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Spectral Analysis and Waveform Modelling of Jangalwar Earthquake (M_w 4.1), Chenab Valley, Jammu

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Abstract: **An earthquake of M_w 4.1 occurred in the Jangalwar area of Chenab valley of Jammu and Kashmir on 29th May, 2017. This earthquake occurred within the source zone of the Jangalwar earthquake of 2013 (M_w 5.7) which was followed by aftershocks for about two months. The current paper presents results on spectral analysis and waveform modelling of this earthquake. Its epicenter was located at 33.110° N, 75.896° E between the Panjal Thrust and Kishtwar Window. From the travel time and waveform inversion, focal depth of the event was located at 11 km. The estimated seismic moment was calculated at 15.4 dyne-cm, source radius of 0.585 km, moment magnitude 4.1, corner frequency of 2.39 Hz and stress drop of 50.6 bars. The focal plane solution of the event indicates thrust movement with the fault plane strike of 323°, dip 39° and rake 100°. The source fault of the event appears synthetic to NW-SE striking Panjal Thrust. This current activity may be related to reactivation of ramp emanating from the decollement or emergence of a new splay from the Panjal Thrust.**

Index Terms: **Epicentral Location, Fault Plane Solution, Source parameters, Seismotectonics, Waveform Inversion**

I. INTRODUCTION

The Jammu and Kashmir region and its adjoining areas have experienced many large to great earthquakes in the past. At present the region is experiencing minor to moderate earthquakes (Bilham and Bali, 2013; Bhat et al., 2013; Pandey et al., 2016). The Jammu and Kashmir region is categorized into seismic zones IV and V (BIS, 2002). The largest earthquake, the region experienced during the last century was Kashmir earthquake of Mw 7.6 which caused huge destruction and loss of lives in Jammu and Kashmir and in Pakistan (Thakur et al., 2006; Bhat et al., 2006). The seismic activity in the Jammu Province is largely concentrated in the Chenab valley between Main Boundary Thrust (MBT) and Main Central Thrust (MCT) (Bhat et al., 2013; Pandey et al., 2016). A shallow focused earthquake of M_w 4.1 occurred in the Jangalwar area (Doda District) on 29th May 2017 at 13:53:25 UTC. The epicenter of this earthquake was located in the Jangalwar area (33.110° N, 75.896° E). This region experienced two moderate earthquakes of M_w 5.7 and Mw 5.2 in 2013 which were followed by about 125 aftershocks of magnitudes ranging from M_w 2 to M_w 4.9 (Pandey et al. 2016). These earthquakes originated at shallow depth within the upper part of the crust above the main decollement. Apart from these two moderate earthquakes, this region has witnessed more than 20 moderate events of M >5 since 1950 (Dasgupta et al., 2000). Historical data and the ongoing seismicity suggest that this region is seismically and tectonically very active (Gavillot, 2014; Pandey et al., 2016; Bilham, 2019). Small to moderate size earthquakes are occurring between the Panjal Thrust (PT) and southwest of Kishtwar Window (KW) (Pandey et al., 2016). However, no earthquake of M_w > 6 has been recorded in Chenab valley region in the recent times (Bhat et al., 2013; Pandey et al., 2016).

Many studies have been carried out to understand the characteristics of the source of earthquakes through Brune's circular model and waveform modelling in the Himalaya and its adjoining areas (e.g. Mitra et al., 2014 and Paul et al., 2018 in Kishtwar region; Parshad et al., 2014 in Nubra valley; Verma et al., 2015 in Kangra region; Verma et al., 2017 and Kumar et al., 2006 in Chamoli region; SriRam et al., 2005 in Himachal region; Sharma and Wason, 1994 in Garhwal Himalaya; Kumar et al., 2005 in Uttarkashi Himalaya; Chopra et al., 2013; Hazarika and Kumar, 2012 and Raj et al., 2009 in Sikkim Himalaya; Gupta and Singh, 1980 in Nepal Himalaya; Singh et al., 1978 in NE Himalaya). Dube and Srivastava (1983) analysed two local

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earthquakes of M 4 and M 5 of 1980 in Jammu region for Fault plane solution and found M 4 event was related to thrust faulting along MBT whereas M 5 was related to activity along the Surin-Mastgarh anticline. Sharma and Wason (1994) calculated the source parameters on the basis of Brune's earthquake source model of the 18 shallow focused local earthquakes of M_L 1.4 to M_L 4.2 in the Garhwal Himalaya and observed stress drop values of 1 bar to 10 bars for the events of magnitude less than 4 and 38 bars for the event of M 4.2 with focal depth of 15 km. Sriram and Khattri (2005) estimated the source parameter for the Dharamshalla earthquake of 1986 of M_b 5.5 and found 2.8 km as its source radius, 36 bars of stress drop value with seismic moment of 2.1 x 10^{24} dyne cm. Kumar et al. (2012) calculated the source parameter and fault plane solution through waveform modelling to understand the source characterization of the moderate earthquake of M_w 5.0 of July 2007 in the Garhwal Himalaya with the help of local broadband data from the 12 seismic observatories installed at different locations in the NW Himalaya and observed reverse faulting with a substantial strike-slip component.

In the current study we used waveform data recorded by seven Broadband Seismographs (BBS) installed in Jammu and Kashmir region to estimate the source parameters and focal mechanism (Fault Plane Solution) of the Mw 4.1 event of 29th May 2017.

II. GEOLOGY AND TECTONIC SETTING

The Jammu & Kashmir region shows almost a complete geological record representing rocks of Proterozoic to Recent within a limited geographic span. It is located in the NW Himalaya, which is the result of a continent-continent (Indian and the Eurasian plates) collision that took place about 50 million years ago (Searle et al., 1987; Thakur 1992; Thakur et al,. 2007). The Himalayan collision tectonics resulted in complex deformation of the lithosphere which continues even today and controls seismic activity in the region (Bilham, 2019). The study region mainly lies between the rupture zones of two major earthquakes, i.e., 2005 Muzaffarabad earthquake of Mw 7.6 and 1905 Kangra earthquake of Mw 7.8. The Jangalwar area lies between Panjal Thrust (PT) and Kishtwar Window (KW) in the Chenab valley. This whole region has witnessed intense folding and faulting due to the continuous Himalayan orogeny which is mainly responsible for the seismicity in this region. Here, rocks of the Lesser Himalaya are exposed as thrust sheets (Bhanot et al., 1975). This whole region is marked by MBT, PT, MCT, KW, Kishtwar Fault (KF) and Chenab Normal Fault (CNF) (Staubli, 1989; Kundig, 1989; Searle and Rex, 1989; Thakur, 1998; Dasgupta et al., 2000) alongwith some local faults Sudh Mahadev Fault (SMF), Chattru Fault (CF), Bhandarkut Fault (BF), Hasti Fault (HF) (Wakhloo and Dhar, 1971; Haq et al., 2019) and some recently identified Quaternary local faults like Janota Normal Fault (JNF), Khandote Normal Fault, Jangalwar Fault (JF), Nathi Fault (NF) and Thanalla Normal Fault (TNF) (Fig. 1).

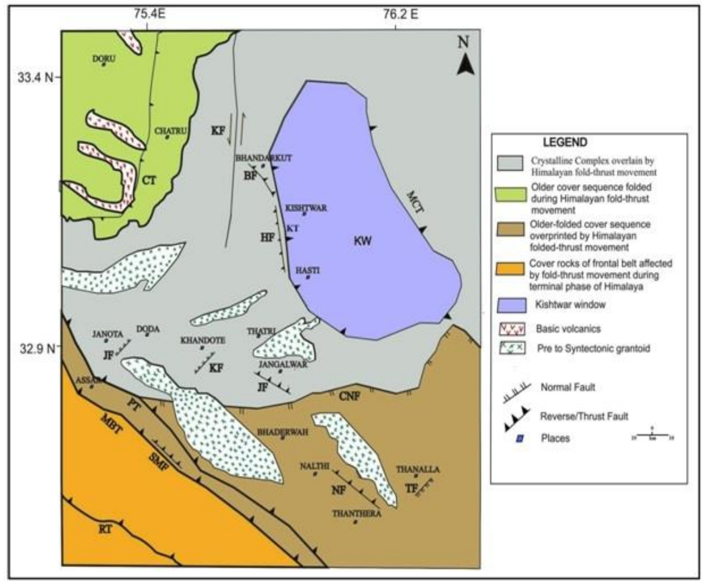

Fig.1: Geological and structural map of Chenab Valley region (J&K), NW Himalaya modified after Singh, (2010). For abbreviation refer to the text: RT, MBT, SMF, PT, CNF, CT, KF, MCT, HF, BF, JNF, KNF, JF, NF, TNF represent regional and local faults within the study area.

The PT zone comprises of Salkhala Formation, imbricate of Lesser Himalayan formations and the Tertiary sedimentary successions of the Outer Himalayan Fold Thrust Belt (OHFTB). The 10-15 km thick crystalline rocks of the Higher Himalayan Zone thrust against MCT in the south across the KW to Thatri near Jangalwar area (Jangpangi 1986). The rocks of Thatri region locally termed as the Chenab Higher Himalayan Crystallines (HHC), is overlain by slate, quartizite, quartzitic slate of the Bhaderwah Formation (Thakur et al., 1995). Structurally the whole region of Kishtwar is widely disturbed and has observed strong folding and faulting as a part of traces of Himalayan Mountain building activity (Singh, 2010; Haq et al., 2019). The Older Quartzites are thrusted over the younger schistose and gneissose rocks along KT, whereas the metamorphic and granitic rocks of Kishtwar Group are thrusted over the younger sedimentary and volcanic rocks of Sinthan Group along CT (Wakhaloo and Shah, 1970; Wakhaloo and Dhar, 1971).

III. DATA COLLECTION

With an objective to understand the Seismotectonics and seismic hazard of Jammu and Kashmir region, the Department of Geology, University of Jammu has established permanent seismic network of seven 3-component Broadband seismographs (digital seismographs) in the year 2009-2010 funded by the MoES, New Delhi. All the observatories are installed in the vicinity of the regional thrusts within J&K, Northwest Himalaya (Table 1). Each seismic station consists of Trillium 240 sensor and Taurus data acquisition system. The timing of the stations is provided by Global Positioning System (GPS) receivers. The seismic data recorded by these instruments are in continuous mode with sampling rate of 100 samples per second. The seismic data of the current earthquake was retrieved from all the seven BBS observatories and used for determination of Epicenter location, Source parameters and Fault Plane Solution.

Table 1: Locations of the BBS observatories along with their litho-tectonic setting

S. No	Station Name / code	Lat. (^{0}N)	Long. (^{0}E)	Altit -ude (m)	Lithology	Tectonic Domain
1.	Jammu (JAMU)	32.731^0	74.870^0	350	Boulder Conglomerate	Outer Himalaya
2.	Rajouri (RAJO)	33.389^0	74.337^0	105	Sandstones	Outer Himalaya
3.	Poonch (PUCH)	33.769^0	74.104^0	1094	Sandstones	Outer Himalaya
4.	Bani (BANI)	32.684^0	75.802^0	1393	Quartzite, phyllite, slate	Lesser Himalaya
5.	Tangdhar (TDAR)	34.655^0	73.938^0	2006	Quartzite, Phyllite, Slate	Lesser Himalaya
6.	Bhaderwah (BHAD)	32.956^0	75.720^0	1697	Quartzitic Slate, Slates	Tethys Himalaya
7.	Dooru (DORU)	33.673^0	74.233^0	1833	Limestone	Tethys Himalaya

IV. DATA ANALYSIS AND RESULTS

Seismograms contain information about the source, site and propagation path and are very useful in estimating source, site and path parameters like epicenter location, source parameters and its focal mechanism. The event of 29th May, 2017 was recorded by all the seven stations and the data was used to determine source parameters and focal mechanism.

A. Epicenter Location of the Event

The exact location of the event was obtained by the identification of different seismic phases in the waveforms with the help of location program Hypo 71 inbuilt in the Seisan software (Havaskov and Ottemoller, 2003). This Hypo 71 program helps in minimizing the Root Mean Square (RMS) values of residuals between the observed and theoretical travel time differences. To determine the depth and location of the event, the arrival times of P and S waves from all the waveforms of all the seven stations and modified 1-D crustal velocity model was used. The velocity model used for the theoretical travel time was modified after Kumar et al. (2009) and consists of six layers, whose depths are at 0.0, 8.0, 20.0, 30.0, 50.0 and 55.0 km with P- wave velocities of 5.27, 5.95, 6.25, 6.95, 7.55 and 7.95 km/s respectively with Vp/Vs ratio of 1.75.

The location parameters on the basis of this velocity model were selected when the RMS values of residuals between the observed and calculated travel times reduced to less than 0.5 for the individual parameters (latitude and longitude) and error associated with depth reduced to less than 5 km.

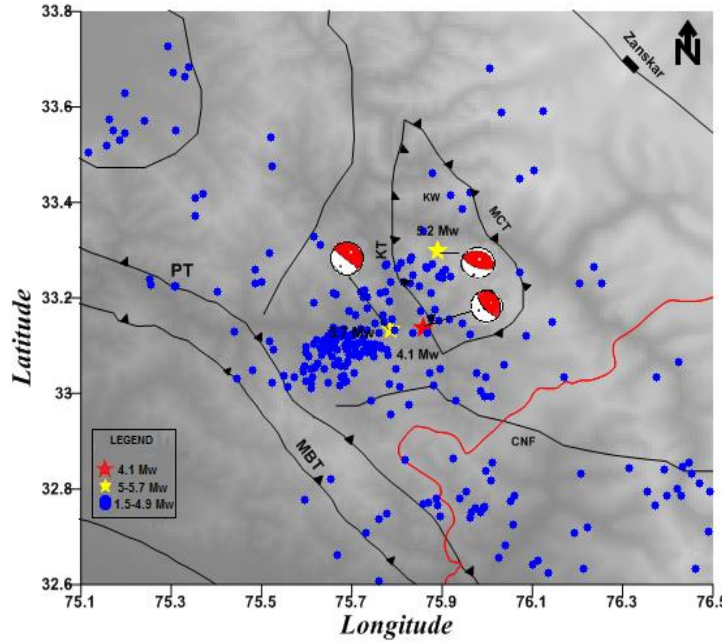

Fig. 2: Topographic map showing seismic activity in the Chenab Valley, Jammu and Kashmir region. Red star represents M_w 4.1 event of 29 May, 2017, Yellow stars represents main events of 2013 (M_w 5.7 of 1 May and M_w 5.2 of 2 August), Blue dots represents the events ranging from Mw 1.5 to Mw 4.9. Beach balls represent the focal mechanism of their corresponding events.

The epicenter location of M_w 4.1 earthquake was observed at 33.110^o N, 75.896^o E. This event is projected on the topographic map of Kishtwar region along with the local events of 2013, which were mostly clustered between PT and KW (Fig. 2). The cluster of these shallow focus events indicates the presence of detachment zone above the decollement depth in this region (Pandey et al., 2016). The focus of this event was observed at the depth of 11 km indicating seismic activity is mostly confined to the upper crust between PT and KW. In the entire Northwest Himalaya the seismicity of low to moderate magnitude events is mainly confined to the upper crust upto the depth of 20 km, mostly concentrated in the north of MBT. Pandey et al. (2016) found low to moderate seismicity in between PT and KW at the shallow depth upto 16 km in the Chenab valley. In the adjoining Kangra-Chamba region majority of small magnitude events are also highly concentrated along the MBT, PT, Chamba Thrust (CT) and CNF (Yadav et al., 2016). In the study region, the rocks belonging to the upper part of the crust have a low strength of strain accumulation in which the rocks go through brittle fracturing. The focus of the event lies above the Himalayan wedge above the basal decollement.

B. Source Parameters

For the estimation of source parameters, spectral analysis based on the Brune's circular model (Brune, 1970) was applied in which source characteristics like stress drop, scalar seismic moment (Mo), source radius (r), corner frequency (f_c) and Moment Magnitude (M_w) were obtained. In the spectral analysis, firstly instrumentation correction was made through deconvolution process which is based on poles and zeros of the instruments along with other system information. The instrument corrected horizontal north-south and east-west components of the waveforms at each station were rotated to acquire radial and transverse components respectively (Sri Ram et al., 2005; Kayal et al., 2009). Following Parvez et al. (2011), the attenuation correction was made through 'Q' and 'n' parameters and the near surface attenuation correction was made through kappa value of 0.04 of Chopra et al. (2012). For the estimation of source parameters the SPEC module inbuilt in Seisan Software was used. A time window length of 2 to 5 seconds was selected individually in transverse and radial components to reduce the P-wave portion and to separate the SH waves (Fig. 3). To attain the displacement amplitude spectra the SH part was converted into the frequency domain. The corner frequency (f_c) and low frequency spectral level (Ω_0) were calculated from the obtained displacement amplitude spectra.

Seismic moment is expressed as:

$$\text{Mo} = 4\pi\rho\beta^3 R\Omega_0 / R_{\theta\phi} S_\alpha$$

The source radius (r) and stress drop ($\Delta\sigma$) were estimated following Brune's circular model (Brune, 1970 &1971) as:

$$r = 2.34\beta/2\pi f_c$$

$$\Delta\sigma = 7M_o/16r^3$$

Where, β is shear wave velocity in the source zone = 3.92 km/sec; ρ is the average density = 2.16 g/cm^3, Ω_0 is the low frequency spectral level; R is the hypocentral distance; $R_{\theta\varphi}$ is the average radiation pattern = 0.63; S_α is the free surface amplification = 2; f_c is the corner frequency defined as the intersection of low & high frequency asymptotes, Ω_0 and f_c were estimated from displacement amplitude spectra. These constants are taken from Bhat et al. (2013) and Pandey et al. (2016).

The spectral analysis reveals the seismic moment, corner frequency, source radius, stress drop vary from station to station. To evaluate the size of an earthquake in terms of moment magnitude (Mw), the estimation of seismic moment is very important. The seismic moment varies from 15.4, 15.2, 15.1 and 15.6 for JAMU, BHAD, RAJO and PUCH respectively. The average value calculated from all the stations for seismic moment is 15.3. This seismic moment value indicates low seismicity level in this region. From the previous studies about this region it was noticed that there was record of only few events with magnitude ≥ 5. Interestingly, it was also noticed that most of the events having large value of seismic moment occurs between PT and KW, supports to our earlier observation that the area is highly active (Pandey et al., 2019).

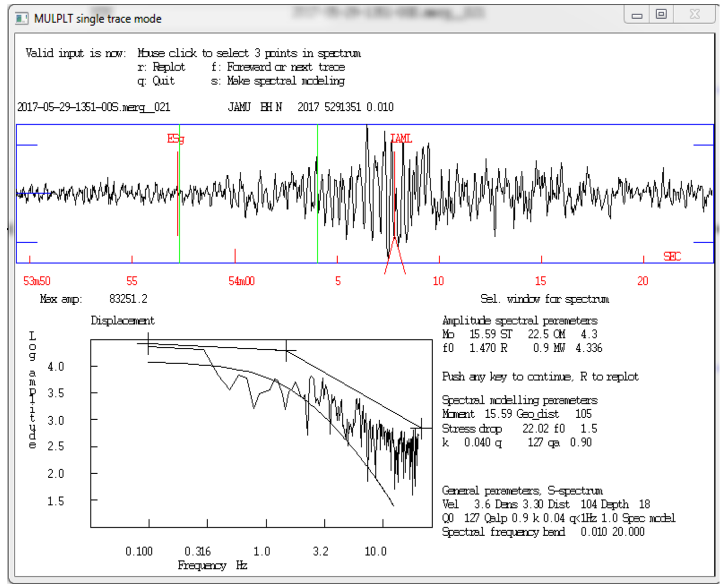

Fig. 3: An example of displacement amplitude spectra of rotated horizontal component of the 29 May, 2017 event (M_w 4.1) recorded by the Jammu station for the estimation of source parameters.

To study the source parameters of an event, it is important to determine accurate corner frequency as other parameters viz., slip velocity, source radius and source duration are directly obtainable from it. The estimated corner frequencies (f_c) were estimated at 2.16 Hz (JAMU), 2.49 Hz (BHAD), 2.94 Hz (RAJO) and 1.69 Hz (PUCH), and the average value at 2.39 Hz. In general, corner frequency follows the scaling law $M_o \propto f_c^{-3}$, shows self similarity of earthquakes, while stress drops are found to be independent over a wide range of seismic moments (Aki, 1967). The source radius calculated from the corner frequencies was 0.585 km. The stress drop estimated in this study was a moderate value of 50.6 bar; since the event is of smaller magnitude it is difficult to make any relation between the stress drop and magnitude. In our earlier study, Pandey et al. (2016) reported minimum stress drop of 3.3 bar for Mw 3.0 and maximum stress drop of 70.1 for Mw 5.7 which occurred between PT and KW and concluded that stress drop increases with increase in magnitude. Stress drop values obtained in this study are consistent with the stress drop values obtained for the same region earlier by Pandey et al. (2016) and also from the other parts of the Himalaya (Verma et al., 2015) suggesting the brittle behavior of the rocks in the upper part of the crust. Stress drop of any event may contrast depending upon the lithology of that area where the event occurred (Aki 1967). Sharma and Wason, (1994) also reported a low stress drop with the value of 38 bar for the Garhwal Himalaya. Verma et al. (2015) reported high stress drop value of 92 bar for the Mw 4.9 in the nearby Kangra region. According to the Brune's (1970) circular model, the stress drop value of any event from one region irrespective of its size should be constant; lower stress drop values signify competent lithology that cannot hold high amount of stress (Pandey et al., 2016). In this case the stress drop of 50.6 was found between the PT and KW which is also consistent with incompetent lithology present in this area which holds high stress accumulation during the stress building process.

C. Focal mechanism through Waveform Modelling

To understand the seismic source of an earthquake, the method of seismic waveform modelling helps in determination of the fault orientation and its characteristics. In this method the synthetic waveforms are generated digitally on the basis of local crustal model and earthquake source parameters. The motion of the ground due to an earthquake is determined by the earthquake source properties and the earth structure. If the earth structure is known, the earthquake source parameters (strike, dip, rake, depth, hypocenter and source time function) can be obtained by minimizing the difference between the observed and synthetics seismograms (Mao W.J. et al., 1994). To obtain the hypocenter location and fault plane solution of the current event waveform inversion was performed with the help of ISOLA software (Sokos and Zahradnik, 2008); it is based on a multiple point sources which uses iterative deconvolution method of Kikuchi and Kanamori (1991). Firstly the seismic data was converted from SEED to SAC format through the Seisan software as SAC format is required as an input data to calculate the moment tensor inversion. To compute the full waveform synthetics (Green's functions) discrete wave number method was used by setting a set of pre-defined point source on a plane or a line given by Bouchon, (1981) and Coutant (1989). After getting a major point source contribution, the equivalent synthetics are subtracted from the data. Then, inversion for the remaining waveform for another point source was done, and so on. Consecutively, the point sources are removed one after another, thus each step involves only source position and onset time (Mandal et al., 2017). These two parameters provide stability of the inversion (Zahradnik et al., 2005). After that spatial grid search method is applied to acquire the best source position (location and depth) and time in the form of absolute value of correlation coefficient between the observed and synthetics which are automatically calculated during least square inversion (Zahradnik et al., 2005). The matching between the observed and synthetics after the best fitting of spatio-temporal positions is characterized by the overall variance reduction in all the components of all the stations (Zahradnik et al., 2005). The four band pass filter (f_1, f_2, f_3, f_4), was applied both to real and synthetic waveforms. The signal to noise ratio curves helps mainly to define f_1, because the noise level (either natural or instrumental) limits the usable low-frequency range (Sokos and Zahradnik, 2013). The solution is finalized after getting good correlation between the observed and synthetics waveform along with the high Double Couple (DC %). We used station dependent frequency range according to the signal to noise ratio and the epicenter distance.

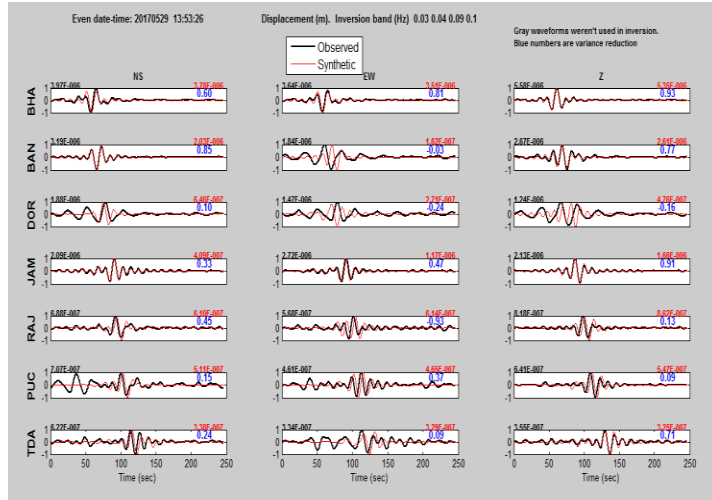

Fig. 4: Correlation plot between the observed and synthetic waveform data of M_w 4.1 event shown in seven stations. Black lines show the observed seismograms whereas the synthetic waveforms are represented by red lines.

For the multiple source moment tensor solution of this event, the data from all the seven stations was used. The deviatoric moment tensor inversion in the ISOLA software was used. For source inversion, the data was processed by applying low-pass filter (<1Hz) to the observed waveform and frequency band between 0.01 and 0.1 Hz with cosine tapering of 5 % was used. The four band pass filter with frequency range of 0.03 0.04 0.09 0.1 was used to make the filtered seismograms noise free (Fig. 4). After observing the normal correlation (>0.4) between the observed and synthetic seismograms along with high DC% the solution was finalized. To constrain the moment tensor solution through deviatoric waveform below the epicenter, a set of 10 point source positions at every 2 km depth below the main shock epicenter starting from 2 km to 42 km was considered. The maximum spatial correlation after inversion was observed at the depth of 11 km for the 5^{th} source position (Fig. 5) signifying a MT solution having ~55% of DC (Double Couple) component and 45% of CLVD (compensated linear vector dipole) component (Fig. 6).

The different correlation values obtained for the different stations may be due to the different velocity structure depending upon the topography and lithology of the area where stations are located. The BHAD station is situated on the quartzitic slate, slates and quartzites of the Tethys Himalaya, shows good correlation between the observed and synthetics seismogram (Fig. 4). The BANI station has also nearby similar velocity structure and also shows good correlation (Fig. 4). The correlation values of the JAMU, PUCH and RAJO stations also show good matching between the observed and synthetics waveforms as these stations lies on the sandstones of Siwaliks and Murrees in the south of the MBT.

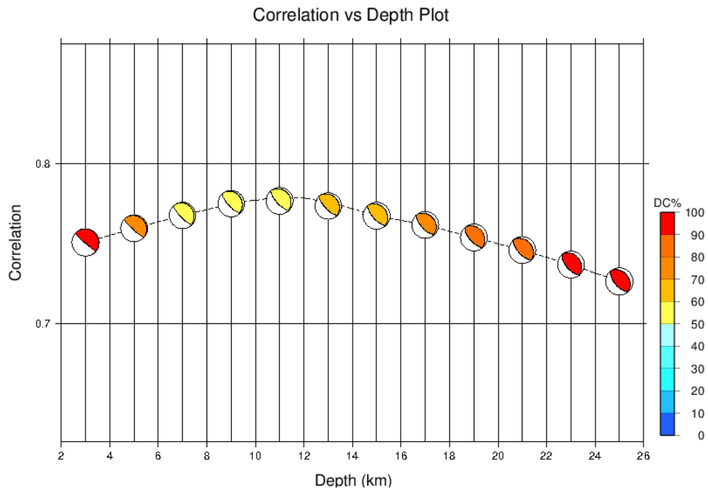

Fig. 5: Correlation vs Depth plot of the M_w 4.1 event in which depth lies at 11 km with more than 50 DC%.

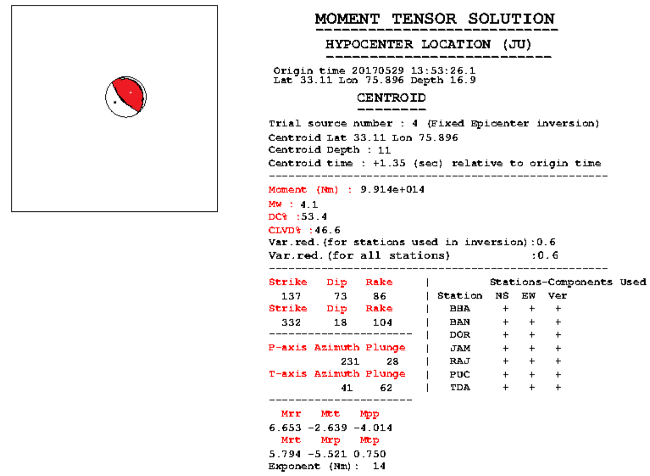

Fig. 6: CMT solution of M_w 4.1 event in Jangalwar region shows the DC% is ~54 and CLVD% is 46 with Centroid depth at 11 km with moment of 9.914e+014.

In DORU station we found high mismatch between the observed and synthetic seismograms and negative correlation values (Fig. 4), may be due to the location of the station which lies north of Pir-Panjal ranges where the velocity model of the area may be different. After verifying with different band pass filters with different frequency ranges the best fit mechanism at the depth of 11 km shows thrust movement with two nodal planes with the strike of 160^o, dip 52^o and rake of 100^o whereas other plane is showing strike, dip and rake of 323^o, 39^o and 77^o respectively (Fig. 6). This emerging thrust may be related to reactivation of ramp emanating from the decollement or emergence of a new splay from PT as the primary source for the current seismic event in the Jangalwar area of Chenab valley.

V. SUMMARY AND DISCUSSION

In this paper, source parameters and moment tensor solution of the of 29th May 2017 Jangalwar event of M_w 4.1 was estimated by waveform modelling of broadband data from a seismic network of seven seismographs deployed in the Jammu and Kashmir. It was observed that the current event occurred in the same source zone where the M_w 5.7 occurred in 2013. The estimated seismic moment was 15.3 with corner frequency of 2.39 Hz and the source radius 0.585 km.

The estimated stress drop of 50.6 bar for this event is comparatively high than the existing stress drop of the earlier same magnitude earthquakes occurred in the same region. This high stress drop may be due to the presence of incompetent rocks which accumulate large stress, which in turn can result in high stress drop values at the threshold limit. Earlier, Bhat et al. (2013) have observed seismic moment of 4.47 x 10^{18} to 6.31 x 10^{21} dyne cm, stress drop values of 0.08 to 28.4 bars and source radius varying from 0.45 to 2.08 km for the 14 local events whose epicenters were located towards the north of PT in the Chenab valley region.

Kumar et al. (2013) also observed seismic moments varying from 3.29 x 10^{17} to 3.73 x 10^{19} dyne cm, stress drop values of 0.1 to 9.7 bars, source radii of 111.7 to 558.9 m and corner frequencies from 7 to 18 Hz. for the 26 local events of M_w 1.0 to M_w 2.5 which occurred from May 2008 to April 2009 in the adjoining Bilaspur area of Himachal Pradesh. In Garhwal Lesser Himalaya, Wason and Sharma (2000) estimated source parameters for the 15 local events of M 2.4 to M 3.3 which occurred from September 1997 to December 1997 and observed seismic moment ranging from 2.89 x 10^{18} dyne cm to 3.90 x 10^{20} dyne cm and stress drop values of 2.97 bars to 83.42 bars for the M 2.4 to M 3.3 events. The spatial distribution of stress drop in the NW Himalaya region suggests high stress drop values for minor to moderate events which occurred to the NE of the MBT and PT. It was also observed that the increasing trend of stress drop values is related to the presence of incompetent rocks at very shallow depth in the upper part of the crust. Pandey et al. (2016) has also observed large number of aftershocks in which most of the activity was found between PT and KW with high stress drop in areas having incompetent rocks and low stress drop in areas with competent rocks.

The stress drop and source radius for the 1st May 2013 event was estimated at 71.1 bar and 3.55 km respectively while corner frequency was 0.397 Hz. The stress drop and source radius of 2nd August 2013 event was estimated at 37.7 bar and 3.13 km respectively while corner frequency was 0.6 Hz. The focal mechanism of M_w 4.1 event shows thrust movement with two nodal planes; one is striking at 160^o with dip of 52^o and other is striking at 323^o with dip amount of 39^o. The northward movement of the Indian Plate towards the Eurasian Plate resulted into the NE directed compression of the Indian Plate (Bilham, 2009; Bilham and Wallace, 2005). The collision between the two plates controls the whole dynamics of the current tectonic activity in this region which led to the control of

NE compression over the Indian Plate. Chaudhary and Srivastava (1974) found the evidence of thrust faulting by 1973 Kishtwar earthquake with its nodal plane oriented towards NNE direction. Mitra et al. (2014) has also observed an oblique thrust at the depth of 16 km which was responsible for 2013 earthquake in the Kishtwar region. The Fault Plane Solution suggested by Global Centroid Moment Tensor (GCMT) catalog of 1st May and 2nd August events of 2013 of Kishtwar region also indicated thrust mechanism (Pandey et al., 2016). A steep frontal ramp near the KW is observed where the depth of the events changes from 13 km to 16 km and the events close to the KW are deeper and having greater dip angle than the shallower events (Paul et al., 2018). Verma et al. (2015) has also observed thrust faulting with NE dipping fault plane for the M_w 4.9 earthquake which occurred in the nearby Kangra region on August 2014 between the Panjal imbricate zone and the Chamba Nappe and suggested that this NE dipping fault plane favours the PT as the source fault for this event. The resemblance of the nodal plane striking 323^o and dip of 39^o for M_w 4.1 event also favours the PT or emergent thrust splay between PT and KW as the source for this earthquake. The steep dip and shallow depth points to the evidence of reactivation of ramp of a new frontal thrust emanating from the decollement or reactivation of blind Himalayan thrust as the primary source mechanism for the present moderate earthquake activity in the Jangalwar and adjoining areas of the Kishtwar region between the PT and South western segment of KW.

CONCLUSION

1) The spectral analysis of M_w 4.1 event reveals seismic moment of 15.3, corner frequency of 2.39 Hz and the source radius of 0.585 km at the centroid depth of 11km with the stress drop of 50.6 bar.

2) The stress drop of 50.6 bar is consistent with the stress drop values obtained from the other parts of the NW Himalaya suggesting occurrence of competent rocks in the upper part of the crust.

3) The fault plane solution reveals thrust movement with two nodal planes with the strike of 160^o, dip 52^o and rake of 100^o whereas other plane is showing strike, dip and rake of 323^o, 39^o and 77^o respectively.

4) The resemblance of the nodal plane striking 323^o and dip of 39^o favours the Panjal Thrust or emergent thrust splay between the Panjal Thrust and Kishtwar Window.

5) This emerging thrust may be related to reactivation of ramp emanating from the decollement or emergence of a new splay from Panjal Thrust as the primary source for the current seismic events in the Jangalwar area of Chenab valley.

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