Annexure B

AN ILLUSTRATIVE EXAMPLE OF DELINEATION OF SOURCE ZONES IN PLATE BOUNDARY REGION OF WESTERN HIMALAYA

This Annexure presents a typical illustrative example on delineation of seismic sources zones (SSZ) for a site in the seismically active plate boundary region of northwest Himalaya. On the basis of the geotectonic characteristics, tectonic features, seismicity patterns, tectonic deformation styles and source mechanisms, a total of 18 area type of SSZ have been demarcated in the seismotectonic map as shown in Figure B.1. The SSZ numbered 2 to 6 are assemblages of the Main Himalayan Seismic belt where a predominantly compressional stress field prevails. The SSZ-7 corresponds to the Kaurik fault system, which constitutes a graben structure marked with extensional tectonics. In SSZ-8, the detachment surface, also referred to as the Main Himalayan thrust (MHT), has a ductile behavior beneath the Higher Himalaya, and so, is a zone of least strain accumulation. Rest of the source zones, excepting SSZ-1, lie in the Trans-Himalaya and are characterized by all forms of deformation styles, including strike-slip, normal, thrust or mixed types.

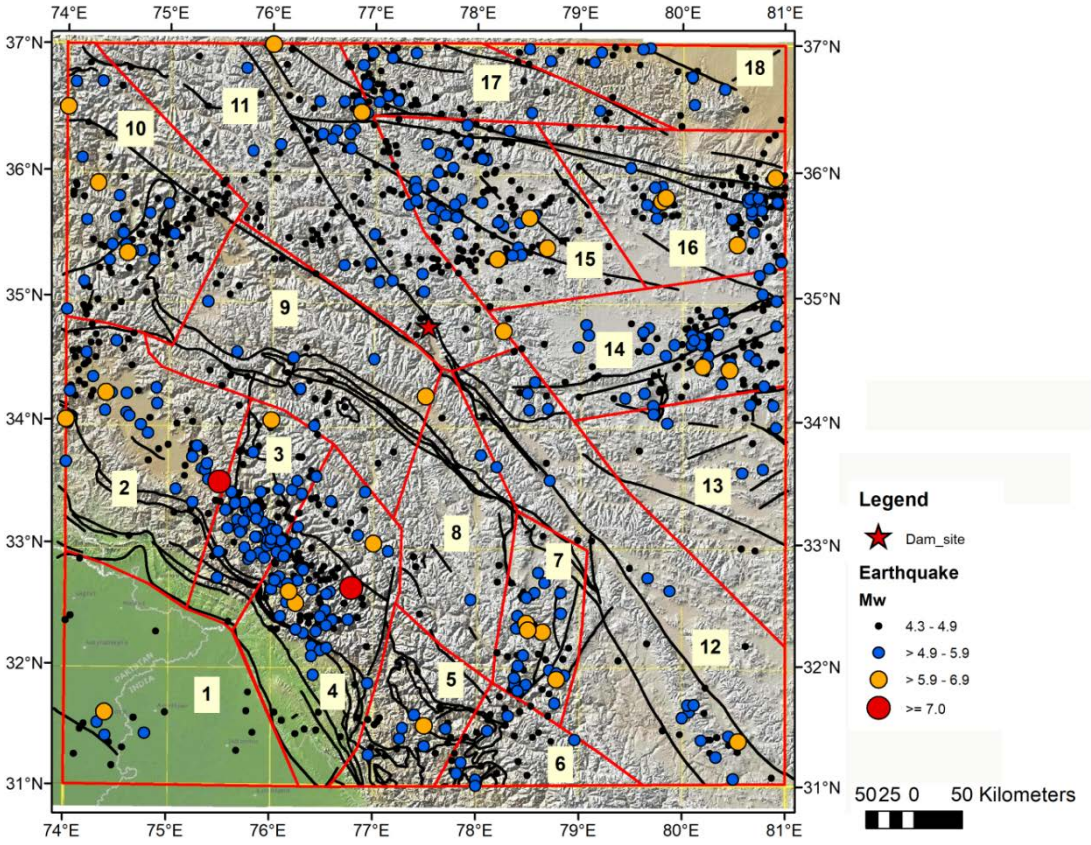

Figure B.1: The 18 seismic source zones identified in the region of study.

The focal mechanism solutions available from the GCMT catalog for 22 earthquakes in the region of study are shown by beach ball symbols in Figure B.2 along with the locations of the corresponding earthquakes in the various source zones.

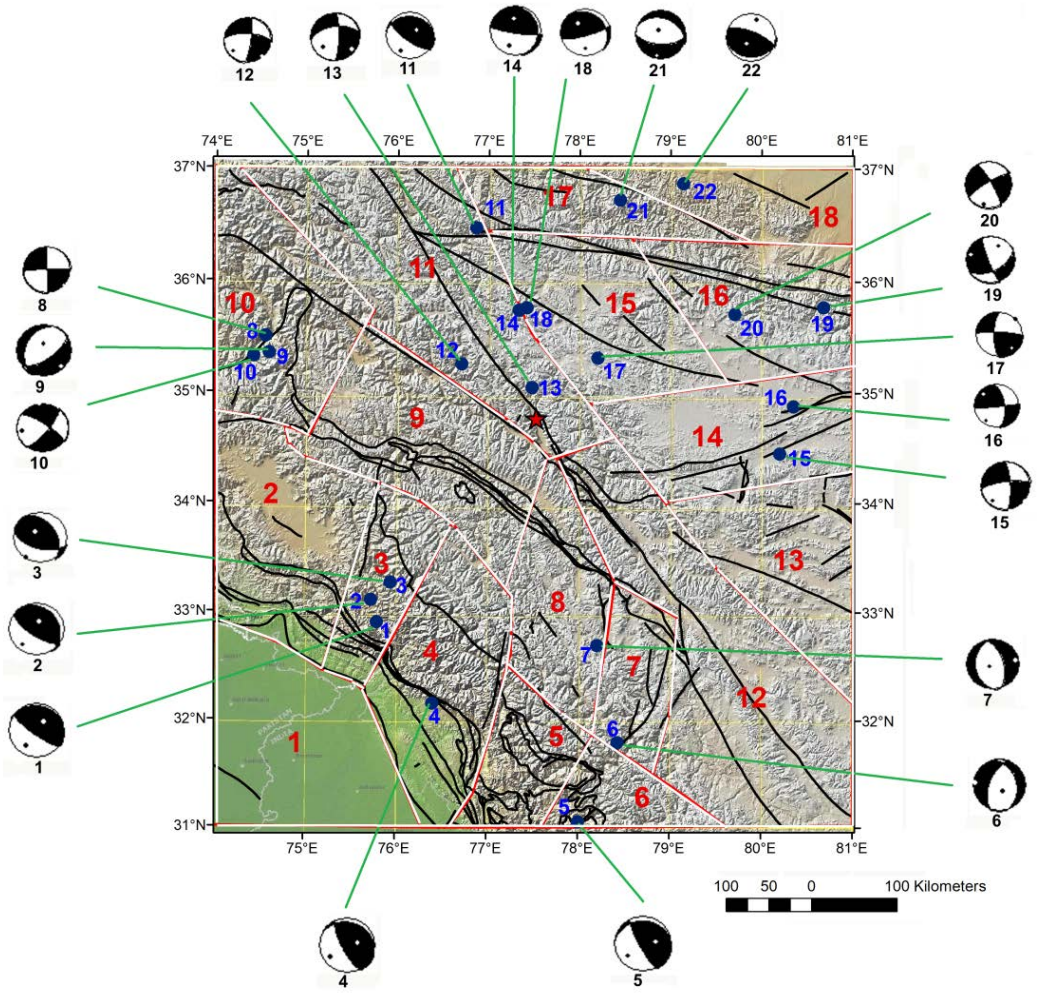

Figure B.2: Seismic Source Zone map with CMT solutions

A brief description on each of the source zones, which is designated by a name, is presented as below.

SSZ-1: Punjab Plains: The Seismotectonic unit of Punjab plains comprises the Alluvial Fill in the Indo-Gangetic Foredeep. It includes Delhi-Hardwar-Sargodha Ridge structure in its south-western part and lies south of the Main Frontal Thrust. This SSZ is seismically not very active though two pre-instrumental era earthquakes of 1827 (M_w 6.1) and 1875 (M_w 5.7) are reported to have occurred in this source. It is conjectured that basement faults, both parallel and transverse to the Himalayan trend, could have generated the earthquakes in this source.

SSZ-2: Kashmir Block: The Kashmir block, falling between Kishtwar fault in the east and Jhelum fault in the west, has been dissected by several tectonic discontinuities paralleling the Himalayan trend such as Main Frontal thrust, Riasi thrust, Main Boundary fault, Vaikrita/Panjal thrust and Wakha thrust. From historical times to recent, this part of the Himalaya is known to be seismically very active. The earliest recorded earthquake of September 1555 (M_w 7.6) locates to the eastern margin of the Kashmir seismic source zone. The 30th May 1885 Kashmir earthquake with M7.0 and focal depth of 12 km at an epicentre distance of 19.5 km west of Srinagar caused a loss of about 3000 human lives in a damage area of 1280 km^2 (Jones,1885). Apart from these two large earthquakes, 69 events of $M_w \geq$

4.3 are reported in this zone during the period from 1963 to 2017. It may be noted that the devastating 8th October 2005 Muzaffarabad earthquake of M_w 7.6 and epicentral Intensity X (on MSK-64 scale), in which over 86,000 people perished, was located to the immediate west of the present area of study.

SSZ-3: Kishtwar Fault Zone: This seismic source zone locates between the Jammu (Akhnoor) re-entrant in the west and the Kangra re-entrant in the east, demarcated by Kishtwar fault and Ravi tear. During the period from 1962 to 2017, a total of 109 small, moderate and moderately high magnitude earthquakes are reported from this source zone. Only one historical earthquake on 2nd September 1669 was of M_w 6.1. The three CMT solutions of the zone indicate predominantly thrust type mechanism.

SSZ-4: Kangra Block: The Kangra block, located between Ropar-Sundarnagar fault in the east and Ravi tear in the west, is dissected by several thrusts paralleling the Himalayan trend, the prominent among which are the MFT, Jwalamukhi thrust and MBT. The M_w 7.8 Kangra earthquake of 4th April 1905 with a focal depth of 20 km and an epicentral intensity of XI occurred in this source zone. This earthquake was responsible for about 20,000 fatalities, heavy damage to property and triggering of innumerable landslides (Middlemiss, 1910). There are records of three more pre-instrumental era earthquakes during the years 1914, 1945 and 1947, all with $M_w \geq 6.0$. The CMT solution of one earthquake indicates thrust faulting.

SSZ-5: Shimla Block: The incidence of earthquake activity within the Shimla block, bounded between Kangra and Garhwal seismotectonic units, is much lesser than that in Kashmir, Kishtwar and Kangra source zones. Only 20 events ($M_w \geq 4.3$) are reported in this source between 1976 and 2017. Two pre-instrumental era events during 1856 (M_w 5.3) and 1906 (M_w 6.4) are also reported.

SSZ 6: Garhwal Block: Tectonically, the major structural discontinuities paralleling the Himalayan trend present in the Kangra and Shimla blocks continue in the Garhwal block as well. A total of 28 low to moderate magnitude earthquakes are recorded in this source. Apart from the lone 1937 earthquake of M_w 5.7, the remaining 27 events occurred between 1977 and 2016. One relatively higher magnitude earthquake during 1986 (M_w 5.8) shows thrust fault solution.

SSZ-7: Kaurik Block: Tectonically, the Kaurik seismic source zone is interesting in the sense that it is the only graben structure falling south of the Indus Suture zone. A total of 46 earthquake events of $M_w \geq 4.3$ are reported in this seismic zone during 1955 to 2014. The most severe recorded and documented seismic event in this zone is the 19 January 1975 Kinnaur earthquake of M_w 6.8, focal depth 12.9 km and epicentral Intensity IX, whose aftershock activity continued till November 1975. The CMT solution of one earthquake during 1977 (M_w 5.0; GCMT) indicates normal faulting.

SSZ- 8: Higher Himalaya: This zone, incorporating the Zanskar mountain range of Jammu & Kashmir Himalaya displays the least seismic activity with only 9 events of $M_w \geq 4.3$ reported between 1965 and 2013. The maximum observed magnitude of M_w 5.5 corresponds to the earthquakes of 31st May 1965 and 11th October 1965.

SSZ-9: Ladakh Block: The Ladakh seismotectonic unit, located between Shyok suture zone in the north and Indus Suture zone in the south, contains the Ladakh range. A total of 32 earthquakes of $M_w \geq 4.3$ are reported in this source during 1916 to 2017. The maximum observed magnitude in this domain is M_w 6.1 associated with the earthquake of 17th May 1917.

SSZ 10: Indus-Kohistan Block: This is a highly active seismic source zone of the western Himalayan syntaxis, demarcated by the Main Karakoram thrust and the Indus Suture zone. The seismic records reveal that a total of 102 earthquakes occurred in this block, out of which 100 events are reported between 1971 and 2017. About 15% of these events are of deeper focal depth (> 70 km) with the maximum observed magnitude of M_w 6.6 associated with the earthquake of 24th September 1943.Three CMT solutions from this source zone show, normal, normal with strike slip component and pure strike slip mechanisms.

SSZ-11: Shyok-Karakoram Block: This source zone is highly active with 118 earthquakes reported from 1963 to 2015. Prior to 1963, 3 events are listed, one each during 1910, 1923 and 1937. The northwest segment of the Karakoram fault (KKF) is the main tectonic feature in this source zone, which passes close to the proposed dam site. The KKF is about 1000 km long strike-slip fault separating the tectonized Shyok-Nubra belt from the Karakoram belt. The available CMT solutions show dextral strike slip motion as well as thrust fault mechanism. The fault plane solutions suggest that the KKF dips steeply towards northeast. The maximum observed earthquake in this important tectonic unit was M_w 6.7on 12th July 1910.

SSZ-12: Karakoram-Indus Block: This is the southeast segment of the Karakoram Fault that is seismically less active than its northwest counterpart comprising SSZ 11. Only 38 earthquakes are reported in this zone between 1966 and 2017 with the maximum magnitude as M_w 6.7 on 6th March 1966.

SSZ-13: Lhasa Block: Seismic activity in this source is even more subdued than in the adjoining Karakoram-Indus source zone. Only 19 earthquakes are reported between 1950 and 2007 with the maximum observed magnitude of M_w 5.6.

SSZ 14: Gozha-Longmu Co Block: This is an east-west trending seismic source zone with 106 shallow foci seismic events. Except one event during 1946, the remaining 105 earthquakes have been recorded during the instrumental period of 1965-2016. Two significant fault strands in this source are the Gozha Co and Longmu Co left lateral faults. The CMT solutions available for two earthquakes in this source also show left lateral strike slip mechanism. The maximum observed magnitude is M_w 6.3 corresponding to an earthquake on 6th November 1946.

SSZ 15 and SSZ 16: Altyn Tagh (West) and (East) Blocks: Altyn Tagh fault (ATF) is more than 1200 km long and lies along the north western boundary of the Tibetan Plateau and the Tarim Basin. Only the far western segment of this continental scale fault traverses within the region of present study. This fault zone has been divided into two source zones: ATF (West) and ATF (East). The maximum observed magnitudes in the two source zones are M_w

6.9 and 6.3, respectively. The ATF is a left lateral fault, which is also supported by the available CMT solutions.

SSZ 17: Karakax-Karaul (West) and SSZ 18 Karakax- Karaul (East) Blocks: The north-eastern most corner of the study region is traversed by ~ 400 km long Karakax fault zone, which is another western splay of the Altyn Tagh fault. This is also a left lateral fault and for the present study, the domain has been divided into West and East seismic source zones. Both segments are seismically active with occurrence of 50 and 27 earthquake events, respectively. The maximum observed magnitudes in the two source zones are M_w 5.1 and 5.2, respectively. The CMT solution of one event in SSZ-17 displays normal faulting whereas solution one event in SSZ-18 indicates normal-oblique mechanism.