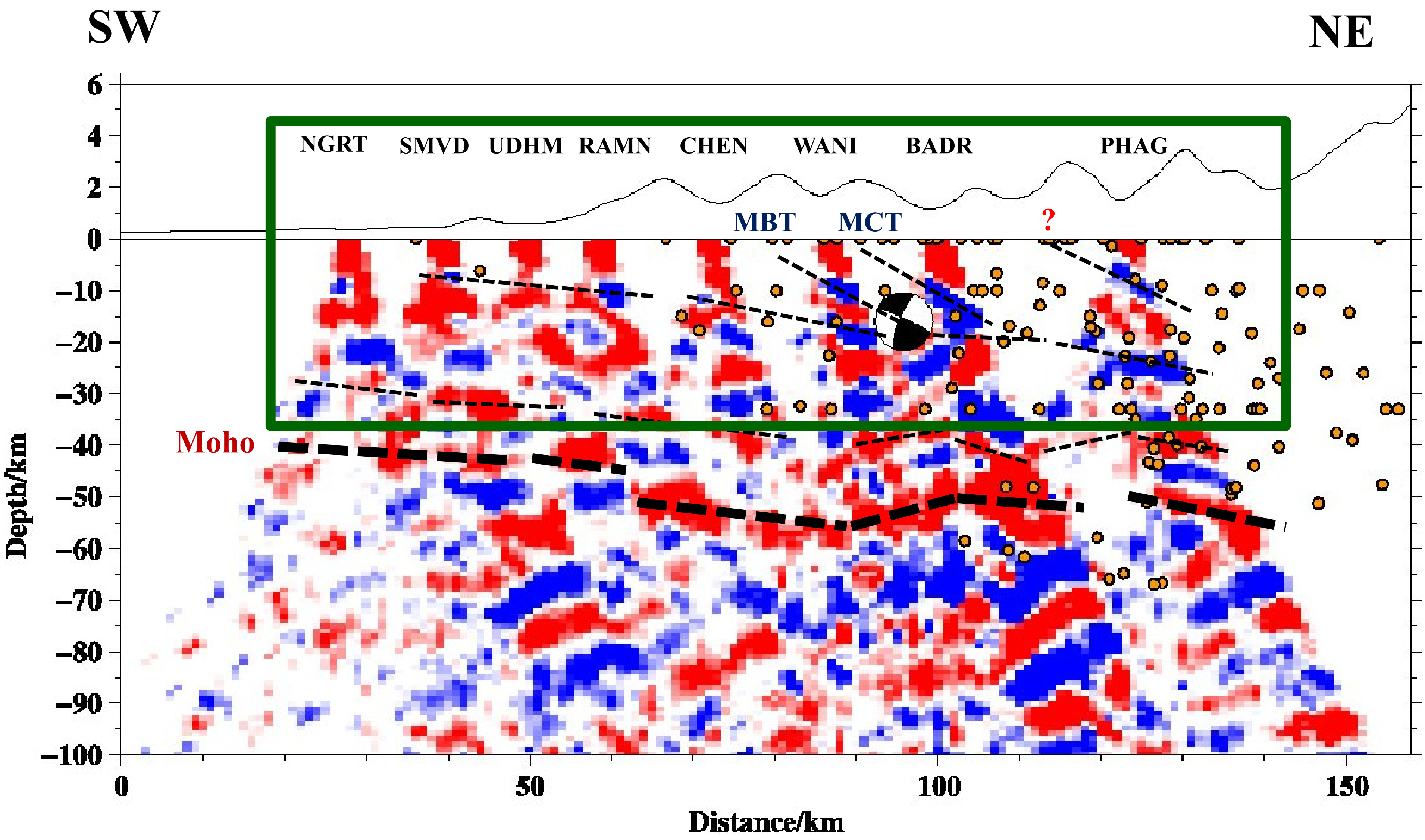
Debarchan Powali, Sharma, Swati, Mitra, S., Wanchoo, S.K., Priestley, K.F. and Gaur, V.K. Lithospheric Structure and Earthquakes beneath Kashmir Himalaya. ***Abstract (T21B-4587) AGU Fall Meeting 2014.***

SW-NE Profile: RF Common Conversion Point (CCP) Stack



- Indian crust underthrusts J&K Himalaya: base highlighted by large impedance contrast boundary
- MHT highlighted by a LVL dipping NE: ~8 km (Siwalik Himalaya) to ~25 km (Higher Himalaya)

SW-NE Profile: RF CCP Stack and Earthquakes



- The 2013 Kishtwar earthquake occurred at the downdip junction between the MBT and the MHT
- Entire crust is seismogenic

Possible Modes of Maximum Slip and M_{max}

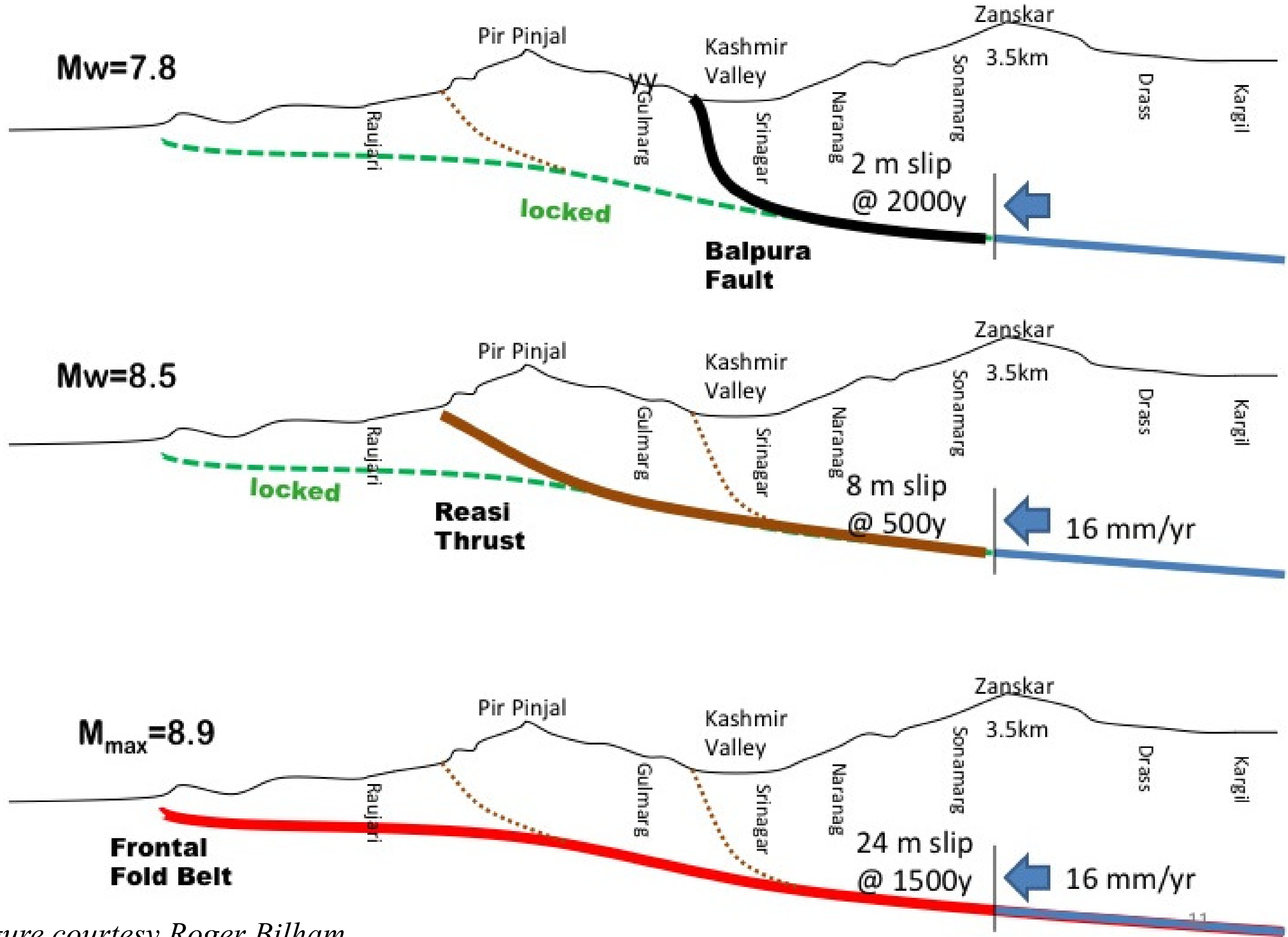
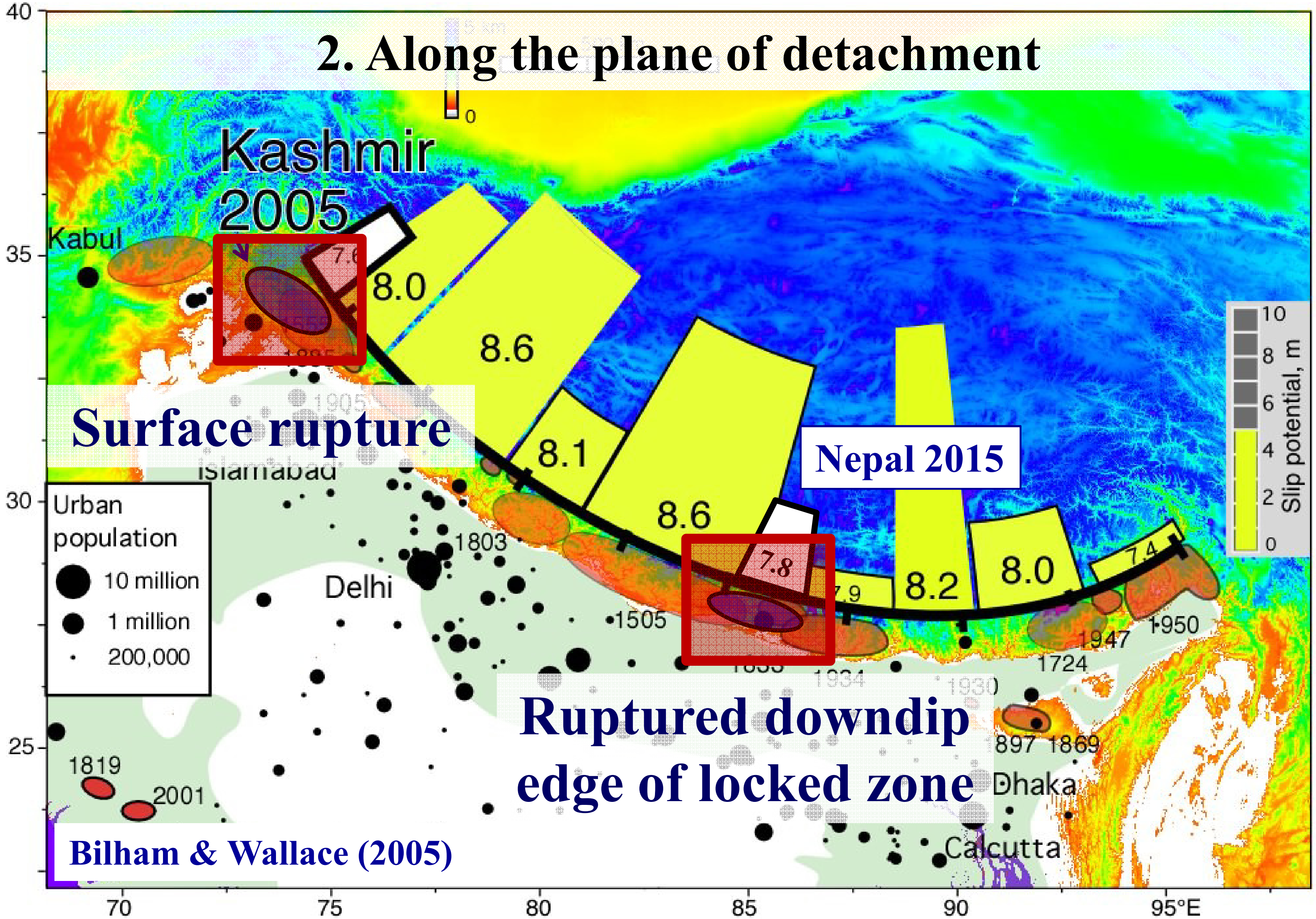


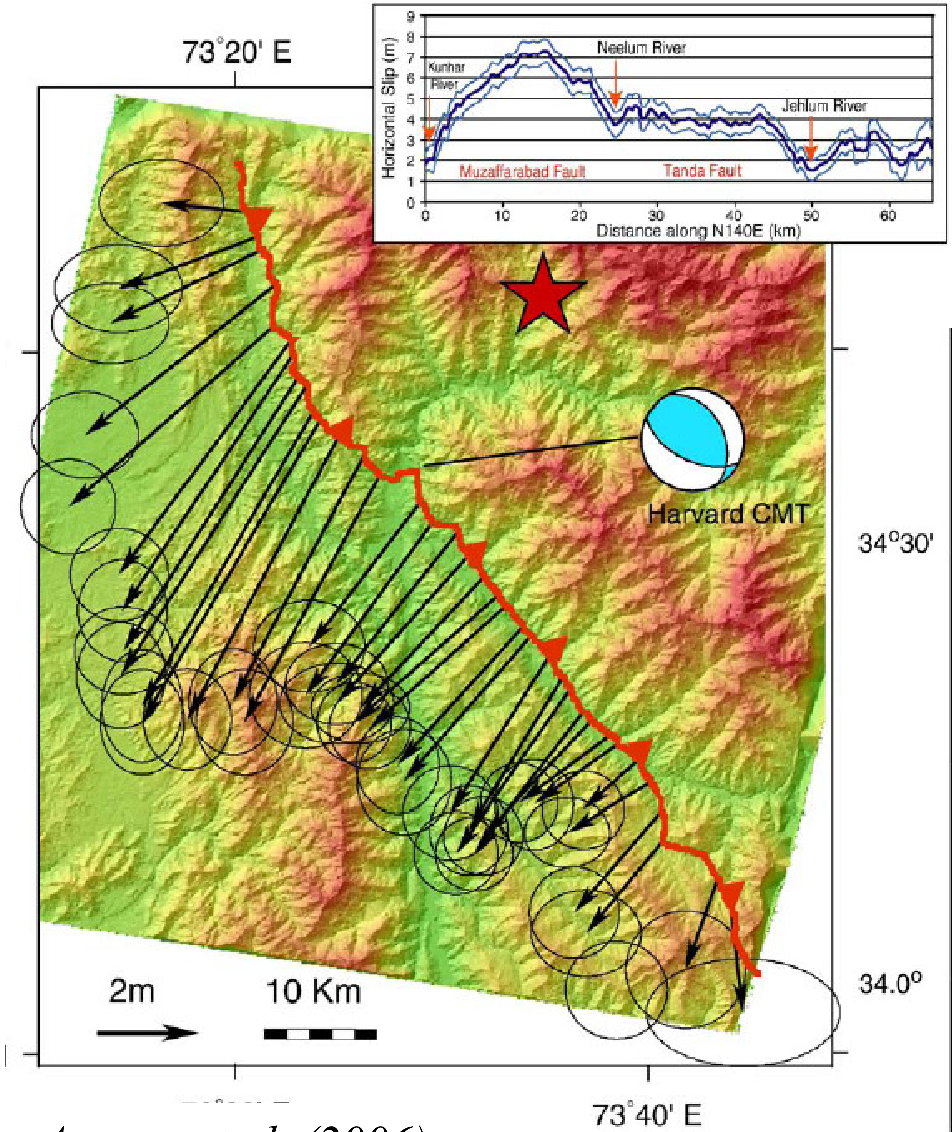
Figure courtesy Roger Bilham

Himalayan Seismicity

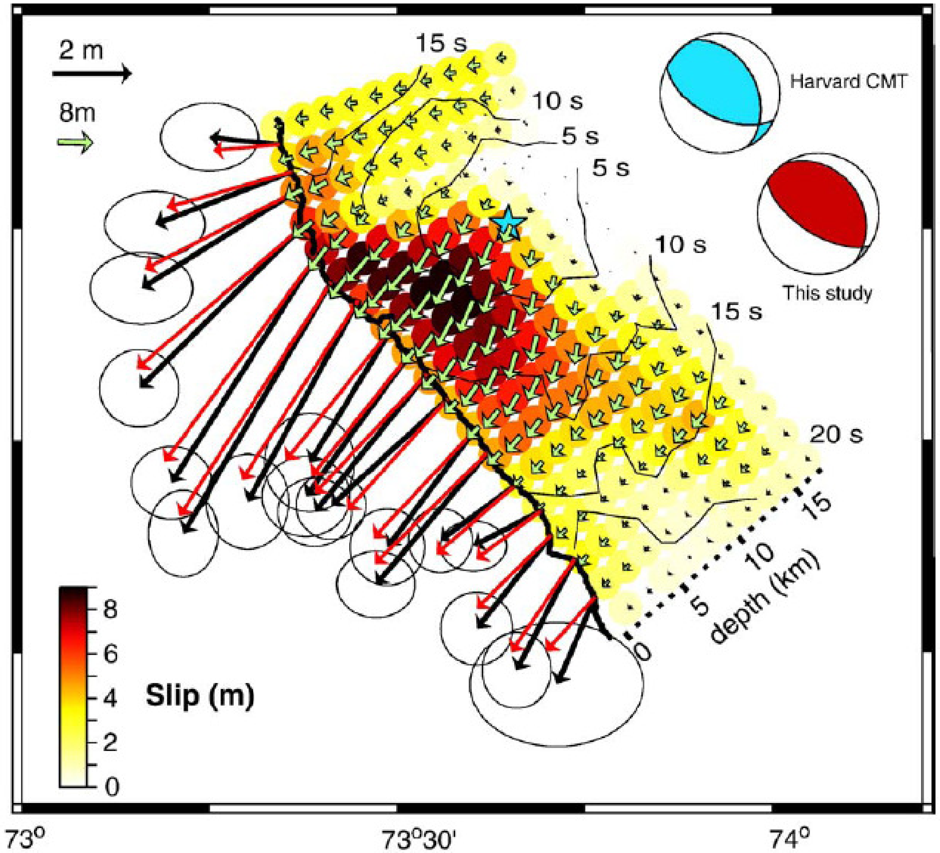


2005 Kashmir Earthquake

- **Muzzafarabad and Tanda Faults**
- **NE dipping (29°) thrust fault**
- **Depth ~11 km**
- **Short rise time between 2s & 5s**
- **Bilateral rupture (v_r ~ 2 km/s)**

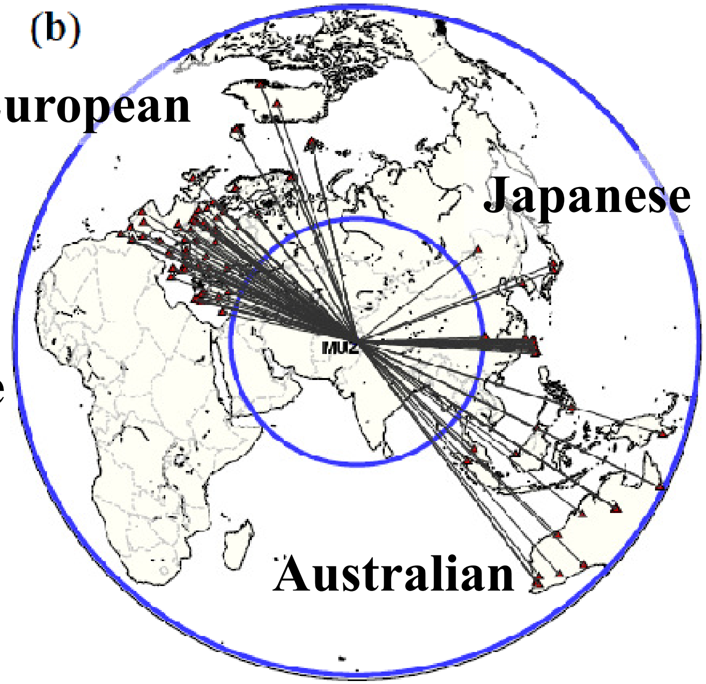


Avouac et al. (2006)



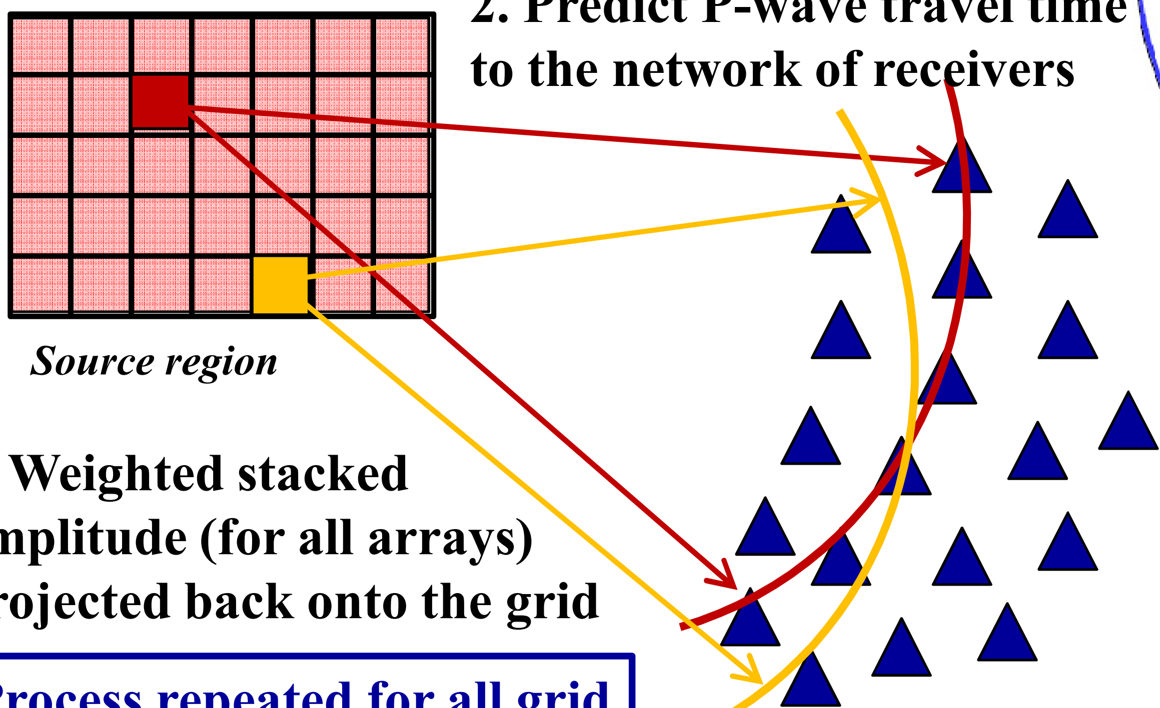
Back Projection: Methodology

Kiser and Ishii (2012)



1. Parameterize the source region as grid of possible sources

2. Predict P-wave travel time to the network of receivers

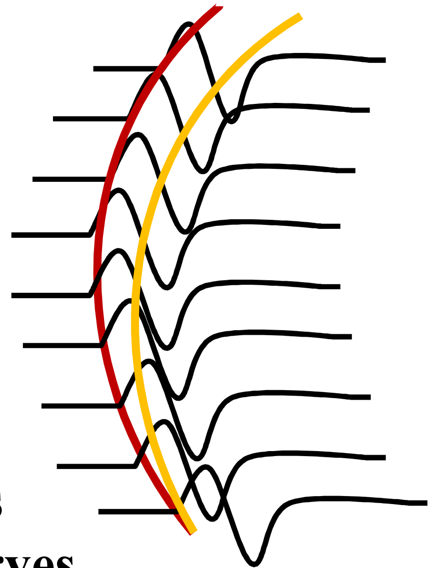


Source region

Array of Seismographs

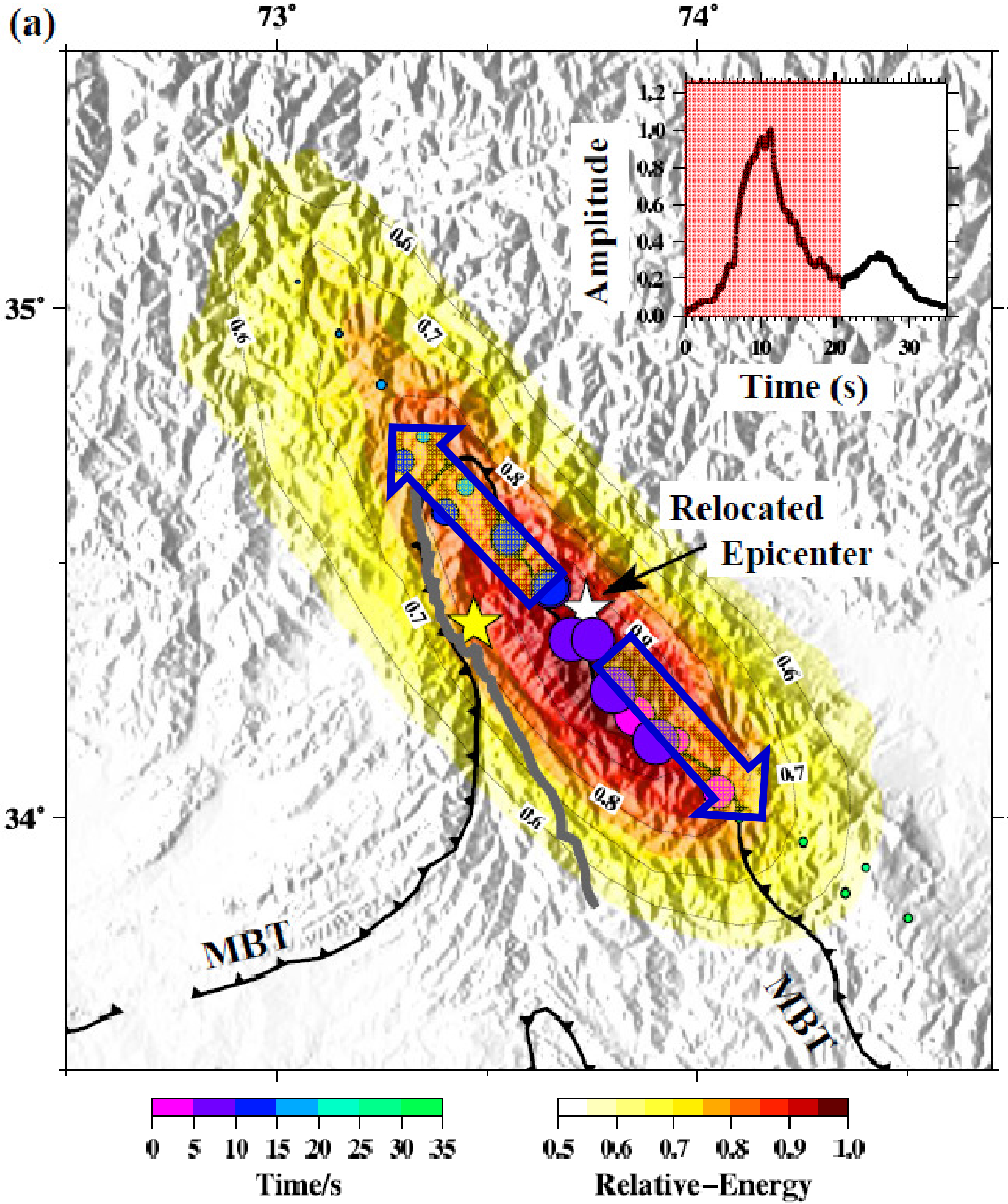
4. Weighted stacked amplitude (for all arrays) projected back onto the grid

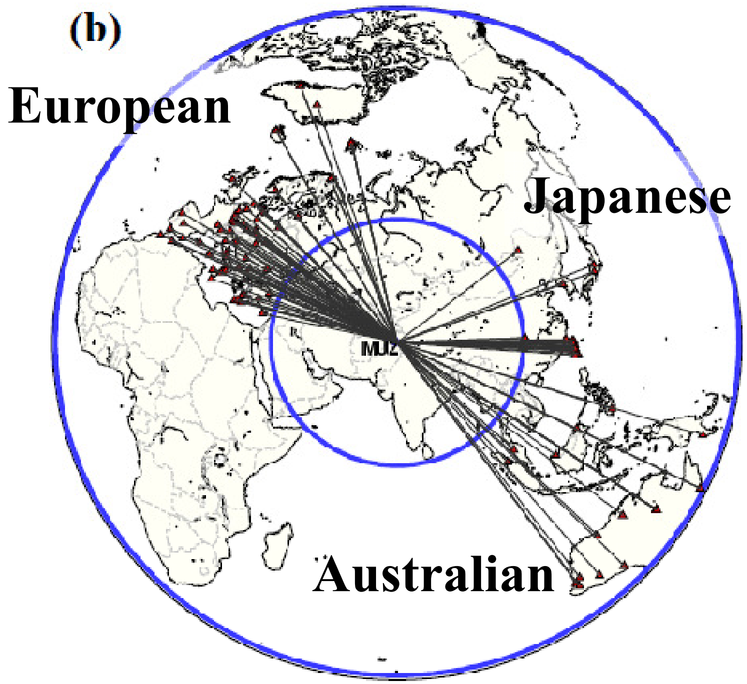
Process repeated for all grid and through time



3. P-waveforms corrected 3-D structure effects are stacked along the predicted travel time curves

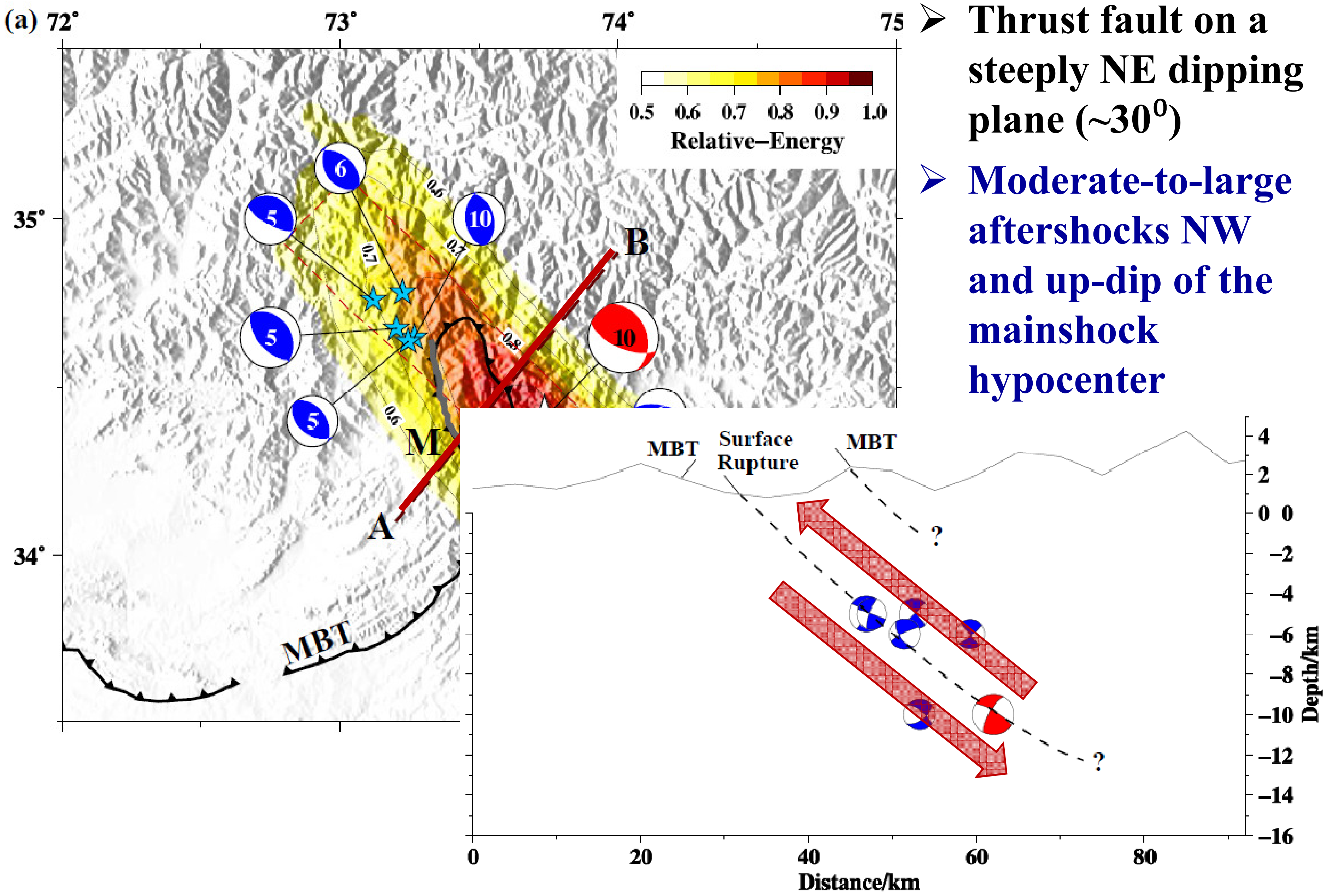
2005 Kashmir Mainshock Back Projection





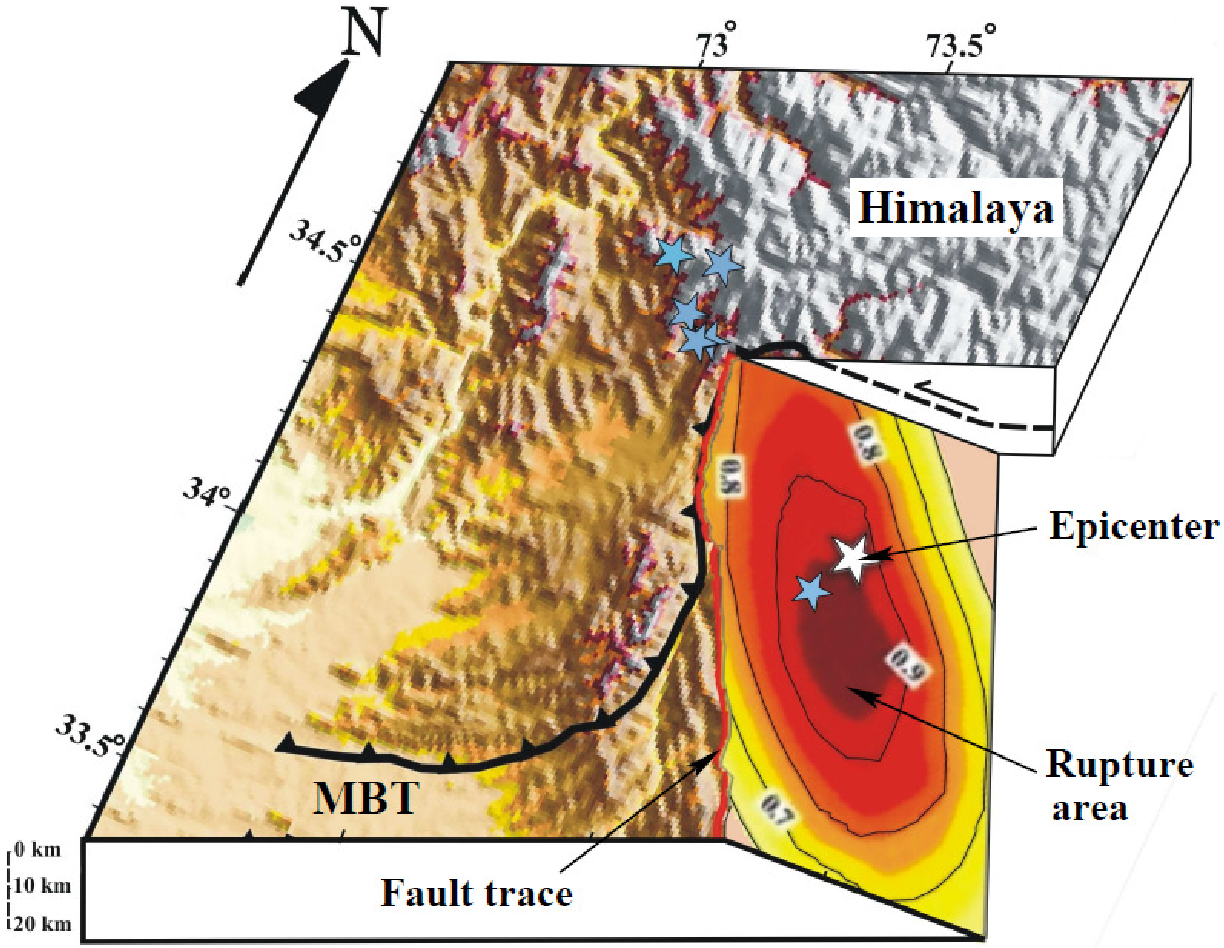
- Compact rupture with short rise time (STF ~20s)
- Bilateral rupture with velocity (v_r) ~ 3 km/s
- Major energy released close to the surface rupture

Mainshock and Aftershock Source Mechanisms

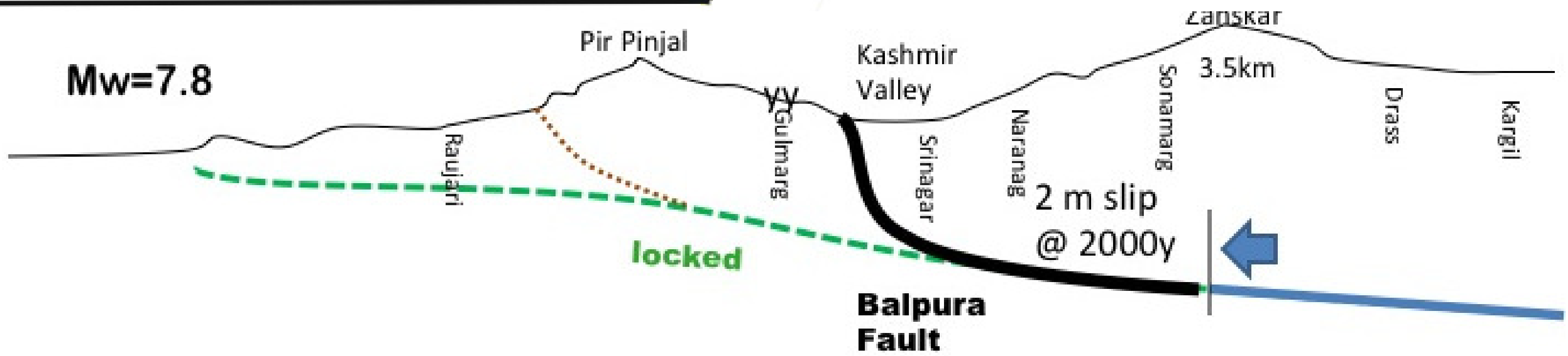


- Thrust fault on a steeply NE dipping plane (~30^0)
- Moderate-to-large aftershocks NW and up-dip of the mainshock hypocenter

2005 Kashmir Mainshock

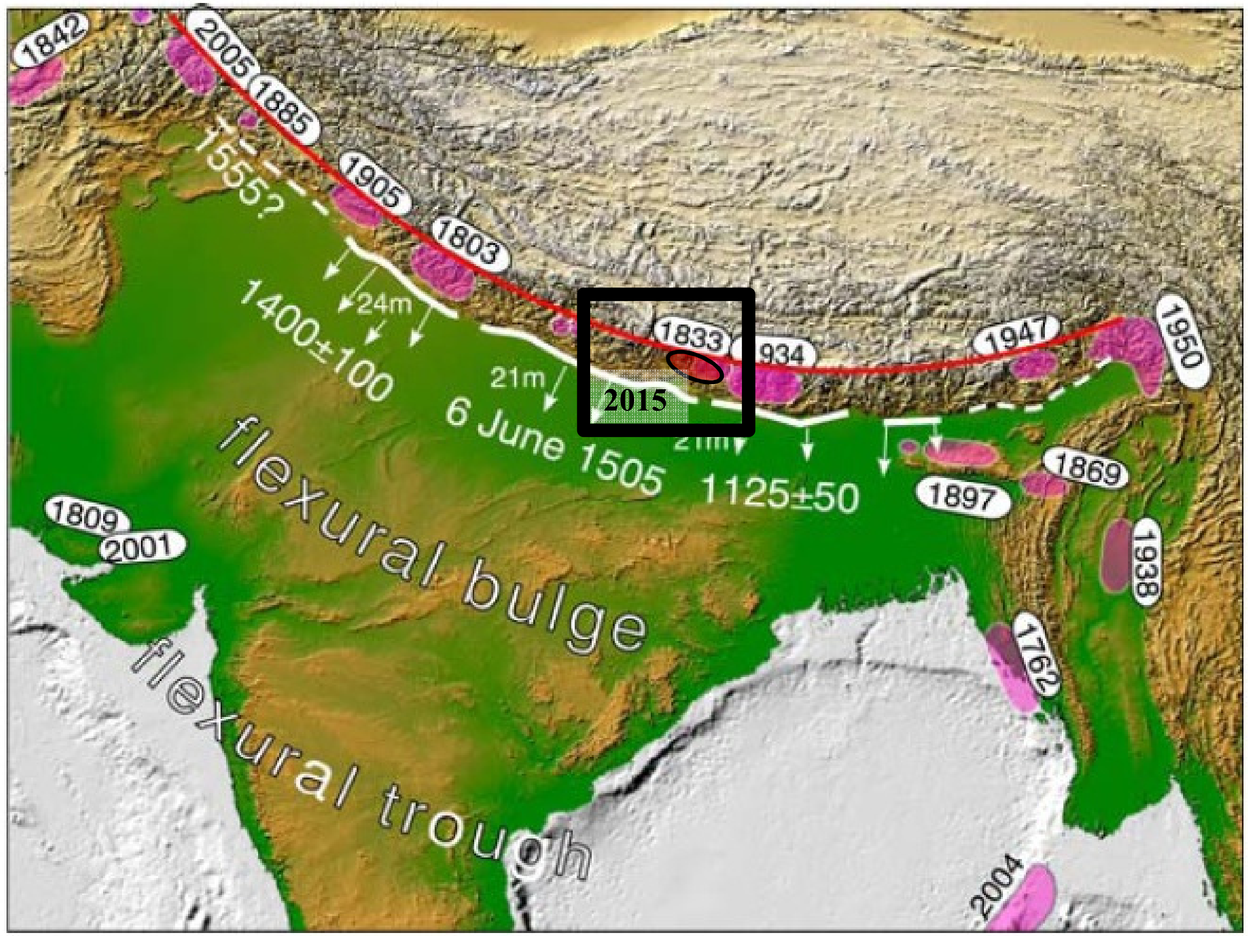


- MBT syntaxis possibly terminated the NW rupture propagation?
- Out-of-sequence thrust fault?



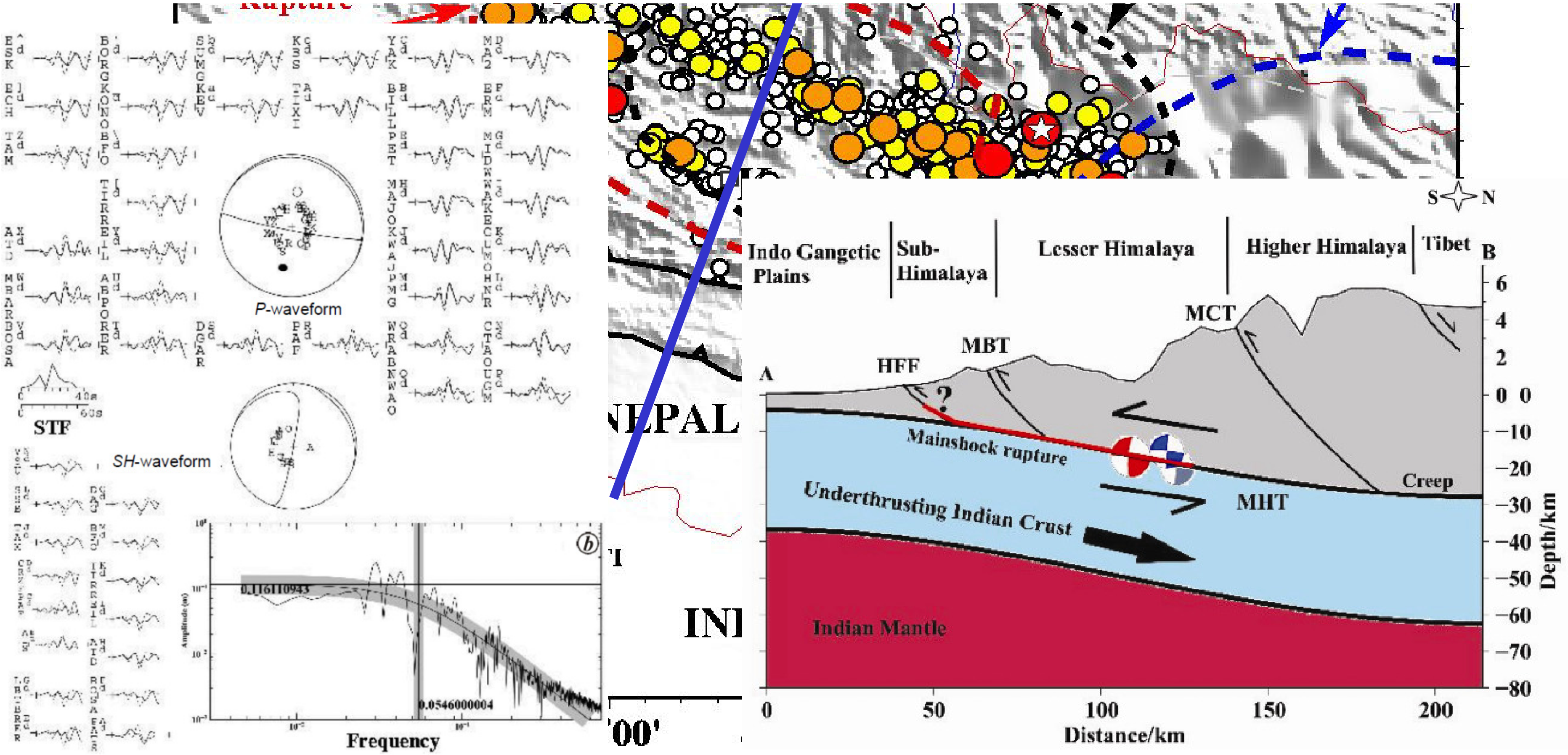
25 April 2015 Nepal Earthquake and its Aftershocks

- **Mainkshock: M_w 7.8 (Gorkha district) Nepal**
- **Largest earthquake to have occurred in this region in the past 81 years.**
- **Followed by M_w 7.3 aftershock on 12 May 2015 (eastern edge)**



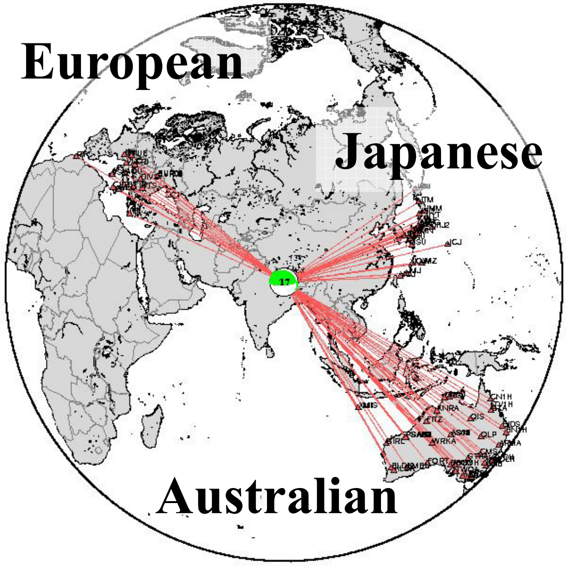
Mainshock: Source spectra (far field) & LP waveform modelling

- Ruptured ~150 x 55 km shallow NE dipping (~5°±3°) fault at 17±3 km depth
- Confined to the frictionally locked downdip segment of the MHT
- Himalaya overthrust the Indian plate by 4.8±1.2 m in SW direction



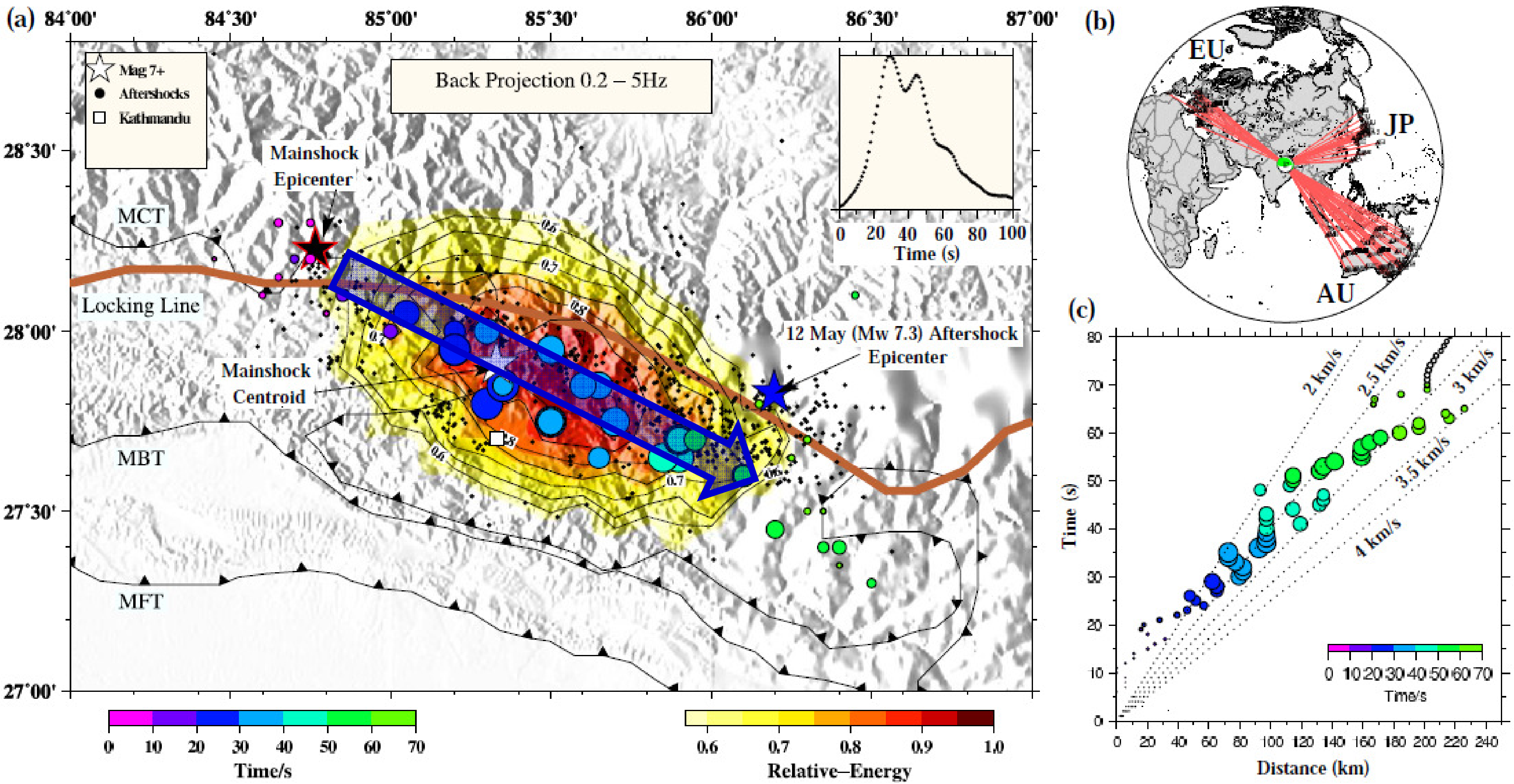
Mitra, S., H. Paul, A. Kumar, S. K. Singh, S. Dey and D. Powali (2015) The 25 April 2015 Nepal earthquake and its aftershocks, ***Current Science, vol. 108, no. 10, pp 19381943, 25, May 2015.***

Rupture Propagation (source time history) from Array Analysis



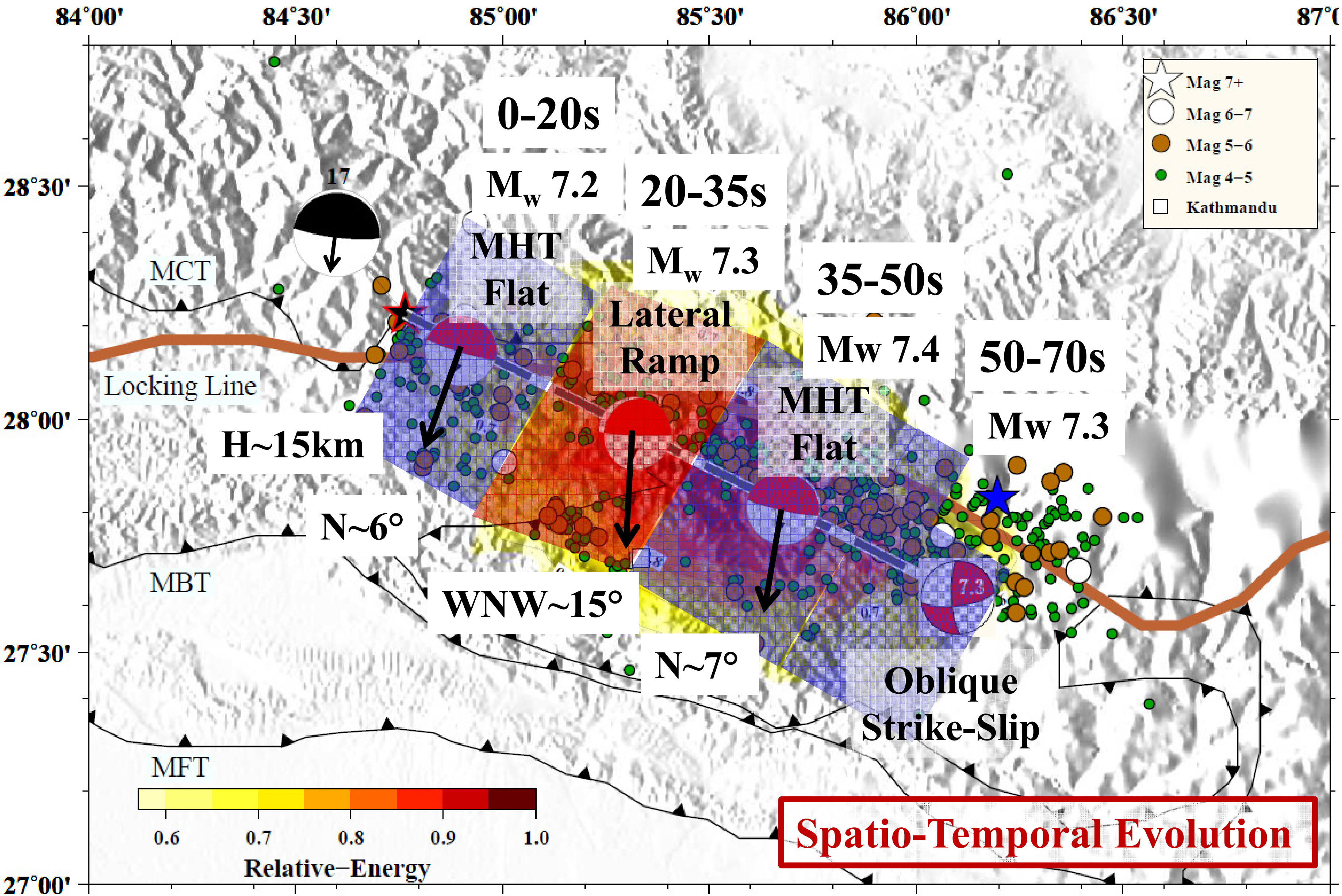
25 April 2015 Nepal (Gorkha) Earthquake

Rupture Propagation (source time history) from Array Analysis

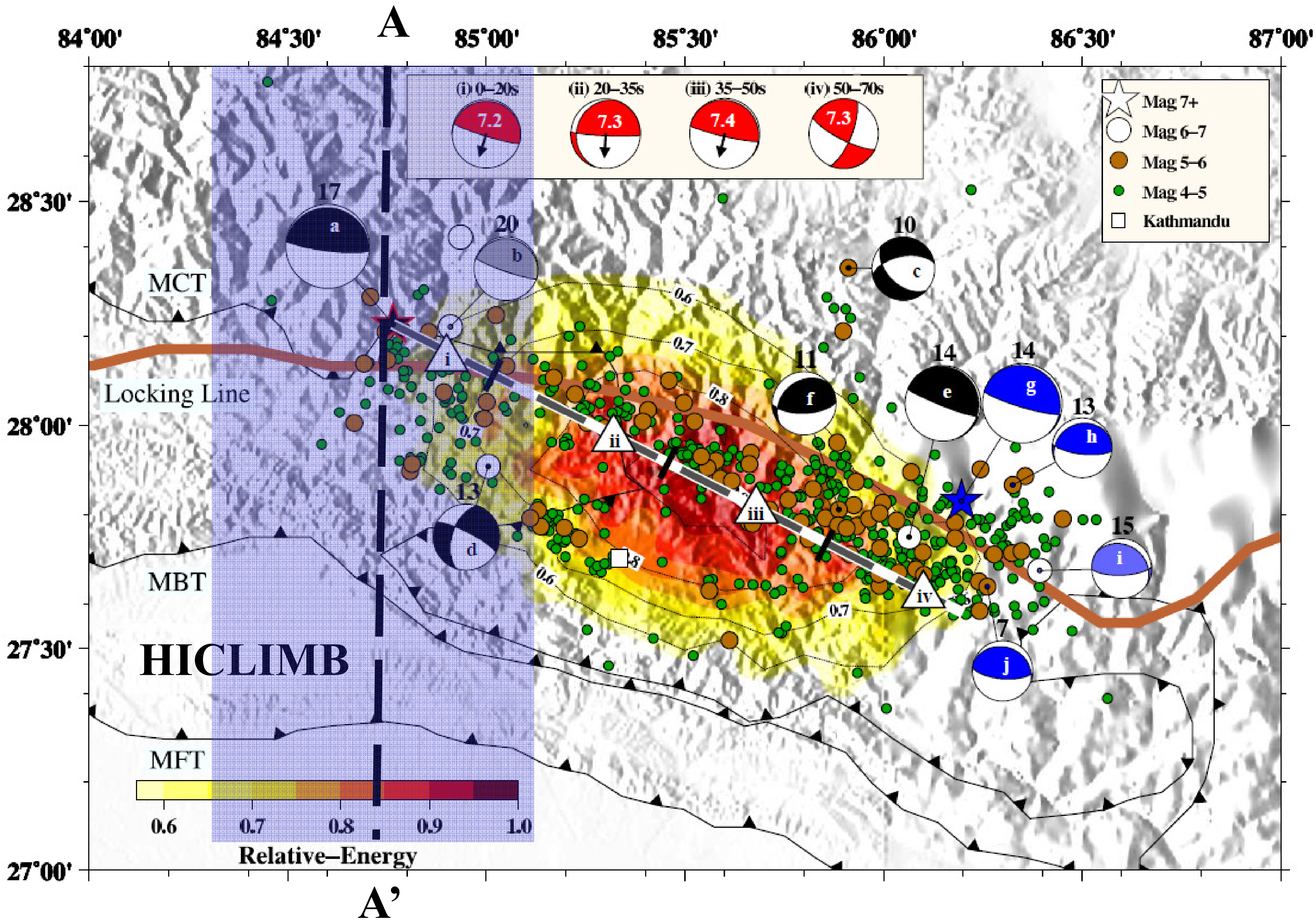


- Unilateral rupture: W → E but with variable v_r ~ 2.1 to 3.5 km/s
- Confined to the downdip segment of MHT

Mainshock Source Mechanism: Multiple Sub-Events

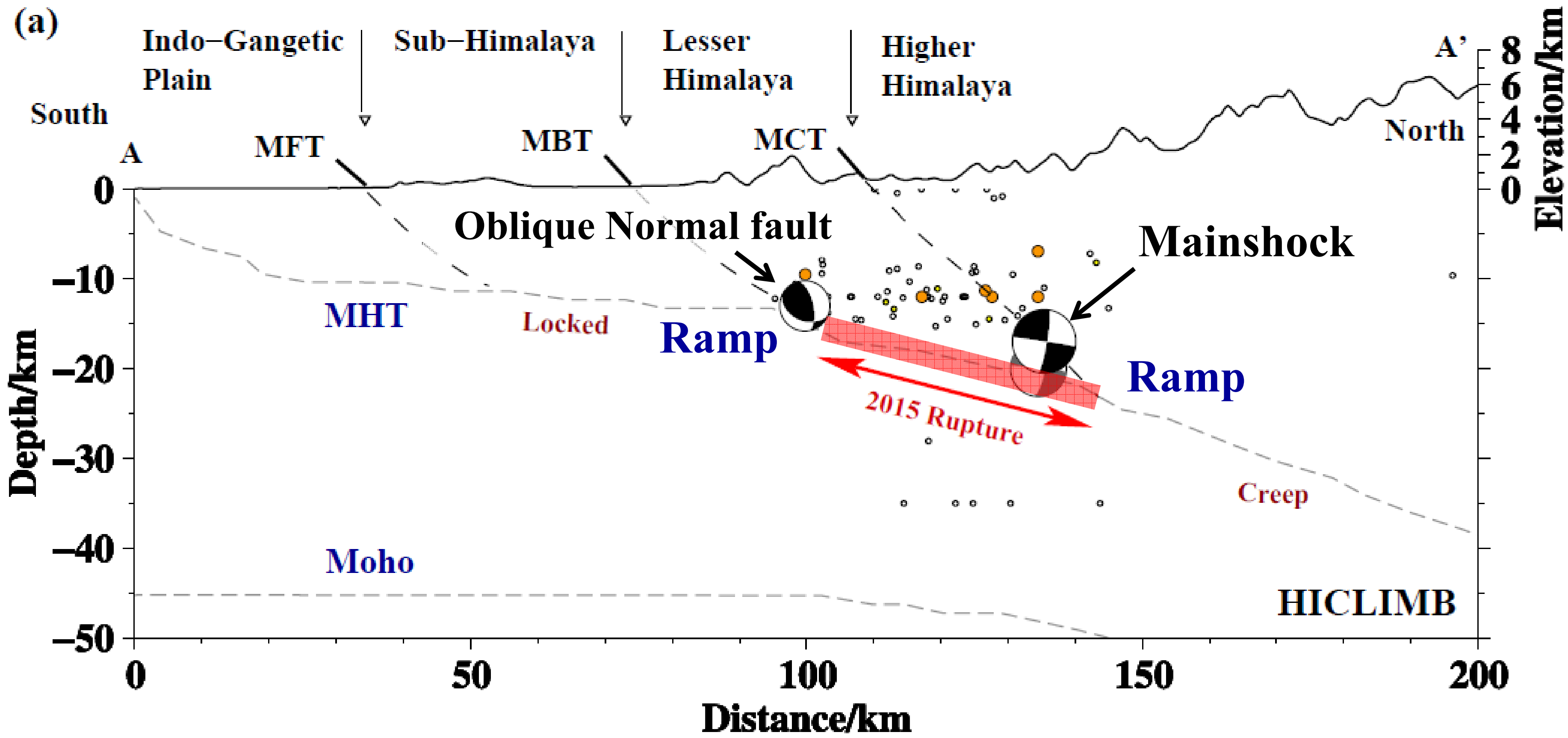


Source Mechanism: Mainshock & Aftershocks

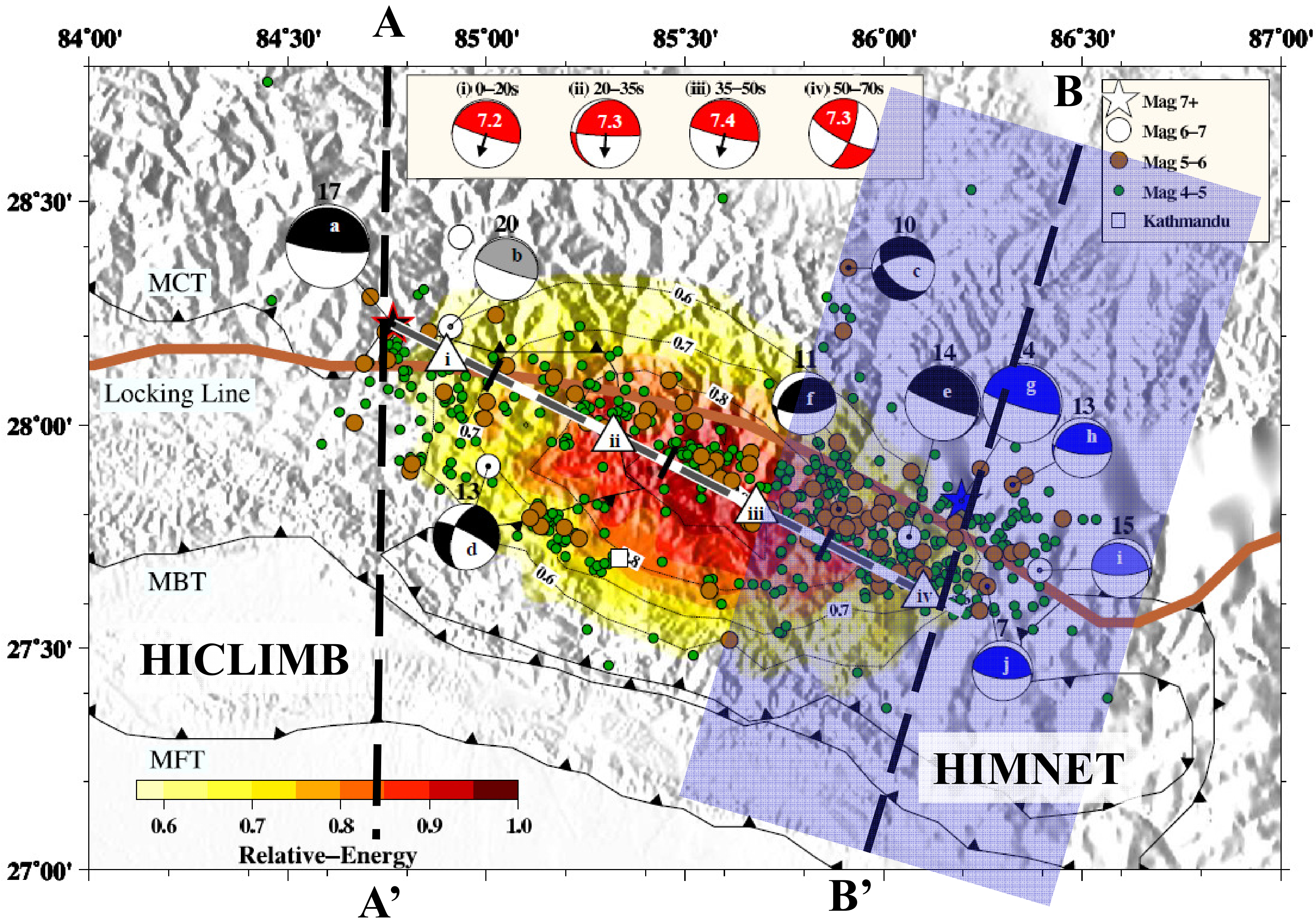


Profile A-A' (HICLIMB)

- Along dip extent of the mainshock bound by Ramps on the MHT
- Normal fault (due to flexure) at the base of the shallow crustal ramp

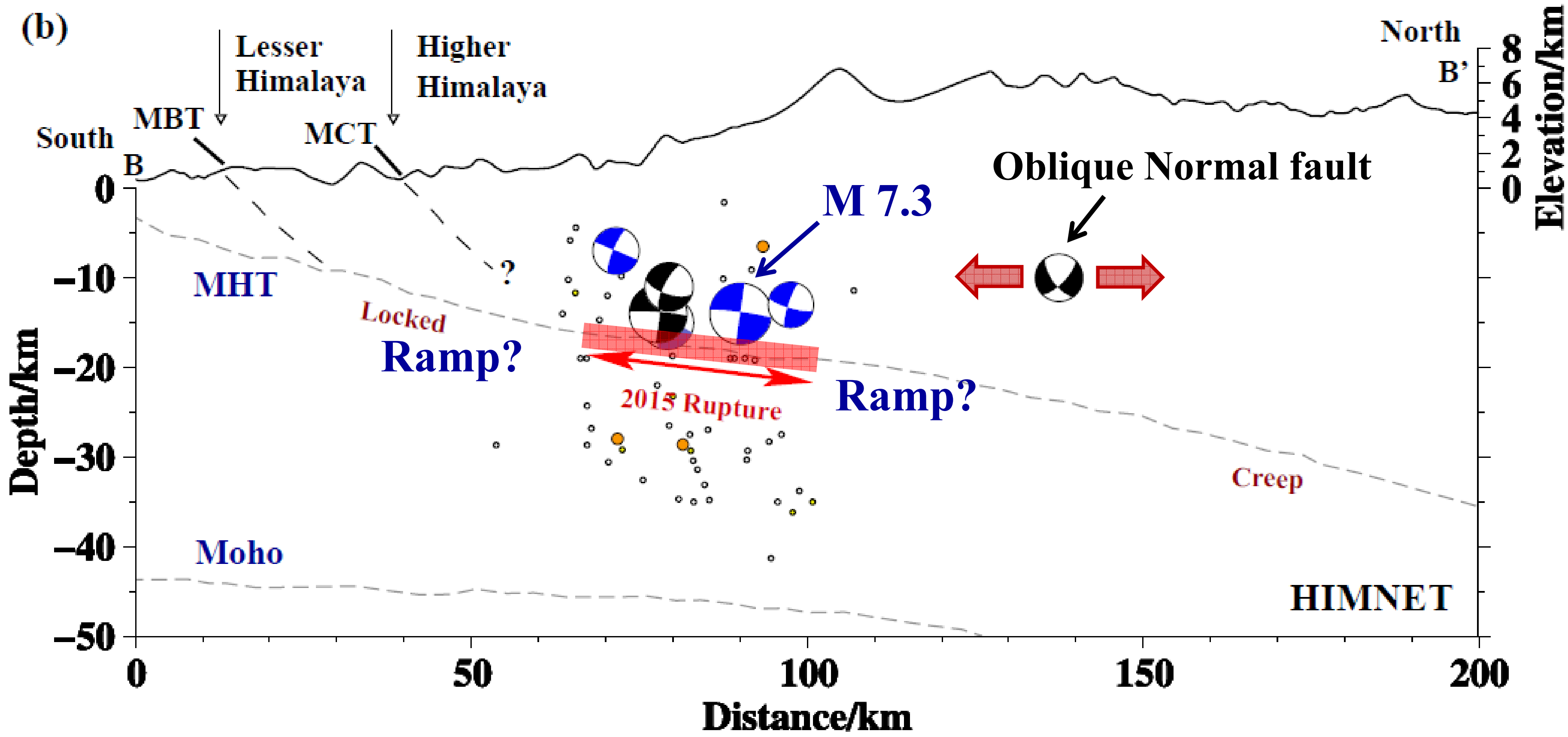


Source Mechanism: Mainshock & Aftershocks



Profile B-B' (HIMNET)

- **Ruptured the down-dip edge of the locked zone on the MHT**
- **Normal fault (due to extension) within the Himalayan wedge**



Summary

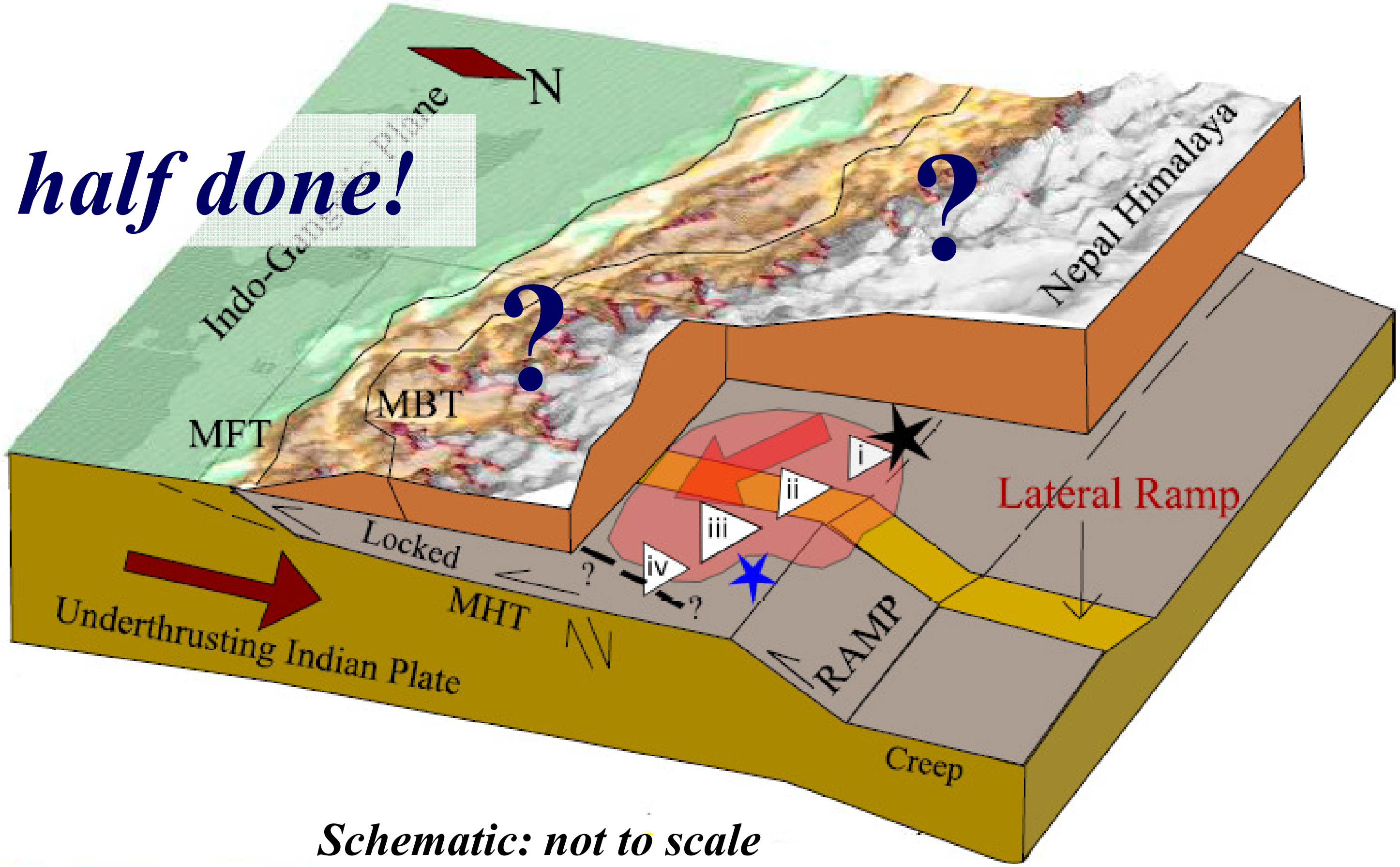
- **Mainshock rupture initiated close to the LL & propagated updip and Eward**
- **(i) 0-20s: MHT flat, $V_r \sim 3.5$ km/s slow buildup, high f, low amplitude pulse**

  (ii) 20-35s: Lateral ramp, $V_r \sim 2.5$ km/s

  (iii) 35-50s: MHT flat, largest amplitude pulse, controlled the CMT solution

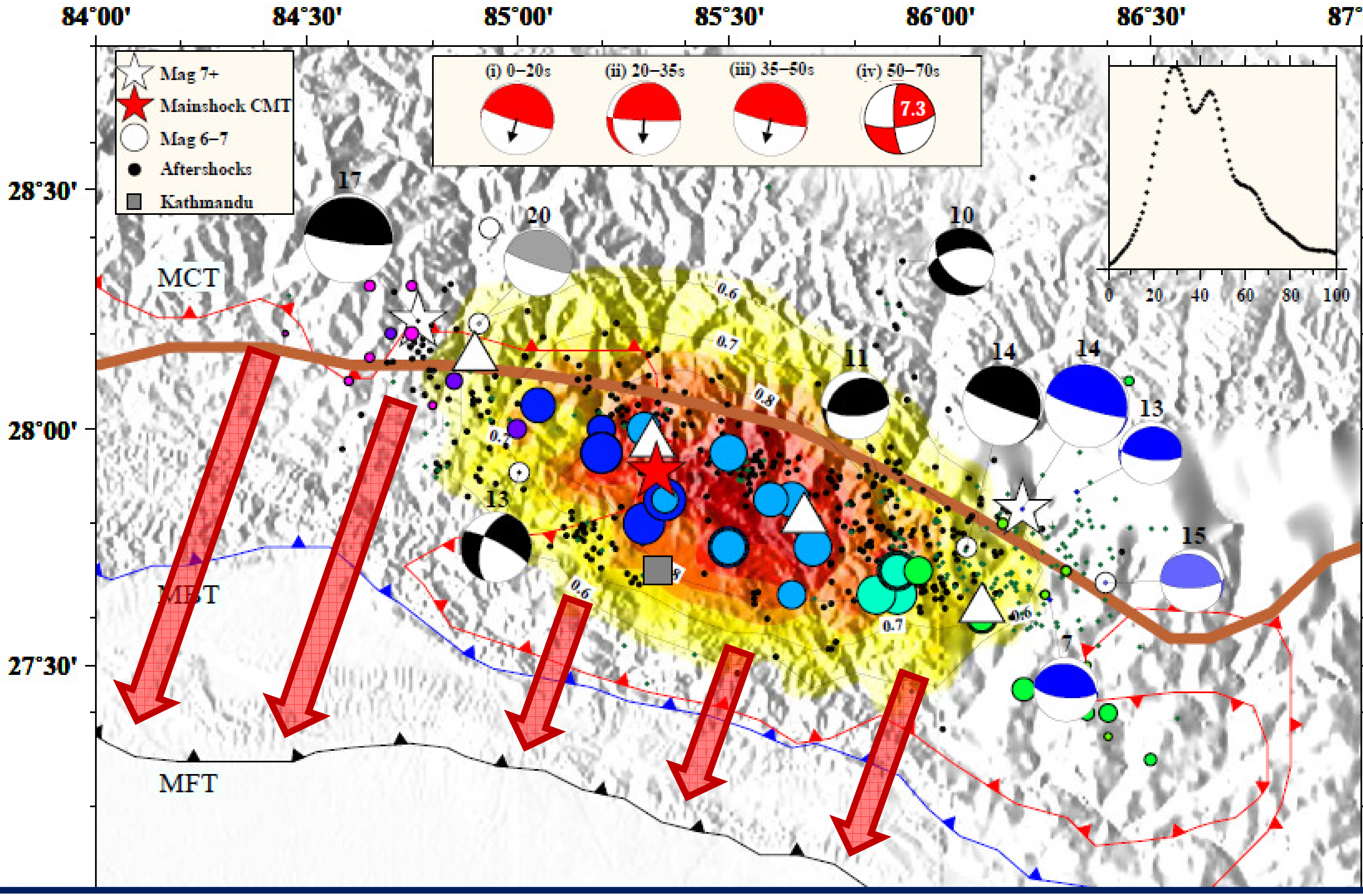
  (iv) 50-70s: Oblique strike-slip fault (Transverse structure?)

Job half done!



Schematic: not to scale

2015 April 25 Gorkha (Nepal) Earthquake and its Aftershocks



Loaded the updip & western segment of the MHT (last great earthquake 1505)

Significantly increased the potential for future great earthquake(s)

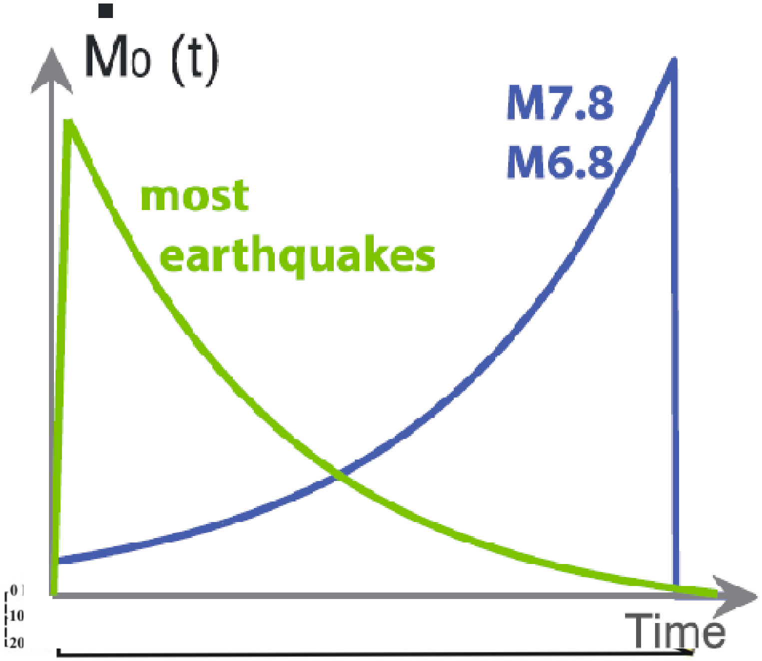
2005 Kashmir (Mw 7.6)

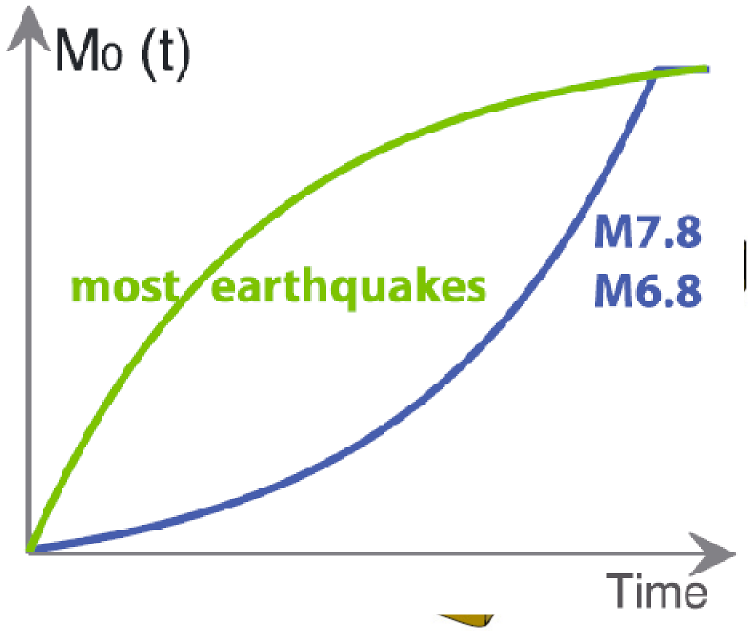
- Steep thrust-faulting event (~30^0)
- Bilateral Surface rupture, energy released within 10 km of surface (more surface waves)
- Short rise time (2–5s) led to severe ground shaking

2015 Gorkha Nepal (Mw 7.8)

- Shallow thrust fault (~10^0)
- Unilateral rupture confined within 8-20 km below the surface
- Slow rupture initiation & slow down over lateral ramp (high freq. deficient) ground motion

Denolle et al. (2015) GRL



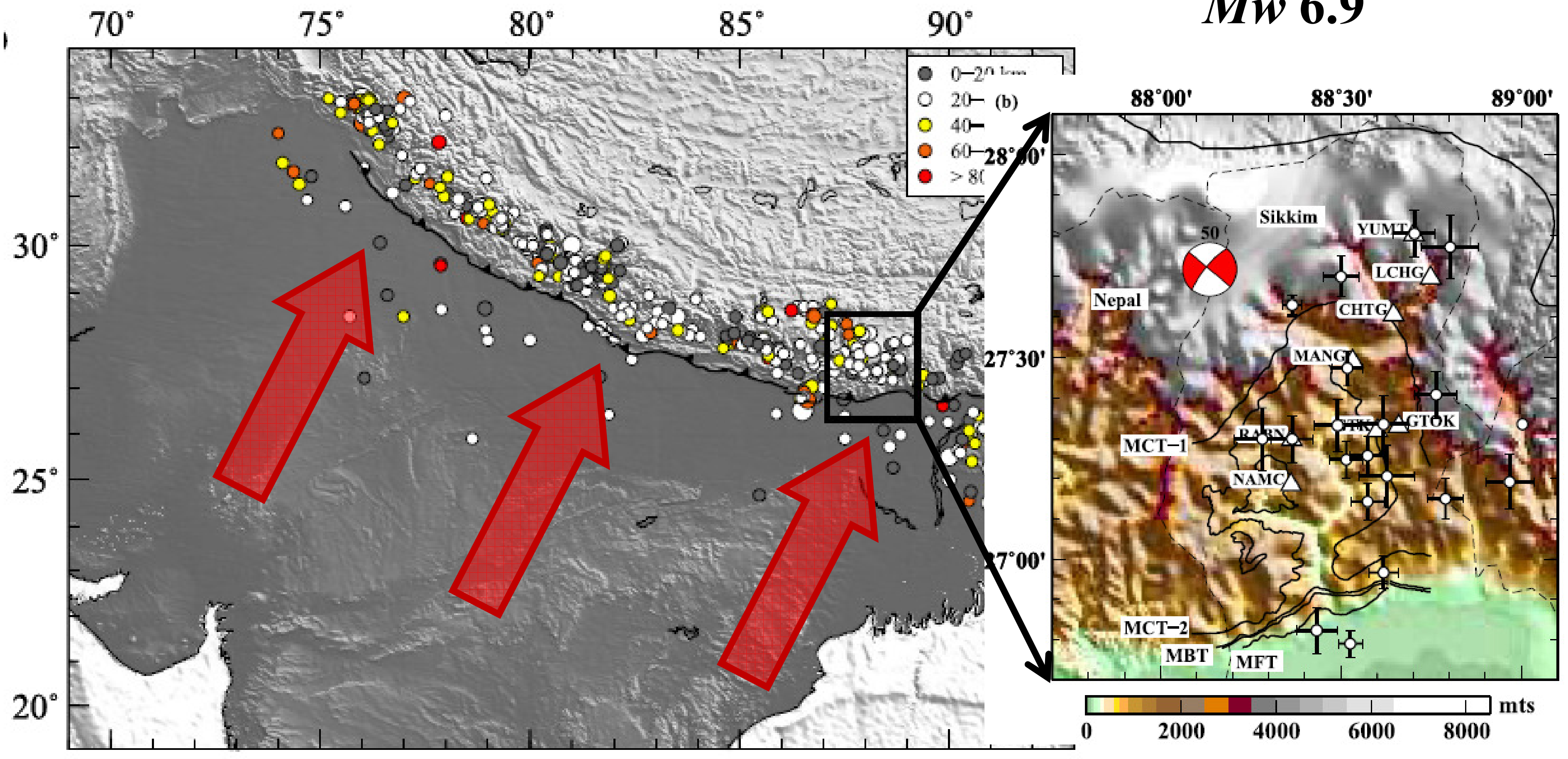


Himalayan Seismicity

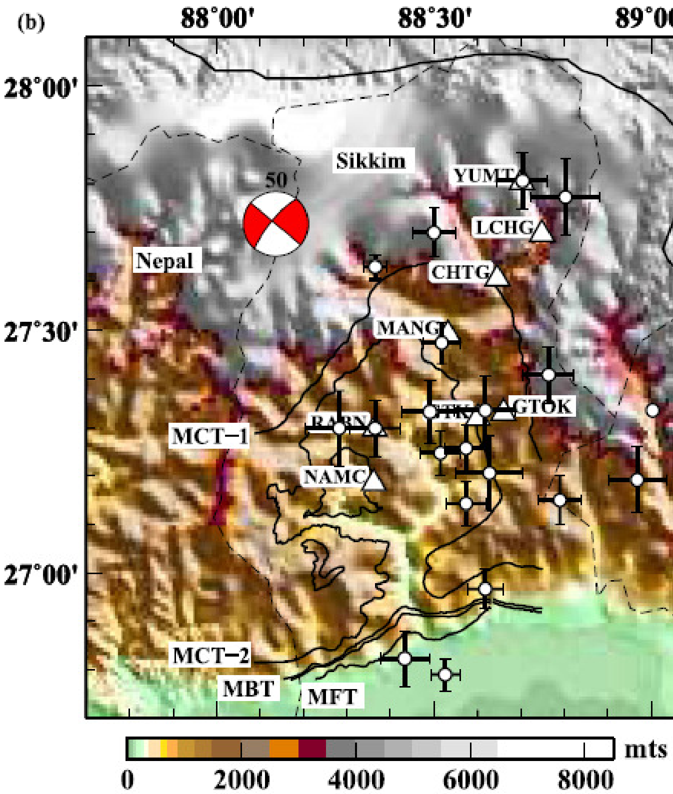
3. Within the underthrust Indian Plate

18 September 2011
Sikkim, India
***Mw* 6.9**

Deep focus (h>40 km) earthquakes



18 September 2011
Sikkim, India
Mw 6.9

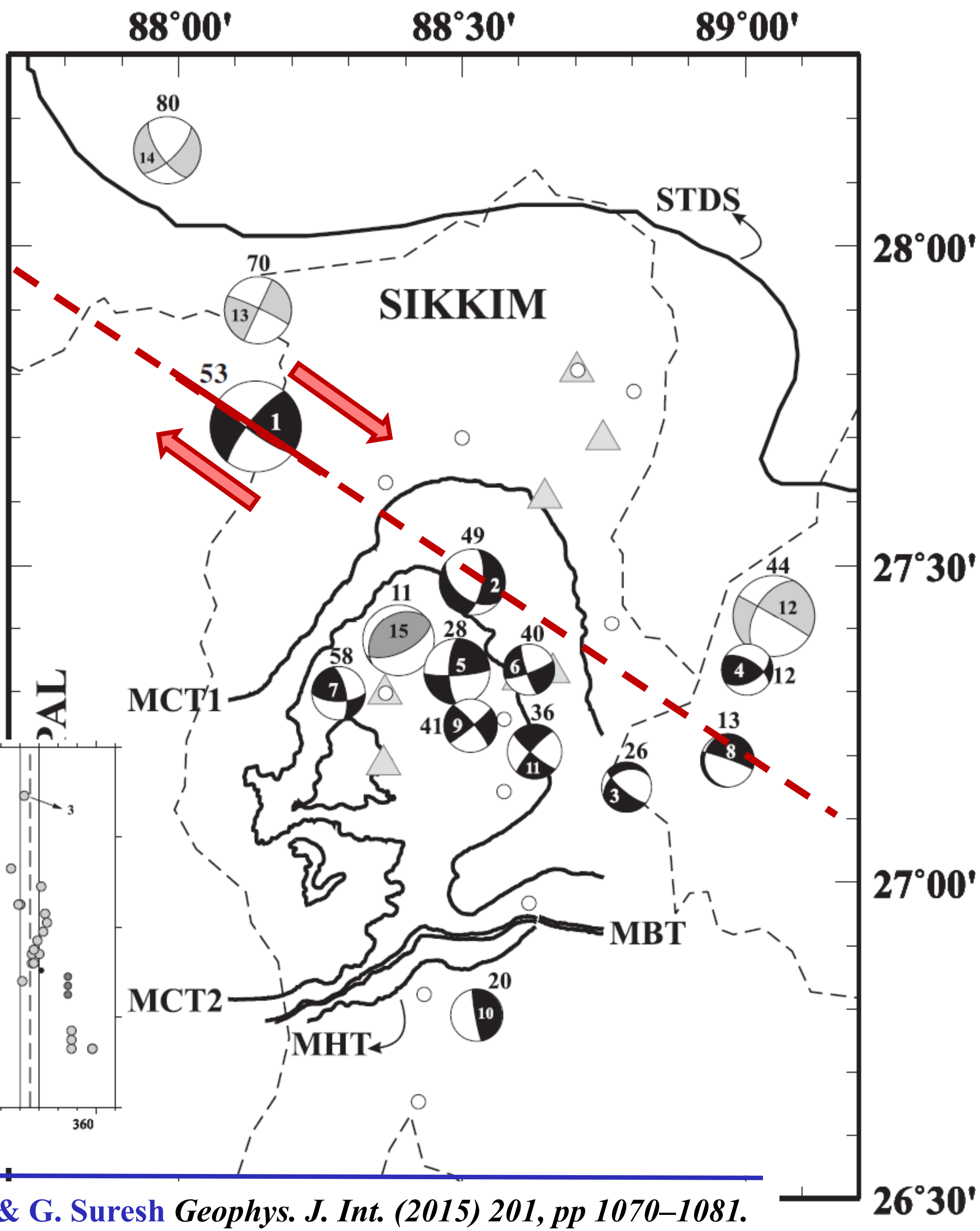


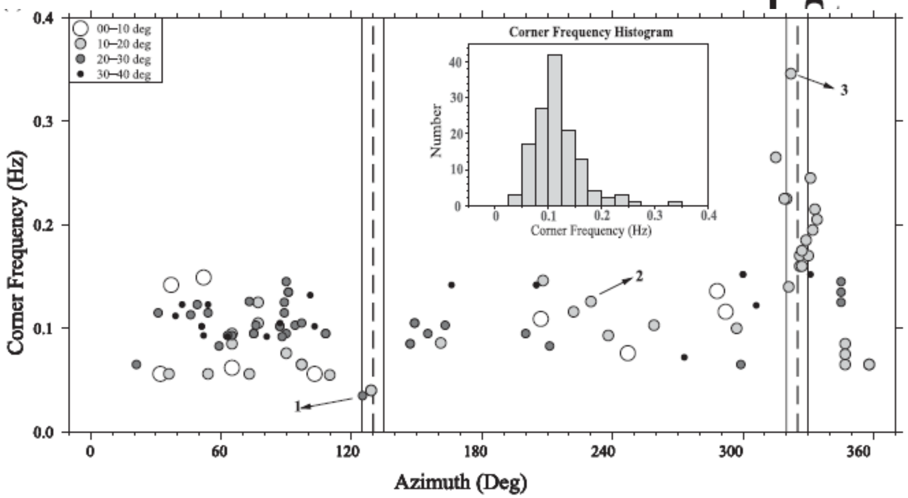
2011 Sikkim Earthquake

(1) Mainshock on near vertical fault, oriented NW-SE oblique to the Himalayan arc

(2) Rupture initiated at SE end of the fault and propagated NW with dextral strike-slip motion

(3) Aftershocks (occurred SE of mainshock) have predominantly strike-slip motion



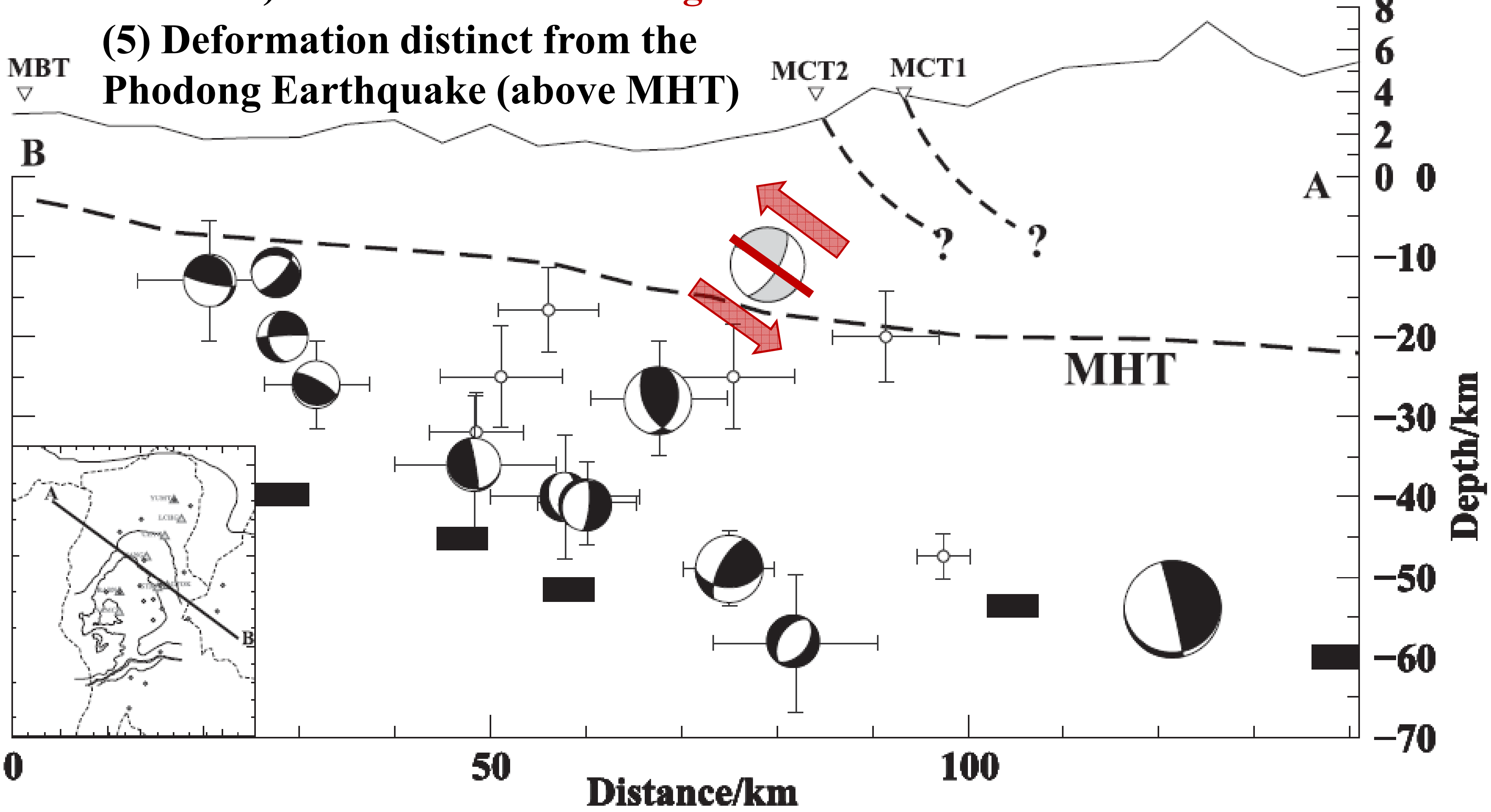


Himangshu Paul, S Mitra, S.N. Bhattacharya & G. Suresh *Geophys. J. Int. (2015) 201, pp 1070–1081.*

(3) Faulting originated at 53±4 km and ruptured at least 20 km of seismogenic lower crust (underthrust Indian Plate)

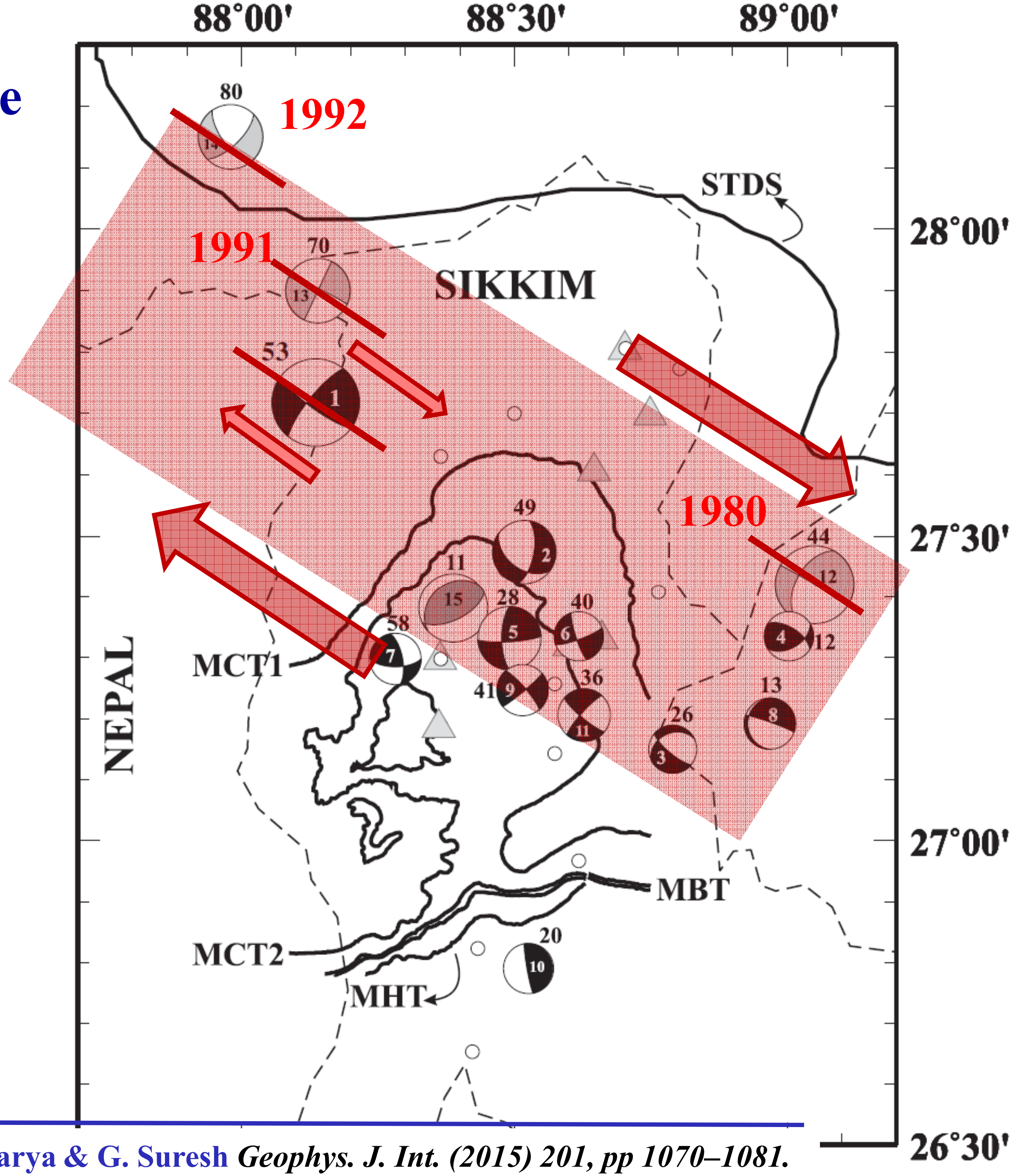
(4) Aftershocks originated between 12 and 50 km depth (within the underthrut Indian crust) – Entire Crust Seismogenic

(5) Deformation distinct from the Phodong Earthquake (above MHT)



Himangshu Paul, S Mitra, S.N. Bhattacharya & G. Suresh *Geophys. J. Int. (2015) 201, pp 1070–1081.*

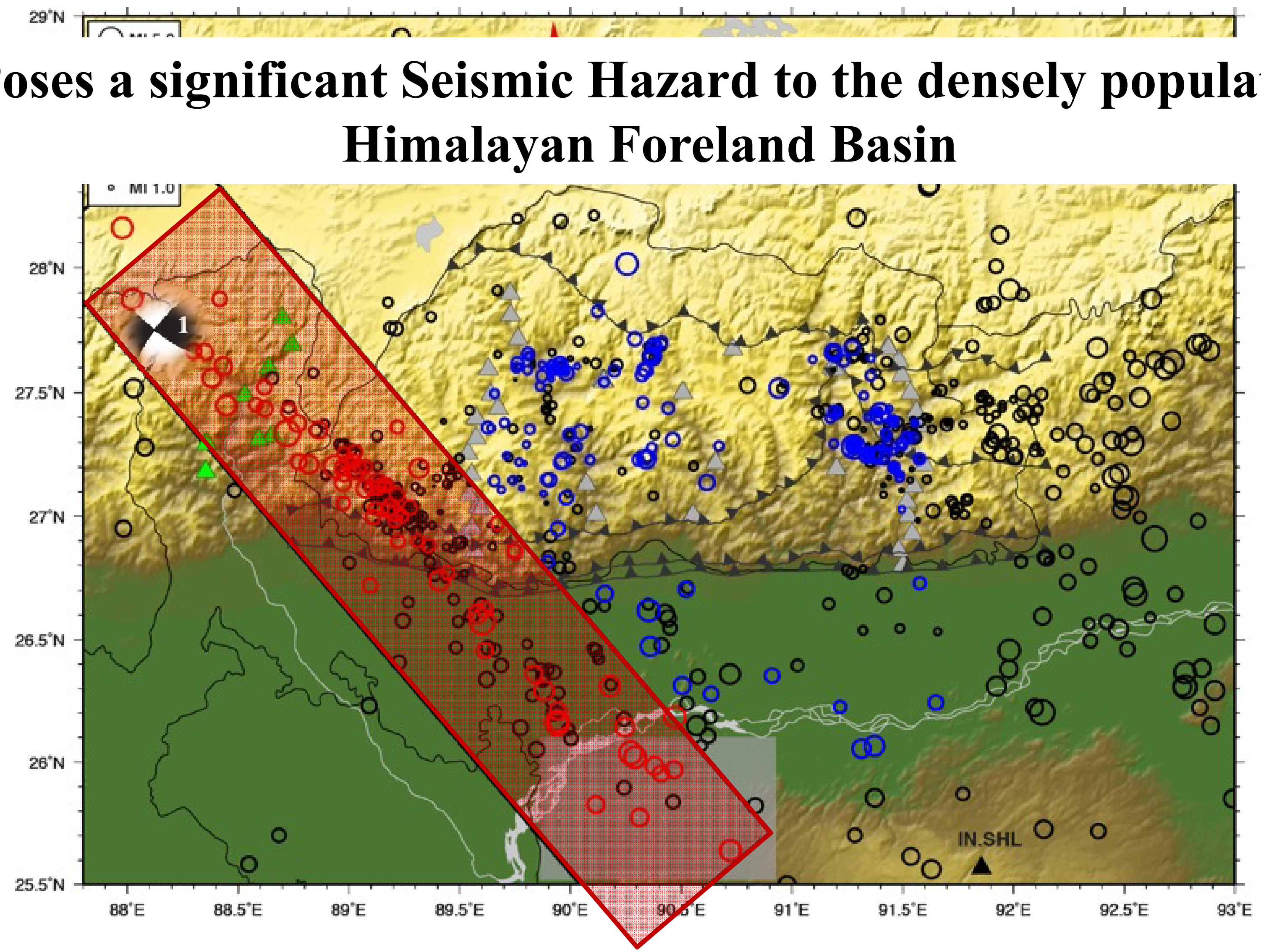
2011 Sikkim Earthquake and Aftershocks



Himangshu Paul, S Mitra, S.N. Bhattacharya & G. Suresh *Geophys. J. Int. (2015) 201, pp 1070–1081.*

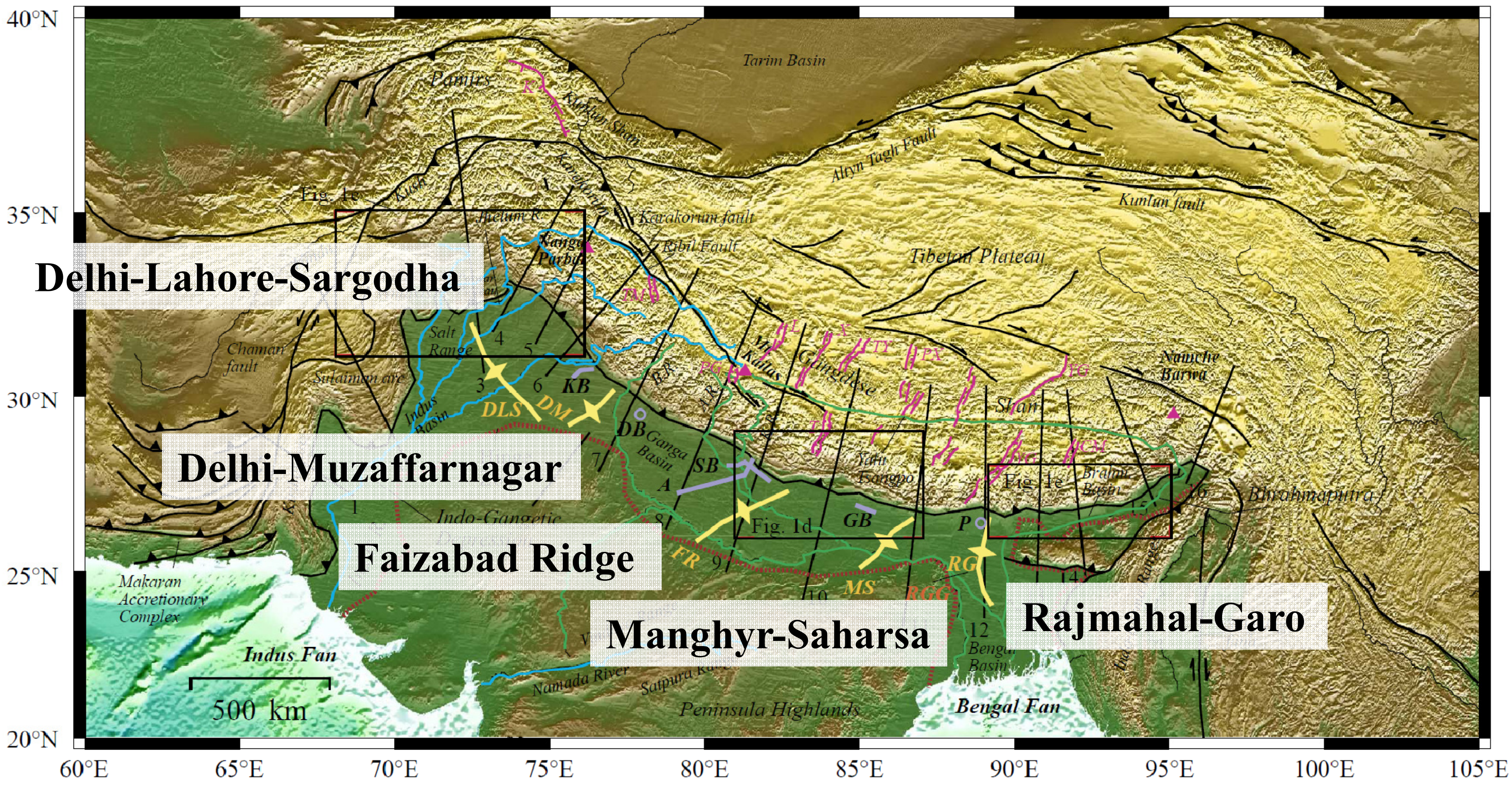
GANSSER Seismic Experiment

Poses a significant Seismic Hazard to the densely populated Himalayan Foreland Basin



Julia Singer, György Hetényi, Tobias Diehl and Eduard H Kissling (2014) Structure of the Orogenic Wedge in the Bhutan Himalaya: First Results from the GANSSER Seismic Experiment, *2014 AGU Fall Meeting Abstract T21B-4573.*

Himalayan Foreland Basin Basement Ridges



An Yin (2000)

Summary

- **Earthquakes within the mountain belt (moderate-to-large) mark the downdip edge of the locked segment on the MHT and the zone of initiation of mega-thrust earthquakes**
- **Mega-thrust earthquakes (partially or completely) rupture the locked segment of the MHT. Structural heterogeneity plays an important role in moderating the rupture**
- **Earthquakes within the underthrust Indian Plate are least understood and poses considerable seismic hazard both within the south of the Himalaya**

Outstanding Question

- **Factors controlling the initiation, rupture propagation and termination of mega-thrust earthquakes?**

Acknowledgements

Seismological Observatory

IISER-K Seismology Group

N-PDF: **Jyotima Kanujia**

PhD: **Debarchan Powali, Jashodhara Choudhury, Swati Sharma, Siddharth Dey, Monumoy Ghosh**

BS-MS: **Shubham Sharma, Soumya Bohidar, Riddhi Mandal**

Computational Seismology Lab

Past Members S. Manna, H. Paul, S. Singh, A. Kumar, T. Ajaay, U. Mannu, Y. Jameel, B. Badrudeen, S. Nandan

Collaborators

K.J. Borah, K.F. Priestley & A. Copley, V. Gaur, S.N. Bhattacharya, & S.K. Wanchoo

Data and Funding

IMD, **NGRI, IRIS-DMC** & **GFZ Potsdam**, GDSN and INDEPTH for data; **SEIS-UK, NERC** and **DST** for funding and Instrument support; **IISER Kolkata, University of Cambridge, IITKGP, UK-IERI, NERC** for financial support and research infrastructure.