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Summary and Conclusion
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The Himalayan arc is the product of collision of the Indian and the Eurasian plate onset at ~ 55 Ma (Gansser, 1964; Molnar and Tapponnier, 1975; Valdiya, 1980; Nakata, 1972; 1986; Nakata et al., 1984; Thakur, 1993; Srikantia and Bhargava, 1998; Jain et al., 2002, 2005). The compression that was responsible for the Indian–Asian collision and resultant formation of Himalayan orogeny, though subdued, has not yet ceased (Nakata, 1989). These two tectonic plates collide at geologic and geodetic convergence rates of 30–50 mm/yr (Ader et al., 2012). Crustal shortening during this collision was largely accommodated by south-directed deformation, tectonic transport and thrusting throughout the 2400 km length of the Himalayas (Searle et al., 1987). Many active faults and neotectonic features have been reported (Valdiya, 1992; Bilham, 2004) that have generated major and great earthquakes (Ambraseys, 2004; Philip, 2006). The Kashmir basin situated in north-western Himalaya has NW-SE trend with strike length of about ~145-150 km and width of ~45-50 km.

The Intermontane Basin situated in the NW part of the Himalayan orogenic system is at ~100 km distance from the deformation front of the Himalaya and is a suitable location to analyze the tectonic structures and their seismic behaviour. Faults are one of the most common geological structures crucial for earthquake studies in the seismically active zone. Several studies of the Mw 7.6 October 05 Muzafferabad earthquake (Avouac et al., 2006; Gahalaut, 2006; Parsons et al., 2006) have suggested increase in the static stress towards northwest and southeast of the rupture zone, which means increase in the earthquake vulnerability of Kashmir Basin. Therefore, the tectonic lineaments which have more relevance to the faults in the region, other than the better-known thrusts like Panjal thrust (PT)/Main Central thrust (MCT), Murree thrust (MT)/Main Boundary thrust (MBT), Himalayan frontal thrust (HFT), Riasi thrust (RT) and Balakot Bagh fault (BBF) vulnerable to potential failure should be delineated, to assess and reduce the earthquake threat. Thus, the tectonic structures and their associated tectono-geomorphic features were mapped to infer the tectonic deformation in Kashmir Basin. In this regard, identification of morphostructural lineaments in the seismically active area provided useful data to interpret seismic
behaviour and deformation scenario in and around Kashmir Basin situated in Seismic Zone V. Besides, being present in seismically active zone, the basin floor covered with Karewas deposits (generally made of sand, silt, clay, laminated clay, conglomerates, lignite beds), has been investigated for the soft-sediment deformation structures. These are structures formed in unconsolidated and cohesionless sediments during deposition or shortly after deposition (Lowe, 1975; Owen, 1996, Owen et al., 2011). These are a record of processes during a deformational event which influenced unconsolidated sediments at or near the contemporary surface prior to, or shortly after burial (Leeder, 1987, Bhattacharya and Bandyopadhyay, 1998). They are linked to various causes (Owen et al., 2011) such as earthquakes (Jones and Omoto, 2000; Moretti and Sabato, 2007; Kang et al., 2010), storm waves (Molina et al., 1998; Chen and Lee, 2013), and tsunamis (Alsop and Marco, 2012). All kinds of earthquake-induced soft sediment deformation structures are called as ‘seismite’ (Seilacher, 1969). The purpose was to determine different types of deformation structures in Karewas deposits, interpret the triggering mechanism and the possible paleo-earthquake magnitude, and to examine importance of these structures in regional tectonics.

Moreover, morphotectonics analysis was carried out catchment wise which is considered as a tool to reveal the intensity of tectonic activity in the tectonically active areas (Wells et al., 1988; Rhea, 1993; Krzyszkowski and Stachura, 1998; Merritts and Vincent, 1989; DerBeek et al., 2000; Lagarde et al., 2000; Raj et al., 2003; Jamieson, et al., 2004; Slingerland and Smith, 2004). Geomorphic indices of active tectonics like hypsometric integral, hypsometric curve, drainage basin asymmetry, mountain front sinuosity and stream-length gradient index etc. are utilized as measure of active tectonics (Keller and Pinter, 1996; Sinha-Roy, 2002). Geomorphic indices have been developed as basic reconnaissance tools to recognize areas experiencing rapid tectonic deformation (Bull and McFadden, 1977). Thus, the geomorphic indices of active tectonics and most of morphometric parameters were applied to assess active tectonic behavior in relation with morphostructural lineaments. In addition to these aspects, the morphometric analysis and drainage characteristics has been applied which offers a quantitative description of basin geometry to understand initial slope or inequalities in the rock hardness, structural controls, recent diastrophism, geomorphic and geological history of drainage basin (Strahler, 1964). Drainage features mostly
stream capture and beheaded streams are investigated for the identification of active fault traces (Schumm, 1977; Bloom, 1979). The other parameters utilized like longitudinal river profiles, sinuosity, cross valley profiles have been applied for interpretation of tectonic influence and has given better information related to subsurface structures. Morphometric analysis carried out has been also applied to assess the flood behavior and soil erosion risk because the unforgotten flood in September 2014 caused massive damage to the life and property particularly in the flood plains and in surroundings of Jhelum River. Due to harsh weather conditions, existence of steep slopes and high structural density (acting as weak planes) towards flanks of Kashmir basin, landslides which lead to huge devastation and loss of precious human life also occurred in September 2014 floods.

In addition to soft sediment deformation structures which were encountered in Karewas deposits spreading over floor of Kashmir basin, the periphery that is eastern and western flank mostly of hard rock’s of Kashmir basin were investigated keeping in view the mesoscopic structures. In this portion of the study, the first purpose was to identify and demarcate different kinds of brittle, ductile and brittle-ductile tectonic structures which were not identified yet in the area. The geometrical and kinematic analysis of minor/mesoscopic structures (e.g., folds, faults, joints and other deformational structures) was carried out to interpret the past tectonic behavior of the area. These are secondary structures formed after lithification in sedimentary or igneous rocks and during or after metamorphism in metamorphic rocks (Davis et al., 2012), records the conditions at the time of their formation. The orientation of these structural features has been used to uncover the information related to deformation history in rocks and to observe the stress field which caused variation in strain and geometry. The structures encountered during the field survey were analysed by their varied geometry and orientation diagrams to evaluate their spatial distribution, paleostress direction and calculation of crustal shortening in the deformed rocks of the area.

Taking all these facts in view, the present research was carried out using various structural and tectonic aspects like investigation of morphostructural lineaments, morphotectonic and morphometric analysis, identification and analysis of soft sediment deformation structures, and various types of minor structures.
The main conclusions made in the present study using the above aspects are given chapter wise below:

8.1. Morphostructural Lineaments: Implication to Seismotectonics and Regional Tectonics (chapter-3)

The current study can be utilized as a primary step to delineate tectonic structures like faults and it will be crucial of removing potential hazard of earthquakes in Kashmir basin situated in seismically active zone (Himalayas). The morphostructural lineaments were extracted by applying the edge enhancement filters (Laplacian and Sobel) and FCC images together with Digital Elevation Model (DEM) derived products like slope, aspect, shaded relief, drainage and elevation map. The DEM has an advantage of giving height values to each pixel which made interpretation easier in 3dimensional representation of geological structures. The output map contains a large number of lineaments which showed associated drainage anomalies and other morphological features. Drainage anomalies like stream capture, beheaded streams, and braided channels associated with subsurface structures are also very crucial in locating structures of active nature, were mostly found associated with lineaments in the area. Moreover, the topographic profiling across the lineaments have supported the existence of faults by highlighting fault scarps, valleys, steep slopes, and subtle benches etc associated with subsurface geological structures. The other evidences used to support the existence of faults were alignment of springs and damming of streams along the faults, were also encountered at a number of places.

The lineaments of geological origin which are identified shows dominance in NW-SE direction with higher concentration towards the flanks of Kashmir basin. Analysis of lineament density distribution has shown maximum concentration of lineaments about 70% on Pir-Panjal side (western flank or southwestern division) which gives hint towards the uplift of SW side as compared to NE side of Kashmir Basin. Moreover, these delineated structures shows maximum resemblance of direction with the direction of regional tectonic structures like Panjal thrust (PT)/Main Central thrust (MCT), Muree thrust (MT)/Main Boundary thrust (MBT), Balakot Bagh fault (BBF) and Riasi thrust (RT) surrounding mainly western side of the Kashmir basin. Furthermore, the drainage development on western flank and flow of
Jhelum River from southeast to northwest in eastern half of Kashmir basin supports NE tilt of Kashmir basin attributed to uplift of Pir-Panjal range.

In the field, several lineaments have been recognized with associated linear features like straight stream channels, linear ridges, and steep slopes, are expression of tectonic faults. One of the new fault identified named as Tosamaidan Fault (TF) by using geomorphic anomalies like damming of stream channel and clear fault trace with least obliteration due to erosion was present in hard rock, is yet to confirm in the field because of the field restrictions. The strike length was possibly more than 25 km, with strike if extended NW matches with Balakot Bagh fault (BBF) source of devastating Kashmir earthquakes in 2005 Mw (7.6). Gulmarg Fault (GF) with NW-SE strike has approximate length of 20 km associated scarp, drainage anomalies, and back tilting along the strike direction at one place and needs more field evidence. There are some linear geological features difficult to locate because surface erosional processes have obliterated their expression towards basin floor covered mainly by alluvium. Thus, satellite data and DEM with 3D advantage can be applied to delineate structural features (faults) of tectonic importance with an advantage of earthquake hazard assessment. The newly identified faults and regional tectonic structures surrounding the basin have same NW-SE trend and shows concordance with the NW-SE distribution of earthquake zones. It confirms that these lineaments with associated geomorphic anomalies and earthquake distribution pattern in the area is strongly controlled by the regional tectonic structures of area and are vulnerable to seismic hazard. The earthquake epicentre depth distribution elucidates the occurrence of shallow depth ∼4-24 km and high magnitude earthquakes are surrounding the Kashmir basin in NW-SE extension. Thus, existence of tectonic structures and historical seismicity record including damaging earthquakes in 1555, 1885 and 2005 in and around Kashmir Basin, gives an ample support to active deformation in Kashmir basin and its surroundings.  At last, we can conclude from the above observations that the ongoing collision of Indian plate and Eurasian plate has given birth to a system of faults and other geological structures, many of which are active today, as evidenced by deadly earthquakes like 2005 Kashmir earthquake Mw ∼7.6 and recently 2015 Nepal earthquake Mw ∼7.9 in Himalayan orogen. To mitigate the disasters of these devastating earthquakes in the Himalaya and the Kashmir basin requires knowledge and consideration of these active geological structures.
8.2. Morphotectonic and Morphometric Analysis: Implication to Tectonics and Natural Hazard (Flood and Soil Erosion Risk) Assessment (Chapter-4)

Drainage characteristics have offered a base to recognize variation in rock resistance, structural control, and hazard assessment of floods and soil erosion. Geospatial techniques have proved to be an efficient tool in delineation and updation of drainage. The updated drainage network has been applied for detailed morphometric analysis of 26 sub-basins of three catchments. The computation of morphometric characteristics reveals that all the three catchments show sixth order stream network, with dominance of first order streams in all the sub-basins. All the three catchment shows sub-dendritic to sub-parallel drainage pattern with fine to moderate drainage texture in sub-basins lying close to Pir-Panjal range. The drainage density shows a decrease from the southwest (Pir-Panjal Range) to northeast (flood plain) side. The zone beginning from SW side is identified as rocky uplands characterized by high, steep hard rock terrain with deep and narrow fluvial valleys, has shown higher concentration of geological structures. The high values of bifurcation ratio and drainage density observed in sub-basins on extreme hill side in SW zone indicates that the drainage has been influenced and shaped by strong structural disturbances, impermeable subsurface material, and mountainous relief. The sub-basins of middle zone shows medium drainage density are covered by tilted lower and upper karewas corresponding to wide and gently sloping pediments lies between high uplands and flood plains. The third zone is a flood plain zone characterized by wide spread alluvial deposits brought by streams from uplands are showing very low drainage density. The drainage density variation elucidates that the sub-basins having impermeable sub-surface material have higher drainage density while as the sub-basins of alluvial part shows low drainage density which is due to permeability and high infiltration capacity. Higher drainage development towards western flank and little deviation in logarithm plot of stream number vs. stream order indicates recent uplift which corroborates the recent uplift of Pir-Panjal range. The mean stream lengths of stream increase with the increase of the order. Smaller mean stream length was observed in higher order streams, this deviation from its general behaviour may suggest that the overall terrain is characterized by high relief and/or moderately steep slopes, underlain the varied lithology and has faced probable uplift across the basin. Elongation and circulatory ratios indicates that most of the sub-basins and all the three
catchments as a whole have elongated shape can be due to tectonically active nature of the area. Thus, thorough investigation of the drainage pattern and the evaluation linear, areal and relief aspects clearly highlighted that the drainage characteristics are noticeably different for different lithologies. The unusual appearance of drainage network associated with lineaments at many places has given hint to the presence of subsurface structures supported by calculation of geomorphic indices and other parameters like longitudinal profiles, river sinuosity etc.

Geomorphic indices were computed in GIS environment and were found efficient tool to analyze the influence of active tectonics in the area. These indices were applied as reconnaissance tool to identify geomorphic anomalies associated with morph-structural features, which are useful to evaluate relative tectonic activity. This is particularly valuable in Intermontane Kashmir basin because of its location in seismically active zone of the Himalaya. A total of seven geomorphic indices were utilized: the stream-length gradient index (SL), basin asymmetry factor (Af), hypsometric integral (Hi), valley floor width to valley height ratio (Vf), drainage basin shape index (Bs), and mountain front sinuosity (Smf); these indices were combined to assess relative tectonic index (Iat). The study area was divided into four classes of relative tectonic activity (class 1 = very high, class 2 = high, class 3 = moderate, and class 4 = low) based on the value of Iat. The total area composed of class 1 (Iat) with an area of about 336.1747 km$^2$ (15.07 %), class 2 (Iat) with an area of about 524.7234 km$^2$ (23.53 %), class 3 (Iat) with an area of about 633.6465 km$^2$ (28.41%), and class 4 (Iat) with an area of about 735.1791 km$^2$ (32.97%). Based on the calculated Iat values, more than half of the area falls in Class 1 and 2 i.e., very high to high tectonic activity. Class 1 and 2 of relative tectonic activity is found in the southwestern and middle part indicative of most active tectonics associated with the uplift of Pir-Panjal range in the area. High values of stream length gradient (SL), hypsometric integral (Hi) and basin shape (Bs) were observed very high in the area which showed evidences of faults and folds. Presence of prominent fault scarps of tectonic origin, straight valleys, deep narrow valleys and deformed deposits corresponds to these class 1 and 2, are dominantly present in upstream side. The mountain front sinuosity (Smf) values suggest that mountain fronts of eastern flank of Pir-Panjal are tectonically active in nature, and the valley floor width to height ratio (Vf) value suggests a high rate of incision associated with tectonic uplift which gives
birth to deep and narrow valleys in upstream area towards Pir-Panjal range. The ‘U’ shaped valleys were encountered towards basin floor indicating continuous widening of river banks. Lastly, the synclinal alluvial floor of Kashmir basin may contain structures but comes in Class 4 of relative tectonic activity class (Iat) i.e., tectonically inactive class, which may be attributed to the continuous surface processes which vanished the structural express and sculptured the area. In the area, most of faults have NW-SE direction; the values of Iat are high and low tend to develop in this direction. The result of the present study confirms the applicability of Iat calculation by using geomorphic indices for assessing tectonic activity.

Moreover, the longitudinal profiles when showing any anomalous behavior can be attributed either to the presence of structural element or to the lithological transition. The longitudinal profiles of some main streams of sub-basins at some portions are highly concave upward suggesting the tectonically active nature of the area. Main steps and/deviation found in longitudinal river profile can be either related to the activity of recent tectonic lineaments or lithological change observed in the area. Some of the streams showed smooth longitudinal profiles attributed to either to same lithology or less structural disturbances. River profiles also showed an abrupt change at the junction of steep slope (Pir-Panjal range side) and the Karewas plateau attributed to lithological transition. In the area, most of the abnormal changes observed in the river profiles are mostly found at places of lineament intersection. The stream course is controlled by slope and is a significant parameter to analyze the channel sinuosity, higher the slope straighter will be stream course with higher velocity. Channel segments were observed more sinuous in the middle and lower reaches where thick column of Karewas and alluvium is present and the underlying hard rocks are not exposed in the river bed. In the upper reaches, sinuosity is mostly low which can be attributed to high stream gradient and high stream power. In the upstream side at some locations, the streams show bends in their path due to presence of structures of tectonic significance. As a result, where rivers in upper reaches showed an intersection with mapped lineaments, their influence was clearly observed from higher sinuosity and channel morphology. Moreover, lineament analysis performed has clearly shown that streams at many places follow the path of lineaments in the area. It can be concluded that streams at many spots are structurally controlled and others are carving out their own path. Assessment of rose diagram of
lineaments has shown NW-SE trend which resembles with the trend of major geological structures and drainage anomalies present in the region. It confirms that these lineaments with associated abrupt deflection in drainage courses and other drainage anomalies are strongly controlled by the regional tectonics of the area.

Lastly, the study demonstrates the usefulness of drainage behavior in categorizing the catchment in terms of flood and soil erosion struck areas. The low drainage density, low frequency, slower runoff, higher overland flow and more human intervention makes low lying areas prone to floods (Jammu & Kashmir flood 2014) during heavy rainfall. The result elucidates that in intense rainfall conditions, there are chances of greater runoff in sub-basin SF 1, 2, 5, 6, 7 and 8 which results floods in downstream plainer area. The factors besides intense rainfall include uncontrolled construction particularly along river banks, floodplains and outlet stream channels without considering flood consequences. The downstream area of SF 10, 12, 13, 14 and in the same way other low lying areas were observed seriously influenced in September 2014 Kashmir flood and may be considered as one of the severe natural hazard event in the history. The 2014 Kashmir flood has affected people, settlement, and infrastructure in the area. Apart from direct damage by floods, the plainer low lying areas faced siltation hazard which caused serious damage to agriculture, infrastructure and other aspects of life. The effective measures to control floods in low lying areas are to reduce the floodplain encroachment, chaotic construction on river banks and outlet, and maintenance and widening of drainage channels. In the area, early flood warning system and adaptation of flood forecasting techniques should be applied to reduce and mitigate the disaster caused by floods.

In contrast, the hilly areas having high slope, structural weak planes, loose upper soil cover (driving rapid physical erosion) and above all indiscriminate human intervention are more prone to soil erosion during harsh weather conditions. Ranking of sub-basins reveal that DS1, DS2 and DS6 in hilly terrain fall in highest rank and are more vulnerable to soil erosion risk. Spatial technology showed application to estimate natural hazards possible due to soil erosion and also minimizing the siltation of the plainer sub-basins that causes serious problems as faced by recent flooding (Sept. 2014) in Kashmir basin. The chances of soil erosion are due to presence of weak planes (structural features) and water seepage through these weak planes acts as lubricant in the hard rock terrain to enhance the movement. On the other hand,
siltation (mud) problems are more in lower plainer sub-watersheds with higher length of over land flow as was faced in 2014 Kashmir flood. Thus, results indicate that the morphometric analysis can be effectively used for categorization of catchments, soil and water conservation and natural resources management at the watershed level. Therefore, immediate attention towards soil and water conservation measures is required to preserve the land from further erosion and to reduce natural hazards.

8.3. Soft-Sediment Deformation Structures: Implications to Triggering Mechanism and Paleoearthquake Magnitude (Chapter-5)

The Intermontane Kashmir Basin containing Plio-Pleistocene deposits with a dominance of beds of different lithologies generally made of sand, silt, clay, laminated clay, conglomerates, and lignite beds; is present in seismically active zone in NW Himalaya. The various kinds of soft-sediment deformation structures observed include load structures like load casts, flame structures, ball-and-pillow structures, Pseudonodules, water-escape structures like dish and Pillar structure, water escape cusps, soft sediments intrusions like clastic dikes and sills, and other deformation structures like convolute bedding/laminations, disturbed laminites, folds and/or slump structures and synsedimentary faults in the Karewas deposits.

The deformation mechanisms and triggering forces of these soft sediment deformation structures have shown a relationship with those known in the literature: 1) load structures occurred due to gravitational instabilities associated with density contrast or uneven loading; water escape structures are related with dewatering, soft-sediment intrusions are associated with injection of liquidized sands into surrounding layer, ductile deformation gave birth to disturbed laminites, gravitational instabilities related with inverse density gradients originated convolute beddings/laminations, slumps are related with gravitational downslope movements, and when the pore pressure is not enough to liquefy the sediments, brittle deformation takes place in the form of synsedimentary faulting. Regional geological scenario and field validation corroborates to seismicity as the most possible triggering mechanism for SSDS in active collision zone in Himalaya rather than the influence of storm activity or deformation related to sediment loading; thus are resultanty inferred as seismites.

The area under investigation has geological and earthquake record related to tectonics of Himalayan thrust system. The soft sediment deformation structures
monitored shows the size and shape similarity to those observed in seismites, and the Karewas sediments with sandy lithology when exposed to earthquakes shows liquefaction prone character. Moreover, the occurrence of soft sediment deformation structures between undeformed sedimentary layers and their areal extent indicates that these structures were as a result of devastating seismic events in the area. Presence of soft sediment deformation structures supported by several lines of evidence reveals that seismic shocks associated to the past seismic activity were the most possible triggering mechanism of these structures in the Karewas deposits of Kashmir basin.

These soft sediment deformation structures with seismic shocks as triggering mechanism can be believed due to relatively large earthquake in past with its epicenter somewhere located in the Karewas basin. Thus, on the basis relation between these seismites and proximity of faults found in the area, it can be assumed that an earthquake of magnitude greater than 5 has struck in the past to the Kashmir basin.

8.4. Structural (Mesoscopic) Study (Chapter-6)

Tectonic structures of meso-scale observed are folds, joints, mullions, boudinage structures crenulation cleavages, fracture cleavage and shear zones, revealed that the area has undergone a local tensional as well as compressional stresses related to the regional one. The investigation for mesoscopic and others structures postulated that the rocks were affected by NE-SW compressional stress (shortening) and shows evidence of latter dextral shear movements.

Presence of highly jointed rocks with systematic, conjugate, through going, and non-systematic joint sets indicate that the area has gone through intense tectonic deformation and are most probably the youngest structures utilized to elucidate paleostress orientation of minimum principal stress ($\sigma_3$) perpendicular to which is development of joints. The area shows dominance of two joint sets with an orientation of NNE-SSW, WNW-ESE, with subordinate NW-SE trending joints sets which were most probably product of $\sigma_3$ which was oriented NNW-SSE, ENE-WSW, and NE-SW respectively. The variation in orientation of the $\sigma_3$ in different joint sets can be attributed to fault-related and fold-related joints grown in different deformation stages in the whole area. An acute and obtuse bisector for the dominant joint planes
corresponds to the directions of maximum ($\sigma_1$) and minimum ($\sigma_3$) principal stresses respectively. The acute and obtuse bisectrix are obtained from stereographic plots by counting along the great circle are acute and obtuse angles between joint planes. The orientation of an acute bisectrix is 53°±5 i.e., NE-SW, while as an obtuse bisectrix obtained has an orientation of 162°±5 i.e., SSE-NNW. Occurrence of conjugate joints with symmetrical fracture planes i.e., conjugate direction makes low angle with the principal stress orientation ($\sigma_1$) indicates their development in compressive stress field. Thus, joints which were developed perpendicular to minimum principal stress ($\sigma_3$), highlighted minimum principal stress ($\sigma_3$) with an orientation of NNW-SSE and that of maximum principal stress ($\sigma_1$) with an orientation of NE-SW which is the direction of maximum compression in the Kashmir Basin.

Calcite and quartz veins which develops just like joints except filled subsequently by precipitated minerals were identified and analyzed. Orientation of veins plotted on rosette diagram shows dominant trend in NNE-SSW, NW-SE, and N-S direction, similarity with joint orientation. Existence of en-echelon veins in limestones and other rocks types gives an indication of dextral shear sense, which is also highlighted by presence of z-shaped folds in the lift limb of meso-macroscopic folds in western flank of Kashmir Basin. Moreover, multiple generation veins were observed by cross cutting relation at different angles with evident displacement in earlier generation veins. Horst and reverse fault formation in veins can be related to existence of both tensional and compressional stresses prevailing after the vein formation. These reverse faults were mostly encountered in thick solitary veins, and the micro-veins (brecciated) observed are found parallel to veins were possibly reactivated by jointing.

Pitch-and-swell structures and boudinage development are also observed more commonly in slates and are less commonly found in limestones. The reason for this is based on competency of boudinage layer and bounding surfaces, the calcite vein in limestones shows possibly same competency to those of underlain and overlain limestone beds. Boudins found in the area were developed in quartz and calcite veins in enclosing slates and limestones by extension in ductile shear zone. In the area, pitch-and-swell structures were also observed in slates with presence of scar folds developed by flow of host ductile layer towards zone of separation, causing localized
bending. The boudins axis or neck lines are observed at some places parallel and at some places perpendicular to the fold axis in the area. Folds analysis postulated NE-SW $\sigma_1$ direction and boudins axis showed NW-SE trend i.e., parallel to fold axis and at some places shows NE-SW trend i.e. perpendicular to fold axis. The direction of $\sigma_1$ was observed 40-50° (roughly NE-SW direction), $\sigma_2$ in 320-350° (NW-SE direction) and $\sigma_3$ in 240-260°.

Crenulation cleavage development was observed in metamorphic rocks with presence of ‘S’- and ‘Z’-shape geometry on right and left limb of fold, indicates asymmetrical crenulation cleavage parallel to axial surface of bigger fold. In the present study, asymmetrical crenulation cleavage is observed with a presence of folds with S- and Z-geometry. These minor folds are developed by overall layer-parallel shortening before the onset of significant buckling and are initially symmetrical with an axial surface perpendicular to the direction of layer-parallel shortening. The crenulation cleavage appearance and formation can be related to D2 deformation and the associated shear displacements along the cleavage planes might have developed during latter stage of D2 or in D3 deformation.

8.5. Structural Analysis of Folds: Implications to Crustal Shortening and Paleostress Analysis (Chapter-7)

The detailed fold profile geometry analysis of the mesoscopic folds has been carried out with an aim to identify the possible kinematics and mechanism for fold development in the Kashmir Basin with complex structural disposition in NW Himalaya. The analysis of these folds encountered in different types of rocks revealed that the area has gone through at least three phases of deformation that is D1, D2, and D3. The rocks of eastern flank of the Kashmir basin shows development of F1, F2, and F3 folds in which F1 folds were observed in a metamorphic rock like Phyllite of Cambrian age with associated pinch-and-swell and occasionally boudinage structures in extreme NE in dense forests which hindered there depth analysis. The F2 and F3 folds were observed in limestones of upper Triassic age, in which F2 folds are roughly E-W trending steeply plunging tight to close folds while as F3 folds in the form of chevron folds possibly N-S trending with sharp and acute hinges showing intense crushing. The fold analysis of western flank shows development of F1 folds that is in the form of ptygmyatic folds with mostly thickened hinges and thin limbs in quartz
veins observed in Dogra slate. In these F1 folds, amplitude/wavelength ratio was very high which cannot be alone by buckling. The variable amount of flattening was observed by the analyzing $t'\alpha/\alpha$ plots of these folds, which revealed that buckling was followed by compressive strain (post-buckling compressive strain) resulted in flattening and to some extent resulted into broken limbs with infrequent boudinage.

Thus, structural analysis elucidates existence of three phases of deformation i.e., $D_1$, $D_2$ and $D_3$ resultant of which gave structural complexity in the form of cleavage, jointing, folding, and thrusting in different rock types. $D_1$ and $D_2$ phase of deformation are observed mainly of ductile nature in the form of layer-parallel shortening and folds while as the $D_3$ phase recognized reveals mainly brittle nature with development of intense fracturing, jointing, and thrusting in the Kashmir basin. Thus, development of minor structures based on overprinting relationships can sequentially be placed into three possible structural stages: (i) layer-parallel shortening; (ii) folding; (iii) thrusting in the Kashmir basin situated in fold-thrust belt of Himalaya.

The geometric analysis of the folds on the basis of dip isogon method, and $t'\alpha/\alpha$ plots elucidates that the folds mainly highlights Class 1C geometry. The folds also showed sub-ordinate geometry of Class 1A, 1B, Class 2 and Class 3 folds observed from $t'\alpha/\alpha$ plots in the area. The $Z/X$ ratios were determined by comparing the $t'\alpha/\alpha$ plot with existing flattening curves for class 1C folds. The flattening with $Z/X$ ratio ranges from 0.2 to 0.9 for different folds indicating that the folds have gone through variable amount of flattening and that flattening followed buckling in most of instances. The folds of the area mainly showed tight nature based on interlimb angle.

Extension, stretch and quadratic elongation was computed using minor folds which showed that the folds range in apparent buckle shortening from 30% to 89% with most of folds having shortening values ranging between 45% and 75% (exclusive of layer parallel strain). The folds of Khanpora area which were formed by layer parallel compression shows shortening value $(e\%)$ of -73%. Thus, extreme shortening has been observed in $F_1$ generation folds of the area. The folds of Beru area show shortening of -34% and -50% for different generation folds. The parasitic folds showed higher shortening as compared to the host folds. The folds of Khajigund area which were observed in Lower karewas, shows estimated shortening value of -
87% and -89%. The extreme shortening measured in folds found near the pediment of Pir-Panjal range can be attributed to the softness of Karewas and recent uplift of Pir-Panjal range. The shortening value estimated for folds of Ganderbal area is -48% for F<sub>2</sub> folds i.e., second generation folds and -10% shortening in F<sub>3</sub> folds i.e., third generation folds.

The Paleo stress direction (σ<sub>1</sub>) applied for the folds development was inferred NE-SW oriented in the Kashmir basin. Besides, the NW-SE trending mesoscopic to macroscopic ductile and brittle-ductile shear structures signifies NE-SW horizontal bulk shortening, which has given birth to all these variety of structures in the Kashmir Basin. These structures were densely encountered towards periphery in different rock types, moreover presence of structures in basement rocks cannot be ruled out which lies below ~1300 m thick unconsolidated Karewas deposits showing wide distribution of soft-sediment deformation structures, faulting and folding of neo-tectonic origin in the Kashmir basin. Thus, presence of structures in marginal hard rocks and deformation of Karewas deposits indicates that Kashmir basin has actively taken part in tectonic deformation in past and continuing till today resultant from the Indian and the Eurasian collision.