Insights into the structure and surface geology of balanced and retrodeformed geological cross sections from the Nizampur basin, Khyber Pakhtunkhwa, Pakistan

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Abstract

The current research work is an attempt to apply the basic geological procedures, methods of geological mapping, surface and subsurface interpretation and restoration of balanced and retrodeformed cross sections from the Nizampur basin, Khyber Pakhtunkhwa, Pakistan. The work also includes the documentation of several surface structural features, i.e., anticlines, synclines and different types of folds and faults exposed in the vicinity of study area. Four central thrust faults were recognized named as Kahi Thrusts along the cross sections. These thrust faults carried the older sequences of rocks over the younger sequences in different portion along the measured cross section. The folded and faulted rocks in the area show that stratigraphic framework comprises of Eocene, Paleocene, Cretaceous and Jurassic succession of rocks. There are Eocene rocks existing in the extreme South of the mapped area with addition of older Cretaceous and Jurassic succession and contains simple and large-scale folds, faults and back thrust. Two structural transect were mapped which encounter different folds and faults, i.e., X-sections AB oriented NS and CD oriented NE-SW. Restoration of the structural transects was calculated and assumed that at the formation of Main Boundary Thrust, the study area was exposed to the tectonic forces which prognosticated 19.5% shortening in rock sequences from Jurassic to Eocene succession along the measured cross section A_B.

Keywords Geological mapping · Retrodeformed X-section · Nizampur basin · KP · Pakistan

Introduction

The study area is located in the Nizampur basin Kahi valley of Khyber Pakhtunkhwa, North West Pakistan. The focused area is bounded with coordinates N 33° 48' 52.99", E 72° 03' 18.80" and is divided into two parts with younger Eocene rocks to the East and sequentially older Paleocene, Cretaceous and Jurassic successions exposed to the West of the mapped area. The study area located in the vicinity of the Main Boundary Thrust fault (MBT) has experienced

intense deformation and shortening resulting in thrust faults and various large- and small-scale folds. This area signifies the foot and hanging wall of the Hissartang fault and Main Boundary Thrust correspondingly. Sandwiched among these two faults, the study area has experienced intense compression (Fig. 1). Recently, diverse approaches have been made to the Nizampur and adjoining area consists mostly on study of sequence stratigraphy, reservoir quality, Geochemistry along microfacies of various successions, i.e., Khan et al. (2020); Hashmi et al. (2018). Awais et al. (2013) mapped and performed structure analysis of a part of Kala Chitta Range near Kahi Nizampur. Other works include Kazmi and Jan, 1997 on geology and tectonics of Nizampur, Yeats and Hussain (1987) studied timing of structural events in Himalayan foothills of northwestern Pakistan. The present work involves surface mapping and structural analysis of two transects oriented NS and NE-WS along with other major and minor structural features.

This research work is aimed at covering the following objectives:

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Fig. 1 Generalized tectonic map of northern Pakistan, showing regionally significant structural boundaries and geographic localities. The black rectangle in the preset marks the location of the study area

(adopted and modified after Calkins et al. 1975, Hylland and Riaz 1988, Hashmi et al. 2018)

- To prepare the stratigraphic framework of the mapped area
- To establish the structural interpretation of folds, faults and all other structural features
- Restoration of the deformed cross sections, leading to calculation of the total shortening in area.

Geological setting of the study area

Tectonically, the mapped area is enclosed by the region of active thrusting and folding in the foreland of the 2489 km long Himalayan highland in Pakistan, therefore, showing

a complicated structural arrangement (Yeats and Hussain 1987). The Attock-Cherat Range (ACR) is positioned between Peshawar Basin on the north and Kala Chitta Range on the south (Burbank and Johnson 1982). The boundary between ACR and Kala Chitta Range is delineated by Hissartang Thrust in Nizampur basin, where it splits the southern slab of ACR from Kala Chitta Range (Yeats and Hussain 1987). Movement along the Hissartang thrust deformed the rocks of ACR and Kala Chitta Range (Ghauri et al. 1991). In ACR, sediments of Pre-Cambrian to Paleocene are outcropping. The ACR bound the area to the north and includes metasedimentary rocks of the lesser Himalayas. The foreland basin strata of the Kala Chitta Range bound the area toward the south (Hashmi et al. 2018). The study area located in the vicinity of the Main Boundary Thrust fault (MBT) has experienced intense deformation and shortening resulting in thrust faults and various large and small-scale folds. In the area, the rocks exposed in the ACR and those exposed at the Kahi gorge are highly folded. The Kahi gorge lies in the Himalayan foothills of Nizampur valley in Khyber Pakhtunkhwa of North West Pakistan. The Kala Chitta Range (KCR) is a part of the active Himalayan Foreland Fold-and-Thrust Belt which has progressively been verged southward in a series of top to the south thrust imbricates along Main Boundary Thrust (MBT), fabricating the regional fault system of Northern Pakistan (Wadood et al. 2019). Tectonic map of northern Pakistan, the black rectangle in the preset marks the location of the study area as shown in Fig. 1 adopted and modified after Yaseen et al. (2021a, b); Hashmi et al. (2018); Hylland and Riaz (1988); and Calkins et al. (1975).

Stratigraphic framework

The study area consists of rocks from Jurassic to Recent lacustrine sediments, including Jurassic Samanasuk formations; Cretaceous; Chichali, Lumshiwal, and Kawagarh formations; Palaeocene; Hangu, Lockhart, and Patala formations, and Eocene; Margalla Hill Limestone (Hashmi et al. 2018). The exposed Formations in the study area are Margalla hill Limestone toward the east of mapped area and Hangu Formation, Lockhart Formation, Patala Formation, Chichali Formation, Lumshiwal Formation, Kawagarh Formation and Samanasuk Formation toward the west of mapped area. The generalized stratigraphic chart of the study area is shown in (Fig. 2c after Awais et al. 2012).

Methodology

Detailed geological field was conducted to study the area. This research project is mostly based on collected data from fieldwork. The applied methods remained conventional including structural and stratigraphic mapping. The collected geological data were organized, examined and presented using software such as Google Earth, Global Mapper, Coral Draw and final MOVE 2016.1 for cross section and restoration. The outcrop studies include location and assemblies of folds, faults, stylolites and all other structural features. The outcrop studies were followed by data collections including the measurement of strike, dip, fault planes and vertical stylolites. The software work covered the preparation of final structural map, followed by several process including identification of research area in Google Earth leading to line work on study area. Line work was then transferred to Global Mapper for corrections. Global Mapper outputs were then transferred to Coral Draw for smoothening the edges and application of further corrections. After completion, data were transferred to 2D Move software for structural modeling of the cross sections and then to calculate the total amount of shortening in study area. The simple shear (flexural slip folding deformation) and total/partial shortening methods were employed for restoration as followed by Yaseen et al. (2021a, b) and Omar et al. (2015), respectively. Preliminary step comprises restoring move on faults for minimizing dislocations on each faults. All the faults listed in the cross section were reinstated by means of the software feature algorithm “2D Move on Fault.” The technique of “Fault parallel flow” is applied to restore the movement contained by a fault where varied values are applied to the attribute unless all the strata became flawlessly restored which display constancy over the fault.

Structural analysis

The study area is tectonically located near Main Boundary Thrust fault, which has ACR toward the North and KCR toward the South as shown in Fig. 1. The stresses enlightened due to deformation of MBT produced several phases of strains and deformations in the exposed successions of rocks along the Khware Khwar section. The succession subjected to the deformational stresses starts from Eocene and lasts up to Jurassic Formations. After deformation, the mapped area displayed several types of structures that are divided into plunging, overturned, major and minor folds along with faults, the four thrust faults KT₁, and anticlines and synclines, as shown in the constructed geological map Fig. 3. Following structural features were observed and represent the deformation in the area:

Fig. 2 a Showing the exposed outcrop with different formations oriented in E–W direction b Generalized structural geometry of study area and sequence of formations along Khware Khwar from oriented

Fold types

The dominant structure feature in study area particularly in Kahi Gorge is folds, which tilted the strata and created deformation. On the basis of geometries of folds, the folds are divided into different geometrical types including symmetrical, asymmetrical, overturned, monoclinical, S & Z types and plunging folds. All of these are explained below individually and shown in (Fig. 4a–d).

Plunging fold

A plunging fold is a fold that is tilted downward in space, parallel to the fold hinge plane. The Samanasuk formation to the extreme north of the mapped area shows double plunging

N–S. c The generalized stratigraphic chart of the study area showing successions from Jurassic to Eocene and it is not up to scale (after Awais et al. 2012)

folds, in which the hinge lines plunge toward the east, example in Fig. 4a.

Symmetrical fold

Symmetric fold, with axial plain in vertical direction, can be observed repeatedly in the Kahi Gorge lies in the vicinity of the cross section AB oriented NS. These folds are observed in Kawagarh formation. An example is shown in Fig. 4b.

Asymmetrical fold

The Kawagarh and Chichali Formation exhibit overturned folds. The axial plains of the folds are in tilted positions from horizontal. The folds of this kind are

Fig. 3 Geological map of the Kahi Gorge section along the Khware Khwar. The two cross sections AB oriented NS and CD oriented NE–SW are constructed which are covering most of the geological structures present in the mapped area

Fig. 4 **a** Showing the Samanasuk formation to the extreme north of the mapped area shows double plunging folds, in which the hinge lines plunge toward **b** Symmetric fold, with axial plain in vertical direction, observed in Kawagarh formation **c** Overturn folds present

in Chichalli and Kawagarh formations **d** Minor folds S and Z types are present in the Paleocene rocks Patala Formation which are evident of shear zone

generally produced either by gravity gliding or in a layer on minor scale that is appreciably inclined (but less than 45 degrees) to the principal shortening direction Fig. 4c.

S and Z type folds

Minor folds can have S or Z shapes depending on their sense of asymmetry and these in turn can give rise to complex refolded shapes. The outcrop patterns developed are typical of the type of superposition of two sets of fold structures. These folds are present in the Paleocene rocks Patala Formation which are evident of shear zone. The geometric disposition of S and Z-folds is extremely useful for deciphering large-scale folds, particularly when exposure is incomplete Fig. 4d.

Monoclinial fold

The Kawagarh Formation between Chichali and Patala formation displays the monoclinial folds in which the one limb exists while the other limb is eroded. Monoclines are folds consisting of two horizontal (or nearly so) limbs connected by a shorter inclined limb. The form of a monoclinial drape fold is controlled in part by the nature of the underlying fault (normal, reverse or vertical) and in part by the mechanical nature of the strata being folded Fig. 5a.

Anticlinorium and synclinorium

A large or major anticline or a syncline on whose limbs are found minor folds, both anti- and synclines, generally asymmetrical and of opposite senses on the two limbs. Kahi

Fig. 5 **a** showing the Monoclinical fold present along the cross section AB in mapped area exposed in Kawagarh Formation **b** showing the Kahi Anticlinorium cored by Hangu Formation and Lockhart Forma-

tion at the limbs **c** illustrates series of anticlinorium and synclorium exposed at the cross section line CD in the Margalla hill limestone of Eocene age

anticlinorium is another dominant structure toward the south before Kawagarh formation. Kahi anticlinorium shows dipping away from center toward the north and the south. Moreover, the Kahi synclorium is present next to the Chichali formation which shows dipping from the north and the south toward the center of the synclorium as shown in Fig. 5b, c, respectively.

Thrust types and nature

The study area shows different types and nature of thrust faults in which older rocks thrust over younger rocks. There are four main thrusts, as shown in Fig. 6a–f. KT1 is the first thrust fault located on the cross section line AB and is present between cretaceous and Paleocene. There is very excellent exposure of the fault with clear fault gouge present at the fault plane as shown in Fig. 6a. KT2 is the second thrust fault where the Jurassic thrust over the cretaceous Formation. KT3 is the third thrust of the area and is located between the Samanasuk formation of Jurassic

age and Kawagarh formation of Cretaceous age. In KT3, Samanasuk formation is thrust over Kawagarh formation as shown in Fig. 6b, c. KT4 is the last thrust present between the Paleocene and Jurassic. At KT4, the Paleocene rocks (Lockhart formation) are thrust over Jurassic rocks (Samanasuk formation), as shown in Fig. 6. The deformation in the research area also produces strains in the form of small-scale faults and gash veins. Figure 6e shows example of such small-scale faults mainly exposed in the nodular Lockhart formation.

Structural modeling of cross sections

The structural features mapped in the study area include variety of folds and faults, i.e., overturned and asymmetrical folds. The perpetual erosion of rock layers on the surface led to difficulties in elaboration of the subsurface modeling. However, after adopting the principal structural and restoration techniques, the geological map of the research area and the two cross sections viz. AB oriented NS and DC oriented

Fig. 6 Displaying the different faults types and nature exposed in the mapped area **a** showing the KT1 where cretaceous thrust over Paleocene having the Fault gouge at the Fault plane. **b** Showing the KT 2 where the Jurassic thrust over the cretaceous Formation **c** show-

ing the KT 3 where the Samanasuk formation thrust over Kawagarh formation **d** and **f** Exhibiting KT4 with Paleocene thrust over Jurassic successions **e** showing small-scale faults mainly exposed in the nodular Lockhart formation

NE-SW was constructed, which result from the transformation of surface data into the subsurface data. These cross sections help us in visualizing the faults to establish the exact number of faults. In order to elaborate our findings and interpretation of the internal structures and their geometries, we made the two cross sections (AB and CD) mentioned earlier and explained below:

Geological cross sections (A–B) and (C–D)

The cross section AB is oriented in NS direction. All the trust faults, i.e., KT1, KT2, KT3 and KT4 along with Anticlinorium and Synclinorium lie on this cross section. The AB cross section throws light on the subsurface information regarding geometries of the above-mentioned structures with respect to their positions in the northwest portion of the research area; as shown in Fig. 7. The AB cross section shows the alluvium covering the Samanasuk formation and Patala formation in the north and the south, respectively. Toward north, this cross section shows KT4 which comes from approximately 300 m depth and has Lockhart formation thrust over Samanasuk formation. The structural transect along the section line AB is perpendicular to the trend of the major structures present in the area and is north oriented. The northern most part of the

Fig. 7 Geological cross section line A–B oriented in north–south direction. The structural transect along the section line AB is perpendicular to the trend of the main structures present in the area and is north oriented

area is covered by the Jurassic rocks Samanasuk Formations. Folding and faulting are very intense in Patala and Chichali Formations. It may be the reason because it is composed of competent and incompetent lithologies. The

incompetent lithology is shale and competent lithology is limestone. There is an anticline and syncline besides the faults present in the area. The anticline contains Samanask Formation in the core and Chichali Formation at the limbs while the syncline consists of Patala Formation at the core and Lockhart Limestone at the limbs. As the overall tectonic transport of the area is toward the south but some thrusts vergence toward the north, consider to be back thrusts. Overall the structural style of the study area is characterized by south verging high angle reverse

faults associated with stresses released during collision tectonics. Such minute observations might be described in regional tectonic framework (thin skinned or thick skinned). The cross section CD is oriented NE-SW covers the structural geometries in the east of the study area. The CD cross section gives detailed information of different series of anticlinorium & synclinorium which are located in the NE and SW of the mapped area. Synclinorium is mostly cored by Patala Formation. The anticlinorium has Margalla hill Limestone in the core, while at the limbs, it has Paleocene succession of rocks (Fig. 8).

Fig. 8 Geological cross section C–D oriented in NE–SW direction gives detailed information of different series of anticlinorium and synclinorium which are located in the NE and SW of the mapped area. Synclinorium is mostly cored by Paleocene successions

Restorations

Restoration of the cross section A–B was performed through three major phases, first applied reverse movements to bring the model back to its original position and then applied simple shear (flexural slip folding deformation) mechanism on every individual stratum to find out the shortening percentage in it, as shown in Figs. 9 and 10. The vertical and lateral changes in style of folding in relation to the rheology of the stratigraphic pile are thoroughly described in Yaseen et al. 2021a, b and Omar et al. 2015, respectively. Following the same, in order to establish the percentage shortening, the subsequent formula is used for calculation as shown in the table as follows;

$$\% \text{ of shortening} = \Delta L / L_r \times 100.$$

Fig. 9 Geological cross section AB oriented N–S constructed in Move suite where all the formations and faults are marked properly for applying the flexural slip folding deformation mechanism

Fig. 10 displaying the retrodeformed strata from Paleocene to Jurassic rocks to its original position with flexural slip folding deformation mechanism

where $\Delta L = L_r - L_d$, L_r = Restored length, L_d = Deformed length, ΔL = Total changed in length.

Deformed	Restored	Total change in length	Percentage of shortening
Length, L_d (m)	Length, L_r (m)	$\Delta L = L_r - L_d$ (m)	$\% = \Delta L / L_r \times 100$ (%)
1610	2000	390	19.5

The above calculations employ that during the formation of Main Boundary Thrust fault, the Kahi area was exposed to the tectonic forces which prognosticated 19.5% shortening in rock sequences from Jurassic to Eocene rocks along Khware Khwar, Kahi Nizampur along the cross section A-B. This further implies that the subject mapped area has been intensely deformed by the tectonic stresses since the formation and existence of MBT which evidently disclose that these forces are the major key inducers for structural variations (Fig. 10).

Discussion

Tectonic forces originating from the formation of MBT caused different types of deformation in the form of folds, faults, synclines and anticlines, etc. This deformation also altered the stratigraphic sequences of the Kahi Gorge area, ranging from Eocene and Paleocene to Cretaceous and Jurassic particularly in the mapped area. The constructed geological map shows the major folds and faults exposed in the Kahi Gorge area are intensely deformed. Folds in the area mostly have east–west orientation, which indicates that north–south compressional stresses were at play. Deformational stresses caused the four Kahi thrusts,

i.e., KT1, KT2, KT3 and KT4, to form. In all these main faults, older sequences have been thrust over younger stratigraphic sequences. The deformations in the area produce large-scale synclines and anticlines in stratigraphic sequences from Eocene to Jurassic rocks due to which several formations repeated frequently while some formations have not been exposed as they formed the cores of anticlines. The restoration of the constructed cross sections AB & CD employs that during the formation of Main Boundary Thrust fault, the Kahi area was exposed to the tectonic forces which forecasted 19.5% shortening in rock sequences from Jurassic to Eocene rocks along Khware Khwar, Kahi Nizampur. This additional infers that the area has intensely deformed by the tectonic stresses since the formation and presence of MBT which obviously reveal that these forces are the major key inducers for structural variations.

The conclusion of our research work is as follows:

- The direction of deformational stresses is north–south which can be demonstrated from orientation of folds and En échelon Gash veins.
- The study area comprises of lithostratigraphy units ranging in age from Jurassic to Paleocene.
- Majority of the structures in the study area are oriented east–west.
- Majority of formation show verging toward the north, while some of the formations verge toward the south.
- The area is severely deformed marked by the southward verging thrust faults. (Kahi-1, Kahi-2, Kahi-3).
- The structural trend of the area shows the north–south oriented compressional stresses.
- The study area is dominated by extensional fractures.

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Declarations

Conflict of interest The author declares that they do not have any conflict of interest.

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