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Present-day stress field in NW Himalaya and surrounding regions based on inversion of earthquake focal mechanisms

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Abstract

Stress field inversion is performed in NW Himalaya and surrounding regions on the basis of 584 earthquake focal mechanisms listed in the data bulletins of the International Seismological Centre (ISC) for the area between latitudes 25°-40° N and longitudes 65°-85° E. Earthquakes in the period of July 1974 to March 2018, with focal depths 10-248 km and magnitude range (Mw 4.7–7.9) have been selected and the inversion of all available solutions is applied to determine the best fitting stress tensor.
Focal mechanism of most of the earthquakes indicates thrust faulting, which confirms northward under thrusting of the Indian Plate along the Main Boundary Thrust (MBT) and Main Central Thrust (MCT) system, and eastward under thrusting along the Burmese Arc. Fault-plane solutions indicate left-lateral motion along the Kirthar-Sulaiman Range and right-lateral motion along the Karakoram Fault, which are in agreement with the expected sense of lateral mass movement for the continental collision model.
A predominant compressional stress regime in the NW Himalaya is represented by a thrust faulting mechanism along NNE-SSW and NNW-SSE trends in NW-India and Nepal regions and in Pakistan and Hindukush regions, respectively and by normal faulting mechanism along WNW–ESE trend in Xizang and Kashmir regions.

Introduction

Focal mechanism solution (FMS) of an earthquake depends on the tectonic stress field prevalent in the earthquake source zone. A population of focal mechanisms can be used to infer the prevailing regional stress pattern in that region. Similar mechanisms of earthquakes in an area can signify a major seismogenic structure, while varying mechanisms can indicate deformation in a complex medium. Therefore, type of faulting, orientation of activated faults and direction of slip along activated faults serve as an important source of information about the stress field and its spatial and lateral variations within the Earth's crust. Knowledge of the spatial distribution of earthquakes in conjunction with their focal mechanisms have been widely used to understand the earthquake generating processes and help constraining evolutionary models of NW Himalaya.

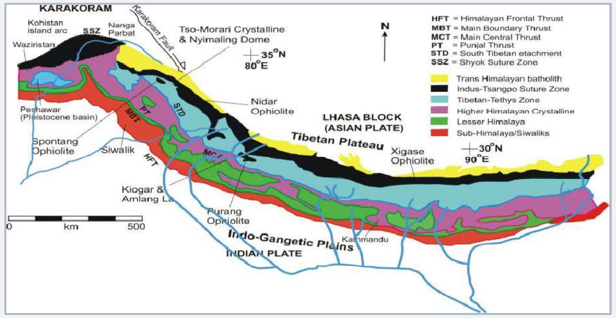


Figure 1. Geotectonic Map of NW Himalaya (after Corfeild et al. 2001).

Tectonic Stress and Faulting Regimes

Principal stress directions in the Earth's crust are frequently close to vertical and horizontal directions. This lead Anderson (1951) to developing a simple scheme connecting the basic stress regimes in the Earth's crust with type of faulting on a pre-existing fault in the crust (see Figure 1). Anderson (1951) distinguishes three possible combinations of magnitudes of principal stresses: the vertical stress is maximum, intermediate or minimum with respect to the horizontal stresses. If the vertical stress is maximum, the hanging wall is moving downwards with respect to the foot wall and the normal faulting is observed along a deeply steeping fault. If the vertical stress is minimum, the crust is in horizontal compression and the hanging wall is moving upwards with respect to the foot wall and reverse faulting is observed along a shallow dipping fault. Finally, if the vertical stress is intermediate, the foot and hanging walls are moving horizontally and the strike slip faulting is observed along a nearly vertical fault. Obviously, the Anderson's classification is simple and does not cover all observations but still it proved to be valid for many seismically active regions and helpful for rough assessment of stress regime (Simpson 1997; Hardebeck and Michael 2006).

Data and Analysis

In this section, the focal mechanism solutions of 584 well located earthquake recorded in the NW Himalaya and surrounding regions (Figure 2), have been inverted to investigate the orientations of the principal stress axes across the NW Himalayan regions. The fault plane solutions are classified based on the rake of slip following Cronin (2004) (table 1).

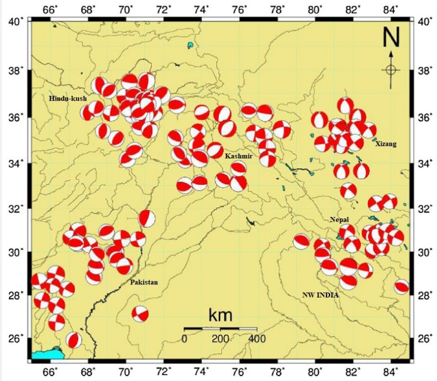


Figure 2. The distribution of the earthquake focal mechanisms and the six studied regions in the NW Himalaya.

Table1: Classification of the focal mechanisms based on the plunge of P, T and B axes (following Zoback 1992).

Plunge of Axes		Faulting Type
P axis	T axis	
Pl ≥ 52°	Pl ≤ 35°	Normal Faulting [NF]
40° ≤ Pl ≤ 52°	Pl ≤ 20°	Normal Faulting combined with considerable strike-slip component [NS]
Pl ≤ 35°	Pl ≥ 52°	Thrust Faulting [TF]
Pl ≤ 20°	40° ≤ Pl ≤ 52°	Thrust Faulting combined with considerable strike-slip component [TS]
Pl <40°(and plunge of B axis ≥ 45°)	Pl < 40°	Strike-Slip Faulting [SS]
All P, T and B axes plunge in the range 25°<Pl < 45° OR Both P and T axes plunge in the range 40°< Pl < 50°		Unclassified type of Faulting [U]

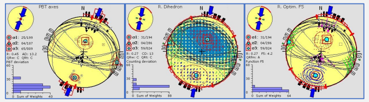
Results and Discussions

The present-day stress field in NW Himalaya and surrounding regions has been investigated based on the inversion of 584 earthquake focal mechanisms recorded in the period between 1974 and 2018 with focal depths between 10 and 309 km and magnitude range Mw 4.7–7.9, listed in the data bulletins of the International Seismological Centre (ISC) and compiled from catalogs of the National Earthquake Information Centre (NEIC) of the USGS, the Department of Geological Sciences, Harvard University (HRVD) and the Lamont Doherty Earth Observatory (GCMT) for the area between latitudes 25°-40°N and longitudes 65°-85°E. We identified six distinct seismic regions for this purpose including NW India, Pakistan, Nepal, Xizang, Kashmir, and Hindukush. The inversion of all available solutions is applied to determine the best fitting stress tensor (Table 2 and Figure 4). The final result is to estimate the orientations of the principal stress axes for each of the study regions (Figure 5).

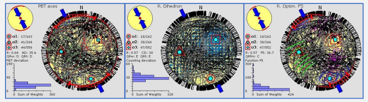
No	Region	Rotational Optimization of Stress Tensor												Stress Regime
		σ1		σ2		σ3		R	R'	F5	SH max	Sh min	Q	
		PL	AZ	PL	AZ	PL	AZ							
1	NW India	31	194	04	286	59	024	0.27	2.27	4.2	12	102	A	TF
2	Pakistan	18	162	38	266	47	052	0.57	2.57	36.7	154	64	C	TS
3	Nepal	24	197	06	105	66	002	0.43	2.43	7.1	20	110	A	TF
4	Xizang	54	018	35	193	02	285	0.89	0.89	30.6	15	105	C	NF
5	Kashmir	44	222	44	058	08	320	0.35	0.35	68.6	46	136	C	NS
6	HinduKush	01	145	05	235	85	045	0.75	2.75	34.7	145	55	C	TF

Table 2. Orientation of the three principal stress axes (σ1, σ2, σ3) in plunge/azimuth format; R: stress ratio; R': stress regime index; F5: misfit function of Delvaux and Barth (2010); (SHmax, Shmin): maximum and minimum horizontal principal stress directions, respectively; Q: quality rank (A is the best, D is the worst) and the stress regime is according to Zoback, 1992 classification.

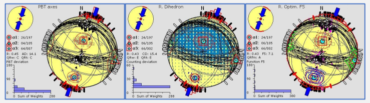
1- NW India



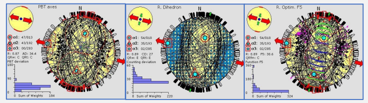
2- Pakistan



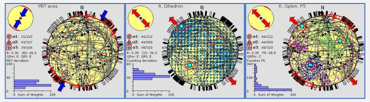
3- Nepal



4- Xizang



5- Kashmir



6- Hindu Kush

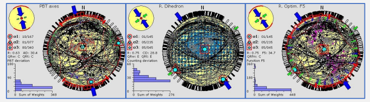


Figure 4. Lower-hemisphere equal-area stereo plots of the selected focal planes and associated slip lines (black dot with outward arrow) of the six seismic zones (left column shows the previous studies and right column shows the current study). Stress inversion results are represented by the orientation of the 3 principal stress axes (a black dot surrounded by a circle for σ1, a triangle for σ2 and a square for σ3). The related SHmax and Shmin orientations are represented by large arrows outside the stereogram. The histogram on the lower left corner of the figures represents the distribution of the misfit angle F5. The small grey symbols inside the stereogram represent the orientations of the related kinematic axes (circle: p axis, triangle: b axis, square: t axis).

The directions of the P and the T axes are shown in Figure 5. Most of the P axes are oriented in the NNE-SSW direction, which are in conformity to the general tectonic trend of the region (Valdiya, 1980; Yin, 2006). Only very few earthquake with normal fault mechanism are oriented in WNW-ESE direction. The T axes have a wide range of orientations, suggesting that reverse faulting earthquakes as well as normal and strike-slip earthquakes are occurring in the area.
A compressional stress represented by a thrust Faulting mechanism along NNE–SSW trend is dominant in NW India and Nepal regions and along NNW-SSE trend is dominant in Pakistan and Hindukush regions.

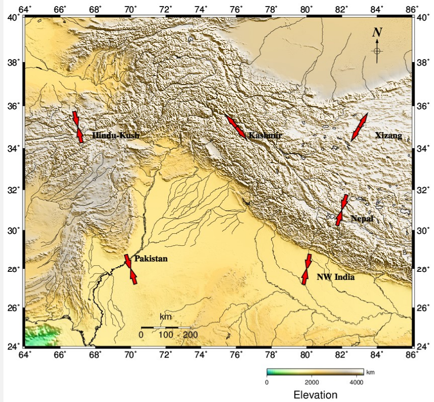


Figure 5. The present-day stress field distribution in NW Himalaya.

Conclusion

The large number of fault plane solutions provided here for the Kumaon-Garhwal Himalaya can provide useful information to synthesis the more detailed seismotectonic model for this region and can be useful for seismic hazard investigations. The stress inversion results show that the maximum compressive stress (σ1) in the NW Himalaya is NNE-SSW, and near horizontal; consistent with the Indian plate movement. While in the Gangetic plain the N-S directed and near vertical compressive stress (σ1) can be explained by flexure of the Indian plate to the south. The occurrence of normal faults with NE-SW (arc-normal) extension in the Lower Himalaya can be linked with arc-normal extension in the Lower Himalaya and as far south as the MBT, as suggested by Hintersberger et al. (2010, 2011).