

## List of Figures

---

**Figure 1.1:** Seismic zonation map of India.....2

**Figure 1.2:**General tectonic map showing the epicentre of 1905 Kangra earthquake & 1975 Kinnaur earthquake, major tectonic breaks ITSZ: Indus-Tsangpo Suture Zone; MCT: Main Central Thrust; MBT: Main Boundary Thrust; HFT: Himalayan frontal thrust; JMT: Jawalamukhi thrust; KWF: Kishtwar fault; SNF: Sundarnager fault; MMT: Main Mantle thrust along with the topography as well as the focal mechanism solutions of some major earthquakes that occurred in the region in the past.( Modified after Tripathi et. al, 2014).....5

**Figure 1.3:**The seismicity recorded during the period using both the catalogues i.e. the WIHG catalogue and the ISC-EHB catalogue in the NW Himalaya along with major structural breaks (HFT: Himalayan Frontal Thrust; JMT: Jwalamukhi Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust; LL: Locking line; SNF: Sundarnager Fault; STD: South Tibetan Detachment; KCF: Kaurik Chango Fault; TSM: Tso-Morari Fault; ITSZ: Indo-Tsangpo Suture Zone; KF: Karakoram Fault). It also signifies the four moderate to strong earthquakes in the form of white solid stars along with their year of occurrences. The earthquake epicenters recorded by WIHG seismic stations are denoted by red solid circles and the earthquake denoted by ISC-EHB stations are denoted by black solid stars. It also represents the earthquakes whose moment tensors are being determined as solid green stars that is discussed in particular afterwards.....16

**Figure 2.1:** The command window showing an example for the sub directories created with the MAKEREA and MAKEWAV command.....23

**Figure 2.2:**The example seismic window shown for the earthquake of 09.07.2013 earthquake event of magnitude ( $M_w = 5.1$ ) recorded at the WIHG seismic stations operated in NW Himalaya.....24

**Figure 2.3:** The command window showing the arrival times of earthquake at different recording seismic stations for the earthquake of 09.07.2013 earthquake event of magnitude ( $M_w = 5.1$ ) recorded at the WIHG seismic stations operated in NW Himalaya.....25

**Figure 2.4:** The flow chart describing the running procedure for the VELEST program by following the above mentioned procedure the minimum 1 D crustal velocity model has been determined for the NW Himalaya region.....27

**Figure 2.5:** The command window describes the program VELMENU operation while computing the minimum 1 D crustal velocity model.....27

**Figure 2.6:** It shows the graphic user interface (GUI) for the ISOLA program utilized for determining the moment tensor focal mechanisms for the local and regional seismic waveforms.....31

**Figure 2.7:**Figure signifies the graphic user interface (GUI) for the ISOLA program showing the utilized 1 D crustal velocity model for determining the moment tensor.....32

**Figure 2.8:**This window presents the graphic user interface (GUI) for the ISOLA program showing the earthquake event details (date, Latitude, Longitude Depth, origin time, magnitude, time window length) reported by the United State Geological Services (USGS) studied for determining the moment tensor.....33

**Figure 2.9:** This window presents the graphic user interface (GUI) for the ISOLA program showing the earthquake event and the selected recording

seismic stations utilized for moment tensor inversion.....34

**Figure 2.10:** This window presents the graphic user interface (GUI) for the ISOLA program showing the seismic waveform after applying the instrument corrections at a selected recording seismic stations utilized for moment tensor inversion.....35

**Figure 2.11:** This window presents the graphic user interface (GUI) for the ISOLA program showing the starting depth for source or earthquake hypocenter and each depth step for source inversion along with the maximum number of sources to be utilized for source depth.....35

**Figure 2.12:** This window presents the graphic user interface (GUI) for the ISOLA program showing the Greens function computation for each earthquake source at different source depths.....37

**Figure 2.13:** This window presents the graphic user interface (GUI) for the ISOLA program showing the Inversion routine for a single earthquake event at a particular frequency band.....38

**Figure 2.14:** This window presents the graphic user interface (GUI) for the ISOLA program showing the real synthetic match for the seismic event after carrying out the Inversion routine program for a particular frequency band...39

**Figure 2.15:** This window presents the graphic user interface (GUI) for the ISOLA program showing the maximum correlation obtained for the focal mechanism solution at different source depths and the Double-Couple is expressed in percentage scale as DC% for the seismic event after carrying out the Inversion routine program for a particular frequency band.....39

**Figure 2.16:** This window presents the graphic user interface (GUI) for the ISOLA program showing the maximum correlation plotted as a function of Double-Couple expressed in percentage scale as DC% with the different grid

searches for the seismic event after carrying out the Inversion routine program for a particular frequency band.....40

**Figure 2.17:** This window presents the graphic user interface (GUI) for the ISOLA program showing the maximum correlation plotted as a function of source position and source time for the seismic event after carrying out the Inversion routine program for a particular frequency band.....40

**Figure 2.18:** This window presents the graphic user interface (GUI) for the Coulomb 3.1 application showing the inputs incorporated required for computing the static stress imparted on the receiver fault due to the earthquake.....42

**Figure 2.19:** The above figure represents the graphic user interface (GUI) for the Coulomb 3.1 application showing the source fault is shown in the region.....43

**Figure 2.20:** The above figure represents the graphic user interface (GUI) for the Coulomb 3.1 application showing the source fault, the epicenter of the source earthquake along with the aftershocks plotted as solid black circle and various other secondary faults as an example.....44

**Figure 2.21:** The above figure represents the graphic user interface (GUI) for the Coulomb 3.1 application showing various options such as depth of computation of the coulomb stress and the frictional coefficient are also needed for the static stress computation.....45

**Figure 2.22:** The above figure represents the graphic user interface (GUI) for the Coulomb 3.1 application showing various options such as strike, dip, rake, type of receiver fault depth of computation and the maximum upto which the static stress is computed as expressed in bars.....46

**Figure 2.23:** The above figure represents the graphic user interface (GUI) for the Coulomb 3.1 application showing the static stress computed as expressed in bars in the study area.....46

**Figure 3.1:** This Figure signifies the error in latitude plotted against the no. of earthquake events obtained with preliminary velocity model.....52

**Figure 3.2:** This Figure signifies the error in longitude plotted against the no. of earthquake events obtained with preliminary velocity model.....53

**Figure 3.3:**This Figure signifies the error in Depth plotted against the no. of earthquake events obtained with preliminary velocity model.....54

**Figure 3.4:** Seismicity plot of the NW Himalaya along with the major tectonic breaks such as HFT: Himalayan Thrust Fault; JMT: Jwalamukhi Thrust; MBT: Main Boundary Thrust; MCT: Main central Thrust; SNF: Sundarnager fault; STD: South Tibetan Detachment; KCF: Kaurik Chango fault; TSM: Tso-Morari fault; ITSZ: Indo-Tsangpo suture zone; KF: Karakoram fault. The yellow triangle specifies the seismic stations utilized in the study. The earthquake hypocenters are specified in the form of green solid circles, blue solid circles and ted solid stars based on its magnitude. The magnitude limit for each of the hypocenter is specified in the figure itself. The elevation colour scale given on the right side is expressed in meters.....55

**Figure 3.5:** Seismicity plot of the NW Himalaya along with the major tectonic breaks such as HFT: Himalayan Thrust Fault; JMT: Jwalamukhi Thrust; MBT: Main Boundary Thrust; MCT: Main central Thrust; SNF: Sundarnager fault; STD: South Tibetan Detachment; KCF: Kaurik Chango fault; TSM: Tso-Morari fault; ITSZ: Indo-Tsangpo suture zone; KF: Karakoram fault. The yellow triangles specify the seismic stations utilized in the study. The earthquake hypocenters are specified in the form of blue solid circles and ted solid stars based on its depth distribution. The depth limit for each of the hypocenter is specified in the figure itself. The elevation colour scale given on

the right side is expressed in meters.....56

**Figure 3.6:** Shows the Seismic network deployed and operated by Wadia institute of Himalayan Geology, Dehradun (WIHG) along with the seismicity plot utilized for 1 D crustal velocity model for estimation in Himachal Pradesh, NW Himalaya, India. The triangles indicate the seismic stations and the hollow red circles indicate the earthquake epicentres.....58

**Figure 3.7:** Shows a comparison between the RMS values with respect to number of earthquakes obtained for the Hypocentres before applying the VELEST (red line) algorithm and after (blue line) applying it. This shows a gradual decrease in minimum and maximum RMS residual values after VELEST is applied.....59

**Figure 3.8:**(a) and (b) shows the minimum 1 D velocity model of seven layers (red line) obtained with VELEST from travel time inversion of P and S-wave arrival times and its comparison plot with the preliminary velocity of Kumar et.al; 2009 (green line) and Kamble et al., 1974 (blue line).....61–62

**Figure 3.9:**(a), (b) and (c) shows the number of earthquake hypocentre and its variation with the RMS residual (blue line) for the two iteration velocity models at an interval of 3.5 Km, 4.0 Km and for the final obtained model at an interval of 5.0 Km.....63–65

**Figure 3.10:**(a) and (b) describes the variation of station corrections with respect to P delay and S delay by taking PULG station as the reference station. Solid black star indicates seismic stations.....67

**Figure 3.11:**(a) and (b) shows the Ray path coverage of the seismic events to reach different stations with respect to latitude and longitude. Solid black circles indicate earthquake hypocenters and solid red triangles shows recording stations.....68–69

**Figure 4.1:** General Seismotectonic map of the NW Himalaya showing the epicentre of 1905 Kangra earthquake and 1975 Kinnaur earthquake. Major tectonic breaks ITSZ: Indus-Tsangpo Suture Zone; MCT: Main Central Thrust; MBT: Main Boundary Thrust; HFT: Himalayan Frontal Thrust; JMT: Jawalamukhi Thrust; KCF: Kaurik-chango Fault; SNF: Sundarnager Fault along with the topography as well as the focal mechanism solutions of some major earthquakes that occurred in the region in the past (Modified from GSI, 1993). The map also shows the relocated earthquake epicentres. LL: The dotted line is designated as locking line (Bollinger et al., 2004). The shadow rectangle signifies the western Himalaya seismic gap between the epicentre of 1905 Kangra earthquake ( $M_w = 7.8$ ) and 1975 Kinnaur earthquake ( $M_w = 6.8$ ). The NE-SW transect AB is also shown in the figure.....**71**

**Figure 4.2:** Relocated earthquake hypocenters achieved through HYPODD program are shown. The earthquake hypocenters are plotted in accordance to its respective magnitude range. Major tectonic breaks ITSZ: Indus-Tsangpo Suture Zone; STD: South Tibetan Detachment Fault; MCT: Main Central Thrust; MBT: Main Boundary Thrust; HFT: Himalayan Frontal Thrust; JMT: Jawalamukhi Thrust; KCF: Kaurik-chango Fault; SNF: Sundarnager Fault along with the topography is shown in the plot.....**76**

**Figure 4.3:** Reduced uncertainty in earthquake hypocentre parameters (Latitude, Longitude and Depth) achieved after the relocations.....**77**

**Figure 4.4:** Relocated seismicity (Latitude and Longitude) plotted as a function of Depth.....**79**

**Figure 4.5:**(a) and (b) showing aplot the Real-synthetic match at various recording stations and the source depth correlation for a magnitude ( $M_w > 5.0$ ) earthquake recorded on date 08.10.2012.....**82–83**

**Figure 4.6:**(a) and (b) showing aplot the Real-synthetic match at various

recording stations and the source depth correlation for a magnitude ( $M_w > 4.0$ ) earthquake recorded on date 11.11.2012. Grey waveforms are not used in inversion.....**83**

**Figure 4.7:** (a) and (b) showing aplot the Real-synthetic match at various recording stations and the source depth correlation for a magnitude (  $M_w > 4.9$ ) earthquake recorded on date 04.06.2013.....**84**

**Figure 4.8:**(a) and (b) showing aplot the Real-synthetic match at various recording stations and the source depth correlation for a magnitude (  $M_w > 4.0$ ) earthquake recorded on date 05.06.2013. Grey waveforms are not used in inversion.....**85**

**Figure 4.9:**(a) and (b) showing aplot the Real-synthetic match at various recording stations and the source depth correlation for a magnitude (  $M_w > 4.9$ ) earthquake recorded on date 09.07.2013.....**86**

**Figure 4.10:**(a) and (b) showing aplot the Real-synthetic match at various recording stations and the source depth correlation for a magnitude ( $M_w > 4.1$ ) earthquake recorded on date 09.07.2013. Grey waveforms are not used in inversion.....**87**

**Figure 4.11:**(a) and (b) showing aplot the Real-synthetic match at various recording stations and the source depth correlation for a magnitude ( $M_w > 4.4$ ) earthquake recorded on date 13.07.2013. Grey waveforms are not used in inversion.....**88**

**Figure 4.12:**(a) and (b) showing aplot the Real-synthetic match at various recording stations and the source depth correlation for a magnitude ( $M_w > 4.4$ ) earthquake recorded on date 29.08.2013.....**89**

**Figure 4.13:**This figure designates the type of kinematics associated with the regional and local tectonic breaks for the study area. The black beach balls are



the eight moment tensors estimated in this study and the red beach balls are the moment tensors adopted from USGS CMT solutions for the historical earthquakes for the NW Himalaya region. The NE-SW transect AB is also marked in the figure. The earthquake epicentres are designated as hollow blue circles and the eight magnitude ( $M_w \geq 4.0$ ) earthquakes recorded analysed in the present study are shown as green solid stars.....**91**

**Figure 5.1:** clearly demonstrates the high and low stress values over the region due to the occurrence of the 1905 Kangra earthquake. Four recently recorded earthquakes in the period from 2012 to 2013 in the epicentral zone of this major western Himalaya seismic event having a magnitude distribution ( $M_w$  4.0 to 4.9) is also shown.....**102**

**Figure 5.2:** clearly demonstrates the high and low stress values over the region due to the occurrence of the 1905 Kangra earthquake with the epicenter of the recent recorded  $M_w$  4.0 earthquake event.....**103**

**Figure 5.3:** clearly demonstrates the high and low stress values over the region due to the occurrence of the 1905 Kangra earthquake with the epicenter of the recent recorded  $M_w$  4.9 earthquake event.....**104**

**Figure 5.4:** clearly demonstrates the high and low stress values over the region due to the occurrence of the 1905 Kangra earthquake with the epicenter of the recent recorded  $M_w$  4.0 earthquake event.....**105–106**

**Figure 5.5:** clearly demonstrates the high and low stress values over the region due to the occurrence of the 1905 Kangra earthquake with the epicenter of the recent recorded  $M_w$  4.4 earthquake event.....**107**

**Figure 5.6:** clearly demonstrates the high and low stress values over the region due to the occurrence of the 1905 Kangra earthquake with the epicenters of the four recently recorded earthquake events.....**108**

**Figure 5.7:**  $\Delta$ CFS computed for 1975 Kinnaur earthquake with the earthquake source acting as major receiver. The aftershocks are plotted as green cross symbol. Major tectonic divisions in the NW Himalaya i.e. Kaurik Fault; ITSZ: Indo Tsangpo suture zone are shown in the map.....**110**

**Figure 5.8:**  $\Delta$ CFS computed for 1975 Kinnaur earthquake with the recent earthquake of  $M_w = 5.0$  acting as major receiver. The aftershocks are plotted as green cross symbol. Major tectonic divisions in the NW Himalaya i.e. Kaurik Fault; ITSZ: Indo Tsangpo suture zone; TSM: Tso Morari fault are shown in the map.....**111**

**Figure 5.9:**  $\Delta$ CFS computed for 1975 Kinnaur earthquake with the recent earthquake of  $M_w = 4.1$  acting as major receiver. The aftershocks are plotted as green cross symbol. Major tectonic divisions in the NW Himalaya i.e. Kaurik Fault; ITSZ: Indo Tsangpo suture zone; TSM: Tso Morari fault are shown in the map.....**112**

**Figure 5.10:**  $\Delta$ CFS computed for 1975 Kinnaur earthquake with the Kaurik fault (secondary fault) acting as major receiver. The aftershocks are plotted as green cross symbol. Major tectonic divisions in the NW Himalaya i.e. Kaurik Fault; ITSZ: Indo Tsangpo suture zone; TSM: Tso Morari fault are shown in the map.....**113**

**Figure 5.11:**  $\Delta$ CFS computed for 1991Uttarkashi earthquake with the earthquake source acting as major receiver. The aftershocks are plotted as green cross symbol. Major tectonic divisions in the NW Himalaya i.e. HFT: Himalayan frontal Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust; STD: South Tibetan Detachment; KCF: Kaurik Chango Fault are shown in the map.....**115**

**Figure 5.12:**  $\Delta$ CFS computed for 1991Uttarkashi earthquake with the MHT (Main Himalayan detachment) detachment acting as major receiver. The aftershocks are plotted as green cross symbol. Major tectonic divisions in the NW Himalaya i.e. HFT: Himalayan frontal Thrust; MBT: Main Boundary

Thrust; MCT: Main Central Thrust; STD: South Tibetan Detachment; KCF: Kaurik Chango Fault is shown in the map.....117

**Figure 5.13:**  $\Delta$ CFS computed for 1991Uttarkashi earthquake with the recent earthquake of Mw = 5.1 acting as major receiver. The aftershocks are plotted as green cross symbol. Major tectonic divisions in the NW Himalaya i.e. HFT: Himalayan frontal Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust; STD: South Tibetan Detachment; KCF: Kaurik Chango Fault; TSM: Tso Morari fault; SNF: Sundarnager Fault is shown in the map.....118

**Figure 5.14:**  $\Delta$ CFS computed for 1999Chamoli earthquake with the earthquake source acting as major receiver. The aftershocks are plotted as green cross symbol. Major tectonic divisions in the NW Himalaya i.e. HFT: Himalayan frontal Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust; STD: South Tibetan Detachment; Alaknanda Fault are shown in the map.....120

**Figure 5.15:**  $\Delta$ CFS computed for 1999Chamoli earthquake with the MHT (Main Himalayan Thrust) acting as major receiver. The aftershocks are plotted as green cross symbol. Major tectonic divisions in the NW Himalaya i.e. HFT: Himalayan frontal Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust; STD: South Tibetan Detachment; Alaknanda Fault are shown in the map.....121

**Figure 5.16:**  $\Delta$ CFS computed for 1999Chamoli earthquake with the significant earthquake of Mw = 5.1 acting as major receiver. The aftershocks are plotted as green cross symbol. Major tectonic divisions in the NW Himalaya i.e. HFT: Himalayan frontal Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust; STD: South Tibetan Detachment; Alaknanda Fault are shown in the map.....123

**Figure 6.1:** shows the transect AB (solid black line) taken across in the WWS-EEN direction cutting through major thrusts starting from MBT (Main

Boundary Thrust) in north to STD (South Tibetan detachment) in South. The major thrust faults through which the transect pass are termed as MBT, MCT, STD from south to north. The earthquake epicentres are indicated by solid Red Cross symbol.....126

**Figure 6.2:** shows the focal depth distribution of seismic events (hollow red circles) across major tectonic boundaries. Such as MBT: Main Boundary Thrust; MCT: Main Central Thrust; STD: South Tibetan Detachment; ITSZ: Indus-Tsangpo Suture Zone; from south to north.....127

**Figure 6.3:** It shows the generalised cross section AB taken across the major tectonic breaks starting from the Himalayan Frontal Thrust (HFT) in the south to Indo-Tsangpo Suture Zone (ITSZ) in the north. This cross section greatly characterizes the status of the Main Himalayan Thrust (MHT) and its sub-surface geometry in the NW Himalaya. The maximum depth of the investigation below the cross section is 50 km. The cross section clearly postulates the locking zone and also the motion velocity of 14 mm/y for the Indian plate in the north direction. The section also shows the two ramps of the MHT plane below the Main Central Thrust (MCT) and the South Tibetan Detachment (STD). The depth range for these ramps is mentioned in the text.....131

**Figure 6.4:** Comparison of the values obtained in this study with others estimated for various regions in the world. The regions are NW Himalayas (Tripathi et al., 2012); Kumaun Himalayas (Singh et al., 2012); Garhwal Himalayas (Gupta et al., 1995); western Himalayas (Mukhopadhyay and Tyagi, 2007); western Greece (Tselentis, 1998); Mt. Etna, Italy, (Pezzo et al., 1995); Sikkim Himalayas (Hazarika et al., 2013); Apennines, Italy (Bianco et al., 2002); and this study (LT =50; WL = 30).....139

**Figure 6.5:** Shows Bouguer gravity anomalies of the NW Himalaya. Major tectonic boundaries in NW Himalaya along with the studied NE-SW profile. ITSZ: Indus-Tsangpo Suture Zone; MCT: Main Central Thrust; MBT: Main

*Boundary Thrust; HFT: Himalayan Frontal Thrust; STD: South-Tibetan Detachment. A SW-NE profile (A-B) is shown along which a lithospheric density model is shown in Figure 6.8.....141*

**Figure 6.6:** Effective Elastic Thickness ( $T_e$ ) based on coherence between the Bouguer anomaly and topography. The best fit is obtained for  $T_e=53$  km...**143**

**Figure 6.7:** Accounted error in residual for different Effective Elastic Thickness ( $T_e$ ) with a minimum observed at 53 km for the NW Himalaya, India-Eurasia collision zone.....**144**

**Figure 6.8:** Observed and calculated response from gravity data (Top) and the corresponding lithospheric model (Bottom) for NW Himalaya – (a) Regional and (b) Residual.....**146**