Estimation of earthquake hazard in the source zones along Indian plate boundary from GPS velocity derived strain rate and moment deficit

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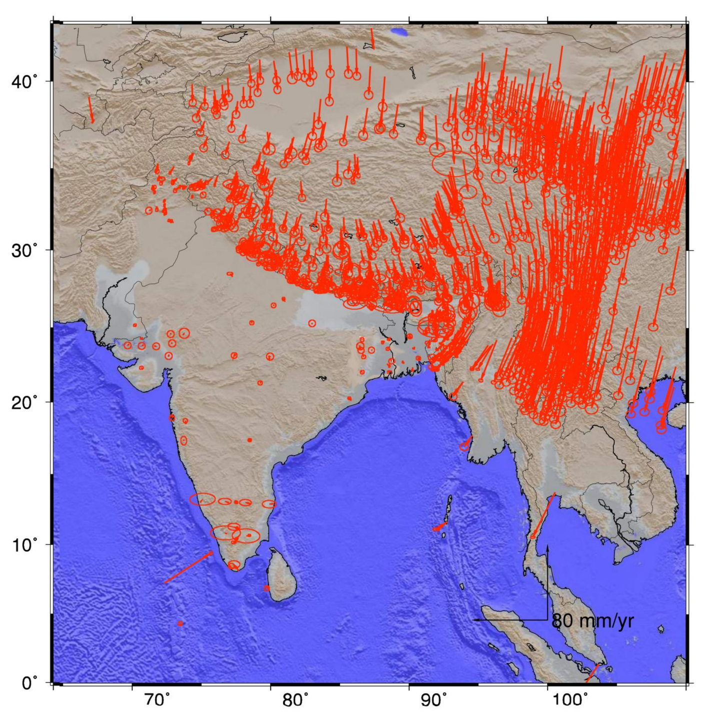
The strain rate tensor across the Indian Plate boundary in Himalaya and part of north Burmese arc is calculated from the horizontal velocities of 1252 GPS stations and represented as continuous strain rate map. From the interpolated scalar strain field data, the areas displaying greater than 104 nstrain/yr are marked as 10 seismic source zones. The low b-values (0.53 to 0.73) and related seismo-tectonics indicate compressive nature of these zones. The high strain zones marked in the foothill Himalaya are areas of fault interactions between Himalayan Thrusts of Tertiary age with transverse older Proterozoic reactivated faults (an integral part of basement ridges on under-thrusted rigid Indian plate). Fault interaction is also prominent in EHS area and in Sagaing Fault, where faults from two different tectonic domains are interacting and getting activated by overall clockwise rotational mass movement around plate interface. For calculating seismic vulnerability, we have computed the geodetic moment rates from the measured geodetic strain rates by empirical formula within 15±2 Km seismic volume in these zones, and compared geodetic with seismic moment rate from earthquake catalogue of 100 years. From the moment deficit, the estimated magnitude of earthquake in 10 seismic source zones are calculated which ranges from 6.5 to 7.4. Our analysis evidences that the Arunachal Himalaya, Sagaing fault, EHS and Himachal Himalaya are posing high seismic threat with possible occurrence of shallow focus 7.1 Mw earthquake.

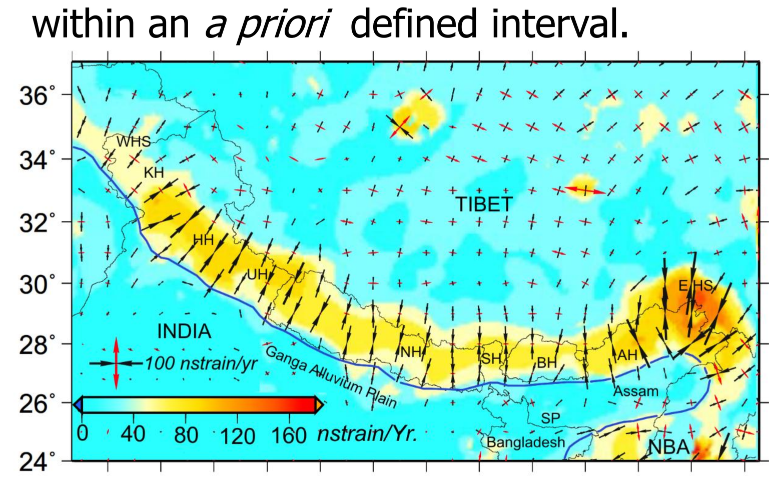
GPS velocity field and strain rate

We have obtained a combined solution of horizontal velocities realised in the common reference frame ITRF08 coming from five different solutions: (a) 428 sites from Kreemer et al (2014) (b) 703 sites from Gan et al (2007) (c) 48 sites from Gupta et al. (2015) (d) 53 sites from Steckler et al. (2016), (e) 16 new stations located in the foothills of Darjeeling-Sikkim Himalayas and in the western part of Bengal basin. The combined solution consists of 1252 horizontal velocities merged to the common frame ITRF08 by the 'velrot' program of GAMIT/GLOBK software package with a RMS fit of 1.02 mm/yr for the 3 velocity components. The ITRF08 velocity field is transformed to India fixed frame by removing the India motion defined by Jade et al. (2017)



GPS velocities of 1252 stations in India Fixed Frame. Uncertainties are at 95% confidence level

The horizontal strain rate (SR) tensor across the Indian Plate boundary was determined using the method developed by Shen et al. (1996, 2007) from the combined horizontal velocities and their uncertainties. The method applies a distance weighted approach on a regular spaced grid in which the contribution of each site velocity at each grid node is weighted by a Gaussian function $\exp(-d^2/\sigma^2)$, where d is the distance between each GPS site and the grid node and σ is a smoothing distance parameter which is optimally determined within an *a priori* defined interval.

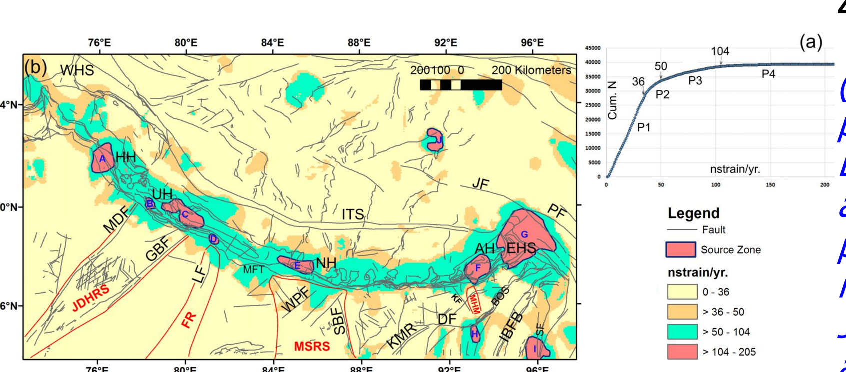


Interseismic strain rate map for Himalaya, Tibet and Northern Burmese arc. The blue solid line indicates the active deformation front. WHS: Western Him. Syntaxis, EHS: Eastern Him. Syntaxis, KH: Kashmir Him., HH: Himachal Him., UH: Uttarakhand Hima. NH: Nepal Him., SH: Sikkim Him., BH: Bhutan Him., AH: Arunachal Him., SP: Shillong Plateau, NBA: Northern Burmese Arc

The 2D SR tensor has been obtained interpolating the 2D velocities on 0.1°×0.1° grid, with σ ranging between 100 and 1500 Km. The SR axes are black for compression and red for extension.

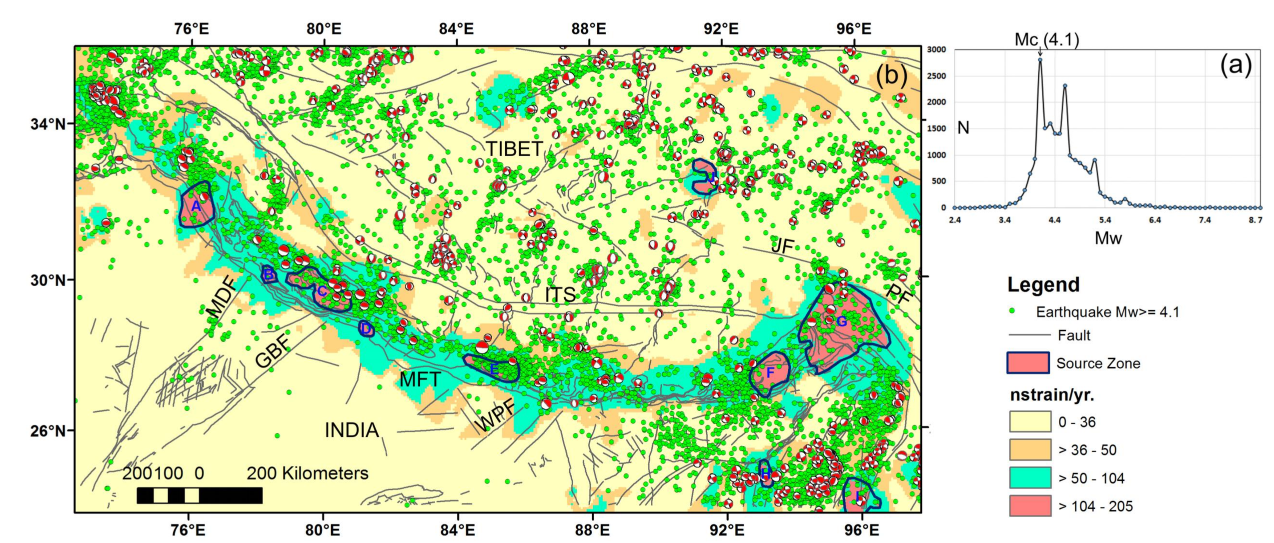
The SR pattern is a scalar accounting for all the tensor components, with an average increasing value from ~60 to ~200 nstrain/yr. A variable amount of SR is displayed along the whole range (map background colour).

Considering as normal the probability distribution of deformation, SR has mean value of 30.48 nstrain/yr and standard deviation of 24.78 nstrain/yr; we will consider "anomalous" the areas with SR greater than 104.82 nstrain/yr (m±3sd=104.82), marking them as zones at high strain rate



(a) The excess probability plot of SR indicates four population domains. (b) The SR between WHS and EHS in Himalaya is represented as colour background according to the four populations delineated in excess probability plot. The areas with SR higher than 104 nstrain/yr. correspond to 10 Seismic Source Zones (A-J) along the margin of convergence between Indian and Eurasian/Sunda plates. The highest values along India and Eurasian plate interface are reached in clusters F and G to +160 nstrain/yr.

Seismic Data



Map showing earthquake data (Mw ≥ 4.1) for period 1905 – 2018 and CMT beach-ball plots for period 1977 – 2018 of the study area. (a) The magnitude completeness of earthquake data is Mw ≥ 4.1 onwards by methodology based on the assumption of self-similarity (Wiemer and Wyss 2000), (b) The earthquake (Mw ≥ 4.1) and CMT beach-ball data are plotted over strain rate data, 10 Seismic source zones and prominent tectonic discontinuities. Note JF: Jiali Fault, PF: Parlung fault, WPF: West Patna Fault, MFT: Main frontal Thrust, ITS: Indus Tsangpo suture, GBF: Great Boundary Fault, MDF: Mahendragarh Dehradun Fault).

Moment rates

The geodetic moment rate is calculated by a modified version of the Kostrov's formula (Kostrov 1974) proposed by Ward (1998b) as $M_g = 2\mu\, As\, Hs \sum Max\,|SR|$ where M_g is geodetic moment rate, μ is the rigidity modulus (3.0×10^{10} N/m² for Earth crust), As is the surface area of the seismic zone, Hs is the seismogenic thickness, SR the strain rate within each area. We have taken Hs as 15±2Km in all the 10 areas, the depth above which majority of earthquake with Mw 5.0 occurred corresponding also to the locking depth in elastic dislocation models in Himalaya and north Burmese arc in our earlier study (Mullik et al., submitted).

The seismic moment rate is calculated for the 10 seismic source zones. For doing so, we have separated the computation for the 10 seismic source zones. We have calculated the seismic moment of each earthquake within 15±2 Km depth by the formula $\log_{10} Ms = 1.5\, Mw + 9.1$ (Kanamori, 1977), where Ms is the seismic moment and Mw is the moment magnitude of the earthquake. Sum of the moments are then normalized by the appropriate time interval to get seismic moment release per year. The seismic moment released per year varies between 0.044 and 7.115 x 10^{20} Nm/yr, with minimum in Zone B and maximum in Zone G.

Seismic Source Zones	Area (Sq. Km)	Geodetic Moment (M_g) rate (10^{20} Nm/Yr.)	Seismic Moment (Ms) rate (10^{20} Nm/Yr.)	(Geodetic moment)/ (Seismic moment)	Moment deficit (10^{20} Nm/Yr.)	Mw expected for total moment release
A	12327.99	2.023±0.045	1.530	1.32	0.4937±0.045	7.1
B	2015.66	0.173±0.004	0.044	3.95	0.1289±0.004	6.7
C	13809.61	1.689±0.038	1.320	1.28	0.3683±0.038	7.0
D	1767.12	0.163±0.004	0.019	8.64	0.1438±0.004	6.7
E	8669.25	0.860±0.019	0.405	2.12	0.4544±0.019	7.0
F	11837.08	1.944±0.043	0.363	5.35	1.5810±0.043	7.4
G	51310.05	7.704±0.171	7.115	1.08	0.5890±0.171	7.1
H	2913.63	0.232±0.005	0.160	1.45	0.0719±0.005	6.5
I	10447.05	1.906±0.042	0.957	1.99	0.9488±0.042	7.3
J	5703.59	0.513±0.011	0.098	5.25	0.4153±0.011	7.0

Geodetic and seismic moment rates for 10 seismic source zones (A-J). The moment deficit and magnitude expected due to total release of the retained moment in the seismic volume at a depth of 15±2 Km for all the seismic zones

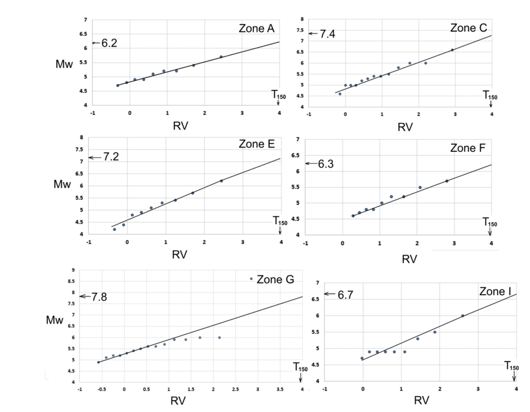
Results

The 2D SR tensor across the Indian Plate boundary in the north is calculated from the horizontal velocities of 1252 GPS stations and their uncertainties. From the interpolated scalar SR field, we have selected areas with ongoing deformation greater than 104 nstrain/yr by statistical procedure and marked them as 10 seismic source zones (A to J) with a capability of generating future mega-earthquakes.

Seismic parameters like b-value, seismo-tectonic character and maximum magnitude earthquake possible in those zones are calculated by Gumbel type III extreme value statistics and also by the empirical relationship between Surface Rupture Length (SRL) and magnitude provided by Wells and Coppersmith (1994).

We have also computed the geodetic moment rates from geodetic strain rates and compared geodetic with seismic moment rate obtained from earthquake catalogue of 100 years in the 10 seismic source zones (A to J) within foothill Himalaya and Northern Burmese arc.

From the calculated moment deficit i.e. moment still retained in the seismic volume up to15±2 Km depth, we have further estimated the future mega-shocks in the 10 seismic source zones. Zone F, I, A and G are highly vulnerable seismically which can spawn a 7.1 Mw shallow focus mega-earthquake in near future. Zone A is an extension area of Kangra Seismic block which has not yielded any big earthquake for nearly 110 years' after 1905 Kangra earthquake (M 7.8). Zone I in the northern segment of Sagaing Fault and Zone F in Western Arunachal Himalaya have no history of large earthquake. Zone G in EHS has not produced any big earthquake in nearly 68 years' after the 1950 Assam earthquake (M 8.6).



Estimated maximum magnitude and its probability plots in Gumbel Type III extreme value statistics over return period of 150 years for zones A, C, E, F, G and H.

Seismic Source Zones	b-value (maximum likelihood method) with error	a-value	Observed Maximum Magnitude (Mw), date and focal depth	Expected Maximum Magnitude (Mw), Type III Gumbel Statistics Return period 150 Yr.
A	0.73±0.13	2.809	5.7 (26.4.1986), 23 Km	6.2
B	-	-	4.5 (29.6.1997), 33 Km	-
C	0.60±0.08	2.298	6.6 (04.05. 1945)	7.4
D	-	-	4.8 (09.09.1982) 33 Km	-
E	0.64±0.06	2.969	6.2 (25.04. 2015) 10 Km	7.2
F	0.65±0.16	1.964	5.7 (22.05.1941)	6.3
G	0.53±0.05	2.361	8.6 (15.08.1950)	7.8
H	0.54±0.01	2.530	6.7 (03.01.2016) 55 Km	-
I	0.62±0.14	2.019	6.0 (15.06.1992) 14 Km	6.7
J	-	-	5.5 (13.01.2016) 10 Km	-

Seismo-tectonic parameters calculated for 10 seismic zones including expected maximum magnitude in source zones by Gumbel (1958) type III extreme value statistics for return period of 150 years.

Seismic Source Zones	Surface Rupture Length (SRL) (Km)	Expected Mw	Maximum displacement (MD) (m)	Average displacement (AD) (m)
A	118	7.2	4.21	1.86
B	57	6.8	1.57	0.77
C	222	7.4	9.89	4.03
D	58	6.8	1.61	0.78
E	186	7.3	7.78	3.25
F	137	7.2	5.15	2.24
G	266	7.5	12.62	5.02
H	88	7.0	2.83	1.30
I	124	7.2	4.50	1.98
J	78	7.0	2.41	1.13

Associated parameters and expected maximum magnitude in the 10 seismic source zones calculated from Surface Rupture Length (SRL) after Wells and Coppersmith (1994).

Seismic Source Zones	Mw by Gumbel statistics return period 150 Years	Mw by Wells and Coppersmith (1994) taking Surface Rupture Length (SRL)	Mw from Moment deficit between geodetic and seismic moments
A	6.2	7.2	7.1
B	-	6.8	6.7
C	7.4	7.4	7.0
D	-	6.8	6.7
E	7.2	7.3	7.0
F	6.3	7.2	7.4
G	7.8	7.5	7.1
H	-	7.0	6.5
I	6.7	7.2	7.3
J	-	7.0	7.0

Comparison between expected magnitudes calculated after Gumbel (1958), Wells and Coppersmith (1994) and from moment deficit. The calculated magnitudes are more or less similar.

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