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RESEARCH PAPER

Stress Pattern Simulation of Compressional Features of Potwar Region and Hazara Basin, NW Himalayas, Pakistan

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Abstract
The research is based on the numerical study of late Cenozoic compressional events of NW Himalayas, Pakistan. The study area lies in Potwar Basin and southern Hazara Basin bounded by north dipping Salt Range Thrust (SRT) and Panjal Thrust (PT) in south and north respectively. Four major thrusts i.e. Panjal Thrust (PT), Nathia Gali Thrust (NGT), Main Boundary Thrust (MBT) and Salt Range Thrust (SRT) are considered as major discontinuities in the study area. The main objective is to observe maximum principle stress (σ1) rotation along major discontinuities and to calculate total deformation. For this purpose, 2D finite element method (FEM) technique has been adopted and Ansys Workbench 19.2 is used, which provides the facility to simulate stress along major thrusts. Material properties i.e. density (2.5 - 2.75), Young's Modulus (70GPa, 100GPa) and Poisson's ratio (0.25) are used to calculate the possible results. Pressure (60MPa) is applied from north and remaining sides of geometry kept fixed. The results obtained show that the direction of maximum principle stress (σ1) is N-S but also rotates at discontinuities at different angles. At some segments along of major thrusts σ1 rotates 40-45 degree and at some points it becomes parallel to the fault plane. These rotations of σ1 are due to the change in material properties and fault angles. Strike slip movement has also been found along some segments of major thrusts.

Keywords: Stress Pattern, Cenozoic, Compressional Features, NW Himalayas, FEM.

Introduction

The study area is a part of regional tectonic setting of Indian Plate, NW Himalayas and comprised of series of thrust sheets propagated from north to south, started developing as a result of Indian- Eurasian Plate collision during Paleogene period (Searle et al., 1997). The study area includes Potwar Basin which contains sedimentary rocks from Pre-Cambrian to Pleistocene age and southern part of Hazara Basin which contains Pre-Cambrian to Eocene sediments (Kadri, 1995; Ahsan & Chaudhry, 2008). To the north of Panjal Thrust, metamorphosed hinterland is present (Baig & Lawrence, 1987) while to the south, Punjab Platform is separated from the basin by Salt Range Thrust (Fig. 1).

The present work aims to predict the stress pattern simulation along major discontinuities i.e. Salt Range Thrust (SRT), Main Boundary Thrust (MBT), Nathia Gali Thrust (NGT) and Panjal Thrust (PT) and to examine the rotation of (σ1 max) along these thrusts. To investigate the influence of applied stresses, 2D finite element method by using ANSYS™ Workbench 19.2 software was applied. For this purpose, calculations have been executed through static

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structural module of ANSYS™ Workbench. Material properties of different rock types such as density, poison ration, young's modulus etc. has been assigned to the model. Numerical results document the stress patterns of both Potwar and Hazara region in which maximum principle stress (σ1) oriented itself N-S direction. Rotation of maximum principle stress (σ1) along discontinuities is also dominant. Moreover, subjected area has been deformed in response to applied stresses under boundary and loading conditions. Displacement of thrusts from its current position is also dominant.

Geological Setting

Study area is the part of NW Lesser and Sub Himalayas of Pakistan (Fig. 1) which developed due to collision of Indian and Eurasian plates about 50 ± 10 Ma ago (Zheng & Wu, 2018). The collision between two major continental plates IP and EP thickens the crust and give rise to the development of Himalayan Mountain Range (Chatterjee et al*.,* 2013). The study area describes Hazara region in the south of Lesser Himalayas (Ghazanfar et al*.,* 1990) and Potwar Basin in Sub-Himalayas (Yeats & Lawerence, 1984). The Lesser Himalayan Zone occurs between the Main Central Thrust and Main Boundary Thrust (Fig. 1) and has experienced numerous stages of contraction (Schelling & Arita, 1991). It extends throughout in Kashmir, Kaghan, Hazara and Swat region covering thick pile of sediments (Ahsan & Chaudhry, 2008). Based on different rocks types, Lesser Himalayas constitute two distinctive zones, Northern metamorphic zone and southern sedimentary zone (Ghazanfar, 1993). Panjal Thrust isolates this discontinuity between sedimentary and metamorphic crystalline rocks. Metamorphic zone of Lesser Himalayas includes medium grade rocks restricted to biotite-garnet phase. Younger Cambrian granite intruded into Pre-Cambrian meta pelite-psammite sequence. This meta pelite-psamite rock sequence is overlain by younger rocks in major basins such as Hazara, Peshawar and Kashmir basins. In Hazara Basin, it is overlain by slates and phyllites (Ahsan & Chaudhry, 2008; Chaudhry et al., 1997; Ghazanfar, 1993).

Low to high grade metamorphic rocks of Precambrian and Paleozoic age is present in Peshwar Basin of metamorphosed hinterland (Ghazanfar, 1993). Thick foreland deposits of Cambrian to Eocene rocks are present between Panjal Thrust and Main Boundary Thrust (Ahsan & Chaudhry, 2008).

Likewise, Sedimentary region is characterized by Cambrian to Eocene rocks occur in range from Panjal Thrust in north to Main Boundary Thrust in south. It extends from Neelam Valley to Hazara region between Murree and Abbottabad to Cherat, Kalachitta and Kohat Ranges (Attock Hazara Fold and Thrust Belt) (Ahsan & Chaudhry, 2008). Moreover, lower part of lesser Himalayas constitutes Paleogene foreland basin sedimentary sequence (De Celles et al., 1998a).

Sub Himalayas is a part of Himalayan foredeep folded belt which is marked in north by Main Boundary Thrust (MBT) and to south by Salt Range Thrust (Ghazanfar & Chaudhry, 1999; Lillie et al., 1987). Sub Himalayas are composed of Neogene Sediments eroded from rising Himalayas and deposited in margin of foreland basin in front of mountain belt deposits (Parkash et al., 1980). Sedimentary rocks are dominant and covered one third part of study area and are limited to the north by Panjal Thrust. Two major locations for the distinction of rock units (i.e. sedimentary rocks and metamorphic rocks) are present along Panjal Thrust (PT) and Main Boundary Thrust (MBT) around apex of Hazara Kashmir Syntaxis (HKS).

More than 6 km thick sedimentation such as sandstone, siltstone, and conglomerates are accumulated in western Himalayan foreland (Jadoon et al., 2003). Interrupted and folded structure of Neogene sediments in foredeep include red molasse of Siwalik Group as well as Rawalpindi Group represent up-thrust like structure in Balakot-Muzaffarbad and Salt Range (Ahsan & Chaudhry, 2008). In Pakistan, Sub Himalayas subdivision includes Potwar Plateau, Kohat Plateau, Salt Range and Trans Indus Ranges (Yeats & Lawerence, 1984).

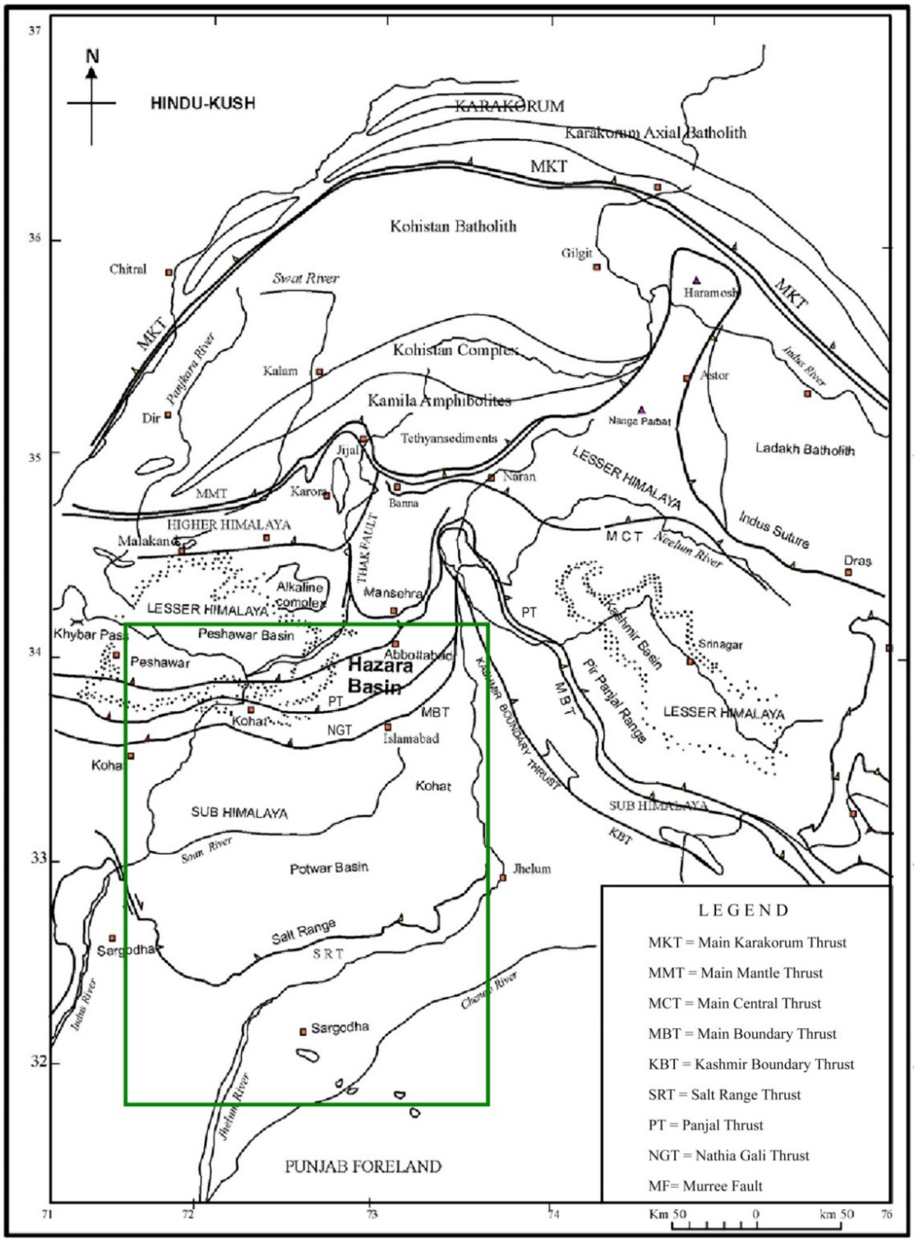

Figure 1. Tectonic map and major thrusts of study area (Ahsan & Chaudhry, 2008)

Data and Methodology

Finite Element Method (FEM) was adopted to perform stress simulation by using ANSYS™ Workbench 19.2. Finite element analysis is a computerized method of cumulative functions to operate in such a way to find the appropriate solution of given model through various processing parameters (Reddy, 1993 and Logan, 2017). It works on the principle of discretization in which geometry is subdivided into finite set of elements and nodes. Instead of solving the functions on entire body of model, discretization helps to solve the operation individually one each element (Fig. 2). Afterward, the solution is formulated by combining the equations of each finite element. Comprehensively, the solution of structural stress analysis typically allows to calculate the displacement at each node and stresses within each element, which is in equilibrium in response to applied loads and boundary conditions (Logan, 2017).

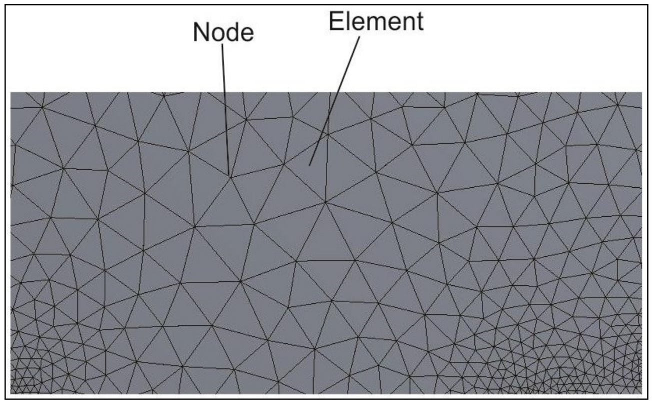

Figure 2. Basic triangular meshing in FEM model

Matrix method is numerically applied in finite element analysis to simply the formulation of each stiffness element equations.

Mathematical solved equation for matrix stiffness matrix is given below:

$$[K]\{D\} = \{F\} \quad (1)$$

Where K is total stiffness matrix (mostly square & symmetric), D is a displacement vector of unknown nodal & F is external load (Logan, 2017). Ansys workbench was used for static structural module.

Formulation of the Problem

Stress simulation along major thrusts in Hazara and Potwar region has been performed using the academic license of ANSYS™ 19.2 and plane stress-strain analysis has been adopted to calculate the appropriate solution of problem. Total four major thrusts i.e. PT (Panjal Thrust), NGT (Nathia Gali Thrust), MBT (Main Boundary Thrust) and SRT (Salt Range Thrust) have been included for stress pattern simulation of the study area where PT (Panjal Thrust) marks the boundary of metamorphic and sediment zones (Fig. 3).

Mechanical properties of these discontinuous strata have been assigned in engineering data. Average values of density, Young's Modulus and Poison ratio have been assumed for different lithologies (Table 1). Given that surface exposed variations in rheology between PT causes the major discontinuity between rocks of present model. Poison ratio has considered to be same for both domains (ν =0.25). The values of these mechanical properties have been extracted from literature (e.g. Afrouz, 1992).

Solution Processor

After upon, working mechanism has been moved towards solution processing parameters. Having assigned material properties to model, connections between contact and target bodies are generated. Frictional connections are distinct in their behavior and can significantly influence the solution of results. Based on given criterion, simulation has been proceeded by defining frictional connection type between fault discontinuities. The value of frictional coefficient is 0.1. Quadratic triangular meshing is selected for gridding the model in segments connected at nodes. Fine triangular meshing is generated where the fault boundary is curved. The area is assemblage of ~3626 contact elements and 7842 mid-nodes (Fig. 4).

Then, boundary and load conditions are applied on the model. As, the main source of stresses direction in NW Himalayas is assumed form north. Given the previous fact that pressure (MPa) is applied from north (negative y-axis direction) keeping x-axis is constant. Rest of three boundaries of mode are locked to fixed support. (Fig. 5). In this way, selected results for solution are undergone form different mathematical matrix equations and generate their appropriate solution of the problem.

Table 1. Mechanical properties of different lithologies.

Rock type	Density (ρ) (g/cm^3)	Young's Modulus (E) (GPa)	Poisson's Ratio ν	Bulk Modulus (Pa)	Shear Modulus (Pa)
Sedimentary	2.6	70	0.25	4.667×10^{10}	2.4×10^{7}
Metamorphic	2.75	100	0.25	6.667×10^{10}	2.8×10^{10}

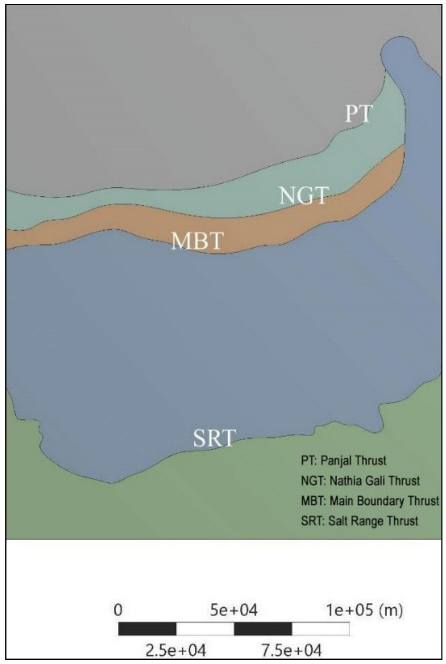

Figure 3. Geometry of study area showing major thrusts including PT (Panjal Thrust), NGT (Nathia Gali Thrust), MBT (Main Boundary Thrust) and SRT (Salt Range Thrust).

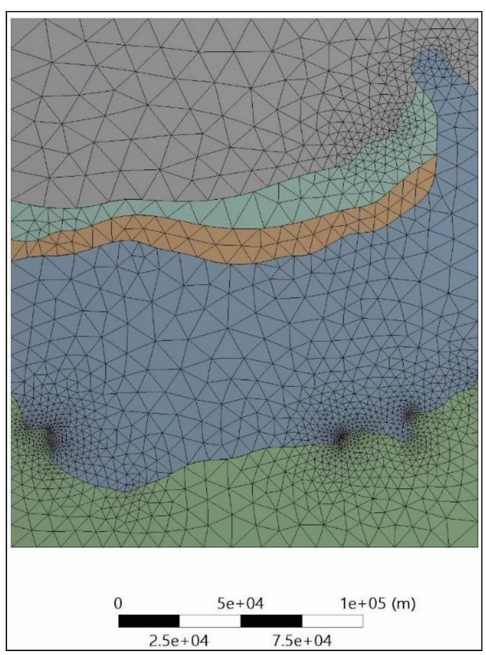

Figure 4. Model mesh with ~3626 contact elements and ~7842 mid-nodes

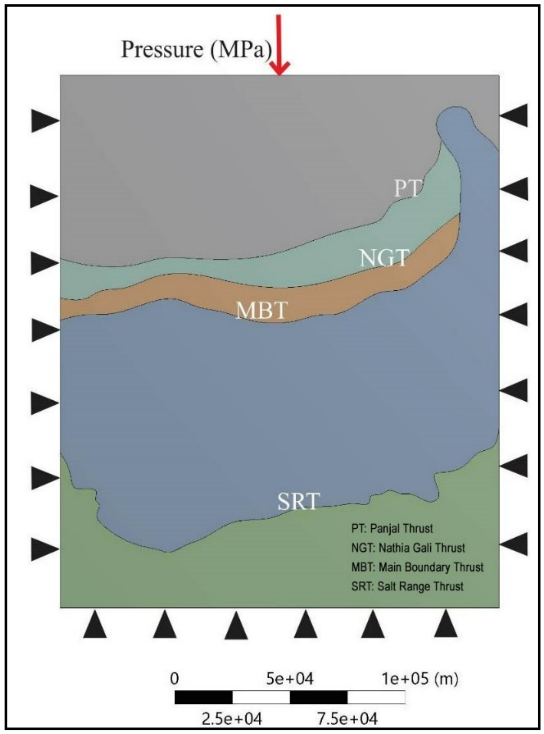

Figure 5. Geometry and boundary conditions used in FEM model. Top edge of model is subjected to load i.e., pressure (MPa) form north direction. Black triangles represent the fixed boundary edges

Results and Discussion

Simulated stress patterns

Figure 6 shows the result of simulated stress patterns in the study area. Applied stress from the north caused compressional regime of thrusts and induced principle stresses (i.e., maximum principle stress (σ1), intermediate principle stress (σ2) and minimum principle stress (σ3) in 2D model. General orientation of maximum principle stress (σ1) is aligned itself in N-S direction that portrays the present tectonics of Potwar and Hazara region, NW Himalayas, Pakistan. Moreover, NE-SW and NW-SE orientation of maximum principle stress (σ1) is also dominant. Horizontal orientation of (σ1) with vertical (σ2) describes the significant strike slip movement along some segments of thrusting. From north to south, (σ1) runs straight in medium having same material properties and marks first rotation at discontinuity present between different rheologies including metamorphic and sedimentary rocks along Panjal Thrust (PT) and at the apex of Hazara Kashmir Syntaxis (HKS) Along NGT and MBT, (σ1) persistently rotates and shows maximum deflection at some places as it aligned parallel to the strike of faults. This also suggests significant oblique slip component of the faults. Rotation along these faults has generally caused by the oblique/inclined geometry of thrust. After passing NGT and MBT, penetrating (σ1) set to align again in its previous N-S direction and shows no rotation due to same material properties. Along SRT, (σ1) comparatively shows less deflection with respect to MBT, NGT and PT. Moreover, Rotation of maximum principle stress (σ1) has also been found to be anticlockwise towards east and clockwise towards west of the model (Fig. 6). It is interesting to note that σ1 is not limited to SRT as it travels further into the south and can cause significant prospect of deformation. However, edge effect is dominant towards NW (top left of model) and cause rotation of (σ1).

The detailed study of maximum principle stress (σ1) and their rotation along thrust boundaries is subdivided the model into following segments.

Panjal Thrust and Hazara Kashmir Syntaxis

Figure 7 shows the pronounced stress patterns along Hazara Kashmir Syntaxis (HKS). Maximum Principle stress (σ1) penetrates the surface and orientated along both limbs of HKS. First rotation of σ1 marks at the apex of HKS. It articulates up to 45° degree rotation of (σ1) caused by the presence of two distinct medium (sedimentary rocks and metamorphic rocks). σ1 shows maximum deflection and align parallel to the eastern limb of HKS. Further, σ1 becomes NE- SW at the tip of PT in eastern limb of HKS.

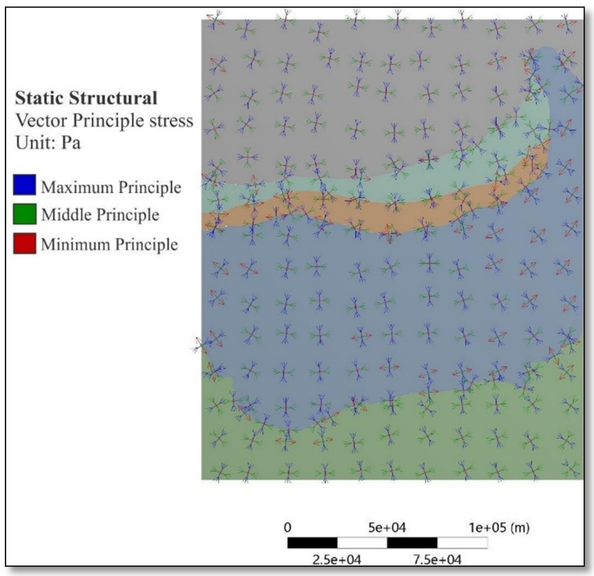

Figure 6. Simulated stress patterns of NW Himalayas, Pakistan

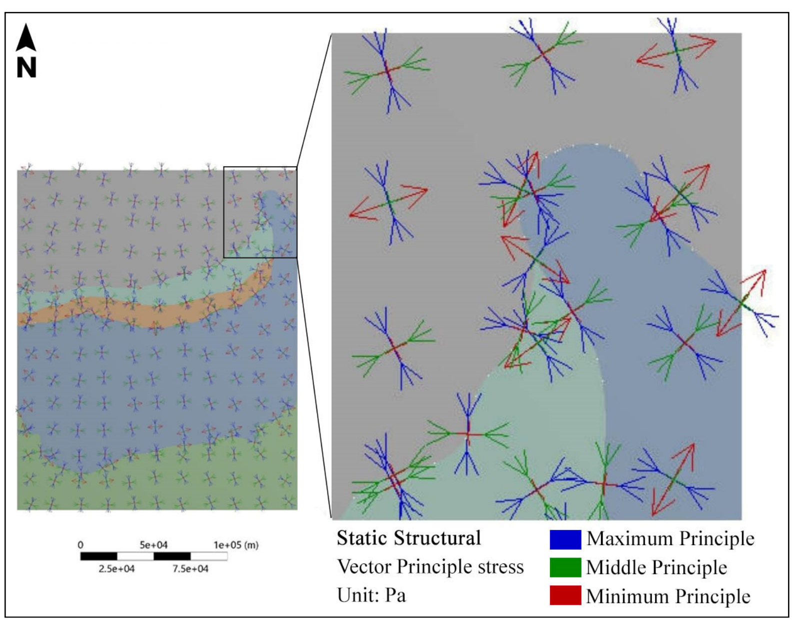

Figure 7. Eastern part of model shows stress patterns along Hazara Kasmir Syntaxis and Panjal Thrust

Figure 7 also illustrate the eastern part of Panjal Thrust at which very first slight rotation of σ1 is marked which is most probably due to change in material properties from sedimentary to metamorphic rocks. Further towards west, it aligns itself along the strike of fault.

Figure 8 shows the central part of Panjal Thrust (PT). Initially, position of σ1 is same as the direction of applied stress. At PT, change in material properties from sedimentary rocks to metamorphic rocks is caused rotation of σ1. Significant NE-SW and NW-SE orientation of σ1 is also present.

Figure 9 illustrate the principle direction of applied stresses along western Panjal Thrust (PT) from which σ1 moves straight toward south.

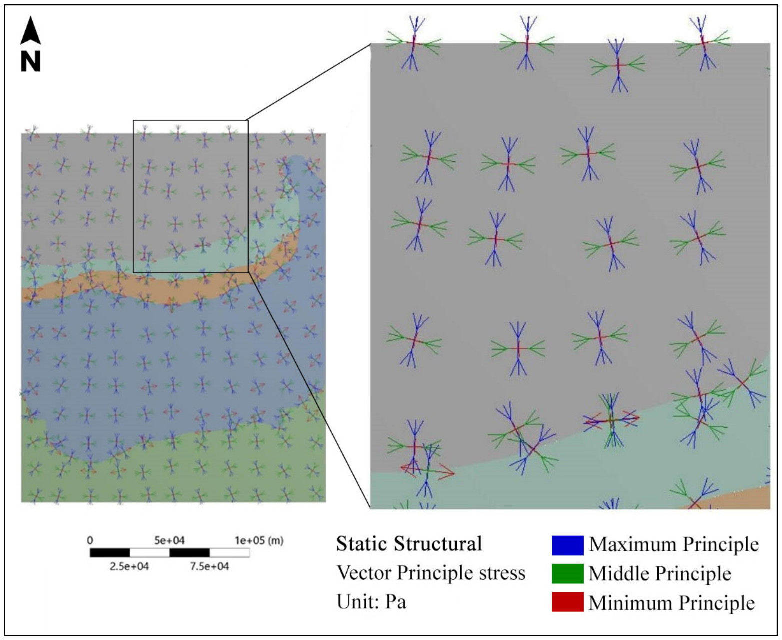

Figure 8. Central part of model shows Stress patterns along Panjal Thrust

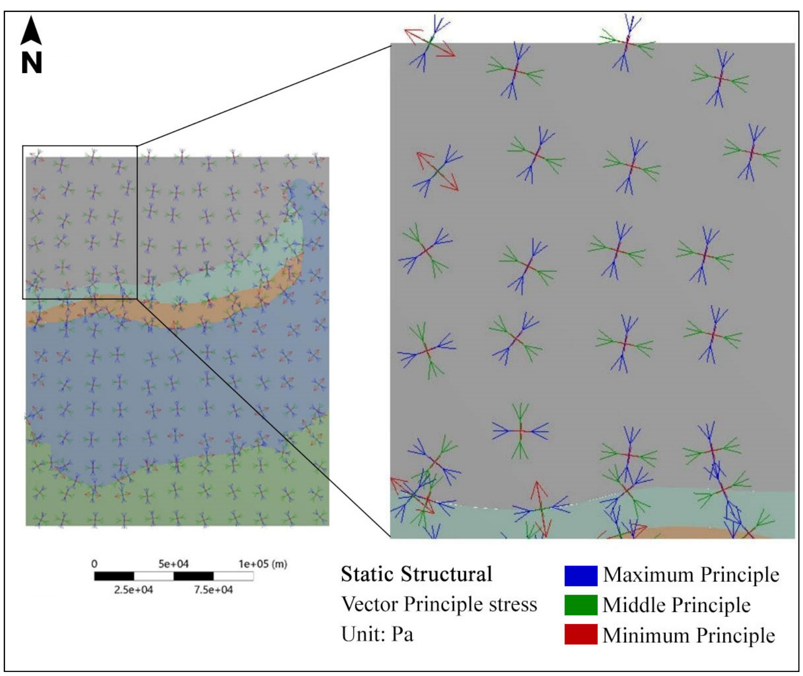

Figure 9. Western part of the model shows stress patterns along Panjal Thrust

At discontinuity along PT, it marks maximum deflection and becomes parallel to the fault plane. Whereas σ1 penetrates at low to high angle into the sedimentary rocks. Edge effect is dominant at the extreme western side of model (top left) and caused clockwise rotation of σ1

Nathia Gali Thrust and Main Boundary Thrust

Figure 10 describes the stress patterns in eastern part of Main Boundary Thrust (MBT) and Nathia Gali Thrust (NGT). The behavior of σ1 at both discontinuities is almost similar which is most likely due to the same material properties among fault boundaries. It is important to note that σ1 align at acute angle to fault plane after passing through major mechanical discontinuity (PT). But in this case no particular distance present between MBT and NGT and caused anticlockwise rotation of σ1.

Figure 11 shows the stress patterns in central part of NGT and MBT where σ1 persistently rotates along fault discontinuities. Along NGT, σ1 orientates NE-SW direction. This rotating σ1 along MBT passes through NGT shows significant strike slip component where σ1 align parallel to the strike of fault (east-west direction). This rotation is most likely due to the inclined or oblique pattern of fault.

Figure 12 show the stress pattern in western part NGT and MBT. The possible reason for the rotation of σ1 is inclined pattern of fault geometries. Along fault boundaries, the behavior of σ1 is multi directional either it is NE-SW or NW-SE direction. Some segments along thrust also marks strike slip movement of thrust.

Salt Range Thrust

Figure 13 illustrates the compressional features along Salt Range Thrust (SRT). By passing from PT, NGT and MBT, σ1 again align itself in its previous N-S direction because significant distance present between SRT and MBT. NW-SE orientated σ1 is also dominant due to decrease in the magnitude of applied stresses and fixed support.

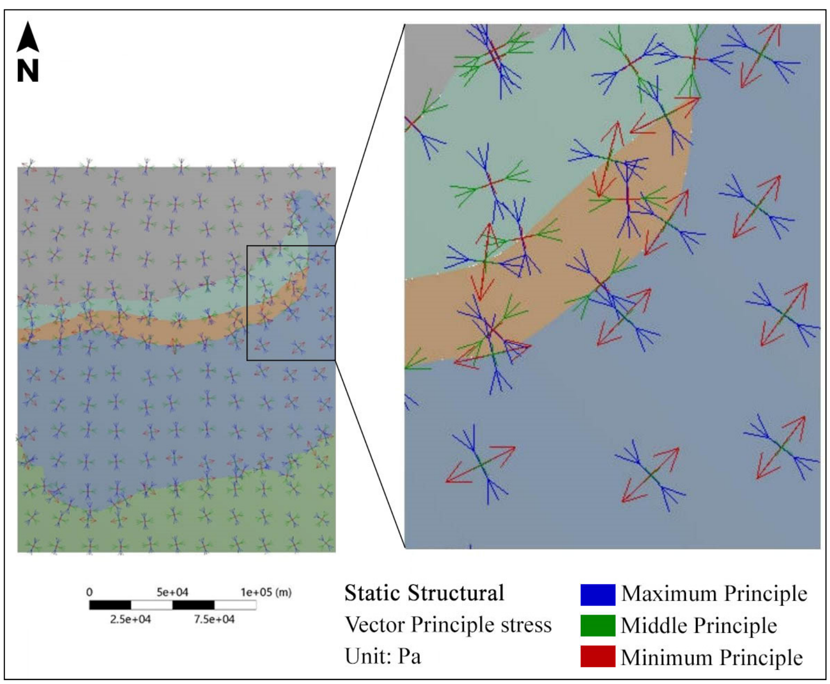

Figure 10. Eastern part of model showing stress patterns along NGT and MBT

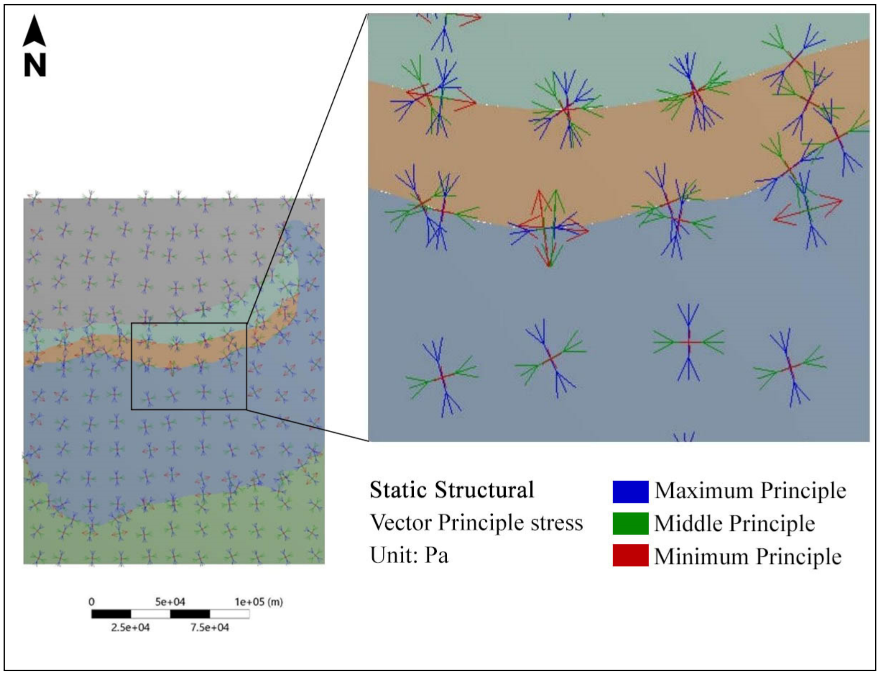

Figure 11. Central part of model showing the stress patterns along NGT and MBT

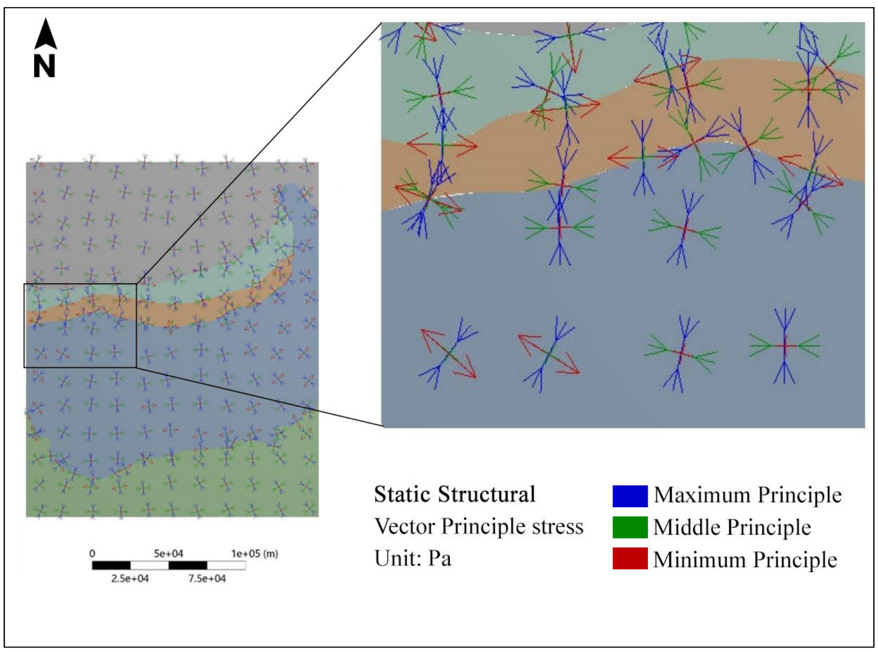

Figure 12. Western part of model showing the stress patterns along NGT and MBT

Along SRT, maximum deflection of σ1 has been acquired. Perpendicular alignment of σ1 changes its direction and becomes parallel to the fault boundary marks strike slip movement. In this case, the decreasing in the value of stress and oblique fault boundary of SRT caused the present alignment of σ1.

No significant rotation of σ1 occurs except where the geometry is oblique (Fig. 14). Slight rotation of σ1 is present but σ1 align perpendicular to the fault. Towards extreme west, σ1 becomes NW-SE which shows the direction of maximum crustal shortening (folding and faulting).

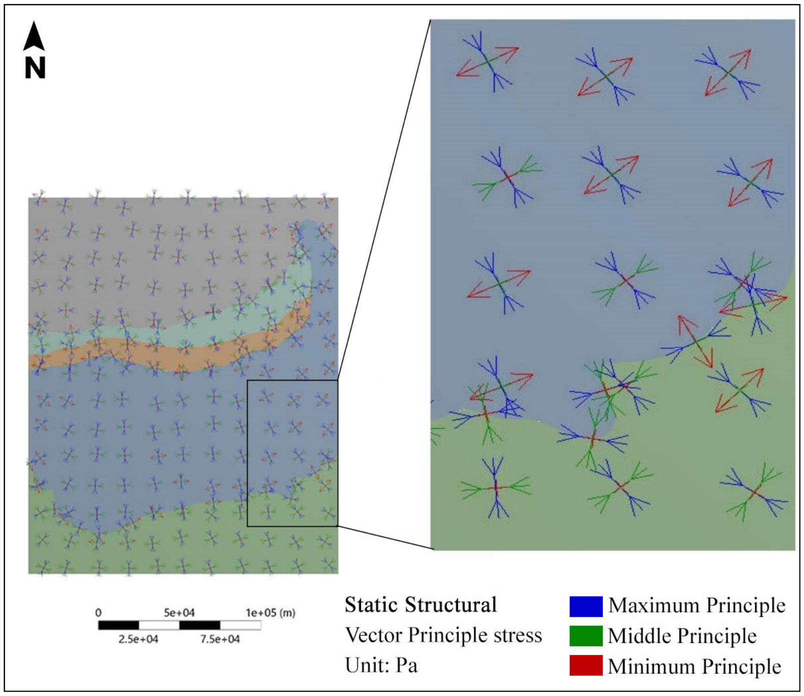

Figure 13. Eastern side of model showing stress pattern along SRT

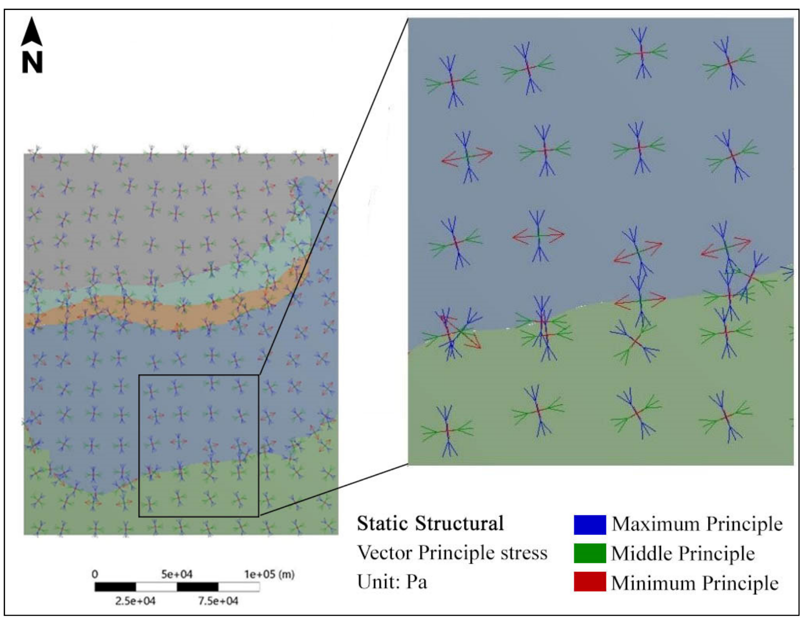

Figure 14. Central part of model showing stress patterns along SRT

It is interesting to note that σ1 further penetrates the Punjab Platform and describes that the stresses are not limited to SRT as it travels further into the south and can cause significant prospect of deformation.

Total Deformation

The area under subjected forces and boundary conditions is assumed to be reactivated in model which shows the different tectonic fashion in terms of deformation style. Style of deformation with decreasing amount of forces controls the behavior of actual geometry (Fig. 15).

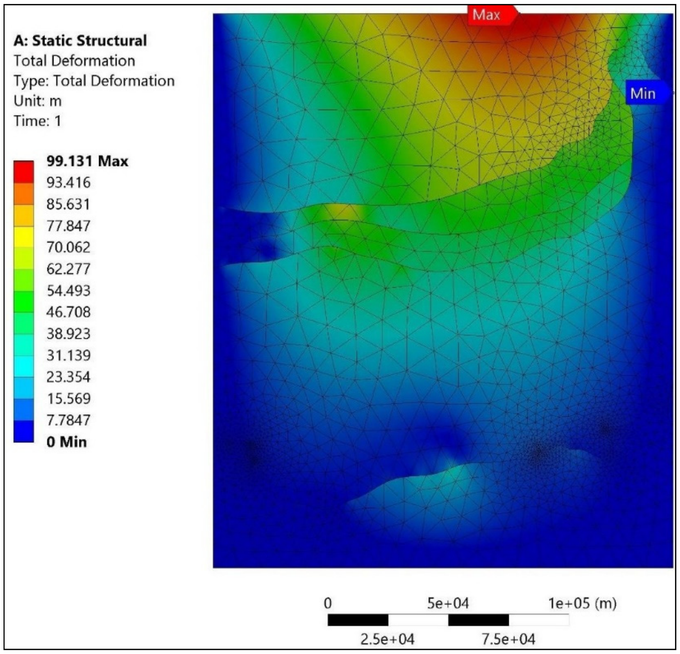

Figure 15. Shows total deformation of material under frictional contacts

It includes the deformation rate in terms of crustal shortening (folding and faulting). The area is not work under given time frame, but it describes the deformation /intensity rate in unit meters. Color bar shows the rate, corresponding to deformation against pressure of 60MPa has applied form north of the model (Fig. 5). Maximum deformation occurs proximal to the source of pressure i.e., at the top of model. Minimum deformation occurs at the terminating point of MBT towards eastern limb of Hazara Kashmir Syntaxis.

No major variations occur except below of PT towards west and middle portion of SRT. Friction contacts cause increase in deformation rate towards west of Panjal Thrust and middle of Salt Range Thrust (Fig. 15).

Discussion

Stress pattern analysis in study area is mainly controlled by regional tectonic setting of Potwar and Hazara region, NW Himalayas. In Potwar and Hazara region, stress patterns deduced from FEM is dominated by N-S alignment of maximum principle stress ($\sigma 1$) suggesting N-S crustal shortening. Compressive stress with NW-SE and NE-SW orientated $\sigma 1$ axis has also been observed in Potwar and Hazara region. Significant stress rotation of ($\sigma 1$) occurs along discontinuity present between different rheologies (Sedimentary and metamorphic rocks) caused by change in material properties. Stress rotations also occur along boundaries of inclined thrust pattern (Fig. 6). With the decreasing magnitude of pressure can also cause the rotation of ($\sigma 1$) (Pascal & Gabrielsen, 2001). According to Anderson, 1951, three types of faults are possible with respect to the orientations of stress axes. FEM based simulated model has reconstructed the stress patterns which predominantly show compressional regime of major thrusts in Potwar and Hazara region along with some segments of strike slip movement. Compression along major thrusts is shown by the horizonal maximum principle stress ($\sigma 1$) and vertical minimum principle stress ($\sigma 3$). Strike slip movement of faults is caused by the horizontal alignment of maximum principle stress ($\sigma 1$) in which intermediate principle stress ($\sigma 2$) is vertical.

Conclusions

The points of conclusions generally associate with three types of stresses and their rotations along major discontinuities in Potwar and Hazara region. The main cause of these stresses in NW Himalayas is due to the Late Cenozoic compression event of Indian Eurasian plates. The general orientation of maximum principle stress is aligned itself N-S direction. Rotation of sigma along thrust boundaries is mainly caused either by change in rheology or by inclined/oblique geometry of different thrusts. However, anti-clockwise and clockwise rotations of maximum principle stress ($\sigma 1$) can be seen at the eastern and western edges of model. These stresses satisfied the present-day tectonics of faults based on their orientation i.e., N-S direction. Strike slip movement has also been found along some segments of major thrust. Material in 2D thin plate is deformed against applied pressure of 60 MPa. Displacement of thrust towards south is prominent and it might cause further thrusting in future.

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