Fault development in the Thakkhola half graben : insights from numerical simulation

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Fault development in the Thakkhola half graben: insights from numerical simulation

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Abstract

Grabens of southern Tibet and the Himalaya represent the Cenozoic extensional tectonic phase, which has affected whole Tibet and northernmost part of the Himalaya. Thakkhola half graben, on the crest of the Himalaya, is one of the north trending grabens that define the Neogene structural pattern of the southern margin of the Tibetan Plateau and is seemingly enigmatic feature in a regionally contractional tectonic setting between the colliding plates. Two-dimensional, elastic, plane-strain, finite element models (FEMs) are generated to simulate the effects of geometry and rock properties on growth of graben faults and their configuration for the Thakkhola half graben evolution. The performed models have shown that the extensional graben faults form at the top of the overburden and propagate downward as we increased extensional displacement. Simulated models have clearly defined the graben bounding faults. Further they are able to suggest that natural grabens have multiple faults on each side rather than single fault. During progressive extensional displacement depth of faulting increases and deformation is mainly localized in downthrown block both in basement and syntectonic deposits. Syntectonic deposit is characterized by normal faulting in tensional tectonic stress field, which is a common feature of the small-scale graben at post rift deformation stage. The width and depth of graben are primarily controlled by the rheology of the upper elastic layer and syntectonic deposits. The applied rock layer properties are able to deduce the first order characteristics of the Thakkhola half graben. Therefore, this simulation constrains probable values for the rock layer properties controlling the Thakkhola half graben evolution. Assumption of the weak zone does not make significant difference on stress distribution and faulting. Thus it seems that the Thakkhola fault system only did not contribute to development of the half graben.

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1. Introduction

The tectonic and structural evolution of the Himalayas and Tibet, since the Eocene collision between the Indian and Eurasian plates, have been mainly controlled by three classes of the structure formed during convergence. The first class of structures includes east-west striking, north dipping thrust fault systems and subordinate fold systems that are related to crustal shortening and thickening. These structures comprise of intracrustal thrusts: Neogene Main Central Thrust (MCT) and Main Boundary Thrust (MBT) system, which strike parallel to the orogen and have been traced for hundreds of kilometers from eastern to western syntaxis of the Himalaya. The second classes of the structures include the east-west striking, north dipping normal faults of the South Tibetan Detachment Fault (STDF) system. These normal faults are developed near the crest of the Himalaya along the southern part of the Tibetan plateau during Oligocene-Pliocene extensional event in the Himalaya and are supposed to have formed synchronously with MCT system. One common explanation for such extension is a gravitational collapse (Burchfiel, et al., 1992; Hodges, et al., 1992), driven by excess gravitational potential energy arising from buoyant crustal root and upwelled asthenosphere (Dewey, 1988; Molnar and Lyon-Caen, 1988; England and Houseman, 1989; Yin, 2000). The tectonics of the southern Tibet and northern part of the Himalayan crest is mostly characterized by third class of structures viz: the north-south striking normal faults and associated grabens and strike slip features.

Normal faults and grabens indicating generally east-west extension are distributed throughout the southern half of the Tibetan Plateau and crest of the Himalaya (Fig. 1). Since their discovery (Molnar and Tapponier, 1978), geologist and geophysicists have been studying on the origin of these grabens (rifts), which are seemingly enigmatic features in a regionally convergent tectonic setting between the colliding plates. Some of the possible explanations include: (1) gravitational spreading of the elevated plateau driven by excess gravitational potential energy (Molnar and Tapponier, 1978), (2) extension in response to regional conjugate strike slip faulting associated with eastward extrusion of Tibet (Armijo et al., 1986), (3) isostatic response to erosion of the mantle lithosphere (England and Houseman, 1989), (4) Lower crustal flow (Royden et al., 1997), (5) oblique convergence between India and Eurasia (McCaferry and Nabelek, 1998), (6) arc-parallel extension (Seeber and Pecher, 1998), and (7) middle Tertiary mantle upwelling in eastern Asia that induced thermal weakening of the lithosphere (Yin, 2000).

The Thakkhola half graben (Fig. 1) is one of many north trending grabens that define the Neogene structural pattern of the southern margin of the Tibetan Plateau. Lying to the southern boundary of the Tibetan plateau and near the crest of the Himalaya, it provides an ample opportunity to understand the east-west extension in Tibet and north-south extensional strain in the Himalaya.

The major problems addressed by this study are (1) stress state of the northernmost part of the Himalaya (especially Tibetan Tethys zone), (2) growth of the graben fault, (3) effect of variation of rock layer properties on development of graben fault system, (4) evaluation of mechanical properties of rock layers that could explain evolution of the half graben. Finally efforts are made to explain the genesis of the Thakkhola half graben.

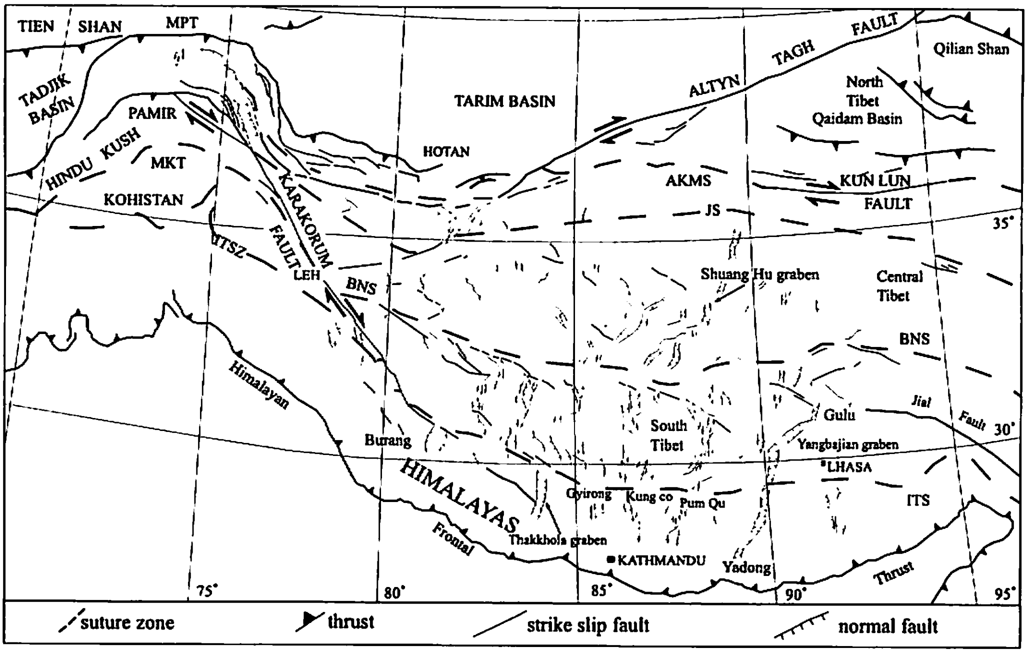


Fig.1 Tectonic setting of the Himalaya-Tibet orogen showing major grabens (modified after Blisniuk et al., 2001) AKMS: Ayimaqin-Kunlun-Mutztagh suture; BNS, Bangong Nujiang Suture; ITSZ: Indus-Tsangpo Suture Zone; JS: Jinsha suture; MKT: Main Karakorum Thrust; MPT: Main Pamir Thrust.

2. Geological setting

2.1. Geologic setting of central Nepal

The Himalayan arc, well defined geographically and convex toward south, extends about 2500 km, from west Nanga Parbat to east Namche Barwa. Gansser (1964) divided into five geographical and political tranverse divisions from west to east they are: (a) Punjab Himalayas (b) Kumaun Himalayas (c) Nepal Himalayas (d) Sikkim and Bhutan Himalayas and (e) Nefa Himalayas. Among these, Nepal Himalayas is the longest and is covered about 30% of the total length. Similar to Gansser's (1964) widely accepted classification of the Himalaya, central Nepal Himalaya, from south to north, can be divided into the following five major tectonic zones (Fig. 2):

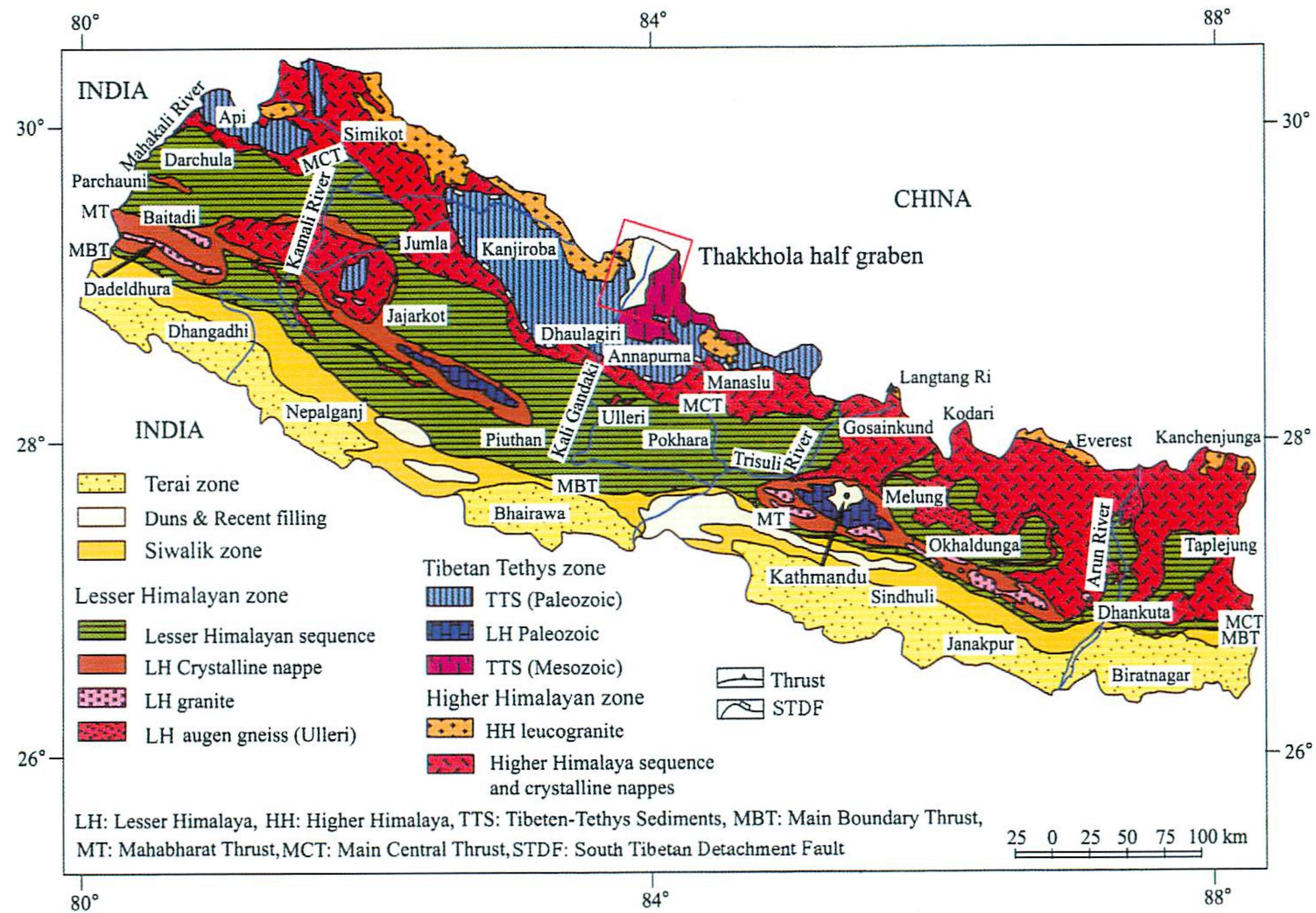


Fig.2 Geological map of Nepal (modified after Upreti and Le Fort, 1999). Rectangle shows the location of the Thakkhola half graben.

Terai Zone
Siwalik Zone
Lesser Himalayan Zone
Higher Himalayan Zone
Tibetan-Tethys Zone

2.1.1. Terai zone

The southernmost tectonic division of Nepal, Terai, represents the northern edge of the vast Indo-Gangetic alluvial basin deposits. In the north it is bounded by Main Frontal Thrust (MFT) whose outcrops are exposed in many places along the southern front of the Siwalik Range (Fig. 2). The sediments of the Teari plain (Pleistocene to Recent with an average thickness of 1500 m) can be differentiated into coarser (proximitiy to Siwalik its precursors) which is often called "Bhawar Zone" and finer farther to the south. The basement rocks below the Terai sediments are experiencing tectonic activity and shares a significant proportion of the current stress accumulation in Himalaya, which is manifested in the development of thrust and thrust propagated fold beneath the sediments (Bashyal, 1998; Chamlagain and Hayashi, 2004). The Himalayan mountain front is continuously propagating to the south through this zone.

2.1.2. Siwalik zone

Siwalik zone is the frontal part of the Himalyan fold-and-thrust belt. It is bounded by MFT to the south and MBT to the north (Fig. 2). In central Nepal, Neogene Siwalik Group consists of about 5 km thick upward coarsening sequence of mudstone, sandstone and conglomerate. As in the other parts of Siwalik zone of Pakistan and northern India, the Siwalik zone of central Nepal comprises three informal units that are referred to as lower, middle and upper members (Tokuoka et al., 1986). Paleocurrent and modal petrographic data from sandstones and conglomerates indicate that these rocks were derived from the developing fold-and-thrust belt and deposited within the flexural foredeep of the Himalayan foreland basin system (Tokuoka et al., 1986; Hisatomi, 1990). The sedimentary foreland basin deposits form an archive of the final stage of the Himalayan uplift and record the most recent phases in the history of Himalayan evolution spanning the past ~ 14 Ma.

2.1.3. Lesser Himalayan zone

The Lesser Himalayan zone is bordered by MBT to the south and MCT in the north (Fig. 2). The Lesser Himalaya of Nepal shows variation in stratigraphy, structuctures, and magmatism. In the east and central, it is characterized by the extensive development of the crystalline thrust sheets and nappes (Kathmandu nappe) that have traveled southward from their root zone (Fig. 2). The Lesser Himalayan zone constitutes a relatively broad tectonic zone, especially in the western Nepal and exhibits relatively subdued topography. The stratigraphy and tectonics of the western Nepal have been documented by numerous workers e.g. Fuchs and Frank (1970), Upreti (1990, 1996), Decells et al. (2001). In western Nepal, between the Burhi Gandaki and Bheri River the crystalline rocks are restricted north of the MCT. This zone is made up mostly of sedimentary, and metasedimentary rocks such as shale, sandstone, limestone, dolomite, slate, phyllite, schist, quartzite ranging in age from Precambrian to Eocene. Further west, crystalline rocks appear as nappes and klippen, and cover much of the Lesser Himalayan terrain (Hayashi et al., 1984).

2.1.4. Higher Himalayan zone

Geologically, the Higher Himalayan zone includes the rocks lying north of the MCT and below the fossiliferous Tibetan Tethys zone (Fig. 2). The northern upper limit of this zone is generally marked by a series of normal faults called South Tibetan Detachment Fault (STDF) system. This zone consists of 10-12 km thick succession of high-grade metamorphic rocks also known as Tibetan slab (Le Fort, 1975). This zone, along the Kali Gandaki, has been divided into three formations viz: Formation I, Formation II and Formation III (Le Fort, 1975). Formation I, which is the lowest unit consisting of kyanite-sillimanite-grade two-mica banded gneisses of pelitic to arenaceous composition. Formation II commonly begins with a coarse quartzite bed several tens of meters thick. It is mainly composed of an alteration of pyroxene and amphibole bearing calc-gneisses and marbles. Formation III is somewhat arbitrary and is characterized by a pelitic to greywacke character and a frequent occurrence of feldspathic layers of an embrechitic type (Le Fort, 1975).

2.1.5. Tibetan -Tethys zone

The northernmost tectonic zone of the Himalaya occupies a wide belt consisting of sedimentary rocks known as Tibetan-Tethys zone or Tethyan sedimentary sequence (Fig. 2). Only the basal portion, which is proximity to Higher Himalayan zone, has undergone very little metamorphism. This zone has been studied by many workers e.g. Bassoulet et al. (1977), Garzanti et al., (1999), and Godin (2003). Tibetan-Tethys zone consists of thick and continuous lower Paleozoic to lower Tertiary marine succession and is composed of limestone, shale, sandstone, quartzite etc. These rocks are considered to have been deposited in a northern part of the Indian passive continental margin (Liu and Einsele, 1994). This zone is well exposed in the Marsyangdi, Thakkhola, Kali Gandaki River and Manang area.

2.2. Characteristic feature of the grabens of the Himalaya-Tibet orogen

Grabens of southern Tibet and the Himalaya represent the Cenozoic extensional tectonic phase, which has affected whole Tibet and northernmost part of the Himalaya. These grabens are mainly distributed along the crest of the Himalaya, southern Tibet and central Tibet (Fig. 1). The major grabens of the Himalaya are, from west to east, Burang graben, the Thakkhola half graben, Gyirong graben, Kungo graben, Pum Qu graben and Yadong graben (Fig. 1). In the Himalaya all the grabens are limited south of the Indus-Tsangpo Suture Zone (ITSZ) except Yadong graben, which extends up to Gulu rift. Since the recognition of the north-south trending graben in crest of the Himalaya and Tibet, (Hagen, 1969; Molnar and Tapponnier, 1978; Armijo, 1986) numerous research have been carried out to improve the state of knowledge of the plateau evolution and east-west extension in the Himalaya-Tibet region. Despite the numerous works there are still diverse arguments about the origin of the graben and plateau formation. The onset of normal faulting, which corresponds initiation of graben, was estimated to commence in southern Tibet and the Himalaya 14 Ma ago (Coleman and Hodges, 1995) about 4 Ma ago (Yin et al. 1999) in central Tibet. However, Blisnuik et al. (2001) reported a minimum age of approximately 13.5 Ma for the onset of graben formation in central Tibet, based on mineralization ages on fault plane.

Molnar and Tapponnier (1978) firstly documented remarkably uniform spacing for north-south trending graben in southern Tibet. Armijo et al. (1986) reported decrease in graben spacing from south to north across the Tibetan plateau. Recently, Yin (2000) extensively documented the spacing of grabens (equivalent to rift as used by Yin, 2000). He defined the graben spacing as a distance between two centers of nearby graben's basin measured perpendicular to the strike of graben. Using above definition, four distinctive zones are recognized (Fig. 1): (1) the Himalayan region (south of ITSZ) (2) the southern Tibet region (between ITSZ and Bangong-Nujiang suture) (3) the central Tibetan region (between Bangong-Nujiang suture and Jinsha suture) (4) the northern Tibetan region (north of the Jinsha suture). Spacing analysis shows the graben spacing in the Himalaya and Tibet decreases systematically from south to north. In the Himalaya it is 191±67 km. In south Tibet it is 146±34 km. Farther north in central Tibet it is 101±31 km. The widely spaced grabens in the Himalaya and Tibet may have been related to the presence of a relatively light crust and a strong mantle lithosphere throughout Tibet (Yin, 2000). Systematic decrease in graben spacing can be attributed to the northward decrease in crustal thickness.

2.3. Geologic setting of Thakkhola half graben

Thakkhola half graben is located on the north-central Nepal between 83° 50'-84° long itudes east and 29° -28° 50' latitudes east and 29° -28° 50' lattitudes north. It lies in Palaeozoic to Cretaceous rocks of the Tethyan Series between STDF system (Burchfiel et al., 1992) to the south and ITSZ to the north (Fig. 3). The ITSZ marks the boundary between the Indian and Eurasian plate whereas STDF is the low angle, north dipping normal fault system located along the crest of the Himalaya. The Thakkhola half graben can be taken as a part of the normal faulting system affecting the whole Tibetan Plateau (Molnar and Tapponier, 1978). It shares uniqueness in several aspects particularly its location close proximity to the Himalayan Range, to the south of the ITSZ and above the STDF. The half graben is bounded by Dolpo-Mugu-Mustang middle Miocene leucogranite (Le Fort, 1975) to the west and Paleozoic and Mesozoic sediments and the Manaslu intrusive leucogranite (Le Fort, 1975) in the east. Comprehensive descriptions of the geology of the Thakkhola and adjacent area appear in Bassoulet et al. (1977), Fort et al. (1982), Garzanti et al., (1999), Godin (2003) and reference therein. Relevant details will be summarized below.

2.3.1. Stratigraphy

The tectonic stratigraphy of the Thakkhola half graben can be explained into two different units i.e. basement and syntectonic deposits. The Tibetan Tethys sedimentary sequence (or Tibetan-Tethys zone) serves a basement whereas half-graben basin filled by lacustrine and fluvial sediment represents the syntectonic deposits.

2.3.1.1. Tibetan-Tethys sedimentary sequence

A well-preserved Tibetan-Tethys sedimentary sequence is exposed in the Kali Gandaki valley (Fig. 3). In this section nearly continuous 10-km thick succession is visible, ranging from Cambrian to early Cretaceous.

The Paleozoic succession is characterized by a calcareous series, mainly comprising massive limestone and calcareous shale and local dolomitic and quartzitic horizons. The lowest part of this section is Sanctuary Formation, which comprises highly deformed black schist, sandstone and limestone. Overlying the Sanctuary Formation is the Annapurna Formation, which is composed of calcareous biotite-grade psamitic and semi-pelitic schist and phyllite. Although there are no direct chronological data, this unit has been interpreted as Cambrian in age, because it is stratigraphically under the Ordovician Nilgiri Formation (Bordet et al., 1971 quoted in Godin, 2003). The overlying Nilgiri Formation is composed of grey micritic limestone, grading upward into pink dolomitic sandstone, calcareous shale, and siltstone. The Ordovician series is capped by calcareous arkose and siltstone unit. The upper portion of the Paleozoic is composed of the alternating gritty dolomite, black shale, and limestone of the Sombre Formation (Silurian-Devonian). The Permian-Carboniferous units consist of a turbidite sequence dominated by calcareous shales with a minor siliciclastic inclusion.

The Mesozoic stratigraphy is essentially composed of Triassic calcareous shale (Thini Formation) grading upwards to Jurassic fossiliferous limestone and black shale (Jomsom, Baggung and Lupra Formations), which are capped by the detrital units (conglomerates, sandstones) of the Early Cretaceous Chukh Group (Bordet et al., 1971).

2.3.1.2. Basin fill stratigraphy

The syntectonic deposit of the Thakkhola half graben is characterized by a thick accumulation of continental debris extended over 90 km from north to south and about 20-30 km from east to west (Colchen, 1999). This pinches out in the southern most tip of the graben where it is about 2 km wide. The basin fills mollase: the Tetang and Thakkhola Formations are separated by angular unconformity. They lie unconformably on the high strain zone of the highly deformed Tibetan-Tethys sedimentary sequence.

Tetang Formation

Tetang Formation is well exposed in the southern, southeastern and eastern parts of the basin. In basal part, it consists of pebble and gravel mainly composed of clasts of quartzite and limestone derived from the Mesozoic bedrock. This is followed by polygenic conglomerates composed mainly of leucogranitic pebbles from Mustang leucogranites in the east. This is overlain by detrital grey layers at the top. Pliocene age has been assigned for the Tetang Formation palynologically (Fort et al., 1982) and by magnetostratigraphically (Yoshida et al., 1984).

Thakkhola Formation

Thakkhola Formation is crop out western and eastern part of the Tetang Formation (Fig. 3). It comprises conglomerates composed mainly clasts of metamorphosed Paleozoic rocks and Mustang leucogranites. This is capped by alternation zone of various facies, lenses of sandstone, imbrication of polygenic conglomerates and lacustrine limestone (Colchen, 1999). Magnetostratigraphic data show the 2.48 Ma for Thakkhola Formation (Yoshida et al., 1984). The sedimentation of the Thakkhola Formation is considered to be late Pliocene to Pleistocene in age.

2.3.2. Tectonic setting of Thakkhola half graben

The structural history of the Himalayan-Tibet system shows the two distinct stages of tectonic phase that took place subsequently. First the development of intracrustal thrusts that started around 24 Ma (for MCT) after that MBT (around 10 Ma) (Gansser, 1964; Stocklin, 1980; Valdiya, 1980; Le Fort, 1981; Chemenda et al., 2000). These thrusts are propagated from north to south as the Indian plate continued to subduct beneath the Eurasian plate since 50 Ma. This phase is responsible for tens of kilometers crustal thickening in the Himalaya. Second phase is characterized by a new tectonic phase involving north-south extension along the STDF (Burchfiel et al., 1992) and east-west directions (England and Houseman, 1989; Colchen, 1999; Yin, 2000). The rift system in southern Tibet including Thakkhola half graben coincides with this new tectonic phase of east west extension.

According to Colchen (1999), the structural pattern of the graben is mainly controlled

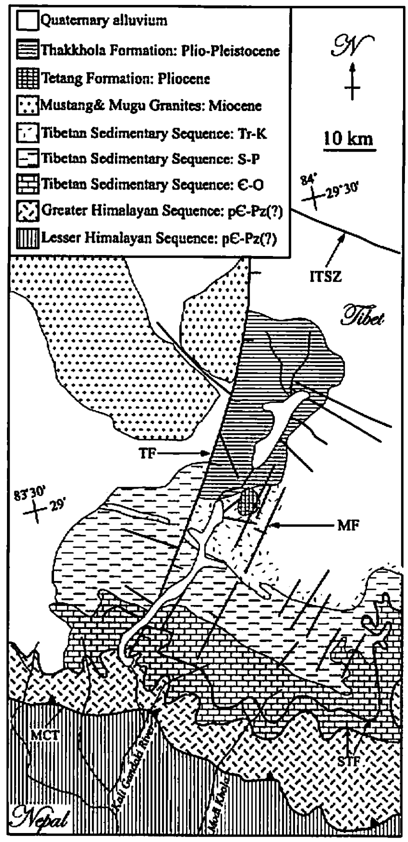


Fig.3 Geological map of the Thakkhola and adjacent area (modified after Hurtado et al., 2001) MCT: Main Central Thrust, STF: normal faults of STDF system, MF: Muktinath Fault, TF: Thakkhola Fault, ITSZ: Indus Tsanpgo Suture Zone.

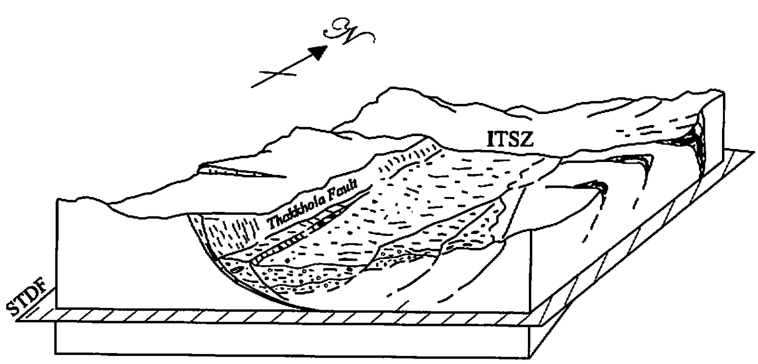


Fig.4 Structural disposition of the Thakkhola half graben. STDF: South Tibetan Detachment Fault system, ITSZ: Indus Tsangpo Suture Zone.

by a series of transverse faults (Thakkhola fault system) and cleavages striking N20° – 40°, which are responsible for the asymmetric nature of the graben (Fig. 3). Thakkhola fault system consists of number of extensional faults extending several kilometers and can be distinctly observed in the western side of the basin. The predominance of the sinistral Thakkhola Fault (or Dangardzong Fault, Hurtado et al., 2001) has caused remarkable asymmetry in the graben (Figs. 3 and 4). Characteristcs of the Thakkhola Fault varies from north to south. The Paleozoic-Mesozoic sequence has intensely crushed and shattered along fault plane. These structures are accompanied by other faults which strike N180°, N115° and N115° -160°. The syntectonic deposit is tilted where it is in direct contact with the fault. The Thakkhola Formation is deformed into NW-SE fold. On the basis of field geological data, Thakkhola half graben cannot be considered as a true rift (Colchen, 1999) whereas Yin (2000) superficially considered all Tibetan grabens including Himalayan graben as rift.

2.3.3. Structural evolution of Thakkhola half graben

The structural evolution of the Thakkhola half graben bears the complex kinematic and geometrical relationship with the STDF and Thakkhola fault (Dangardzong fault of Hurtado et al., 2001). According to Hurtado et al., (2001) during Miocene, Thakkhola fault was developed synchronous with the motion of the Annapurna detachment (a normal fault of STDF system). The clock-wise rotation of the Thakkhola fault due to its scissors-like kinematics is responsible for the development of the half garben. Part of this rotation has also been accommodated by the segmentation of footwall along east-striking oblique-slip faults. Paleostress analysis (Colchen, 1999) reveals a succession of compressional and extensional regimes. In the first phase N-S compression has occurred resulting the development of the Thakkhola fault, which was followed by extensional regime with occurrence of strike slip faults, perhaps ~14 Ma ago as suggested by Coleman and Hodges (1995). Next extensional phase occurred during Pliocene to Pleistocene (Tetang and Thakkhola period) mainly in WNW-ESE direction that relates to the development of the half graben.

2.3.4. Mechanism of graben formation

Grabens are common extensional features of the continental regions. Particularly they are dominant structures of ancient and modern continental rifts. However they are also associated with plateau uplift and doming e.g. grabens of the Himalaya, southern Tibet and Colorado Plateau. The classical mechanism of graben formation was first suggested by Vening Meinesz (1950) (as quoted in Melosh and Williams, 1989). According to him continental crust can be treated as elastic layer floating on a denser fluid substratum formed by the topmost mantle layer and graben can be formed as an extension on the upper portion of the brittle elastic layer. The first stage is the formation of a planar normal fault with a dip of 60° in accordance with Anderson's (1951) theory of normal faulting in response to crustal tension. The downbending of the crust on the downthrown side produces a supplementary tension, which initiates the formation of second normal fault at a position of maximum bending, calculated to be 65 km from the original fault. The newly initiated fault propagates downward, again with a dip of approximately 60° then a downward narrowing wedge subsides isostatically, as the adjacent parts of the crust bend upwards to form the rim uplifts. In this model the new fault can incline either toward the original fault (antithetic fault) or parallel to the original fault (synthetic fault). This model is valid only for the rock unit cut by the initial normal fault that can be approximated by a floating elastic plate. Thus for small grabens (1-10 km wide), which do not extend to such a great depths, this explanation is plausible.

Alternatively, McKenzie (1978) suggested the lithospheric stretching mechanism in which hot asthenospheric material upwells beneath the thinned lithosphere and the geothermal gradient within the lithosphere steepens in proportion to the thinning. The heating and thinning of the mantle part of the lithosphere causes isostatic uplift, but this is outweighed by subsidence caused by thinning of the continental crust unless the initial lithosphere is unrealistically thick. Thus there is an initial subsidence contemporaneous with the stretching.

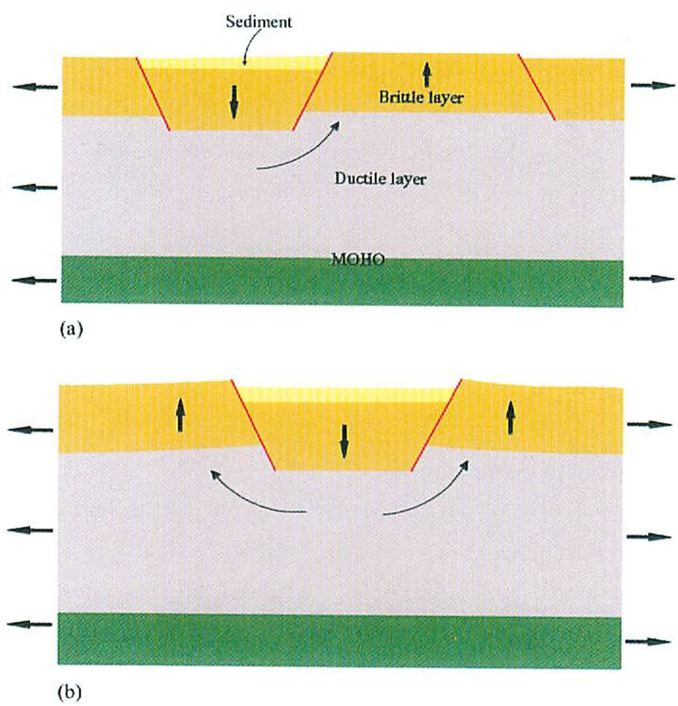


Fig.5 Graben formation by wedge subsidence (modified after Bott and Mothen, 1983) (a) Subsidence compensated by horst uplift (b) Subsidence compensated by elastic upbending.

Bott and Mithen (1983) presented the wedge subsidence hypothesis (Fig. 5). In contrary to Vening Meinesz's (1950) model they assumed lower layer as ductile rather than completely inviscid. They forwarded the energy balance calculations, which indicate that the mechanism depends on the occurrence of substantial deviatoric tension, but it requires a much smaller extension than the McKenzie's lithospheric stretching hypothesis. This mechanism is effective where the geothermal gradient is relatively high to allow ductile flow of lower crust, and the friction on the fault must be less than that on the dry rock. In comparison, this model is more appropriate to explain shallow depth garbens, which are confined within the crustal level of the earth. Regarding Thakkhola half graben, the geological and geophysical evidences support the Bott and Mithen's wedge subsidence hypothesis. The underlying Higher Himalayan sequence with low velocity zone of lower crust might have acted as a ductile layer over which Tibetan Tethys sequence extended forming north trending grabens in the Himalaya-Tibet orogen.

3. Modelling of half graben

A two-dimensional plane-strain elastic finite element method was applied to understand the genesis of the Thakkhola graben. The plane strain assumption is justified because grabens are generally much longer than width. Results of the numerical simulations depend entirely on the several rock layer properties and boundary conditions. Since the rock layer properties of the upper crust are relatively well known, the poorly unknown parameters are constrained to the limited range so that simulated models reveal the realistic results. Therefore, this modelling not only shows the genesis of the Thakkhola half graben, but also predicts probable values for the properties controlling the evolution.

The purpose of the numerical simulation is to investigate stress distribution and development of the Thakkhola half graben. We assume that rock layers deform elastically until Mohr's stress circle reaches the Mohr-Coulomb failure envelope, after which faulting occurs, the condition can apply for the upper crust. Here, σ_1 and σ_3 are the maximum principal compressive stress and minimum principal compressive stress, respectively. Before we present the result of model experiments, we explain model geometry, boundary conditions and rock layer properties used in this modelling.

3.1. Model geometry

Thakkhola half graben in the Himalaya probably formed by gravitational spreading of the elevated plateau driven by excess gravitational potential energy and it is kinematically related to STDF system. To explain the genesis of the graben, cross-section given by Colchen (1999) has been chosen and is simplified according to similarity of the rock layer properties. East-west cross-section represents the structural configuration of the graben. The overall length of the model is about 56 km and thickness varies up to 12 km (Fig. 6). Two types of geometry have been used: with and without detachment fault (Thakkhola fault). The detachment fault is considered as a weak zone. It is not possible to show slip along the fault in the proposed numerical model. Therefore the assumption of weak fault zone is justifiable. Further structural data of the region have revealed that the Thakkhola fault merges with the STDF system decollement at depth in a listric-geometry (Hurtado, et al., 2001).

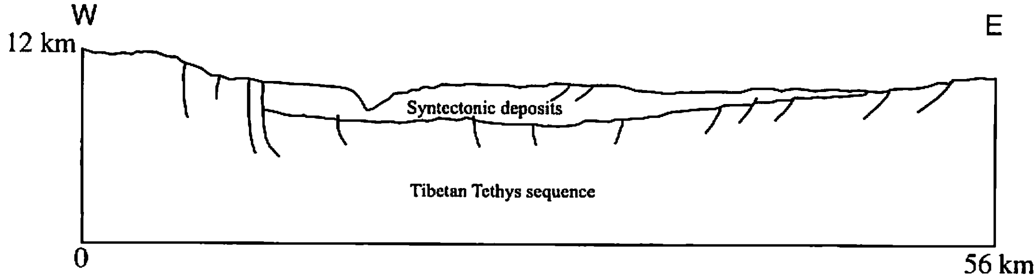


Fig.6 E-W structural cross section of the Thakkhola half graben (modified after Colchen, 1999).

3.2. Boundary condition

Selection of the boundary condition is one of the crucial steps to simulate the tectonic processes. In order to mimic the natural situation, we impose simple boundary condition representing the present day plate kinematics in the southern Tibet. In all models, the

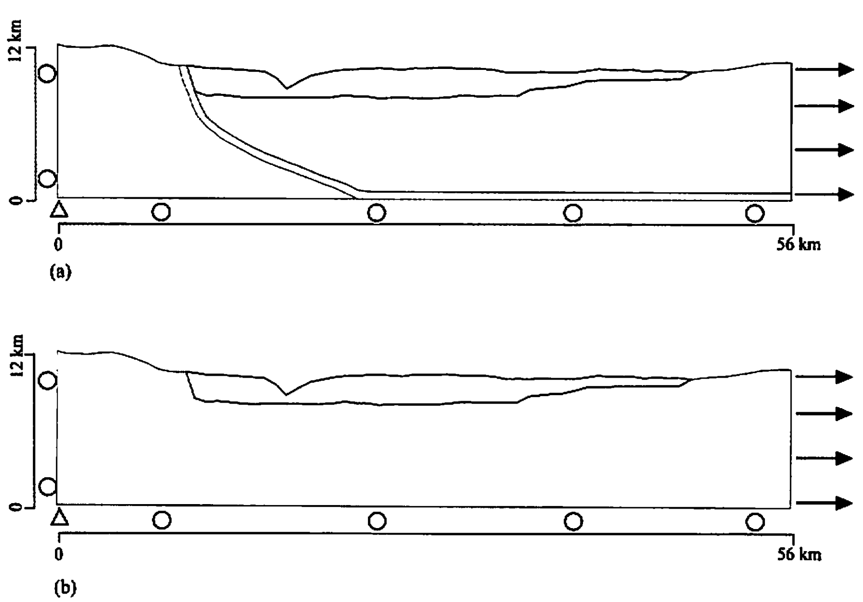


Fig.7 Geometry and boundary condition of model. (a) with detachment fault (b) without detachment fault.

upper surface is free. The lower boundary is only permitted to deform horizontally. The nodes along the left boundary of the each model can only move vertically whereas from the right side of the models, we imposed extensional displacement progressively from 10 m to 50 m to produce horizontal extension at the rate of 1 mm/year (Jouanne et al., 2004) (Fig. 7).

3.3. Rock layer properties

Results of numerical modelling strongly depend on several rock layer properties, geometry and model dimension. Therefore several of the rock layer properties were varied systematically to explore their effect on the structural evolution of the Thakkhola half graben. For the sake of simplicity in calculation, the entire model was divided into two layers excluding weak detachment zone taking enough caution of tectonostratigraphy. Each layer has been assigned with distinct rock layer properties giving emphasis on the dominant rock type. We performed parametric calculation using different values of key parameters, e.g. density, Young's modulus, cohesion and friction angle (Fig. 8). We adopted

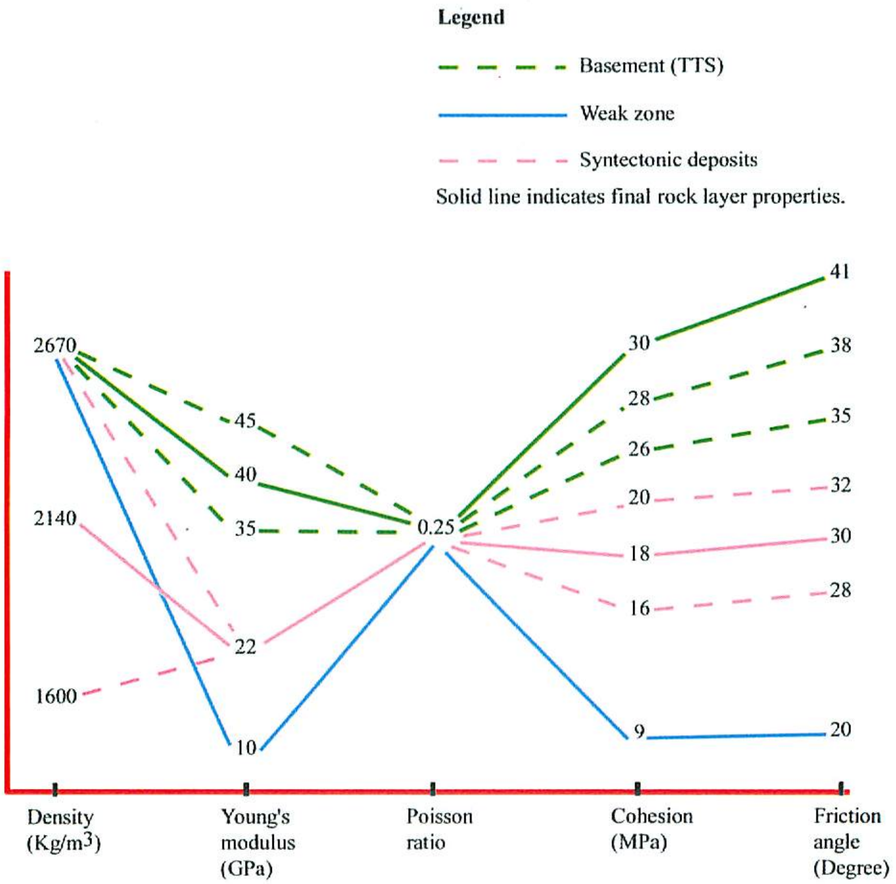


Fig.8 Chart showing the variation of rock layer properties during computation.

the most suitable set of layer properties for calculation, which is shown in Table 1.

Table.1 Rock layer properties

layer	lithology	density (kg/m³)	Young's modulus (GPa)	Poisson ratio	cohesion (MPa)	friction angle (degree)
TTS	limestone, shale, sandstone	2670	40	0.25	30	41
syntectonic deposit	conglomerate, siltstone, glacio-lacustrine sediments	2140	22	0.25	18	30
fault zone	crushed rock	2670	1	0.25	9	20

3.4. Failure analysis

To observe the growth of graben fault system, failure analysis was carried out. Mohr-Coulomb criterion was used to find the proximity to rock failure.

Since the analysis is carried out in plane strain, it is possible to calculate the value of third principal stress (σ^*), which is perpendicular to $\sigma_1 - \sigma_2$ plane using the equation

$$\sigma^* = \nu(\sigma_1 - \sigma_2) \quad \cdots\cdots (1)$$

Where ν is the Poisson ratio (Timosenko and Goodier, 1970; Hayashi and Kizaki, 1972). After comparing the values of σ_1, σ_2 and σ^*, we can recognize the newly defined σ_1, σ_2 and σ_3 as the maximum, intermediate and minimum principal stresses respectively. As shown in Fig. 9, the Mohr-Coulomb criterion is written as a linear relationship between shear and normal stresses,

$$\tau = c - \sigma_n \tan\phi \quad \cdots\cdots (2)$$

Where c and ϕ are the cohesive strength and the angle of internal friction respectively. Failure will observe when the Mohr's circle first touches the failure envelope (Fig. 9). It takes place when the radius of the Mohr's circle, $(\sigma_1 + \sigma_3)/2$, is equal to the perpendicular distance from the center of the circle at $(\sigma_1 + \sigma_3)/2$ to the failure envelope,

$$\left(\frac{\sigma_1 - \sigma_3}{2}\right)_{failure} = c\cos\phi + \left(\frac{\sigma_1 - \sigma_3}{2}\right)\sin\phi \quad \cdots\cdots (3)$$

According to Melosh and Williams (1989), the proximity to failure is the ratio between the stress and the failure stress and is given by

$$p_f = \left[\frac{\left(\frac{\sigma_1 - \sigma_3}{2}\right)}{\left(\frac{\sigma_1 - \sigma_3}{2}\right)_{failure}}\right] \quad \cdots\cdots (4)$$

When the ratio reaches one (P_f =1), failure occurs, but when P_f < 1 stress is within the failure envelope, rock does not fail. The proximity to failure reveals which parts of the model are close to failure or already failed by generating faults.

The type of faulting has been determined by the Anderson's theory (1951). According to his theory three classes of faults (normal, strike slip and thrust) result from the three principal classes of inequality that may exist between the principal stresses.

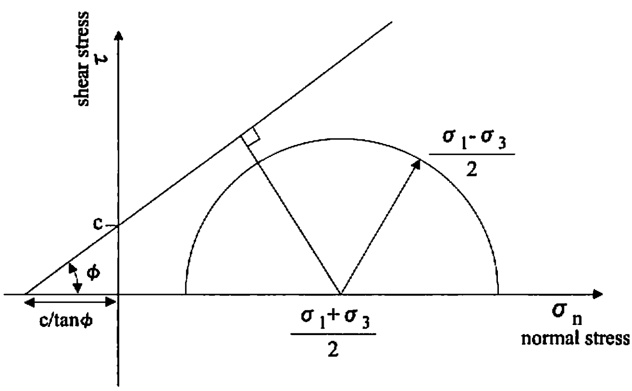


Fig.9 Mohr-Coloumb criterion.

4. Modelling results

Primarily based on the geologic cross-section (Colchen, 1999), the stress regime of northernmost part of the Himalaya was simulated using elastic rheology under plane strain condition. Since model consists of two types of geometries (with and without detachment fault), the simulated stress regimes are explained with respect to both model geometries. Gravitational force is taken into account and horizontal extension is applied progressively.

4.1. Stress field

4.1.1. Stress field with detachment fault

This model assumes detachment fault as a weak zone. This zone resembles Thakkhola fault system in nature. Since the model cannot simulate the slip on the fault this assumption bears some meaning in this regard. The rock layer properties for this zone are assigned in such a way so that it could simulate the slip along the detachment. The stress field under 10 m horizontal extensional displacement is shown in Fig. 10a. Compressive nature of the stress is found in all layers. Lower magnitude of σ_1 and σ_3 is observed in upper part of the model. The magnitude of maximum (σ_1) and minimum (σ_3) compressive stresses increases with depth. The orientation of σ_1 and σ_3 is vertical and horizontal respectively. With increasing horizontal extensional displacement, extensional stress is dominantly observed in the upper portion of both layers (Fig. 10b). Such stress field is responsible to induce normal faulting in the extensional regime. Some attempts are made to show the effect of density contrast between the basement rock and syntectonic deposits on the stress field. Lowering the density contrast, the magnitude of the stress increases on the syntectonic deposits domain whereas decreases with increase in density contrast. Unfortunately there is no effect on the stress orientation except slight variation in stress magnitude.

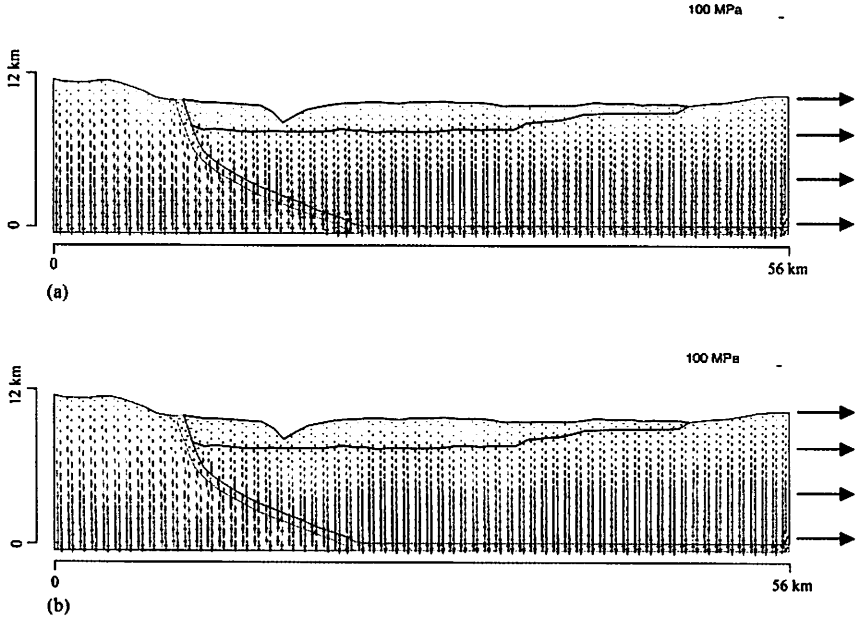


Fig.10 Stress field at (a) 10 m (b) 50 m horizontal extension with detachment fault. Red bar in stress field shows tensional stress.

4.1.2. Stress field without detachment fault

No significant changes are found on stress state and stress magnitude in the case of without detachment fault compared to the case with detachment fault. In the initial stage of extension, mostly compressive state of stress is observed (Fig. 11a). With increasing horizontal extensional displacement, extensional stress is dominantly observed in the upper portion of both domains (Fig. 11b), and could be considered as a productive stress field to cause normal faulting in extensional tectonic environment. No significant changes are observed in the stress field though density contrasts are applied.

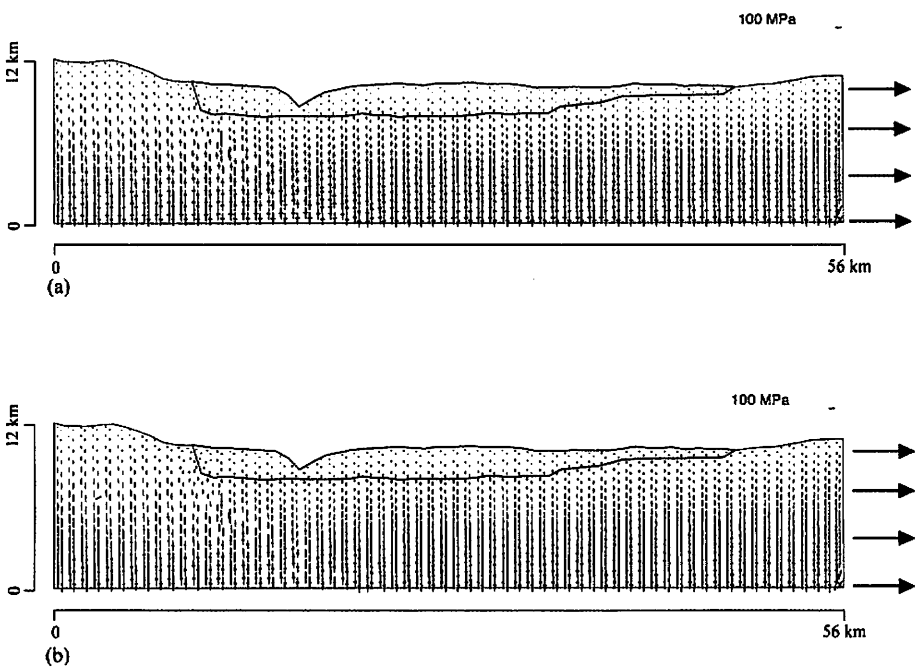


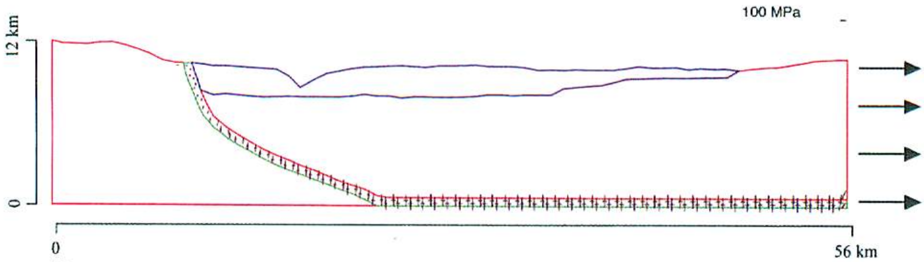
Fig.11 Stress field at (a) 10 m (b) 50 m horizontal extension without detacment fault. Red bar in stress field shows tensional stress.

4.2. Pattern of Mohr-Coloumb failure

The failure pattern is analyzed using Mohr-Coloumb criterion (Melosh and William, 1989) as described above. Since one of the objectives of the present modelling is to investigate effect of the detachment fault on development of the Thakkhola half graben, it is reasonable to describe failure pattern separately for two different cases: with and without detachment fault.

4.2.1. Case I-with detachment fault

The region where failure has taken place during progressive extension from 10 m to 50 m are analyzed to understand mode of faulting and their implication to the development of the Thakkhola half graben. Principal stresses with red bar denote failure in tension and with black bar for failure in compression. At the initial extension of 10 m both layers are free from failure. As the applied extension is progressively increased, the zone of failure both in tension and compression extends in depth. Normal faulting in compression may be, because of compression resulting from overlying material, which opposes the extensional tension. After applying 20 m extension faults are developed only in basement rock nearby weak zone. But no faults occurred within the half graben (Fig. 12a). With increasing extensional displacement, failure elements are observed around weak zone in basement. Some failure elements are localized either side of the gorges of the Kali



(a)

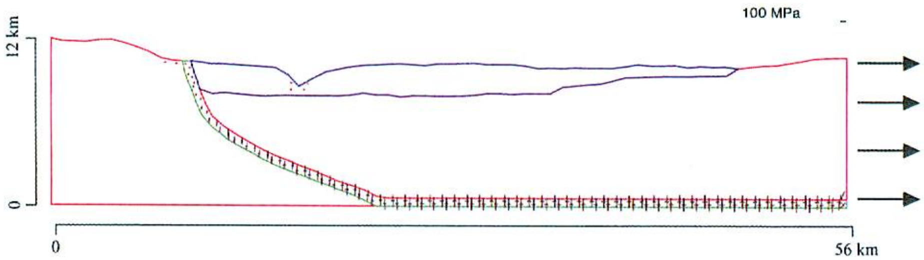
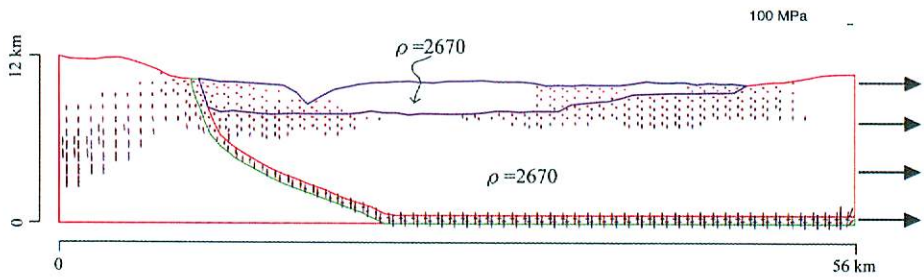
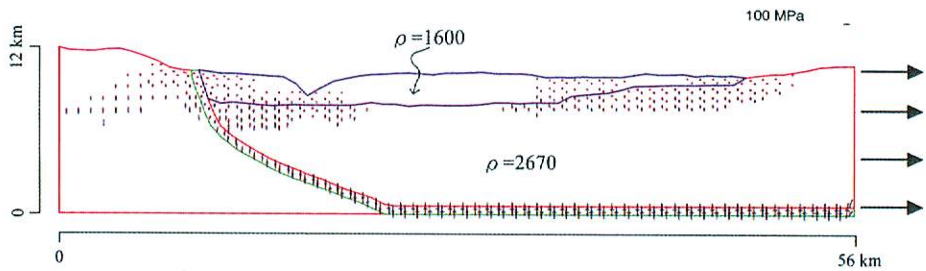


Fig.12 Failure elements at (a) 20 m (b) 30 m (c) 40 m (d) 50 m horizontal extension with detachment fault.



(a)



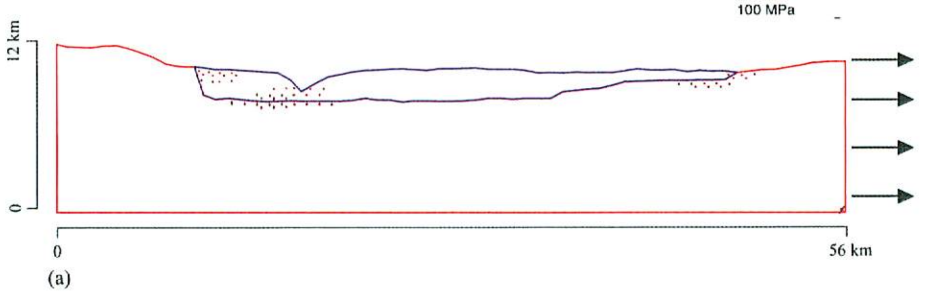
(b)

Fig.13 Failure elements at 50 m horizontal extension with detachment fault (a) increasing (b) decreasing density of the syntectonic deposits.

Gandaki River, which is the effect of geometry of the model (Fig. 12b). During 40 m extensional displacement failure elements are developed on the upper part of the basement and western part of the syntectonic deposits (Fig. 12c). These failure elements correspond to the graben bounding faults. After applying 50 m extensional displacement failure elements are extensively developed in both domains (Fig. 12d). Notable difference is observed on failure during the density variation of the syntectonic deposits. With increasing density, more elements are failured in the basement (Figs. 12d and 13a). Conversely, decreasing density results few failure elements in the basement (Figs. 12d and 13b). The overall pattern of failure replicates the nature.

4.2.2. Case II-without detachment fault

In this case also failure analysis was carried out in progressive horizontal extension to compare the effect of detachment fault on graben development. No failure is observed till 20 m extensional displacement. During 30 m extension, few elements are failed around gorges of the Kali Gandaki River. This is the effect of the topography. Under the 40 m extension failure elements are developed on the top of the basement and western part of the syntectonic deposits (Fig. 14a). Increasing extension failure elements are developed extensively in both layers (Fig. 14b). As compare to model with detachment fault, the failure elements in this model are deeply rooted. In contrast to the model with detachment



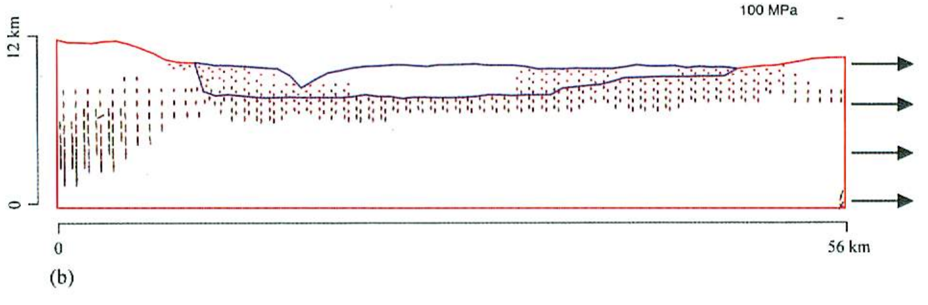


Fig.14 Failure elements at (a) 40 m (b) 50 m horizontal extension without detachment fault.

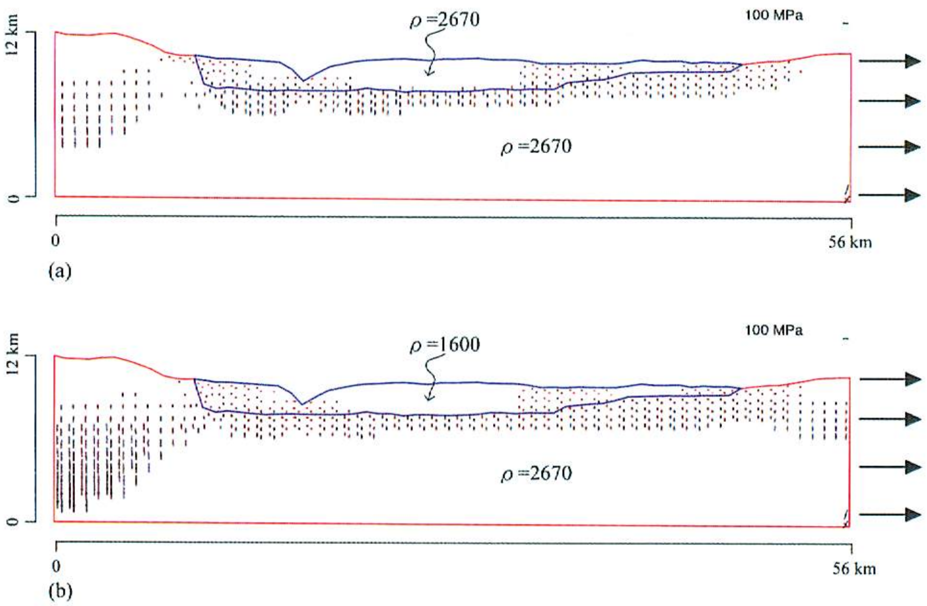


Fig.15 Failured elements at 50 m horizontal extension without detachment fault (a) increasing (b) decreasing density of the syntectonic deposits.

fault, increase in density of syntectonic deposits, few elements are failed in the basement (Figs. 14b and 15a). Conversely, decreasing density failure elements are developed beyond the graben bounding faults, which are rooted deeply and cannot precisely reconcile the nature (Figs. 14b and 15b). This indicates that the initial fault together with rheology has significant effect on depth of the fault and the width of the graben.

5. Discussion

5.1. Model set-up

The finite element models, presented and discussed above, have been performed with two-dimensional space, with a simple present-day geometry of the Thakkhola graben assuming homogeneous and isotropic material within the individual layer. In nature the behaviour of rocks is not homogeneous and isotropic. Furthermore, the rock layer properties used in this simulation are not experimentally determined. We performed series of test calculation using different values of key parameters. Finally, we adopted only the most suitable set of rock layer properties for calculation. However caution has taken to avoid wide fluctuation from their real values. Further, we assumed that the crust behaves elastically though it is brittle-elastic-plastic in nature. Although our models remain simple, assumed data are consistent with existing field data.

5.2. Stress state in Himalaya-Tibet orogen

Numbers of authors made attempts to assess the state of stress in the Himalaya and adjacent areas (Cloetingh and Wortel, 1986; Shanker et al. 2002, Chamlagain and Hayashi, 2004). Nakata et al. (1990) deduced the N-S direction of the maximum horizontal principal stress (σ_{Hmax}) for eastern and central sectors of the Himalaya using type and strike of the active faults. He further noted that the direction of σ_{Hmax} have changed following the change in the direction of the relative motion between the Indian plate and the tectonic sliver which have detached together along the transcurrent faults in the Eurasian plate. These studies clearly indicate that regional direction of σ_{Hmax} is consistent with relative plate motions at least in the central sectors of the Himalaya. The stress state of the northern most part of the Himalaya and Tibet is quite different due to its different tectonic regime and structural configuration. Immediately north of the highest peak of the Himalayas, the tectonic regime is dominated by east-west extension, which is dominantly characterized by strike slip and normal fault system (Blisniuk et al., 2001). The cause of the Tibetan extension and its relationship to the change in elevation of Tibetan Plateau are of fundamental importance to the continental tectonics. One common explanation for the Tibetan crustal extension is gravitational collapse driven by excess gravitational potential energy. In this regard numbers of study have been carried out. Based on the results of the numerical simulation on dynamics of the continental plateau uplift, there is general agreement that east-west extension in Tibet was triggered by elevation of the plateau to the point when topography-related extensional stresses exceeded compressional stresses related to the continent-continent collision (England and Housman, 1989). Further, fault plane solutions of the central Tibet indicate large components of normal faulting under extensional stress regime (Molnar and Tapponier, 1978). The kinematics drawn from microtectonic measurements has revealed the similar state of stress in southern Tibet (Tapponier et al, 1981).

Paleostress analysis in the Thakkhola basin (Colchen, 1999) has successfully shown polyphased faulting and stress direction with relative chronology: (a) N-S compressional stress regime with dextral and sinistral conjugate strike slip fault (b) extensional regime with recurrence of strike slip faults in normal faults 14 Ma ago (Coleman and Hodges, 1995) (c) extensional regime during Tetang and Thakkhola periods (Pliocene probably to Pleistocene). Now it is clear that the Thakkhola graben has suffered series of extensional and compressional stress regime during its evolutionary history. Numerical models also show the tensional nature of the stresses in the upper part of the models. Lower part of the models is characterized by higher magnitude of compressive stresses. In an extensional regime, the maximum principal stress (σ_1) is vertical whereas minimum stress (σ_3) is horizontal (Anderson, 1951). Since the orientation of σ_1 and σ_3 stresses is vertical and horizontal respectively, the applied boundary condition is suitable for simulating extensional fault system. With increasing horizontal extensional displacement, tensional stress is dominantly observed in the upper portion of both layers. This stress field is in good agreement with the normal faulting in the extensional regime of the Thakkhola half graben fault system. Changes in horizontal extensional displacement do not affect the stress distribution pattern throughout the simulation. Further changes in rock layer property only show slight effect on magnitude of stresses. Thus it can be concluded that the stress regime in the Thakkhola half graben is mainly controlled by its tectonic boundary condition rather than litho-mechanical property of the formations.

5.3. Development of graben faults in Thakkhola half graben

Thakkhola graben is bounded by two major normal faults: Thakkhola fault in west and Muktinath fault in the east. These faults extend up to ITSZ to the north and STDF to the south. Thakkhola fault has caused significant asymmetry in the graben and merges to STDF decollement at depth in a listric geometry. Apart from these, numerous submeridional faults with synthetic and antithetic nature have been mapped both in syntectonic deposits and basement rock. The extensional graben faults form at the top of the overburden and propagate downward. At the initial stage of extension, faulting mainly occurred eastern and western side of the models, which correspond with the major graben bounding faults. The model can suggest that natural graben have multiple faults on each side rather than single fault and is realized in the model where diffused failure elements are observed. The spacing between these failure zones clearly replicates the graben widths. However the failured elements in the western sector of the model is deeper than that of eastern sector, which is charecteristic for the development of the half graben. In this regard this simulation confirms the first order characteristics of the Thakhola halt graben development. The models also conclude that the structural development of the half graben depends sensitively on the rock layer properties. Assumption of the weak zone does not make significant difference on stress distribution and faulting. Thus it seems that the weak zone (equivalent to the Thakkhola fault system) did not only contribute to development of the half graben. Instead topographical loading and tectonic boundary condition might have played important role.

5.4. Factors controlling graben width and depth

Factors controlling graben width and depth have not been completely understood yet. Numbers of factors may have significant effect on graben width e.g. rheoloy, depth of initial fault. Golombeck (1979) pointed out the effect of layer discontinuity in material properties. But it is not always true that the initial fault will always terminate in such a rheological discontinuity. In some situations, plane of weakness, local inhomogeneties or stress concentrations may be effective factors. Melosh and Williams (1989) showed that the depth of the initial normal fault primarily control the width of the graben rather than depth of the mechanical layer discontinuity. In this study, proposed models have revealed that the density of the syntectonic deposits have control on the graben width together with initial detachment fault. Increasing density of the syntectonic deposits has resulted increase in depth of the failure elements, which in turn increase the width of the graben (Figs. 12d and 13). But the reverse effect was observed in the models without initial detachment fault (Figs. 14b and 15). Thus the width and depth of the graben are mainly controlled by rheological discontinuity and initial detachment fault. However effect of state of stress in the brittle crust cannot be ruled out as proposed by Reiter et al. (1992).

5.5. Seismicity in Nepal Himalaya

The territory of Nepal is characterized by a very intense microseismic activity. The whole area is seismically active, but lateral variations are also observed. Microseismic activity is particularly active in eastern and far-western Nepal with small clustering in central Nepal Himalaya. A detailed study of microseismic events reveals that three distinct clusters i.e. in eastern Nepal it lies between longitudes 86.5° E and 88.5° E, central Nepal 82.5° E and 86.5° E (south east of the Thakkhola graben) and western Nepal 80.5° E and 82.5° E (Fig. 16). This clustered zone is directly related to interseismic deformation. The

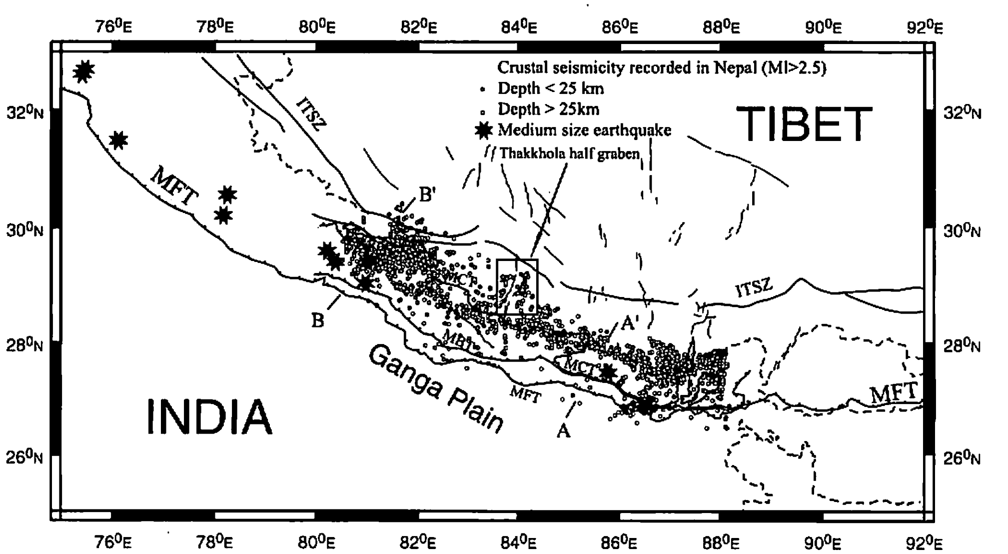


Fig.16 Microseismicity Map of Nepal monitored between May 1994 and January 1998 (modified after Jouanne et al., 2004).

projection of the microseimic events on geologic cross sections reveals a noticeable change in shape of cluster in western and central Nepal. In central Nepal it shows rounded form lying in vicinity of the mid crustal ramp wheras in western Nepal it has horizontally elongated shape along a gently dipping segment of the MHT (Fig. 17). These clustering

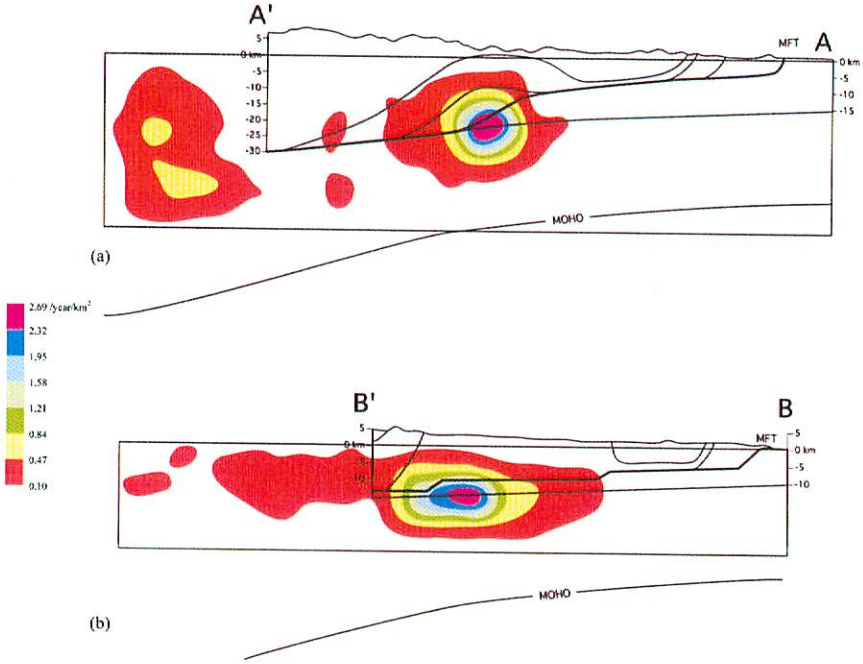


Fig.17 Density distribution of epicenters (a) central Nepal (b) western Nepal. "Reprinted from Journal of Asian Earth Sciences, vol. 17, Pandey et al. "Seimotectonics of Nepal Himalaya………, p710, (1999) with permission from Elsevier".

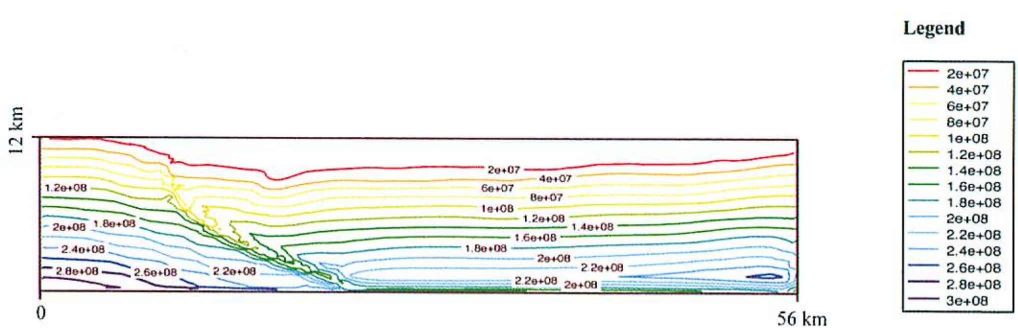


Fig.18 Critical cohesive strength in Pa (with detachment fault at 50 m horizontal extension).

microseismic zones are attributed to stress accumulation in the interseismic period during which the decollement beneath the Lesser Himalaya probably remains locked with aseismic creep, which is located beneath the Higher Himalaya (Pandey et al. 1999).

Seismicity in southern Tibet is quite different. It has experienced numbers of deep-seated mantle normal fault earthquake sporadically (Chen and Kao 1996). Mostly microseismic events tend to be localized near the main active N-S normal faults in southern Tibet. Microseismic data show the intense and continuous activity along the Pum Qu graben. Thakkhola and Kung Co grabens show continuous moderate seismicity (Fig. 16). Therefore it is clear that most of the microseismic events are concentrated along the N-S grabens and active normal faults of the southern Tibet. Further, higher critical cohesive strength (CCS) around the graben bounding faults (Fig. 18) corresponds to high seismicity zone (Fig. 16) of the Thakkhola graben. Thus it can be predicted that graben extension is still in progress along the Thakkhola fault.

5.6. Proposed mechanism for genesis of Thakkhola half graben

Despite the numerous researches, there is still debate on graben evolution in the meaning of east-west extension in the Himalaya-Tibet orogen. In this context the gravitational collapse driven by the excess gravitational potential energy can simply explain the viable mechanism for this most debated topic. Yin (2000) proposed general model for all Himalaya-Tibet rifts giving emphasis on asthenospheric upwelling beneath Himalaya and Tibet. According to the model, upper crustal normal faults sole into the ductile shear zone in the middle and the lower crust. The mantle lithosphere is thinned in response to extension either by brittle faulting in upper crust or ductile flows in the lower crust. Because of lithospheric thinning, mantle asthenosphere is upwelled and have produced synrifting magmatism in rift valley. This model can explain the origin of the Baikal rift and Shanxi graben in southeast Siberia and north China. However there is no evidence of magmatism in the Thakkhola half graben. Thus Yin's (2000) model can be ruled out.

It is suggested that Tibetan Plateau uplift and east-west extension are responsible for the Thakkhola half graben evolution. The most debated point is timing of plateau uplift and east-west extension. Garzione et al. (2000) argued that the Tibetan Plateau attained its current elevation prior to east-west extension using isotopic composition of meteoric water ($\delta^{18}o$). Further, they reported that the initiation of the Thakkhola half graben extension is constrained between 10 and 11 Ma based on magnetostratigraphy of the older Tetang Formation. Based on the field information and our modelling results, we proposed schematic model (Fig. 19). Since the onset of subduction, the Indian plate deformed in different stages. According to Chemenda et al. (2000) subduction of the Indian plate caused the formation of huge accretionary prism and the failure of subducted crust (Fig. 19a). After the first break-off (Fig. 19b), delamination occurred by which Indian upper crust started to underplate with Eurasian lithospheric mantle (Fig. 19c). This caused onset of uplift in Tibet. After the second break-off, whole regime switched to compressional state and MCT was formed at around 24 Ma (Fig. 19d). And it is believed that STDF was formed coeval with MCT in this stage. Because of buoyancy, crustal flow occurred beneath the Tibet by which Eurasian lithospheric mantle is replaced by Indian upper continental crust (Fig. 19e). This major event around 14.5 Ma (Coleman and Hodges, 1995) caused

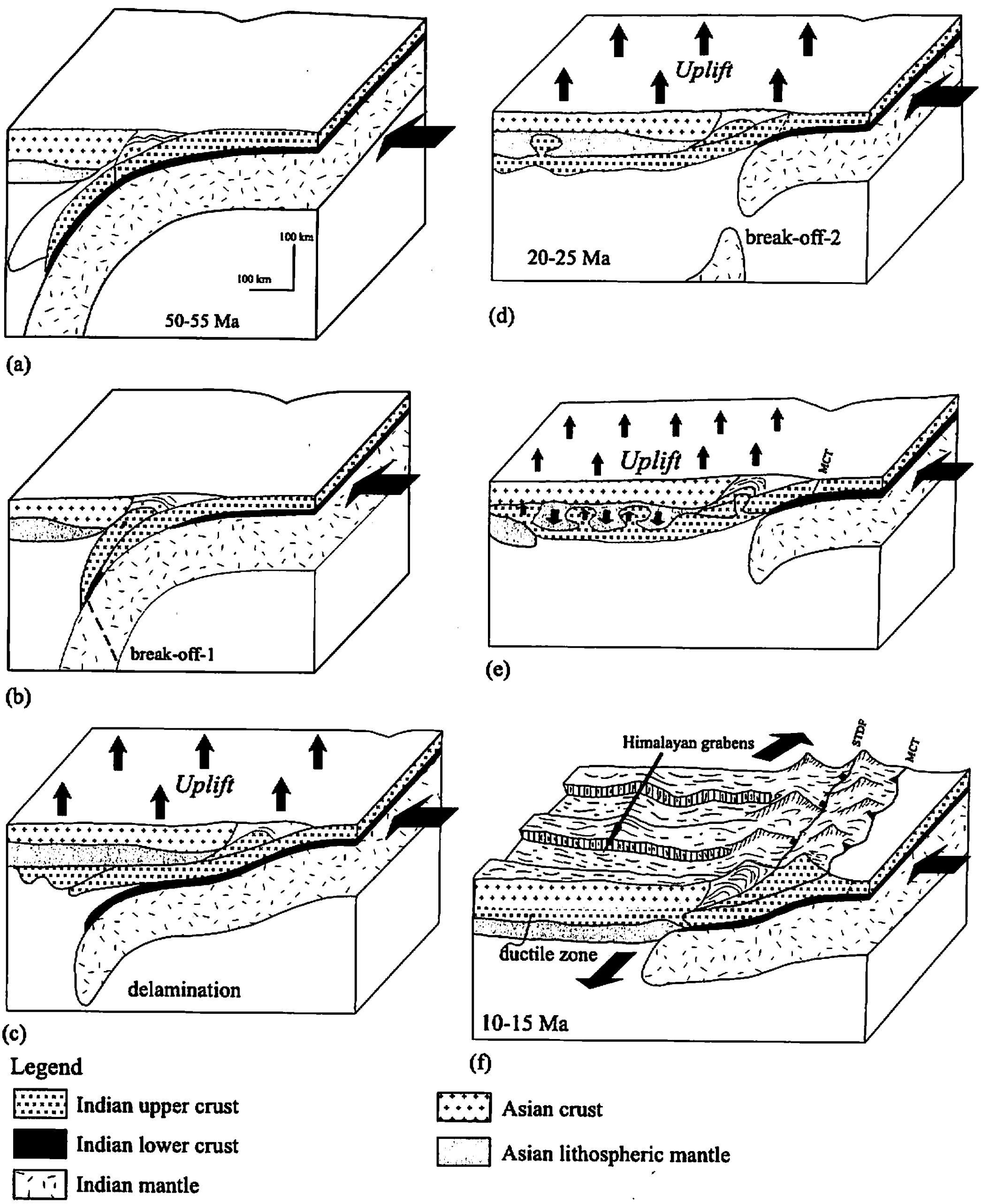


Fig.19 Schematic model showing the tectonic evolution of the Himalyan grabens.

significant uplift in Tibet and it attained maximum elevation. In this stage topography related excess gravitational potential energy (GPE) of the Himalayan-Tibetan Plateau relative to the surrounding lowland area exceeds the compressional stresses related to the continent-continent collision, which caused the east-west extension in the Himalayan-Tibetan orogen (Fig. 19f). The excess ΔGPE is given by

$$\triangle GPE = \int_{-h}^{z} \triangle \rho gz dz$$

Where h is the elevation of the plateau above the reference lowland, z is the depth, $\Delta \rho$ is the density contrast between the plateau and lowland at depth z, and g is the acceleration due to gravity. The geochronological data have also shown that this event occurred after plateau attained its maximum elevation (Coleman and Hodges, 1995; Garzione et al., 2000). This major extensional phase was solely responsible for the initiation of the Thakkhola half graben in the crest of the Himalaya. After the initiation of the Thakkhola fault, hanging wall block in response to extension subsided isostatically. For the mechanism to be effective, low velocity zone (partially molten) beneath the Himalaya-Tibet might have allowed ductile flow of the lower crust. Further extension in the graben might have caused due to movement along the Karakoram fault and STDF. Hurtado et al. (2001) argued that the Dangardzong fault (equivalent to the Thakkhola fault) and its kinematics with the Annapurna detachment (normal fault of the STDF) played crucial role during its development. However, our numerical models, constrained only with simple extensional boundary condition, reveal no significant difference either with or without detachment fault in development of the half graben. Instead, rock layer properties are found to be sensitive to graben evolution. Although numerous factors may have contributed to the formation of north-south trending graben, their relative roles are often debated. But the extension caused by topographical loading and its excess gravitational potential energy could be the major factors. Admittedly, role of basal shear, rheologic structure and tectonic boundary condition cannot be ignored.

6. Conclusions

Thakkhola half graben is one of many north-south trending grabens that define the Neogene structural pattern of the southern margin of the Tibetan Plateau and is seemingly enigmatic feature in a regionally contractional tectonic setting between the colliding plates. Gravitational collapse driven by the excess gravitational potential energy can explain the viable mechanism for development of north-south trending grabens in southern half of the Tibet and Himalaya. Two-dimensional plane-strain elastic finite element models illustrate the mechanism involved in the graben development and constrain the possible rock layer properties.

The extensional graben faults were formed at the top of the overburden and propagate downward. During the progressive extensional displacement failure elements are concentrated at two extremities of the graben, which directly correspond to the graben bounding faults. Simulated models can suggest that natural grabens have multiple faults on each side rather than single fault, which can be realized in model where diffused failure elements are observed. However these faults initiate nearly in the same time, but not exactly, simultaneously. Further increasing extensional displacement, depth of faulting increased. Deformation is mainly localized in downthrown block both in basement and syntectonic deposits. Syntectonic domain is characterized by normal faulting in tensional tectonic stress field, which is the common feature of the small-scale graben at post rift deformation stage. The width and depth of graben are primarily controlled by the rheology of the upper elastic layer and syntectonic deposits. The depth of the initial normal fault is also important parameter that controls graben width and subsidence. Graben growth faults are found to be very sensitive to rock layer properties of the formations. The applied rock layer properties are able to deduce the first order characteristics of the Thakkhola half graben. Therefore this simulation constrains probable values for the rock properties controlling the graben evolution. Assumption of the weak zone does not make significant difference on stress distribution and faulting. Thus it is argued that the weak zone (equivalent to the Thakkhola fault system) did not only contribute to development of the half graben. Although numerous factors may have contributed to the formation of north-south trending graben, their relative roles are often debated. But the extension caused by topographical loading and its excess gravitational potential energy could be the major factors. Admittedly, role of basal shear, rheologic structure and tectonic boundary condition cannot be ignored.

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