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Tectonic Stress Analysis of Shivnath-Salena Area, Using Stress Response Structure

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ABSTRACT

The geological mapping of the Shivnath-Salena area and structure analysis of the same area were conducted in the Lesser Himalayan sequence, Far West Nepal, unveiling the characteristics of kinematics and the associated stress field in the region. The area comprises of the Salena Formation and Chachura Formation. The Salena Formation is sandwiched between the Pachkora Thrust and Dudulakhan Thrust, and the Chachura Formation occurs between the North Dadeldhura Thrust and Pachkora Thrust. The Salena Formation is composed of light grey and white quartzite and black slates that are intensely deformed, with folds. The Malena Anticline and the Lamalek Syncline are the intraformational folds observed in the study area. Superimposed folding was also observed. The Chachura Formation comprises Paleocene to Late Eocene green sandstone, grey and purple shale, and approximately 1 m thick grey fossiliferous limestone. This study interprets stress-response structures to show the tectonic stress field in the Salena Formation. Twenty-seven fault slip data (slickenside) were collected in the field and used to determine the stress regime by applying the stress inversion technique. The direction of the maximum principal stress axes is interpreted as NE-SW. The average value of the stress index R' is about 0.30, indicating an extensional tectonic stress regime in the study area. As $\sigma 1$ is vertical, R = R' in the study area suggests normal faulting in an extensional regime.

Keywords: Structure, Slickenside, Stress, Extensional, Tectonic.

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INTRODUCTION

The Earth's processes are dynamic, and lithospheric movement continues to form divergent, convergent, and transverse tectonic plates. The collision between these tectonic plates results in fracture formations and reactivation, combining the driving pressure ratio (R'), stress ratio (R) and regional field stress (far-field stress). The superposition of many small strain increments is the product of continuous deformation. Under a specific stress level, the stress response structure demonstrates how strain increases in diverse directions and to varying degrees Slickensides are smoothly polished lineations that typically form within rocks along shear cracks and fault surfaces. They are assumed to record slide motion and mechanical abrasion that occurs during faulting (Ortega-Arroyo and Pec 2020; Tjia 1964). The slickenside data can ascertain the stress on the faulting plane and slip on the bedding plane faults on the flolding regimes (Michael 1984). The general agreement is that the collision of continents/plates formed the Himalayan fold-thrust belt (Argand 1924; Klootwijk 1984). The Indian plate and Eurasuan plate collided about 55 Ma (Klootwijk 1984) forming the Himalayan range of 2400 km long. The collision of the two continental plate and continuous convergence (post collisional deformation relults in mega thrusting and folding in the Himalaya. The Himalyan range will be subdicided into Sub-Himalayas, Lower (Lesser) Himalayas, Higjer Himalayas and Tibetan Himalayas (Gansser 1964). The study focused on the severely folded, thrusting, and deformed Lesser Himalaya in Far West Nepal. The ongoing convergence (Gansser 1964; Windley 1996),

The study area is located in the Baitadi District of the Far Western Nepal between latitudes 29°24′0″ to N 29°30′0″ and longitudes 80°32′0″ to 80°32′0″ (Figure 1). The area is situated about 840 km west of Kathmandu, and it is connected to other parts of the country through the Mahakali Highway, running north-south and joining with the East-West Highway.The study area belongs to the complexly folded, thrusted, and deformed zone of the Lesser Himalaya. The fold-thrust belt consists of stratigraphical (Bashyal 1982, 1986; Dhital 2008, 2022) and structural (DeCelles et al. 2001) complex belt of predominantly Proterozoic sedimentary and

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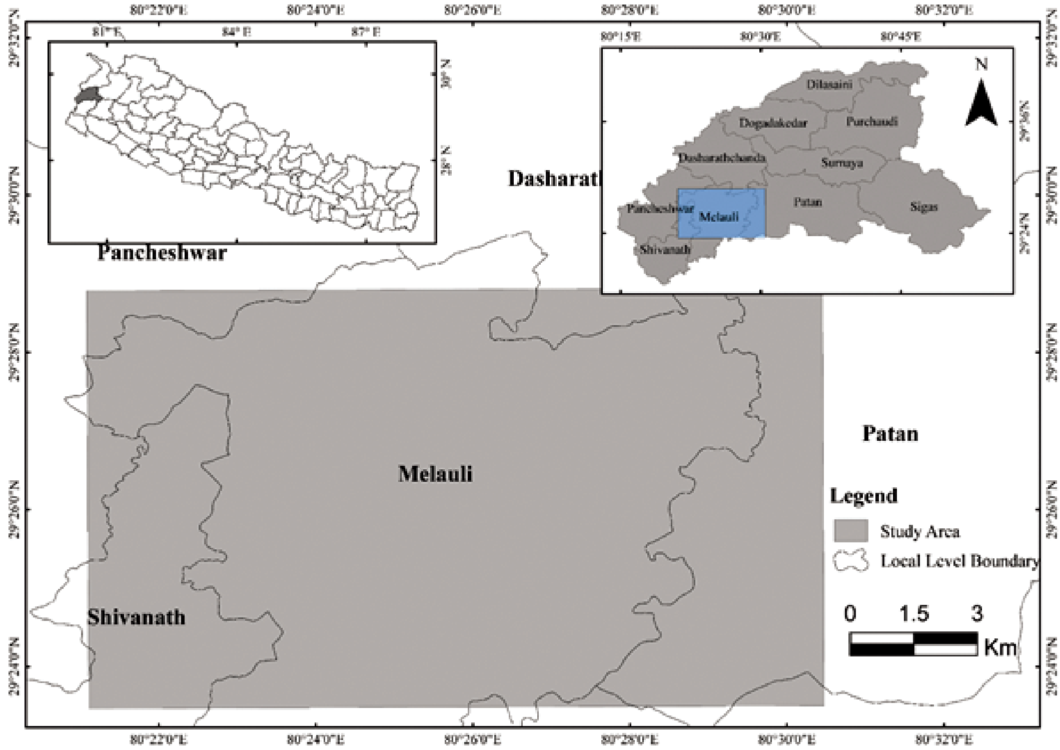

Fig. 1: Political map of Nepal and Baitadi district showing the study area.

metasedimentary rock sequences (Bashyal 1986; Hagen 1969; Heim and Gansser 1939; Khan 1969; Thapa 1977; Upreti 1999).

This paper's key objectives are to present the findings from recent structural and paleostress analyses using the slip data observed in the folded and thrusted zone of Far West Nepal. This part of the Lesser Himalaya has received limited study in the past. The paper aims to contribute to the understanding of the geological characteristics of the region by presenting the paleostress analysis findings.

In the research area, significant slip directions and gently to moderately plunging slickensides and lineations were exposed. Slickenside data are utilized to determine the stress regime that led to the formation and reactivation of these fractures and faults. Paleostress was calculated using fault slip data, including fault plane orientations and slide directions, collected in the field. The paleostress tensors were generated by using a stress inversion technique following a geological field investigation was carried out in the study region.

According to the relative scale of the intermediate axis, which is determined by the stress ratio R, the stress regime is divided into three categories: extensive/pure/compressive strike-slip, radial/pure/strike-slip extensive, and strike-slip/pure/radial compressive. (Delvaux et al. 1995). Fault plane and slip line orientations are used to compute the four parameters of the reduced stress tensor, and they are; the principal stress axes $\sigma1$ (maximum compression), $\sigma2$ (intermediate compression), $\sigma3$ (minimum compression), and the ratio of principal stress differences $R = (\sigma2 - \sigma3)/(\sigma l - \sigma3)$ (Angelier 1989).

METHODOLOGY

Several materials have been used to meet the objectives of the present research (Figure 2). The topographic map of Melauli (sheet no 2980 10B) is used in the field to make a comprehensive geological map. Research papers, journals, bulletins, and documents were collected from the Central Library (Tribhuvan University), the Department of Mines and Geology (DMG), Survey Department and other sources.

The fieldwork primarily focused on the preparation of the geological map and the identification of slickensides in the exposures. Traverses were conducted along rivers, valleys, ridges, gravel roads, and foot trails. In the field study, rock types were identified based on the color of the rock, grain size variation, composition, texture, fabrics, and mineralogical relations. Lithology was observed and recorded, and various structural features such as foliation plane, bedding plane, the fold axis's trend and dip , hinge trend and plunge, slickenside trend and plunge, and lineations were measured.

The measured slickenside trend and plunge data from the field, along with bed attitudes distinguishing

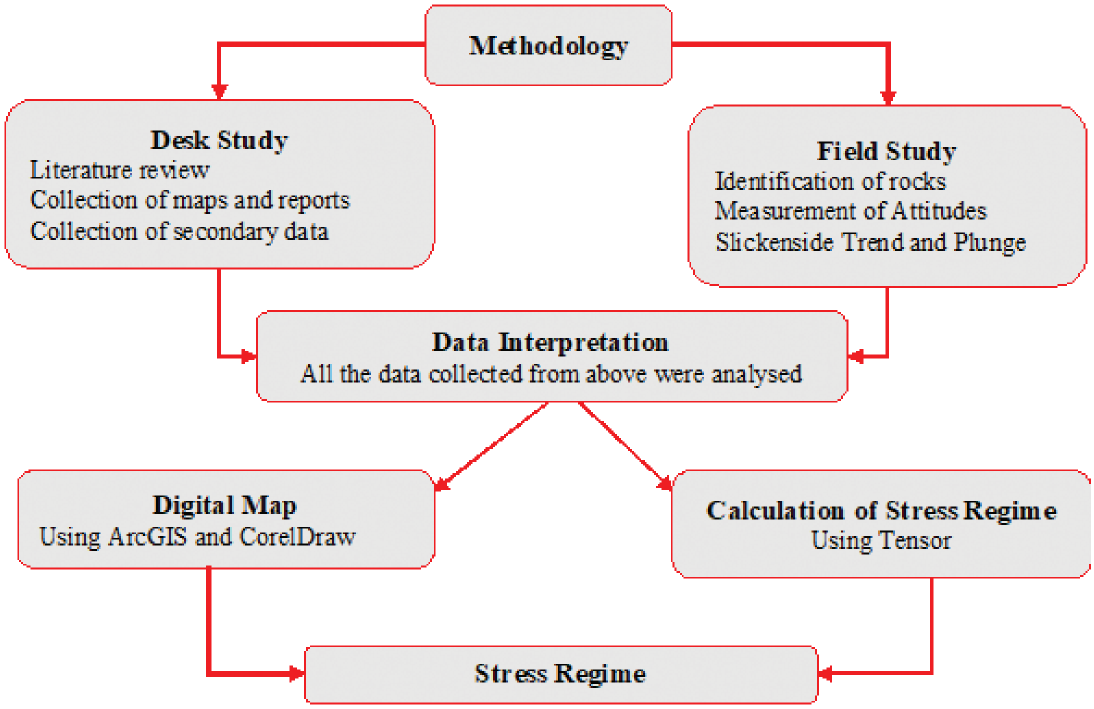

Fig. 2 : Flow chart represents the procedure used during the research.

footwall and hanging wall, are plotted in the Tensor software. The "TENSOR" process uses progressive rotation to maximize the outcomes using the graphic inversion method. It calculates the tensor around each axis by experimenting with different values of R. Fault categories are then ascertained by comparing the acquired value, or R, with the standard values.

GEOLOGICAL SETTING

The study region belongs to the Lesser Himalayan sequence of Baitadi district around Melauli, consisting of the Salena Formation and Chachura Formation (Dhital 2008; Phuyal 2022; Sapkota 2022), (Figure 3). The Pachkora Thrust (PT) separates the lithounits. The Salena Formation, which consists of quartzite and slates, is positioned between the north-dipping Dudilakhan Thrust (DT) and the south-dipping Pachkora Thrust. The Salena Formation in the area is intensely folded. The region has a complicated folding pattern with numerous fractures, local faults, tight to isoclinal folds, and quartz veins that point to a robust tectonic effect. The Lamalake Syncline and Malena Anticline are the major regional folds in the area, where numerous local and field-scale folds are observed. (Figure 3) in the area indicating the strong tectionic activities. This formation comprises of laminated, thinly - to thickly -bedded, fine-grained to crystalline quartzite interbedded with wavy to planar, weak to highly foliated, light grey to dark black slates. Well-preserved mud cracks and cross-lamination indicate the sedimentary origin. Slickensides and stretching lineations are predominantly observed in the beds of the Salena Formation. The complicated folding in the area can be described as superimposed folds due to the presence of recumbent to tight folds, lengthy axial traces, and tight hinges.

The beds regularly strike S 80° E, and the dip is 30°. In some sections, northeast of Salena, the rocks dip at angles ranging from 35° to 58° to the north. The light grey to green slate is intensely deformed with a pencil cleavage structure. A few small magnetite bands are traced in this section. Similarly, in the southern section of Salena, white quartzite with black slate is continuously interbedded. This region is also profoundly folded and deformed, with dips averaging between 15° and 70° in the northwest and southwest directions.

Along the road cut from Lamalek to Melauli, a sharp fault exposes the Tertiary rocks consisting of red-purple shale transitioning to grey shale, light grey and white quartzite, sandstone in green color, and ferruginous quartzite of the Chachura Formation. The Paleocene and Eocene Chachura Formation represents an interesting section of the Lesser Himalaya.

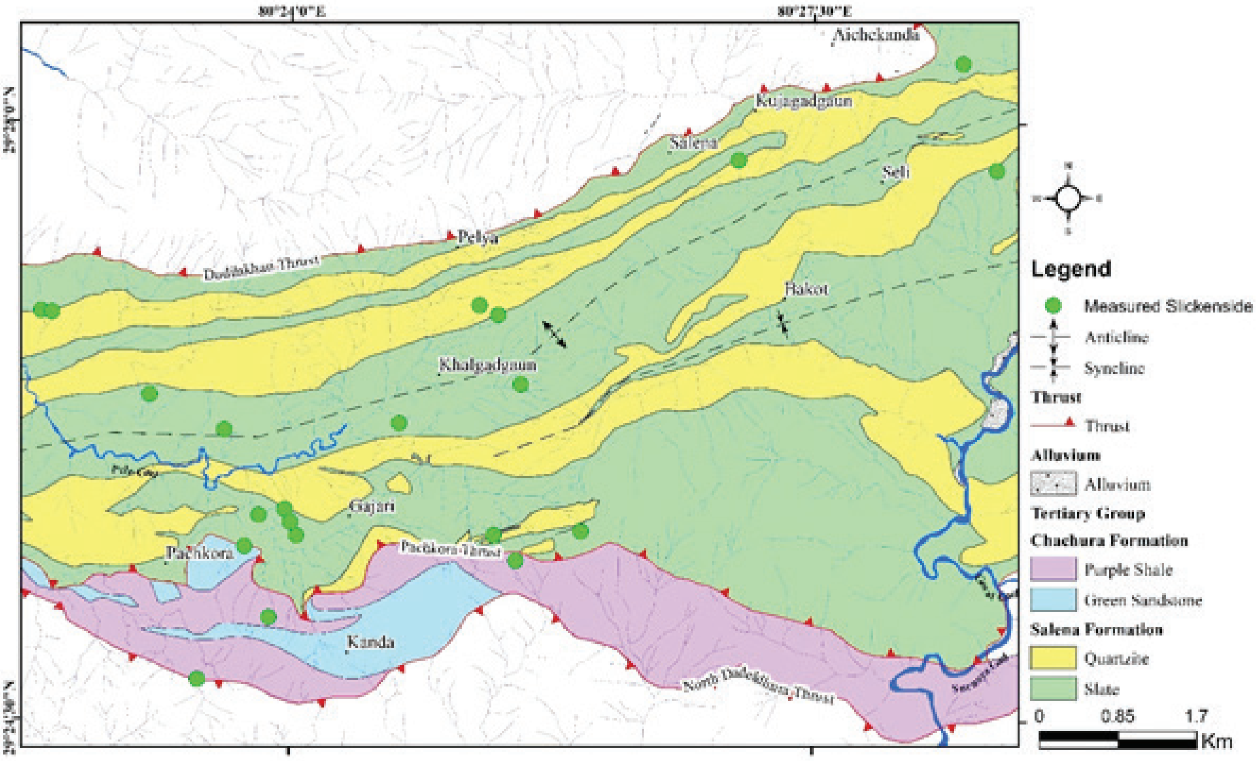

Fig. 3: Geological Map of Study area showing lithology distribution and location of measured Slickenside.

the Tertiary Group is situated between the north-dipping Pachkora Thrust and the south-dipping North Dadeldhura Thrust with overturned sequences. This zone is the Allochthonous one of the Lesser Himalaya (Dhital 2015). The sequence consists of interbed of red and grey fragile mudstone and shale with grey-green greywacke sandstone and subordinates light grey thinly bedded and compacted limestone consisting of lenticular Nummulites (Dhital 2008; Sapkota 2022). The slickenside and stretching lineation are sparsely observed on the bed of green sandstone. The exposure shows an upward finning sequence indicating the deposition in the shallow marine environment. The new Melauli Bajar consists of fragile purple shale interbedded with green sandstone. About 100 m north of new Melauli Bajar, grey shale consists of Bivalvia fossils.

PALAEOSTRESS RECONSTRUCTION

The research area's thrusting and folding zone, which has significant slip directions and gentle to moderately plunging slickenside lineation, is utilized to determine the stress regime that led to the formation and reactivation of these fractures, folds and faults. Several folds are formed in the area, during the folding, slip often occurs on the plane between different lithologic or bedding units (Michael 1984). The slickenside formed on these bedding surfaces have the same information as slickensides on the true faults. Thus, it can be used in the stress inversion (Michael 1984).

Palaeostress was calculated using data on fault slip (fault plane orientations and slide directions) collected in the field (Figure 4). A extensive geological field investigation was conducted in the study area to collect the slip data (slickenside); and the palaeostress tensors were obtained by applying a stress inversion technique. Palaeostress was initially constructed by the Right Dihedron method developed by Angelier and Mechler (1977) as a graphical method for determining the range of possible orientations of o1 and G3 stress axes in fault analysis.

The orientation reference grid used in the Right Dihedron technique is pre-determined to show up as a rectangular grid on the stereonet in the Schmidt projection of the lower hemisphere. (Delvaux and Sperner 2003). The right Dihedron method has been used to conduct the plaeostress reconstruction along the Salena Shivnath area in the study area. The type of tnsor is represented by stress regime calculation (Delvaux et al. 1995; Delvaux et al. 1997).

The stress ratio R has not yet been estimated using the Right Dihedron approach: only the orientations of σ1, σ2, and σ3 have been studied previously. However, upon closer examination of the Right Dihedron counting nets, it becomes apparent that their patterns vary depending on whether the stress tensor is compressional, strike-slip, or extensional. To represent this pattern as a parameter function would provide an estimate of the stress ratio R.(Delvaux and Sperner 2003). Brittle structures such as slickensides can also be used as stress indicators. The inversion method is based on supposing that a) stress is uniform and never changing in space and time and b) the fault plane slip in the maximum direction of the applied shear stress (Bott 1959; Delvaux and Barth 2010; Etchecopar et al. 1981). For this. slickenside lineation is used for calculating movement between the footwall block and the hanging wall block (Ju et al. 2012).

The stress regime is classified into radial/pure/strike-slip extensive, extensive/pure/ compressive strike-slip, or strike-slip/pure/radial compressive, as a role of the relative scale of the intermediate axis, given by the stress ratio R (Delvaux et al. 1995). Fault plane and slip line orientations are used to compute the four parameters of the reduced stress tensor, and they are; the principal stress axes σ1 (maximum compression), σ2 (intermediate compression), σ3 (minimum compression), and the ratio of principal stress differences R = (σ2 - σ3)/(σl - σ3) (Angelier 1989). The vertical stress axes represent the stress regime; if σ1 is vertical, it is extensional, and if σ2 is vertical, it is strike-slip, and it is compressive if σ3 is vertical. Furthermore, the stress regime relates to the ratio of principal stress differences R (Ju et al. 2012).

Slip data (slickenside) were measured during the field observation, and paleostress was computed by applying a stress inversion technique to the slickenside measurements. Paleostress is calculated and displayed using Tensor software (Figure 5).

Fig. 4: Stress-response structures in the study area showing slickenside and thearrow line showing the direction.

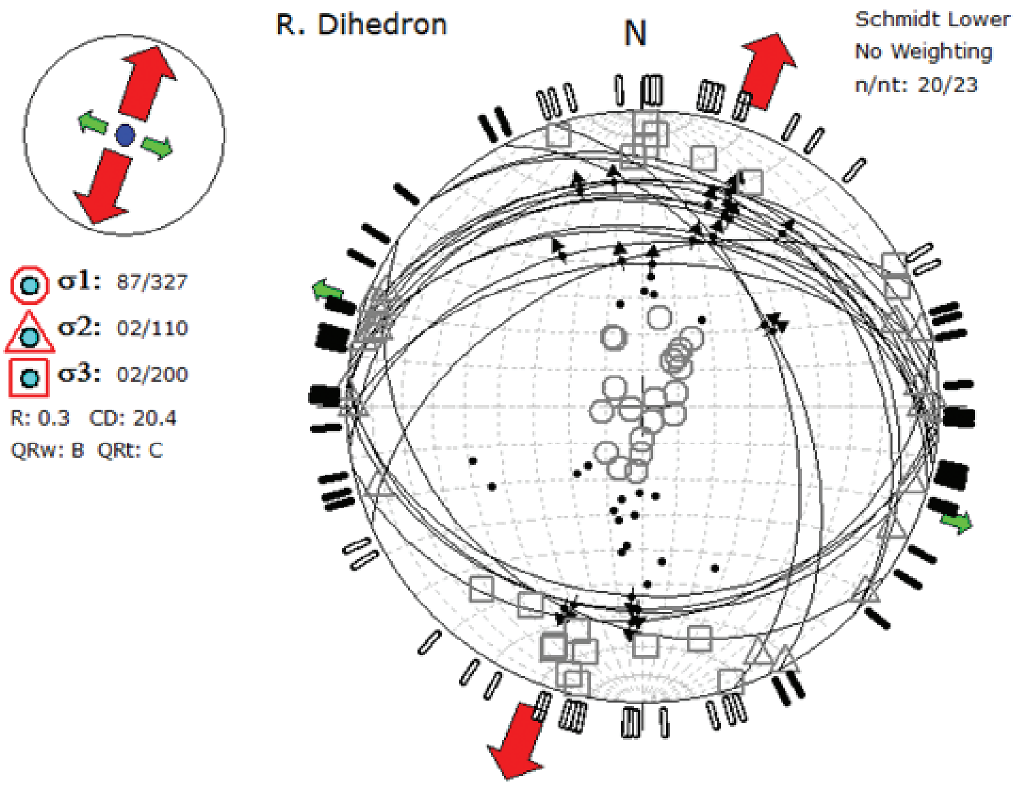

Fig. 5: Palaeostress tensor graphic solutions along the Melauli-Salena route. Slip lines are shown by a black dot with two arrows for strike-slip faulting, an inward direction arrow represents reverse faulting, and an outward direction arrow represents normal faulting. Extensional deviatoric stress is indicated by the outward arrow, while compressional deviatoric stress is indicated by the inward arrow.

DISCUSSION

The different tensor types are defined using stress regimes (Delvaux et al. 1995; Delvaux et al. 1997). Each of the Tensor's vertical regimes is either extensional or strike-slip depending on whether σ1 or σ2 are vertical; if σ3 is the vertical axis, the regime is compressive. The ratio of principal stress differences, R, is related to the stress regime (Figure 6).

faulting during folding in the NE-SW direction. The folds' axial traces also reveal the direction of stress, which is NE-SW.

CONCLUSION

The tectonic stress in Shivanath-Salena is reconstructed using stress-response structures (slickensides). Maximum (σ1) principal compressive stress occurs on average 87/327 (dip angle/strike), intermediate (σ2) principal compressive stress occurs on average 02/110 (dip angle/strike), and minimum (σ3) principal compressive stress occurs on average 02/200 (dip angle/strike). The stress index R in the study area averages 0.30, indicating an extensive stress regime in Shivanath-Salena.

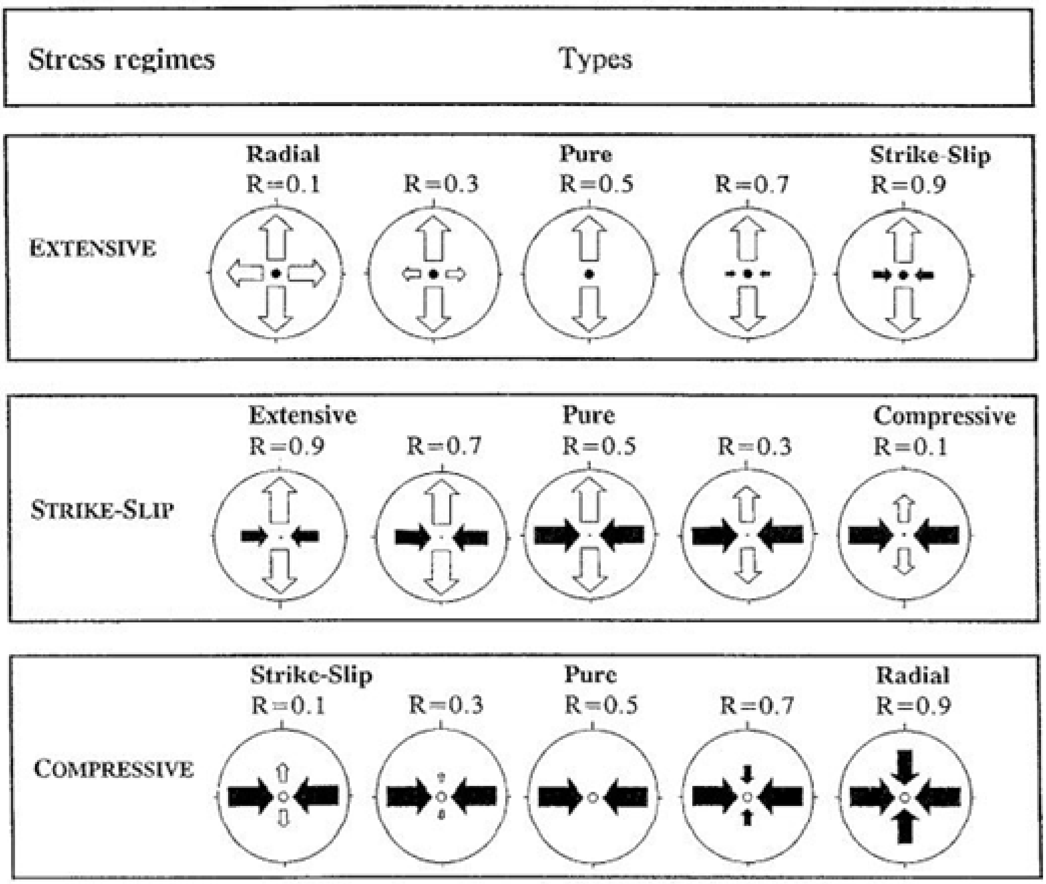

Fig. 6: Different stress regimes and their representation. In the function of the stress ratio R, arrows show the azimuth of the horizontal stress axes, with their length corresponding to the relative stress magnitude. Tensile deviatoric stress axes are represented by white outward arrows, whereas compressive deviatoric stress axes are indicated by black inward arrows. The solid circle for extensive regimes (a1 vertical), the dot for strike-slip regimes (a2 vertical), and the empty circie for compressive regimes (03 vertical) represent the vertical stress axis (Deivaux et al. 1995).

The Himalayan tectonic stress regime was investigated from the stress pattern of earthquakes. Such a study revealed that it is represented by NNE-SSW compressional stress in Nepal and India and NNW-SSE in Pakistan and Hindukush Himalaya (Ali et al. 2021). Paudyal et al. (2008) used the orientation of compressional and tensile stress axes using a fault plane, and they found NE-SW compressional stress in Eastern and Western Nepal.

In a recent study using slip data (slickensides), the stress index was calculated through the inversion method (Right Dihedron method). The study identified an extensional region supporting normal

Tectonic deformation can be better understood by reconstructing the tectonic stress field in the studied area. The analysis suggests extensive stress in the NE-SW direction, indicating the region's probable involvement in folding processes, demonstrated by bedding slip faults under extensive stress.

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