JOURNAL INDIAN ASSOCIATION OF SEDIMENTOLOGISTS ISSN NO 2582 – 2020
Vol. 39, Issue 1, 2022, pp. 96-101
DOI: **https://doi.org/10.51710/jias.v39i1.235**

Assessment of Velocity pattern of Lithotectonic Segments of the Kashmir Himalaya: Constraints from GPS measurements

Arjun Singh, GM Bhat, Yudhbir Singh

Postgraduate Department of Geology, University of Jammu, Jammu
Email: bhatgm@jugaa.com

Abstract

We present the estimated horizontal velocities of different lithotectonic segments of the NW Himalaya using data recorded by the eighteen GPS observatories installed in the Jammu and Kashmir region. The data was acquired from 2016 to 2019 and was processed using high precision GAMIT/GLOBK software. With respect to ITRF08 reference frame, the site motion in the region varies from 35 mm/yr to 45 mm/yr towards north-east. The India fixed site motion was estimated using the Ader's Euler pole of rotation. This yielded site motion varying from 2.4 to 11 mm/yr towards south-west and is consistent with the reported plate motion in the Northwest Himalaya. Further study with additional GPS networks is expected to provide precise estimates of deformation in the locked and creeping zones of the main Himalayan thrust in the Northwest Himalaya.

INTRODUCTION

The Jammu and Kashmir region lies close to the northern edge of the Indian Plate active margin. The tectonics of the region is controlled by the collision of the Indian Plate with the Eurasia Plate resulting in the progressive differential deformation of various segments of the Himalayan Arc. Global Positioning System (GPS) has been used as a useful tool in investigating global plate motions and regional tectonic movements (Argus and Heflin, 1995; Larson et al., 1997). A few tectonic studies using GPS have been done for the region (e.g., Jade et al., 2020, Kundu et al., 2014; Schiffman, 2013). Compared with other regions of the Himalaya, geodetic or neo-tectonic characteristics of the Kashmir region have not been well known because of the lack of adequate GPS network; however, Stevens et al. (2015) used published GPS data from several studies for determining interseismic plate coupling on the Main Himalayan Thrust (MHT) along the entire Himalayan arc. In the current study we used GPS data from the 18 permanent GPS stations (8 new GPS observatories and 10 GPS observatories from Kundu et al., 2014) to investigate the horizontal velocities in Jammu and Kashmir and their relationship with the tectonic settings of the region. We analyzed three years of data (2016 to 2019) from our 8 new GPS sites constructed on geologically stable monuments. These observatories are located at Jammu (JAMU), Rajouri (RAJO), Poonch (PUCH), Bani (BANI), Bhadarwah (BHAD), Doru Shahabad (DORU), Pampore (PAMP) and Tangdhar (TANG). Finally, the station velocities relative to the ITRF08 reference frame were converted to Indian Reference frame (IRF).

The main Himalayan thrust (MHT) often referred as decollement is commonly considered as the store house of earthquakes (Bilham et al., 1997; Jouanne et al., 1999; Avouac, 2003; Bettinelli et al., 2008) whose splays constitute the mega thrusts like Main Frontal Thrust (MFT), Main Boundary Thrust (MBT) and Main Central Thrust (MCT). During interseismic span the locking is mainly considered to be stored at the brittle and frontal part of MHT (Seeber and Armbruster, 1981; Ni and Barazangi, 1984; Molnar, 1990). The seismic processes viz., pre-, co- and post seismic deformation in earthquake cycle have long been measured by geodetic methods, predominantly via continuous GPS (cGPS) readings. The cGPS allows determining the kinematics of the thrusts to understand the earthquake scenario in the region with reasonable accuracy. The horizontal surface velocity driven position time series is used to measure precise plate motion when it is linear and non transient. For even decades, the secular horizontal plate motion at a particular place can be disturbed by post-seismic irregularities (Freymueller et al., 2008), which is reflected in the present study at the Tangdhar (TANG) site located in the north Kashmir. Generally a mega seismic event is very improbable to alter the consistency of plate motion rate well over million years (Gordon and Stein, 1992; DeMets et al., 2010). The concept of secular motion is well associated with the pace of tectonic plate motion, however it is contradictory as the available geodetic data lags duration when compared with the occurrence period of earthquake that can be decades to hundred years (McCaffrey, 2008). Moreover the sudden transient episodes act as the main cause that disrupt the linear motion of tectonic plate, and the available geodetic data is short and unclean, hence it is hard to partition these modeled motion from the steady and continued plate motion (McCaffrey, 2009). Regardless, the global accessibility to the geodetic observations is still accruing to the substantiality required to graph the strain rate distribution and to establish the parameters for deformation with exact tectonic structures (Bastos, 2010).

The two major earthquakes recorded in Kashmir region were 1555 and 2005; the 2005 Kashmir earthquake epicentered at Muzaffarabad, arised at Indo-Kohistan seismic zone on a 75 km mega thrust (Gahalaut, 2009). While considering the 1555 earthquake would have released the past stored strain energy and further a fresh accumulation of strain with derived present-day moment rate in the region, the residual amount of stored energy, if measured presently can suggest whether the region has enough potential to generate a devastating earthquake of Mw>8 or 9 in the near future. To accomplish the goal of estimation of strain budget that leads to mega earthquake in the region, it is imperative to understand accurately the velocity field. The new velocity field of the Jammu and Kashmir region presented in this paper is based on the data from eighteen cGPS sites including 8 GPS observatories of Jammu University and 10 GPS observatories of Kundu et al. (2014) in the Jammu and Kashmir region.

DATA ANALYSIS

The data was processed using high precision GAMIT/GLOBK software (King and Bock, 2005). The GPS observations were recorded as 24 hour file with 30 seconds sampling interval. To enhance the stability of overall network and to connect the regional sites data to global reference frame, 20 sites (YAKT, TIXI, PIMO, TCMS, KARR, PERT, ULAB, XMIS, CUSV, COCO, LHAZ, NRIL, URUM, LCK4, HYDE, IISC, DGAR, SUMK, POL2, KIT3) from permanent International GNSS Service (IGS) were included in the processing. The IGS data was acquired from Scripps orbital and processing centre (SOPAC). The GAMIT program was used as source for various input files required to obtain the daily basis loosely constrained position estimates. GLOBK program takes account of all the loosely constrained results and create error and outlier free coordinate time series and velocity estimates

GPS time series

The time series and velocity vector are the two tools that make the base for any geodetic study. The time series plots were generated in the International Terrestrial Reference frame 2008 (ITRF08) and Indian fixed reference frame. A time series is a plot that presents how coordinates shift with time. The X-axis shows the time and Y-axis shows the displacement and slope represents each day position (Position in three dimensions: North-South, East-West, and Vertical i. e., up-down). The inclination of position dots represents the trend of the sites motion and for each plot (North-South, East-West, Vertical) northward is positive and southward is negative. If the trend of slope is positive, the site motion is northward and for negative it is southward (Fig. 1). The present study displays motion in the northeast and southwest direction at all the 18 sites in ITRF08 and IRF respectively (Fig: S1-S16). To view the Position Time Series, click here https://drive.google.com/file/d/1Tb6SyPbPX39zajC0MYAcE-749q8VIxr_/view?usp=sharing). The site motion shows a transient and non-linear behaviour at each displacement component.

This yielded site motion varying from 2.4 to 11 mm/yr towards south-west. In India fixed reference frame a small quantity of displacement was observed at JAMU site located at the edge of the Indian plate, which is likely due to deformation in the frontal lithotectonic segments of the Kashmir Himalaya. The estimated site velocity of our eight new sites is consistent with the reported plate motion by Kundu et al. (2014) (Table 1) whereas, the site TANG is located in the downdip rupture zone of the 2005 Kashmir earthquake that shows a large southward motion different from the adjoining sites (URII and MULG). The possibility of slope instability at TANG site is least as it is situated at the hard basement rock and also spur slope is very gentle. This observed anomalous motion near TANG site is also reported by Kundu et al. (2014) and Jade et al. (2020) with respect to their observatories. Similar postseismic deformation has been reported along the ruptured zone of Kashmir 2005 earthquake by Jouanne et al. (2011). The derived site motion (9.3 mm/yr towards N195^{o}) using continuous GPS data from 2016 to 2019 at TANG is small against the reported motion (15.4 mm/yr towards N207^{o}) at the nearby site KERN using campaign data from 2010-2011 (Fig. 3). This difference is obviously due to small duration (one year) in case of KERN site. However in either case the results are anomalous as compared to the adjoining sites. This large southward anomalous behaviour could also be related to the complex structural setup (thrust system and strike slip faults in the region) around the western syntaxial bend adjoining the TANG and KERN locations. However, this requires a detailed understanding of the influence of post seismic deformation and tectonic setting of the region. Installation of additional observatories shall help in the characterization of this anomalous motion in the westernmost part of the Kashmir valley.

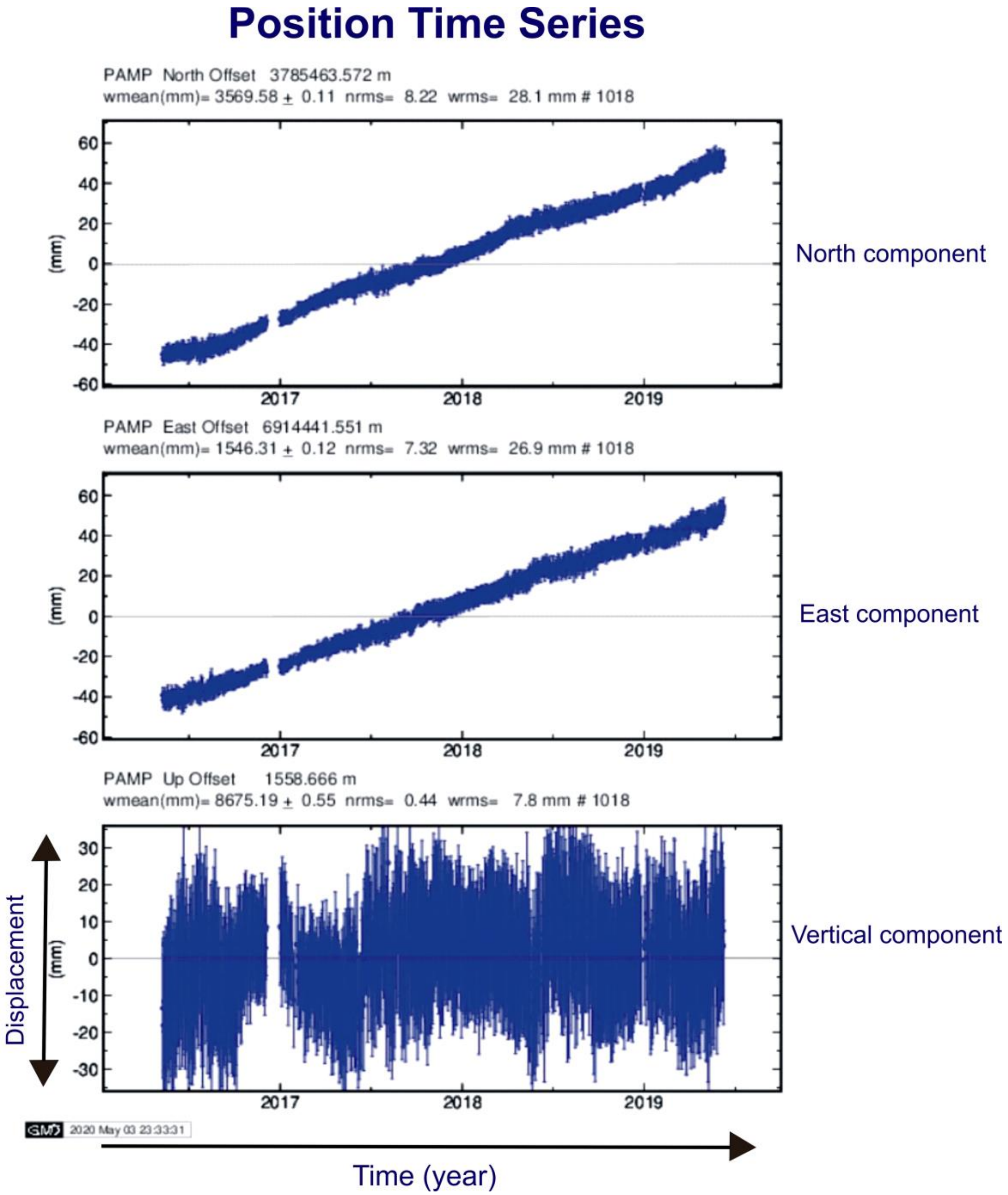

Fig. 1 The time series plot of Pampore site (PAMP) in Kashmir shows north, east and Up (vertical) component. The plot represents the motion in north east direction in ITRF2008.

Plate motion in the region

The India fixed site motion was calculated using the Euler pole of rotation recommended by Ader et al. (2012) with parameters like latitude 51.4±0.3°N, longitude -1.34±3.31°E, Rotation rate 0.5029±0.0072°/Myr. The displacement-time series shows significant seasonal variations at each site. In ITRF08 reference frame, the site motion in the region varies from 35 mm/yr to 45 mm/yr towards north-east (Fig. 2). We used the Euler pole of Ader et al. (2012), which was also used by Kundu et al. (2014), to calculate the site motion in fixed India plate.

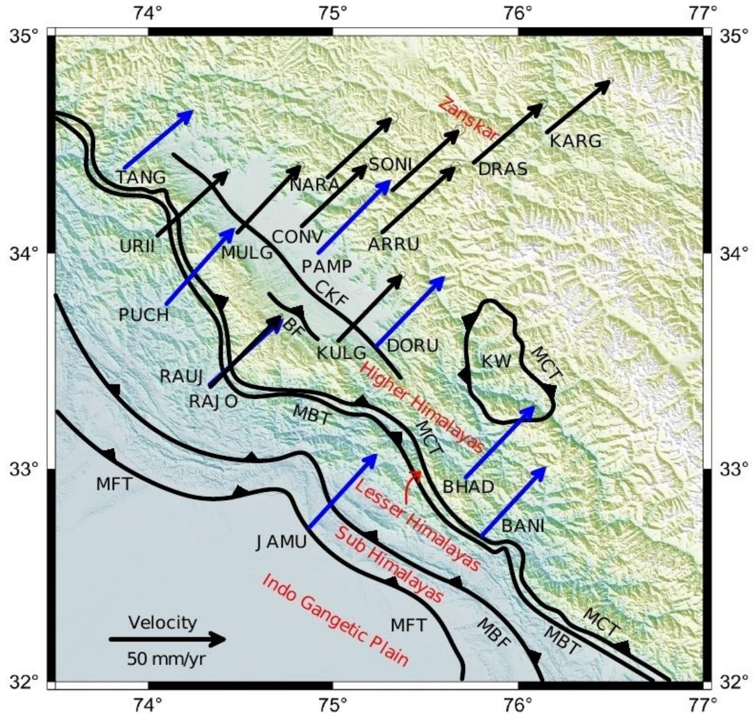

Fig. 2: Horizontal site velocity in the study area in ITRF08 reference frame. The new GPS sites data is represented by blue colour vectors. The black vectors represent the site velocity reported by Kundu et al. (2014).

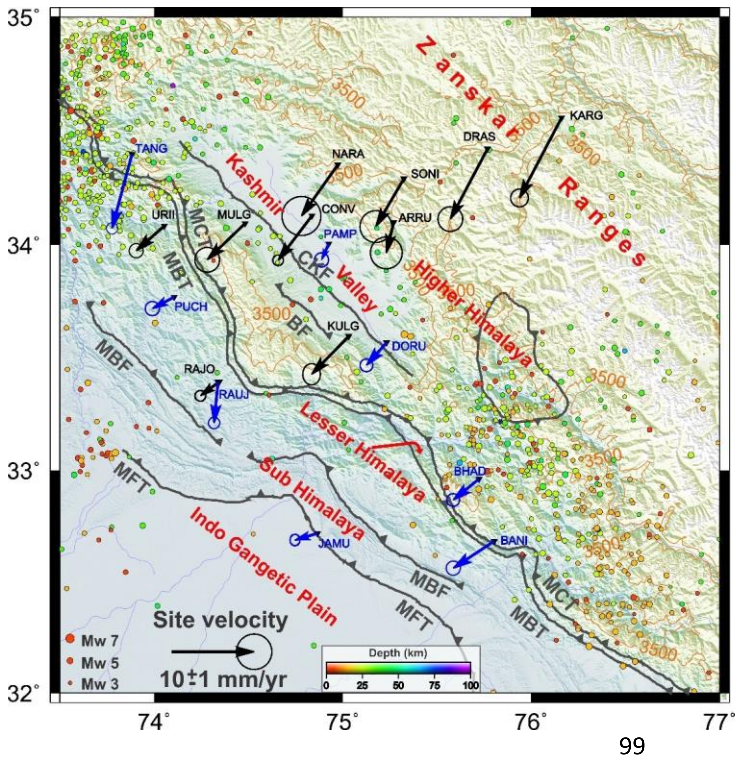

Fig. 3: The figure shows the plate motion in the fixed India plate frame (using Euler pole of Ader et al., 2012) at eight newly installed continuous GPS sites in the Kashmir Himalaya. The filled circles show the seismicity in the region during 1970 to July 2020 listed in the ISC catalogue. The size and colour of the circle indicate the magnitude and focal depth of the earthquakes respectively. The 3.5 km of topographic elevation is shown by orange colour curve. The black curved lines indicate major fault units in the region, i.e., MFT-Main Frontal Thrust; MBF- Main Boundary Fault; MCT-Main Central Thrust; BF-Balapora Fault; CKF- Central Kashmir Fault.

Table. 1: Horizontal site velocity in the study area derived from ITRF08 and IRF.

Sites	Long	Lat	GPS site velocity (mm/yr)			
			ITRF08		Fixed India Plate	
			East	North	East	North
JAMU	74.867	32.718	29.6 ± 0.07	33.0 ± 0.08	-2.74 ± 0.07	-0.82 ± 0.08
RAJO	74.339	33.393	31.3 ± 0.08	28.8 ± 0.08	-0.48 ± 0.08	-4.96 ± 0.08
PUCH	74.106	33.770	28.9 ± 0.1	33.0 ± 0.1	-2.64 ± 0.1	-1.4 ± 0.1
BANI	75.804	32.683	27.7 ± 0.1	30.7 ± 0.1	-4.97 ± 0.1	-3.28 ± 0.1
BHAD	75.723	32.961	29.3 ± 0.09	31.4 ± 0.09	-3.13 ± 0.09	-2.55 ± 0.09
DORU	75.233	33.568	29.6 ± 0.09	31.2 ± 0.09	-2.44 ± 0.09	-2.75 ± 0.09
PAMP	74.926	34.005	30.8 ± 0.1	31.9 ± 0.1	-0.87 ± 0.1	-1.95 ± 0.1
TANG	73.883	34.400	28.7 ± 0.08	24.7 ± 0.08	-2.42 ± 0.08	-8.99 ± 0.08
KARG	76.161	34.559	27.0 ± 0.5	22.8 ± 0.5	-5.1 ± 0.5	-9.7 ± 0.5
DRAS	75.768	34.423	29.4 ± 0.7	25.6 ± 0.7	-4.5 ± 0.7	-8.5 ± 0.7
SONI	75.325	34.292	28.7 ± 0.9	26.6 ± 0.9	-3.4 ± 0.9	-5.8 ± 0.9
ARRU	75.271	34.100	31.3 ± 0.9	28.7 ± 0.9	-0.9 ± 0.9	-3.7 ± 0.9
KULG	75.032	33.596	27.5 ± 0.5	29.3 ± 0.6	-4.5 ± 0.5	-4.6 ± 0.6
NARA	74.974	34.353	27.5 ± 1.1	26.2 ± 1.1	-4.4 ± 1.1	-6.2 ± 1.1
CONV	74.837	34.129	27.9 ± 0.3	26.9 ± 0.3	-4.1 ± 0.3	-5.4 ± 0.3
MULG	74.483	34.095	27.5 ± 0.7	29.8 ± 0.7	-4.6 ± 0.7	-4.4 ± 0.7
RAUJ	74.346	33.394	30.0 ± 0.3	30.6 ± 0.3	-2.3 ± 0.3	-1.7 ± 0.3
URII	74.054	34.084	30.5 ± 0.4	28.3 ± 0.4	-3.4 ± 0.4	-3.0 ± 0.4

Conclusion

The present study indicates gradual increase in the site velocity (Fixed India plate) from southwest to northeast in the Kashmir region, which is similar to the other segments of the Himalayan region (Jade et al., 2020; Kundu et al., 2014; Schiffman et al., 2013). Moreover, in the ITRF frame our velocity results are similar to those of other parts of the Himalaya (Bilham et al., 1997; Jouanne et al., 1999; Banerjee and Burgmann, 2002; Avouac, 2003; Ader et al., 2012; Schiffman et al., 2013; Kundu et al., 2014, Jade et al., 2020) which most likely suggests the buildup of strain on the underlying seismically active detachment, where great and major Himalayan earthquakes are assumed to occur (Seeber and Armbruster, 1981). If the fault fragment is creeping up to the surface, contrary to the locked segment that generate comparatively flat geodetic velocity gradient across the fault, fault-crossing geodetic velocity show sharp gradient or offset (Y Li, 2020) and in the present study the gradual variation in the azimuth of site velocity from northeast to southwest was observed which represent oblique convergence in the Kashmir region. In the fixed Indian plate, the region with lower site motion probably indicates higher plate coupling, which eventually highlights certain targets for subsequent studies for strain accumulation and seismic moment buildup. Further the lateral high and low coupling variations along the Himalayan Arc will also counsel the segmented behaviour of Main Himalayan thrust. Additionally, with the use of continuous GPS data and measured slip deficit can help in finding out the probable earthquake zones on MHT and shall help in mitigation of future damage due to potential mega-events in the region.

Acknowledgements

The data has been generated in the present study through eight GPS observatories installed in Jammu and Kashmir region under the MoES funded Research project No. MoES/P.O.(Seismo)/1(147)/2012 to GM Bhat. We are grateful to Vineet Kumar Gahalaut, Joshi Catherine and Rajeev Kumar Yadav of

NGRI for their help in processing the GPS data by Arjun Singh.

References

Ader, T., Avouac, J. P., Liu Zeng, J., Lyon Caen, H., Bollinger, L., Galetzka, J., Genrich, J., Thomas, M., Chanard, K., Sapkota, S.N., Rajaure, S., Shrestha, P., Ding, L., Flouzat, M. (2012). Convergence rate across the Nepal Himalaya and interseismic coupling on the Main Himalayan Thrust: Implications for seismic hazard. *Journal of Geophysical Research: Solid Earth*, *117*(B4).

Argus, D. F. and H. B. Heflin, Plate motion and crustal deformation estimated with geodetic data from Global positioning system, Geophys. Res. Lett., 18, 1973–1976, 1995

Avouac, J. P. (2003). Mountain building, erosion, and the seismic cycle in the Nepal Himalaya. *Advances in geophysics*, *46*, 1-80.

Banerjee, P., & Burgmann, R. (2002). Convergence across the northwest Himalaya from GPS measurements. *Geophysical Research Letters*, *29*(13), 30-1.

Bastos, L., Bos, M., & Fernandes, R. M. (2010). Deformation and Tectonics: Contribution of GPS Measurements to Plate Tectonics–Overview and Recent Developments. In *Sciences of Geodesy-I* (pp. 155-184). Springer, Berlin, Heidelberg.

Bettinelli, P., Avouac, J. P., Flouzat, M., Bollinger, L., Ramillien, G., Rajaure, S., & Sapkota, S. (2008). Seasonal variations of seismicity and geodetic strain in the Himalaya induced by surface hydrology. *Earth and Planetary Science Letters*, *266*(3-4), 332-344.

Bilham, R., Larson, K., & Freymueller, J. (1997). GPS measurements of present-day convergence across the Nepal Himalaya. *Nature*, *386*(6620), 61-64.

DeMets, C., Gordon, R. G., & Argus, D. F. (2010). Geologically current plate motions. *Geophysical Journal International*, *181*(1), 1-80.

Freymueller, J. T., Woodard, H., Cohen, S. C., Cross, R., Elliott, J., Larsen, C. F., Hreinsdottir, S & Zweck, C. (2008). Active deformation processes in Alaska, based on 15 years of GPS measurements. *Active tectonics and seismic potential of Alaska*, *179*, 1-42.

Gahalaut, V. K. (2009). Coulomb stress change due to 2005 Kashmir earthquake and implications for future seismic hazards. *Journal of seismology*, *13*(3), 379-386.

Gordon, R. G., & Stein, S. (1992). Global tectonics and space geodesy. *Science*, *256*(5055), 333-342.

Jade, S., Mir, R. R., Vivek, C. G., Shrungeshwara, T. S., Parvez, I. A., Chandra, R., Babu, DS., Gupta, V.S., Ankit., Ranjana, S.S.K & Gaur, V. K. (2020). Crustal deformation rates in Kashmir valley and adjoining regions from continuous GPS measurements from 2008 to 2019. *Scientific reports*, *10*(1), 1-11.

Jouanne, F., Awan, A., Madji, A., Pêcher, A., Latif, M., Kausar, A., Mugnier, J.L., Khan, I & Khan, N. A. (2011). Postseismic deformation in Pakistan after the 8 October 2005 earthquake: Evidence of afterslip along a flat north of the Balakot-Bagh thrust. *Journal of Geophysical Research: Solid Earth*, *116*(B7).

Jouanne, F., Mugnier, J. L., Pandey, M. R., Gamond, J. F., Le Fort, P., Serrurier, L., Vigny, C & Avouac, J. P. (1999). Oblique convergence in the Himalayas of western Nepal deduced from preliminary results of GPS measurements. *Geophysical Research Letters*, *26*(13), 1933-1936.King, R.W., and Bock, Y., (2005). Documentation of the GAMIT GPS Analysis Software Release 10.2, Report. *Mass. Inst. of Technol., Cambridge, Mass.*

Kundu, B., Yadav, R. K., Bali, B. S., Chowdhury, S., & Gahalaut, V. K. (2014). Oblique convergence and slip partitioning in the NW Himalaya: Implications from GPS measurements. *Tectonics*, *33*(10), 2013-2024.

Larson, K. M., J. T. Freymueller, and S. Philipsen, Global plate velocities from the Global Positioning System, J. Geophys. Res., 102, 9961–9998, 1997.

McCaffrey, R. (2008). Global frequency of magnitude 9 earthquakes. *Geology*, *36*(3), 263-266.

McCaffrey, R. (2009). The tectonic framework of the Sumatran subduction zone. *Annual Review of Earth and Planetary Sciences*, *37*, 345-366.

Molnar, P., & England, P. (1990). Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg? *Nature*, *346*(6279), 29-34.

Ni, J., & Barazangi, M. (1984). Seismotectonics of the Himalayan collision zone: Geometry of the underthrusting Indian plate beneath the Himalaya. *Journal of Geophysical Research: Solid Earth*, *89*(B2), 1147-1163.

Schiffman, C., Bali, B. S., Szeliga, W., & Bilham, R. (2013). Seismic slip deficit in the Kashmir Himalaya from GPS observations. *Geophysical Research Letters*, *40*(21), 5642-5645.

Seeber, L., & Armbruster, J. G. (1981). Great detachment earthquakes along the Himalayan arc and long term forecasting. *Earthquake prediction: an international review*, *4*, 259-277.

Stevens, V. L., & Avouac, J. P. (2015). Interseismic coupling on the main Himalayan thrust. *Geophysical Research Letters*, *42*(14), 5828-5837.

Y, Li. (2020). Geodetic observation and modelling of fault deformation in the Tibetan Plateau (*Doctoral dissertation, Université Côte d'Azur).*

Received: 16th March, 2022
Revised Accepted 23rd March, 2022