Compressive Stress and Thrust Faulting Deformation Analysis in the Himalayan Fold-thrust Belt

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Abstract

The Himalayas represent one of the few places on earth where continental crust is attempting to underthrust continental crust. As the Indian plate underthrusts the Himalaya, it warps down in response to an advancing orogenic load and keeps the entire Himalayan mountain arc seismically active. Even today the Himalayas continue to develop and change the structures by the movement between Indian and the Eurasian plate. From this viewpoint, a two-dimensional finite element model is generated to investigate most common structural pattern thrust fault and compressive stress in the Himalayas. It is beyond the scope of the present work to show whether the slip occurs on such a simulated fault or not. The numerical study has been performed considering the present convergence rate of Indian plate and rock layer properties of central Himalayan profile. Results show that the compressive stress and normal faults have primarily developed in the deeper region of Tethys Himalaya, Lesser Himalaya and Sub-Himalayan sequences whereas with increasing boundary displacement and changing layer properties, thrust faults have developed in the shallower depth in the respective layers and finally having a tendency to highly concentrate in southern part of the model. Thus the thrust faults predicted by the numerical model show the similar tendencies with the sequence of southward thrust development found in the Himalayan orogenic belt. Moreover, the simulated faults along the frontal part of Himalayas are the most common faults in field which influenced the present neo-tectonics of the region.

Introduction

The Himalayas are not merely a geographical feature, a range of mountains; they epitomize a people's civilization identity that goes back to the dawn of history. If these majestic mountains were not there, the rain clouds sweeping up from the Indian Ocean would have passed over the Indian subcontinent into central Asia leaving it a burning desert. The Himalayan mountain system developed in a series of stages 30 to 50 million years ago. The mountain range was created from powerful earth movements that occurred as the Indian plate pressed against the Eurasian continental plate. Even today it continues to develop and change, and earthquakes and tremors are frequent in the area (Pandey et al., 1999). The Himalayan mountain range provides a spectacular natural laboratory for the study of continental collision in the uplifted section of crust. Pioneering geological investigations have already delineated the fundamental tectonic framework of the Himalayan territory. Based on the field-laboratory studies, numerical modeling of various aspects of collision tectonics have been studied by many earth's scientists (e.g. Molnar and Tapponier, 1975; England and Thompson, 1984; Sato et al., 1996; Shanker et al. 2002). Nevertheless, the collisional influences on the orogenic processes of the Himalayan mountain range have not been fully understood yet.

In order to understand the fascinating effects of the collision on the Himalayan structures and tectonics, a 2D finite element method

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has been employed under plane strain condition. In this paper, we mainly examined the compressive stress and thrust fault on the structural cross profile of Himalayas applying the present convergence rate and the elastic rheology. For these reasons, primarily the efforts have been made to calculate the compressive stress field then the thrust faults have been developed from such stress field by 2D finite element method with Mohr Coulomb failure criterion. Finally, the results of the simulation have been discussed and compared with previous studies in the region.

Geologic Setting and Major Structures of Himalayas

In order to analyze thrust fault, a cross profile has been taken from Nepal Himalya. The Nepal Himalaya is one of the most dominating Himalayan panorama, placed in the central part of Himalayan range (Fig. 1). The region is best for studying the Himalayan orogenic belt because of its continuous exposures of the tectonostratigraphic units from top to bottom along a N-S transect (Le Fort, 1975; Upreti, 1999). Tectonostratigraphycally it consists of the Tethys Himalaya, Higher Himalaya, Lesser Himalaya and Sub-Himalaya zones. These zones are separated into major fault systems: the South Tibetan Detachment System (STDS) between the Tethys and Higher Himalaya, the Main Central Thrust (MCT) between the Higher and Lesser Himalaya and the Main Boundary Thrust (MBT) between the Lesser Himalaya and Sub-Himalaya. The other important structure is the Main Frontal Thrust (MFT). The MCT in Nepal is traditionally defined as a ductile shear zone (Brunel, 1986). The Higher Himalaya consists of Late Proterozoic-Early Paleozoic metasedimentary rocks (Le Fort, 1975; Peacher, 1989). The Lesser Himalaya in Nepal is composed of 10 km thick succession of Proterozoic, Upper Paleozoic and Cretaceous-lower Miocene sedimentary rocks. The peak metamorphic temperatures in the Higher Himalaya increase along the MCT (Peacher, 1991). In the northern part of the Lesser Himalaya, the rocks are metamorphosed to upper greenschist facies and metamorphic isograds in the footwall of the MCT are inverted, progressing from chlorite to garnet. The kinematic history of the thrust belt involved a general southward progression of main phases of thrusting from Eocene to present (DeCelles et al., 2001).

Approaching The Model

Method

A two-dimensional finite element method has been adopted for numerical modeling of compressive stress and fault pattern on the geological profile model of the region. As stated earlier, the method has been quite widely applied for calculating stress and deformation fields in elastic and or visco-elastic medium. Since a general formulation of the method has been given in number of excellent textbooks (e.g. Zienkiewicz and Cheung, 1967), here described very briefly the method.

In the present calculation, the nodal displacements have been taken as the fundamental unknown parameter which to be estimated. In an equilibrium state, the total energy of a system consisting of elastic medium and external forces should remain at a minimum. Based on this, giving the material properties of the medium and external forces acting at nodes, one can obtained the nodal displacements and then calculate the strain and stress field of the medium. Next, the faults are developed from the calculated stress field by Mohr-Coulomb failure envelope. Since 2D stress fields of the numerical models are calculated under the plane strain condition, the third principal stress is given; it acts perpendicularly to the section plane and can be obtained from the theory of plane strain as:1), where, is Poisson's ratio (Timoshenko & Goodier, 1970). Since the values of , and for every elements have been computed, calculation can define which one is the maximum, intermediate and minimum compressive stress among them. The 2D stress field of each model is envisaged with the newly calculated principal stresses, and After calculating the stress field in each model, it is possible to describe in which element the fault will occur according to the Mohr-Coulomb failure criterion.

Failure envelope. This takes place when the radius of the Mohr circle, is equal to the perpendicular distance from the center of the circle at to the failure envelope. It is possible to calculate the proximity to failure for each elemen.

Whenever the value of is less than 1.0, the Mohr circle is inside the failure envelope and it indicating that no fault, on the other hand fault occurs if the value is above 1.0. Faults are then classified applying the Anderson theory (1951). He assumed that all the principal stresses are either horizontal or vertical. This theory predicts three types of observed faults, thrust, strike-slip and normal fault, depending on which the nature of distribution of principal stresses. Andersonian predictions of the orientation of each type of fault are consistent with many observations (e.g. Sibson, 1994).

Model Geometry and Boundary Condition

A two-dimensional finite element model has been constructed based on the structural geologic cross section (Kaneko, 1997) of the Nepal Himalaya, which is shown by a X-Y line. The model profile is about 335 km long with a depth of about 52 km consisting of five rock layers: Pre-Cambrian basement, Higher Himalaya, Lesser Himalaya, Tethys Himalaya and Sub-Himalay. The rock properties of the layers. The dip of the convergent slope of Indian sub-plate is to the horizon. The elements used are triangle with three-nodes for the model, and the boundary condition are set-up considering the N-S convergence of Indian Sub-plate beneath the Eurasian plate. The different boundary displacements (100-700 m) are derived from convergent velocity multiplied by period. The present convergence velocity - 2 cm/year across the Himalayan front (Bilham et al., 1997; Cattin and Avouac, 2000; Lave and Avouac, 2000) are imposed perpendicular to the right-side wall. These imposed displacements are vectors having horizontal and vertical components. The upper surface is free to deform horizontally and vertically. The left side edge is fixed horizontally and left corner bottom node is fixed in all direction.

Importance and Limitation of Finite Element Modeling

The model focuses on aspect of the central Himalayan region where the crustal deformation is dominated by brittle processes, which are approximated by an elastic rheology. The elastic limit obviously varies with depth, so that the values adopted represent an average strength based on the grade of rocks in the model. The depth of brittle deformation is about 20-30 km. Most surface earthquake hypocenters concentrate in the depth range 5-20 km, i.e. in the upper half of the continental crust (Lyon-Cane and Molnar, 1983). Bott (1990) pointed out that the uppermost 20 km of the continental crust is elastic and represents the strong and cool layer of the upper lithosphere. However, in the collision zone, where the cold lithosphere underthrusts, elastic behavior occurs at greater depths. The aim of the present modeling is discussing the thrust fault in the brittle layer of the upper crust through a simple 2D analysis. The results of simulation are certainly compared quite well with the previous studies. The main limitation of the model is that it is strictly a 2D elastic model. In fact, to elucidate the more realistic deformation pattern in a mountain belt; further study with a more realistic 3D elasto-plastic model is required.

Interpretation of Results and Discussions

How to Set-Up Model

The finite element model presented and

discussed above has been produced from geologic profiles after Kaneko (1997). In order to generalize the profile, the geometry was slightly modified and rearranged taking into account other profiles by Lyon-Caen and Molnar, 1983; Upreti, 1999; etc. After producing the primary profile, finite element method applied with 2D space and simple geometry of the convergent belt assuming the homogeneous and isotropic material within the individual layers. In nature the behavior of rocks are not homogeneous and isotropic; furthermore, the rocks layer properties are used in the simulation are not experimentally determined. As a consequence, we have tested the model using varying values in order to find the effect on the stress field. Finally, we adopted only the most suitable set of layer properties for the calculation. We assumed that the crust behaves elastically though it is visco-elastic-plastic in nature. The present simulation models remain simple and assumed data are consistent with known field data.

General Distribution of Computed Stress and Fault

Stress distribution and faults are computed throughout the grid as generated by the displacement boundary condition and layer properties. The representative model of stress field for displacement boundary condition 500 m and 700 m. The boundary displacement simply corresponds to the convergence of the Indian sub-plate relative to the Eurasian plate. The calculated stress exhibits mainly compressive stress pattern in the entire which coincides with the local as well as regional compressive stresses in the Himalayas (Molnar et al., 1977; Chandra 1978; Shanker et al. 2002). The direction of principal stresses are almost same throughout the models whereas they slightly deviated along the upper part of model and along the bottom part of Pre-Cambrian basement layer with increasing convergent displacement. The basal part of the model shows a strong magnitude of compressive stressthat decreased gradually toward the shallower depth. The failure analysis demonstrates the realistic fault pattern and their proper location in the model. From the simulated failed elements, it is clear that the maximum principal stress is distributed horizontally, resulting the thrust fault which are mainly localized in the Tethys Himalaya, Lesser Himalaya and Sub-Himalaya.

Effect of Model Parameter Variation on Stress and Fault

The mode of stress and fault is primarily influenced by model parameters (e.g. boundary conditions and layer properties). With regards to the boundary condition, a runs have been conducted imposing different convergent displacements. During these runs, it is observed that the stress and faults of all models are similar to each other; with increasing convergence displacement, the magnitude of principal stresses and failed elements increase slightly which is clearly observed in the Tethys, Lesser Himalay and Sub-Himalayan rock units.

With respect to layers rock properties (density, Poisson's ratio, Young's modulus, cohesion and angle of internal friction), it is attempted to investigate the mode of faulting for different layer properties in order to identify the suitable condition that are likely to led to form the thrust fault in the model. For this purpose, layer parameters of the model are varied one at a time, keeping others constant. The final parameters of the layer properties. It is observed that the cohesion and angle of internal friction are significantly effective in increasing the number of failed elements in the Tethys Himalaya, Lesser Himalaya and Sub-Himalaya than other properties. Thus the magnitude of stresses and faults are not only governed by the model boundary conditions but also by the applied values of different model's layer properties.

Tendency of Faulting of Different Grade Rock Layers

Such relations are drawn based on the intensity of fault development in different grade rock layer of the model. The model profile taken from the Nepal Himalaya underlain by different grades of metamorphic to sedimentary rocks, including psammitic schist, augen gneiss, metapelites, quartzite, metabesites, migmatite, orthogneis, sandstone, siltstone and so on (Le Fort, 1975; Upreti, 1999). The metamorphic rocks of the area are divided into six metamorphic zones based on the changes of mineral assemblages in metapelite (Kaneko, 1995 and 1997). From the viewpoint of metamorphic grade, the Lesser Himalaya (LH) and Tethys Himalaya (TH) are belonged to the chlorite, biotite and garnet zones (temperature range) whereas the kyanite zone (temperature range) mainly dominates in the Higher Himalaya (HH). The Sub-Himalaya comprises of recent sedimentary rocks (Table 1; Upreti, 1999). Such rock species are adopted to examine thrust fault in the proposed model. Model exhibits that the simulated faults are frequently localized within the low-grade rock units such as in the Tethys Himalaya, Lesser Himalaya and Sub-Himalaya. Thus, these scenarios suggest that the low-grade rock layers might be more vulnerable to develop faults than the high-grade ones in the regime.

Comparison with Previous Studies

The simulation shows the distribution of compressive stress and thrust fault in the profile model of Himalayas. The general characteristics of stress and fault interpreted However, interpretation of the simulated model remains less definitive to some extent because of the limitations of the elastic 2D modeling. Despite these limitations, the model still allows for a simple comparison with the previous studies in the regime. The results of the simulation compared quite well with the cross profile of Himalayas using recording neotectonics based on active fault studies and focal mechanism solution of earthquakes of the area. The simulated thrust faulting to initiate at depth and to transmit to surface area of the Tethys Himalaya, Lesser Himalaya, Sub-Himalaya and along the frontal part of MFT and finally their tendency to propagate southward with increasing convergence displacement correspond well with the sequence of thrusts development in the Himalayan mountain belt (DeCelles et al., 2001). The distribution of thrust fault in the Lesser Himalaya and Sub-Himalayan region seems to be associated with the Himalayan major thrusts, e.g. MBT and MFT forming the north dipping imbricate zone as reveled by field study (Nakata, 1989). The thrust fault is also consistent with the focal mechanism solutions of earthquakes in the region (Molnar et al., 1977; Chandra, 1978). Focal mechanism solutions of earthquakes gave the same general pattern of thrust faulting in the Himalayan region. Moreover, model shows the existence of thrust fault in the frontal part of the Himalayas which are related to neotectonics in the central Himalaya (Nakata et al., 1984).

Tectonic Synthesis of Simulated Faults at Present Collision

Today our understanding of the geology and tectonics of the Himalaya have greatly advanced. It was built on the works of a large number of geologists for over one and a half century. As a result, the Himalayas is perhaps geologically the most well know part of the world. Intensive studies were made here on the problems of the inverted metamorphism, tectono-thermal evolutionary history, magmatism, foreland basin development and seismotectonics etc. Despite these advances in the Himalayan geology, a great deal of uncertainties still exists regarding the basic tectonic framework, origin of the inverted metamorphism and the tectono-thermal evolution of the Himalaya. A variety of models have been proposed to explain the structural development and tectonics in the Himalayas (Molnar and Tappornier, 1975; Seeber et al., 1981, Hubbard 1996; Upreti, 1999).

Meanwhile, the principal thrusts MCT, MBT and MFT show shallowing depth towards south suggesting southward migration of the main deformation front. Neotectonic activity and active faulting related to the thrusts are observed on the surface in some restricted segments. The MCT remains largely inactive except for some reactivated segments showing lateral strike-slip movement as in central Nepal. The MBT in certain localized areas exhibits neotectonic activity (Nakata, 1989). The MFT shows active faulting and associated uplift. The MFT represents a zone of active deformation between the Sub-Himalaya and the Indian plain, which demarcates the present day principal tectonic displacement zone between the stable Indian continent and the Himalayas with a convergence rate of 20 mm/yr (Lave and Avouac, 2000). Active faulting is observed along the MBT and MFT in the Himalayan front of southeast Nepal. In the present study, we simulated the faults applying the convergent displacement and layers properties at present condition. The results of the simulated model revel that the faults are generally intensely concentrated along the elongation of real MBT and MFT suggesting that this area (frontal) might be active which is consistent with the present day neotectonic activity in the Himalayas.

Conclusions

A numerical model is employed to examine the thrust faults in the Himalayas. The model simulated using the rock layer properties and boundary conditions (convergent displacement). The rock layers of the model characterizing the high grade metamorphic rocks in the Pre-Cambrian basement and Higher Himalaya and the low grade rocks in the Lesser Himalaya, Tethys Himalaya and Sub-Himalayan sequences are defined by means of elastic parameters. The performed simulations showed that cohesion and angle of internal friction are more important together with boundary conditions to develop the thrust fault. It is observed that thrust fault is intensely localized southward from the Tethys Himalaya to Lesser Himalaya and finally Sub-Himalayan sequences which corresponds to the southward sequence of thrust development in the Himalayan orogenic belt. The model also shows that the frontal part of the Himalayas is more vulnerable to develop fault suggesting the active nature of the regime; this is consistent with the characteristics of neotectonics based on the active fault studies in the Himalayas. The Himalayan front is the most active fault zone in the entire Himalayas (Nakata, 1989). Thus, the simulated thrust fault might play a significant role in understanding the neotectonics in the Himalayas at the present collision.

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