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Balanced cross-section across the Siwaliks of the Trijuga Valley, eastern Nepal

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ABSTRACT

The strata of the Siwalik Group in the Trijuga area has a total thickness that exceeds 5000m. It is dissected by two thrusts, repeating the succession three times and forming a longitudinal Dun Valley. A balanced cross-section has been constructed across the Siwalik Range in the Trijuga valley showing that the Main Himalayan Thrust (MHT) lies at the depth of about 5.2 km from the surface. The Main Frontal Thrust (MFT), Kamala Tawa Thrust (KTT), Marine Khola Thrust (MKT) and Main Boundary Thrust (MBT) all ramp-up from the MHT. Along with these faults, fault-bend anticlines associated with these thrusts have shortened the Siwalik of the area. The shortening across the area has been calculated to be approximately 33.7 km.

Key words: Siwalik; Trijuga valley; Balanced cross-section; Shortening; Fault-bend fold

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INTRODUCTION

The Siwalik Range is composed of a fold-and-thrust belt tectonically bounded by the Main Boundary Thrust (MBT) in the north and the Main Frontal Thrust (MFT) in the south. The MFT is the youngest and southernmost major thrust fault in the Himalayan fold-and-thrust belt (Gansser, 1964), which accommodates 50-100% shortening across the Himalaya (Lavé et al., 2005). This thrust rises from a regional décollement, or bed-parallel fault, known as the Main Himalayan Thrust (MHT), which underlies the entire Himalaya (Seeber and Armbruster, 1981; Zhao et al., 1993). The MFT is very active and all the mega-quakes in MHT are transported to the surface along this fault (Sapkota et al., 2011; Bollinger et al., 2014). Several thrusts are present within the Siwalik rocks repeating the succession and also forming the Dun valleys. Trijuga is a Dun valley in Eastern Nepal, where younger recent sediments unconformably overlie the Miocene-Pliocene strata of the Siwalik Group. The valley fill to the north of the Trijuga Nadi has a higher elevation than those of the south suggesting that they may be tectonically uplifted, and the Central Churia Thrust (CCT), also referred to as the Kamala Tawa Thrust (Pradhan et al., 2005) which underlies the area, is still active (Kimura, 1997).

Balancing is a simple test of geometric validity of a geologic cross-section (Dahlstrom, 1969) that has been mainly used for understanding the structural geometry and development of fold-and-thrust belts (Suppe, 1983, 1985; Suppe and Medwedeff, 1990). They are used for calculating the shortening of the area by the restoration of the deformed cross-section (Bally et al., 1966; Dahlstrom, 1969; Elliott, 1983).

The study area lies in Udayapur and Saptari districts within the Trijuga Valley (Fig. 1). The geology of this area was mapped under the geological mapping program of Petroleum Exploration Block -9, at scale of 1:250,000 which shows several thrusts (Pradhan et al., 2005). For this study we carried out an extensive field survey of the area to prepare a geological map at a more detailed scale of 1:25,000. This paper summarizes the most important results of the study and presents the balanced cross-section to understand the deep structure and shortening in the area.

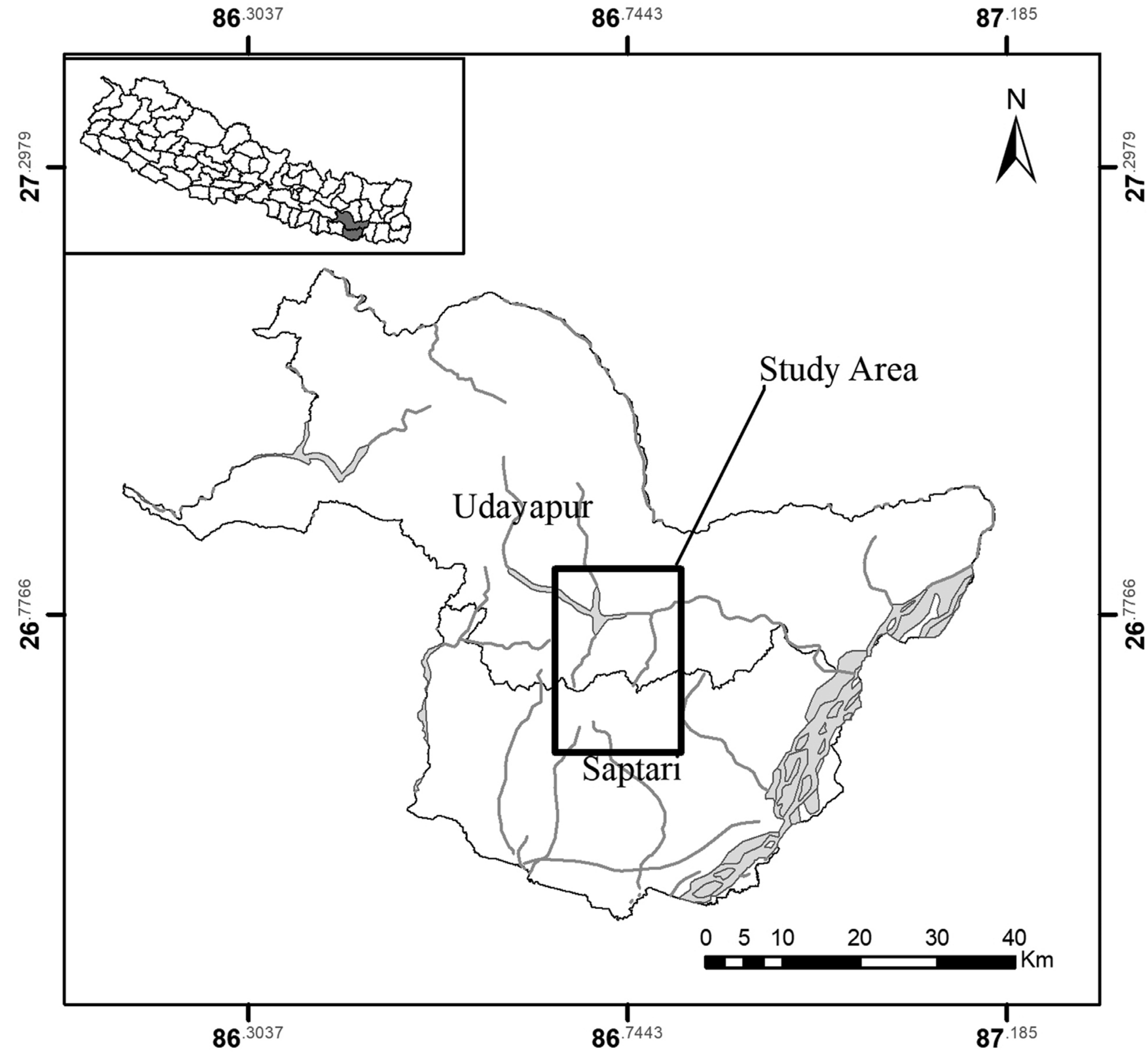

Fig. 1: Map of Udayapur and Saptari districts showing the study area.

MATERIAL AND METHODS

Detailed route maps were prepared along the well-exposed sections to establish the stratigraphy of the area based on three-fold classification system of the Siwaliks, i.e. Lower, Middle and Upper Siwaliks. Geological boundaries throughout the study area were defined along the various traverses and interpolated between them using the topography. The faults are identified directly in outcrops, as well as by the stratigraphic position of the rocks and also extended in map view using topographic breaks with the help of satellite images. The dip of faults was assumed to be equal to those of rocks in the hanging wall as would be expected in classic fault-bend-fold theory (Suppe, 1983).

For the preparation of balanced cross-section, the surface data obtained from the field study were used as well as images from a seismic reflection survey carried along the study area by Lee et al. (2017).

During preparation of the balanced cross-section, the steps followed were:

a. A line perpendicular to general trend of strikes was selected and a topographic profile was constructed along the line.

b. The geology observed along the line including rock types, dip of beds, lithological boundaries and location of structures is added to the profile.

c. The kink method was used for the construction of cross-section and bedding thickness was preserved for line length balancing. The kink method is based on the assumption of flexural slip folding, where dip angles varies only across the axial surfaces. Here, each dip measurement defines a zone of constant dip and all the contacts and bedding follow that constant dip within the zone. The boundaries of the constant dip zones are the lines that bisect angles between adjacent dips.

d. The cross-section is restored between the pin points by measuring the lengths of the deformed stratigraphic horizons and drawing those as straight lines of the same length.

RESULTS

Geology of the area

The Siwalik rocks of the area are classified into Lower Siwalik (LS), Middle Siwalik (MS) and Upper Siwalik (US), based on lithology and increasing grain size. The Siwalik rocks are distributed in three belts by Kamala Tawa Thrust (KTT) and Marine Khola Thrust (MKT) and constitute the Outer and Inner Churia Ranges to the South and North respectively of the Trijuga Nadi (Fig. 2). The total thickness of the Siwalik in the Trijuga area exceeds 5000 m (Fig. 3).

The LS is exposed in two belts between the KTT-MKT and the MKT-MBT belts constituting the major portion of Inner Churia Range. It consists of alternating beds of variegated mudstone, grey-greenish grey siltstone and very fine- to medium-grained grey sandstone. Sandstones are highly indurated due to calcareous cementing (Fig. 4a). The sandstone proportion increases and mudstone also becomes sandier up-section. Spheroidal weathering patterns and fining upward cycles are observed within the LS. The thickness of the LS is about 1650 m.

The MS is exposed in two belts between the MFT-KTT and the KTT-MKT over both Outer and Inner Churia Ranges. The main lithology of the MS is thick- to extremely thick-bedded, medium- to coarse- grained, grey, micaceous and cross-bedded sandstone with thin intercalations of black colored finely-laminated mudstone and grey colored siltstone. The sandstone

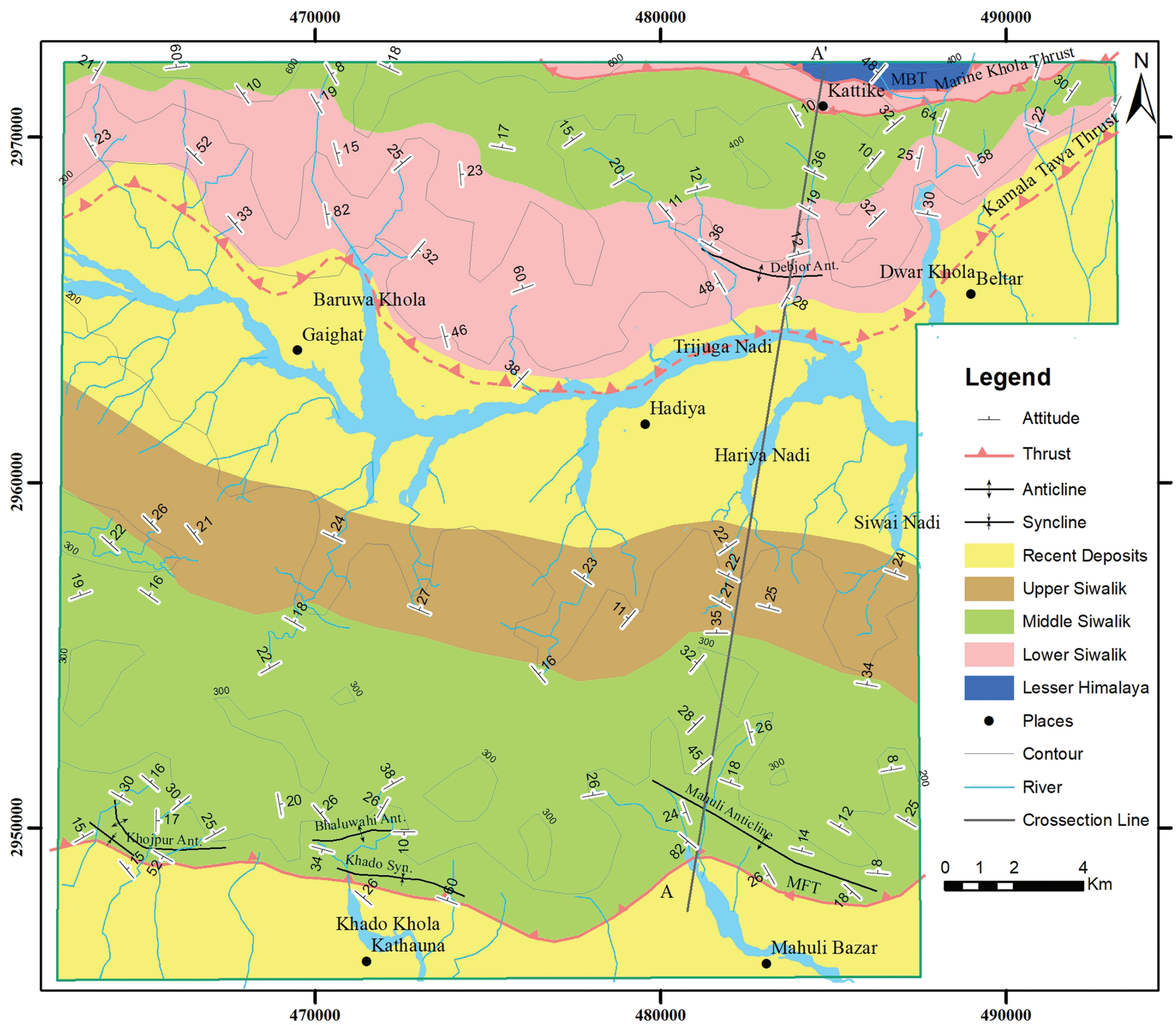

Fig. 2: Geological Map of Trijuga valley, eastern Nepal.

is medium- to coarse-grained with "pepper and salt" appearance with sub-ordinate amount of mudstone and siltstone in lower part and coarse-to-very coarse-grained pebbly sandstone with fining upward cycles passing into mudstone and siltstone towards the upper part. The sandstones show multi-stored structure with abundant sand balls and mud balls (Fig. 4b) and frequent tree trunk and coal patches. Plant fossils are present in some mudstone beds. Calcareous concretions are also present in the MS. The thickness of the MS is about 2600 m.

The US is exposed only between the MFT-KTT belt in the Outer Churia Range. It mainly consists of mud-dominated matrix-supported conglomerate as well as sand-dominated matrix and clast-supported conglomerate which are poorly cemented and lose with mudstone and sandstone in subordinate amount (Fig. 4c). Sand-dominated and pebble sized clasts are present on lower portion, whereas mud dominance increases towards upper part and clast size also ranges from pebble to cobble. The thickness of the US is about 750 m.

Geological structure

The Siwaliks of the area are bounded by the MFT in the South and the MBT in the north. The Kamala

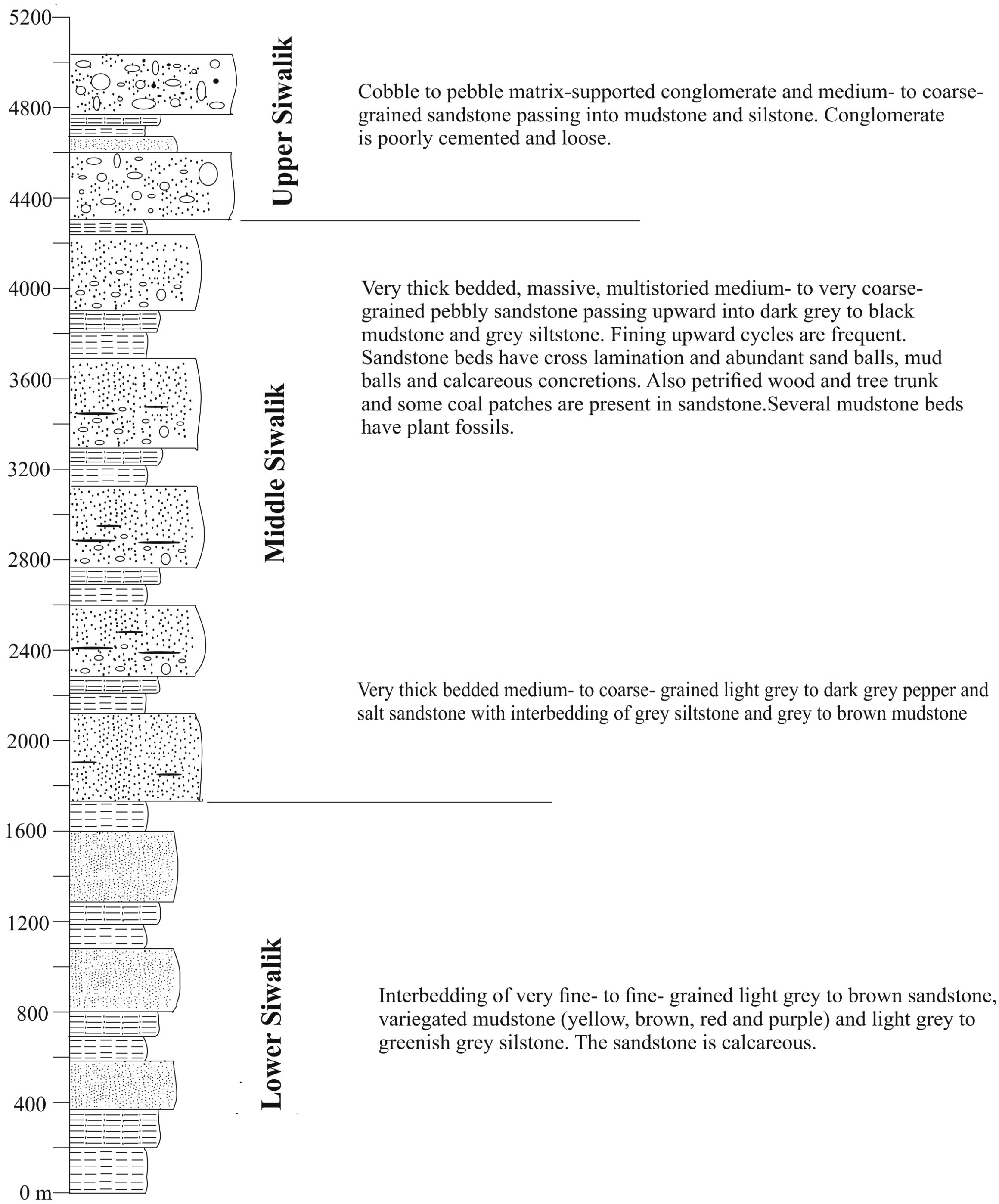

Fig. 3: Generalized stratigraphic column of the Siwalik Group of the Trijuga area.

Tawa Thrust (KTT) and the Marine Khola Thrust (MKT) are located between these faults and repeat the Siwalik rocks three times in the area along a north-south transect (Fig. 3). The MFT is the youngest and southernmost major structure in the Himalayan fold-and-thrust belt. This thrust rises from a regional décollement lying at a depth of around 5.2 km as observed in balanced cross section. The MFT is marked at the topographic break between the Siwalik Group and younger fluvial sediments of the Gangetic plain. The MS beds just above the thrust are highly deformed forming many local folds, faults and joints. Few frontal anticlines and synclines are present just north of the MFT.

The KTT is not exposed in the Trijuga area due to coverage by recent deposits. Younger US rocks lie in the footwall and older LS rocks in the hanging wall of the thrust. The LS beds above the thrust are highly deformed, forming some local anticline and syncline structures. The MKT has younger MS rocks in the footwall and older LS rocks in the hanging wall. It is identified by the stratigraphic position of the rocks. It passes through Kattike Village. The MBT is marked

Fig. 4: Field photographs (a) Variegated mudstone of LS (467123 E, 2968644 N) (b) Sand balls and mud balls observed in MS sandstone (465287 E, 2950023 N) (c) The US exposure (482056 E, 2957466 N) (d) Joints in MS sandstone north of MFT (465398 E, 2949649 N) (e) MFT outcrop placing MS strata over Quaternary deposits (d) (464896 E, 2948936 N) (f) Shear Zone near MBT (488055 E, 2971095 N).

by the occurrence of Lesser Himalayan metasediments above the Siwalik rocks. Shear zones are observed near the MBT (Fig. 4f).

The area is folded by many regional and local scale folds. East-west trending Mahuli Anticline (Pradhan et al., 2005), Bhaluwahi Anticline and Khojpur Anticline are observed as frontal anticlines north of MFT. Both the limbs of Mahuli Anticline are observed with steeply 60º-80 º south dipping southern limb and 10°-25° north dipping northern limb. Similarly, the Bhaluwahi Anticline has 10°-34° south dipping southern limbs and 15°-35° north dipping northern limbs.

Synclines are also observed towards western side only and not along our cross-section area. The Khado Syncilne passes through Khado Khola. It is a tight syncline with southern limb 26°-60° north dipping and northern limb 20°-60° south dipping.

Small-scale anticlines and synclines are also present north of KTT. The rocks near thrust are highly deformed. The MS sandstone beds north of MFT show well developed 2-3 set joints (Fig. 4d). The LS sandstone beds north of the KTT show well developed joints along the bedding plane.

Balanced cross-section across Trijuga Valley

A balanced cross-section was constructed across Trijuga Valley shown by line AA' in Fig. 3, which is perpendicular to the general trend of strikes (Fig. 5a). The footwalls of the MFT and MBT are the pin points of the cross-section.

The MFT is the leading imbricate fault of the study area, which is marked by the topographic break between Siwalik rocks and younger fluvial-alluvial deposits. The bedding dips in the hanging wall of MFT are 20°-35° suggesting the fault bedding cut-off angle between MFT and the MS is probably not greater than 35°. The depth of décollement is given by the intersection of axial surface of the back limb of that anticline overlying the MFT and the MFT. The MS rocks are exposed just above the MFT. An anticline is present just north of the MFT, and is likely related to this structure. A seismic reflection profile carried out here showed a 35 degree north dipping fault that becomes more or less horizontal at 350 m depth (Lee et al., 2017).

After passing the anticline the beds gradually decrease in dip. The US rocks are present after passing north of the outer Churia Range. The gradual flattening of the beds towards of the MFT thrust sheet suggest the concave upward shape of the MFT. The field measurements are consistent with observed reflectors in the seismic profile (Lee et al. 2017). A large portion of US is covered by recent deposits of the Trijuga Nadi. Seismic study showed the thickness of recent deposits around 250m (Lee et al., 2017).

On the north bank of the Trijuga Nadi, after the recent deposits, LS rocks are observed. As the older LS rocks overlie the younger US rocks, there is another splay thrust known as the KTT. This thrust is buried under the recent deposits and no field evidence is observed. Seismic study showed this KTT is buried and inactive (Lee et al., 2017). As the thrust exposes the LS on the surface, it suggests that the décollement underlies the LS at the depth. The bedding dips in the hanging wall of KTT are 20°-30° suggesting the fault bedding cut-off angle between KTT and the US is probably not greater than 30°. Therefore, the KTT is believed to have a hanging wall flat geometry. An anticline is observed north of KTT with short southern limb dipping 20°-40°south and forming a tight anticline. This anticline suggests the presence of another splay thrust of the KTT. Seismic study showed an apparent offset at 120 m depth with north side being uplifted about

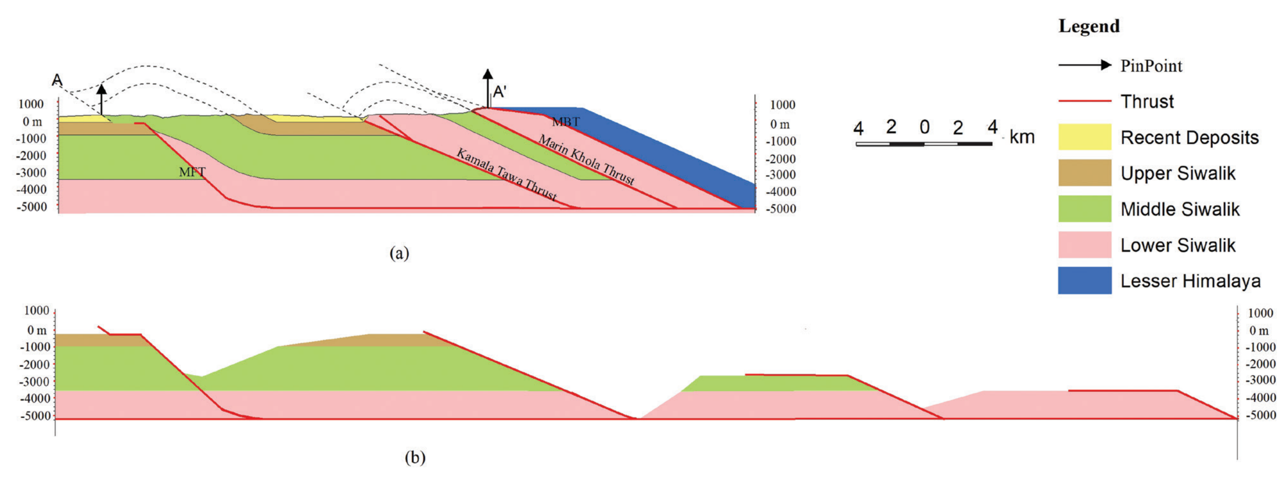

Fig. 5: (a) Balanced cross-section and (b) Restored cross section along A-A' in Fig. 3.

20-30 m but no such displacement at the surface suggesting the splay thrust is no longer active (Lee et al., 2017). After the anticline the LS beds are continuously north dipping at about 12°-31° and pass into MS. The MS beds show slightly decreasing north dipping and again increases towards the LS observed above it. Since the older LS overlies the younger MS, there is another splay thrust, the MKT. The fault-bedding cutoff angles between MKT and MS is not greater than 35° as the bedding dips in the hanging wall of MKT are 20°-35°.

The Lesser Himalayan metasediments bedding-foliation dips about 35°-40° in the hanging wall of the MBT suggest that the MBT dips 35° or more to the north. But a thrust shear zone observed in field shows very shallow dipping of about 10° in the upper part. We interpret this dip to be representative only of the shallowest fault.

The total shortening across the cross-section line is the result of shortening caused by each individual thrusts and folds within the area. The thrusts are restored and folds are unfolded to restore the cross-section (Fig. 5b).

Before restoration, the separation of the pin points is 22.9 km. After restoration, the separation of the points is 56.6 km. Therefore, the total shortening along the section is about 33.70 km, i.e. 60%. Similarly, the shortening due to MFT is about 5.9 km, shortening due to KTT is about 11.7 km and shortening due to MKT is about 16.1 km.

DISCUSSION

Geological mapping of the Trijuga valley shows that the Siwalik of the area is a typical fold-and-thrust belt with several thrusts and associated folds as in the other sections of the Nepal Himalaya (e.g. Schelling and Arita 1991; Mugnier et al., 1999; Pradhan et al., 2004, 2005). The MFT, KTT, MKT and MBT are the major thrusts within the area. The MFT rises form the décollement at depth of ~ 5200 m as observed in the balanced cross-section (close to the depth of 5260 m proposed by Lee et al., 2017). In other nearby areas, the décollement lies at shallow depth of 2 km around Bardibas (Almeida et al., 2018), about 6 km in Hetauda area (Schelling et al., 1991), about 6.9 to 8 km in Bagmati area (Schelling, 1992) and nearly 4 km in the Bheri-Karnali area (Mugnier et al., 1999) which implies that there must be lateral ramps along the MHT at different depth from where the MFT rises to the surface.

The area is folded by many large-scale folds; Mahuli Anticline, Khado Syncline, Bhaluwahi Anticline and other small-scale folds and joints locally deforming the area. These anticlines are the frontal anticline formed as the result of shear fault-bend folding associated to the MFT (Lee et al., 2017). The balanced cross-section across the AA' section shows shortening of 33.7 km (60%). The shortening value is in range with of other areas, 17 km (40%) in Hetauda area (Schelling et al. 1991), 20 km (40%) in Eastern Nepal (Schelling and Arita 1991), 20 km (40%) in Bagmati area (Schelling 1992), more than 17 km (40%) and 40 km (51%) along two sections in the Karnali-Bheri region (Mugnier et al. 1999). The calculated shortening value varies as the variation in depth of décollement.

Of the 33.7 km shortening of the area, 5.9 km is due to the MFT, 11.7 km due to the KTT and 16.1 due to the MKT. The shortening calculated form area of uplift method on Seismic reflection profiles show lower value of minimum shortening as Lee et al. (2017) show 3.7 km due to MFT and 10.5 km due to KTT. Similarly, in Bardibas region about 50 km west of our study area Almeida et al. (2018) calculated 1.8 km shortening along the Patu Thrust and 1.7 km along Bardibas Thrust, the two fault strands of MFT. The shortening is greater in the older thrusts towards the north as they have under older gone more deformation.

CONCLUSIONS

The Siwalik Group in the Trijuga Valley is divided into Lower, Middle and Upper Siwalik based on the rock types present which shows overall coarsening upward nature. The Siwalik succession is more than 5 km thick in the area. Geological mapping around the area shows distribution of Siwalik rocks in three belts along north-south. The balanced cross-section constructed across the area shows the presence of décollement within the Lower Siwalik at the depth of 5.2 km from the surface and has listric shape. The MFT, KTT, MKT and MBT are the major thrusts of the area and several folds present around the area have shortened the area. The shortening within the Siwalik of the area due to these thrusts and folds is 33.7 km or 60% out of which 5.9 km is due to the MFT, 11.7 km due to the KTT and 16.1 due to the MKT.

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AUTHOR'S CONTRIBUTIONS

The field work was conducted by R. Acharya, S. Khanal, S. P. Kandel and R. Dhakal. R. Almeida and J. Hubbard are team members of seismic study from the Earth Observatory of Singapore and permitted to use of their data and involved in revision of manuscript. S.N. Sapkota and L. P. Paudel were responsible for overall supervision of the study.

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