ORIGINAL PAPER-EXPLORATION GEOLOGY

Effects of transpression on the rocks exposed at the Jhelum Fault Zone in the east of Potwar Basin, Pakistan: implications on the subsurface deformation pattern

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Abstract

Jhelum Fault is the north–south-oriented major structural lineament originating from the Hazara-Kashmir Syntaxis and extending southwards towards the Mangla Lake. Geographic extent, nature and significance of Jhelum Fault are the subjects which have been approached by different researchers in the past. The previous research provides enough evidence for the presence of Jhelum Fault as well as they discourse its surface extent. None of the previous research addresses the subsurface model of this fault; consequently, its surface extent has been ambiguous and variably reported. The current research takes into account both the surface lineament as well as the subsurface behaviour of the deformed strata to draft the most reasonable depiction of this fault. Field data were coupled with satellite image of 1.5 m ground resolution to produce the geological map of the study area at 1:25,000 scale. The subsurface model was created along four traverse lines by considering the lateral extent of the structures and their shifting trends on the geological map. The stratigraphic package was taken from the nearby hydrocarbon exploratory well data (Missakeswal-01 well of OGDCL) as no rocks older than middle to late Miocene were exposed in the area. The consistent through-going map extents of many faults in the study area prove that faults are playing the major role in the tectonic evolution of the Jhelum Fault Zone. In the subsurface model, the same faults show very little stratigraphic throw, which signify the major stress component to be associated more with wrenching than pure compression. Therefore, most faults in the area are of transpressional nature having dominant lateral component with relatively smaller push towards west on steeply east dipping faults. The model also shows the positive flower structure with dominantly west verging fault system with few east verging back thrusts. The subsurface proposed model shows that the Jhelum Fault is extendible southwards to the Mangla Lake in the subsurface; however, it acts like a continuous shear zone on the surface where there all the shearing is accommodated by tight refolded fold axes. The east–west shortening does not exceed 14.5% which shows smaller compression in the study area. The 3D model further clarifies the model by showing the consistency of the fault system along strike.

Keywords Mangla Lake · Jhelum Fault · Mapping · Modelling · Transpression · Flower structure
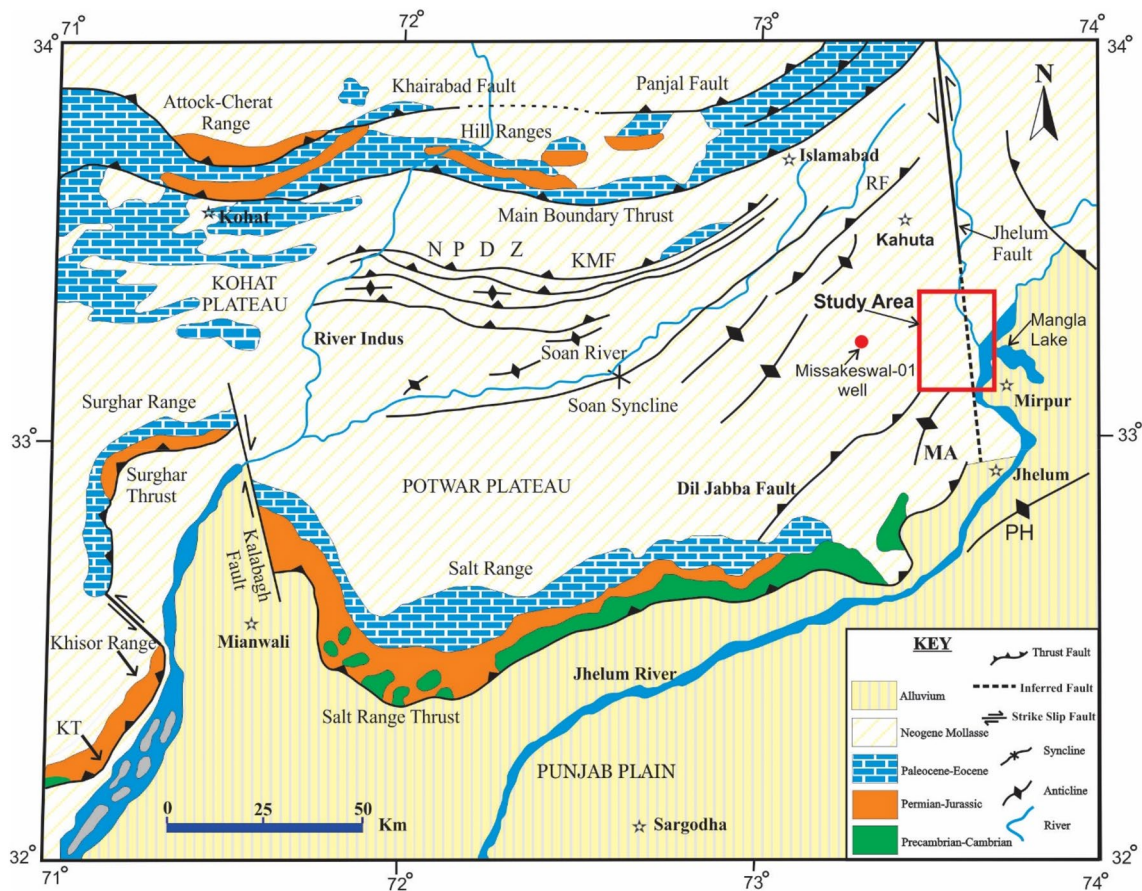
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Introduction

The study area is located in the North Pakistan and is a part of the northwest Himalayas. It lies towards the southeast and south of Sub-Himalayas and Hazara-Kashmir Syntaxis, respectively (Fig. 1). This research is based on the effects of Jhelum Fault Zone (JFZ) on the rocks present in the northwestern neighbourhood of Mangla Dam and the structural features associated with this fault. JFZ is a strike-slip fault zone which is a prominent structural feature present in the area. Previous studies show that various authors have worked

Fig. 1 Tectonic map of a part of North Pakistan (modified after Jaswal et al. 1997). Rectangle in the map shows location of the study area. In map NPDZ=Northern Potwar Deformed Zone; KMF=Kheri Murat Fault; RF=Riwat Fault; KT=Khisor Thrust; PH=Pabbi Hills; and MA=Mahesian Anticline

on the Hazara-Kashmir Syntaxis (HKS) on different aspects, which are given as follows.

Verchére (1866 and 1867), Lydekker (1883) and Wadia (1931 and 1934) are the pioneer of the HKS but more attention has been given to the work of Wadia. Wadia (1931) used the term "Syntaxis of the Northwest Himalaya" for the HKS and explains the tectonics, structure and stratigraphy of the syntaxis. He made an extensive model by dividing the area into eight stratigraphic and mappable units. Calkins et al. (1975) described the deformation pattern of the area and said that the western limb of HKS has been developed through two phases of deformations. They also described the structure and stratigraphic sequence of the rocks present in the area which ranging in age from Precambrian to Miocene. Bossart et al. (1984 and 1988) used major and minor geological structures and described, that the area had passed through at least two different phases of deformation. They construct a tectonic model for the area which shows that the syntaxis was previously an early nappe units developed by overthrusting of early Himalayan rocks. The nappe units are then deformed into a structure in the form of a shear

zone which is lastly followed from northwest to southeast by the tectonic transport of overthrust units. Bossart et al. (1990) analysed the structure and palaeomagnetic parameters of the Murree Formation along the core of the HKS. They observed a clockwise rotation of 45° of the axial zone of HKS comparative to the Indian shield rocks.

Munir and Mirza (2007) studied the stratigraphic sequence exposed along Balakot-Bagh Thrust (BBT) which is responsible for 2005 Kashmir earthquake. They concluded that the shales of Kuldana Formation act as a decollement on which Murree Formation thrust over the Siwaliks sequence along the BBT. Iqbal et al. (2014) carried out the study of structure and stratigraphy of four sections in the Kotli District, Azad Jammu and Kashmir. They reported that the rocks present in these areas are sedimentary and ranging in age from early Pliocene-Recent. They also concluded that rocks are highly deformed as result of two prominent faults in the area, i.e. Himalayan Frontal Thrust (Riasi Fault) and Fagosh Fault. The Riasi Fault rides the Murree Formation over Dhok-Pathan Formation while Fagosh Fault which lies within the core of Fagosh Anticline in Chinji Formation is

an intraformational fault. The study area has been affected by the left-lateral movement of Jhelum Fault (JF) which goes down through the western margin of HKS along the linear trend of the deep gorge of Jhelum River (Kazmi 1979). Monalisa and Khwaja (2005) proposed a regional tectonic model on the basis of focal mechanism solutions of the area and concluded that JF is a left-lateral nature and has the same orientation as Chaman Fault and thus generates synthetic shears. In 2004, a geological map (sheet no. 43G/11) at a scale of 1:50,000 have been published by the Geological Survey of Pakistan (Akhtar et al. 2004) which covers the study area of the present research. The study area is entirely composed of molasse sediments of Siwaliks Group that ranging in age from middle-late Miocene to Pleistocene and consists of the rock units of Chinji, Nagri, Dhok-Pathan, Soan and Mirpur formations (Iqbal et al. 2015).

Geographically the area is situated along banks of the Jhelum River, Azad Kashmir. It is bounded by the reservoir of Mangla Dam in the east and covers a part of the Potwar Plateau in the west (Fig. 1). Rawalpindi-Dadyal road provides an easy access to the study area. This road is well metalled and passes almost horizontally along the northern top of the study area (Fig. 2). The main objectives of the current research work are to generate a detailed geological map and to establish a possible 2D/ 3D model for the geometry of the Jhelum Fault Zone and its associated rocks deformation.

Geological framework

Regional tectonics

Pangea (a super-continent) was formed by the drifting of all continents during Palaeozoic Era (Kazmi and Abbasi 2008), and its assembly was completed in Permian time (Windley 1984). The Gondwana that covered the southern
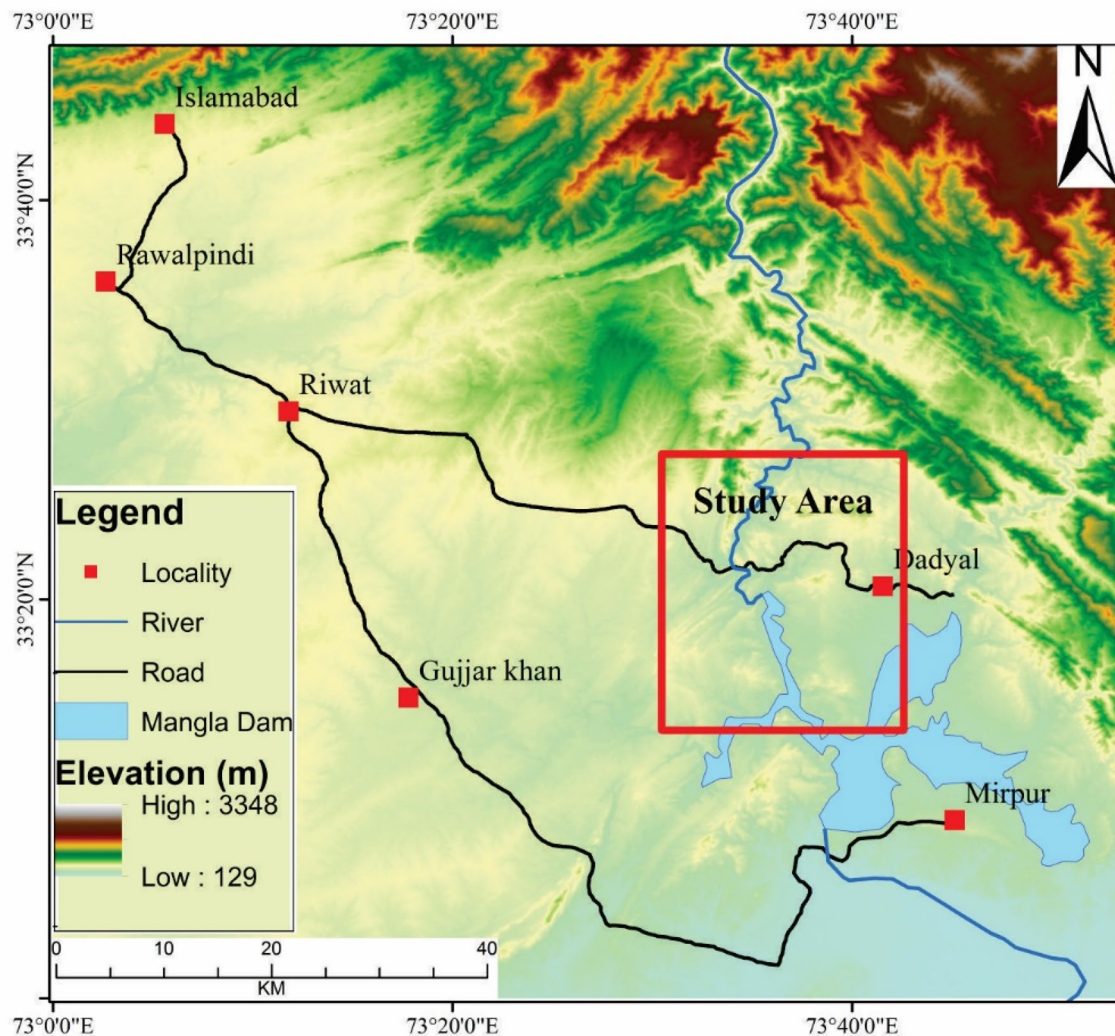
Fig. 2 Map (DEM) showing the accessibility of the area

part of the Palaeozoic Pangea resulted from the rearrangement of Rodinia (a prior super-continent), that survived at about ~ 1000 Ma (Rogers et al. 1995). Pangea remained intact as a single landmass for a period of 100 Ma until the Jurassic, when it was divided into two major land-masses, Laurasia and Gondwana in the north and south, respectively, separated by great Tethyan Ocean (Windley 1984).

Tectonics of the Indian Plate

The Indian Plate belongs to the east of its mother land Gondwana (Valdiya 2002). The continent–continent collision between the Indian and Eurasian Plate gave rise to a spectacular feature on the surface of earth known as Himalaya (e.g. Dewey and Bird 1970, Fig. 3). This feature (chain of Himalayan Mountains) was originated after the separating and northward drift of Indian Plate from Gondwana at about 130 Ma ago (Johnson et al. 1976). The ocean that was present between the Indian and Eurasian Plate was named as Neo-Tethys, which was start consuming in response to northward drift of the Indian Plate towards the Eurasian Plate. This consumption of the Neo-Tethys was facilitated by opening of the Indian Ocean to the south of the Indian Plate, the transform movement along an Owen-Fracture Zone and Ninety-East Ridge that are located towards the southwest and southeast of Indian Plate, respectively (McKenzie and Sclater 1976, Fig. 3, 4). A series of arcs developed

within the Neo-Tethys before the continent–continent collision, as a result of intra-oceanic subduction, are named as Kohistan–Ladakh, Nuristan and Kandahar (Treloar and Izatt 1993). The origin of these arcs due to magmatism was completed at about 40 Ma, after which the basin present to the north of Kohistan–Ladakh arc become closed and gave rise to Andean type of continental margin due to collision of this arc with Eurasian Plate (Petterson and Windley 1985).

Himalayas

The orogeny of the Himalayan is defined by the Indus-Tsangpo Suture in the north, the right-lateral strike-slip Sagaing Fault in the east, the left-lateral strike-slip Chaman Fault in the west and the Main Frontal Thrust (MFT) in the south (LeFort 1975). Geographically, the Himalayan Range lies between its eastern and western syntaxis as represented by the Namche Barwa and Nanga Parbat peaks (Yin 2006). The Himalayan is an east–west trending orogeny developed since ~ 50 Ma in the result of continuous collision between Indian and Eurasian plates (Beck et al. 1995; Faisal et al. 2014). Different scientists gave different classifications of Himalayas. DiPietro and Pogue (2004) divided it in ten different zones. This classification raised confusions in the location of Main Central Thrust (MCT). Hodges (2000) gave classification in which he divided Himalayas into six zones. Another classification based on the metamorphic/igneous
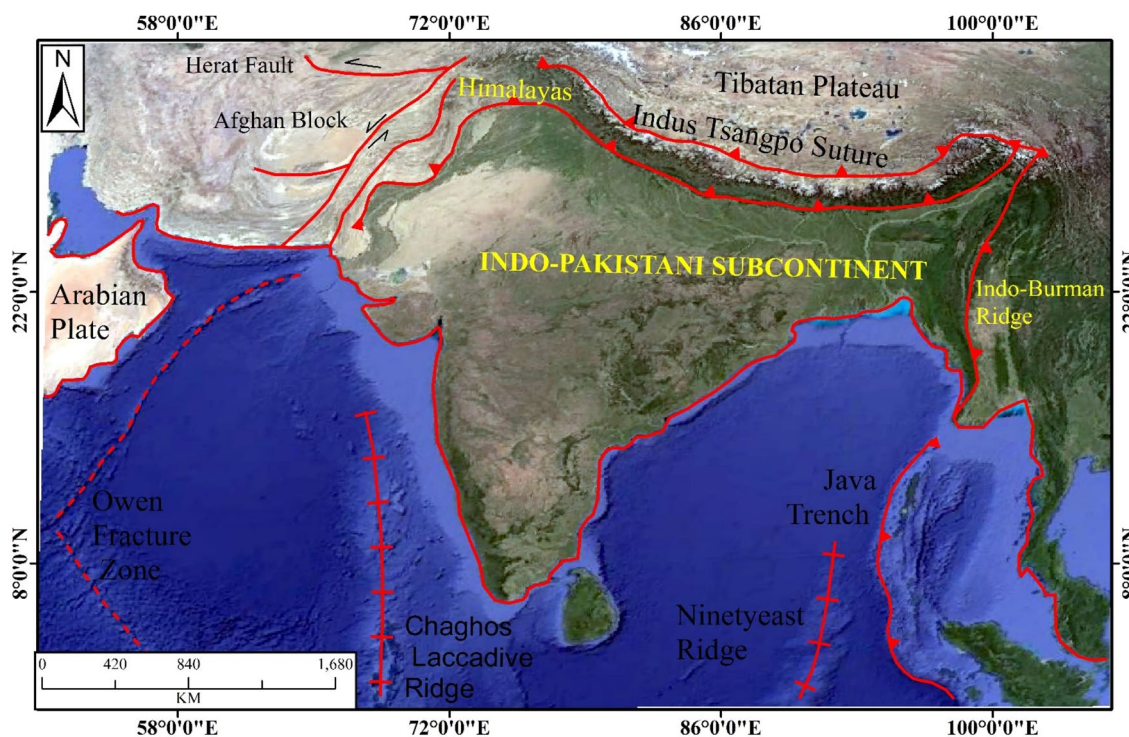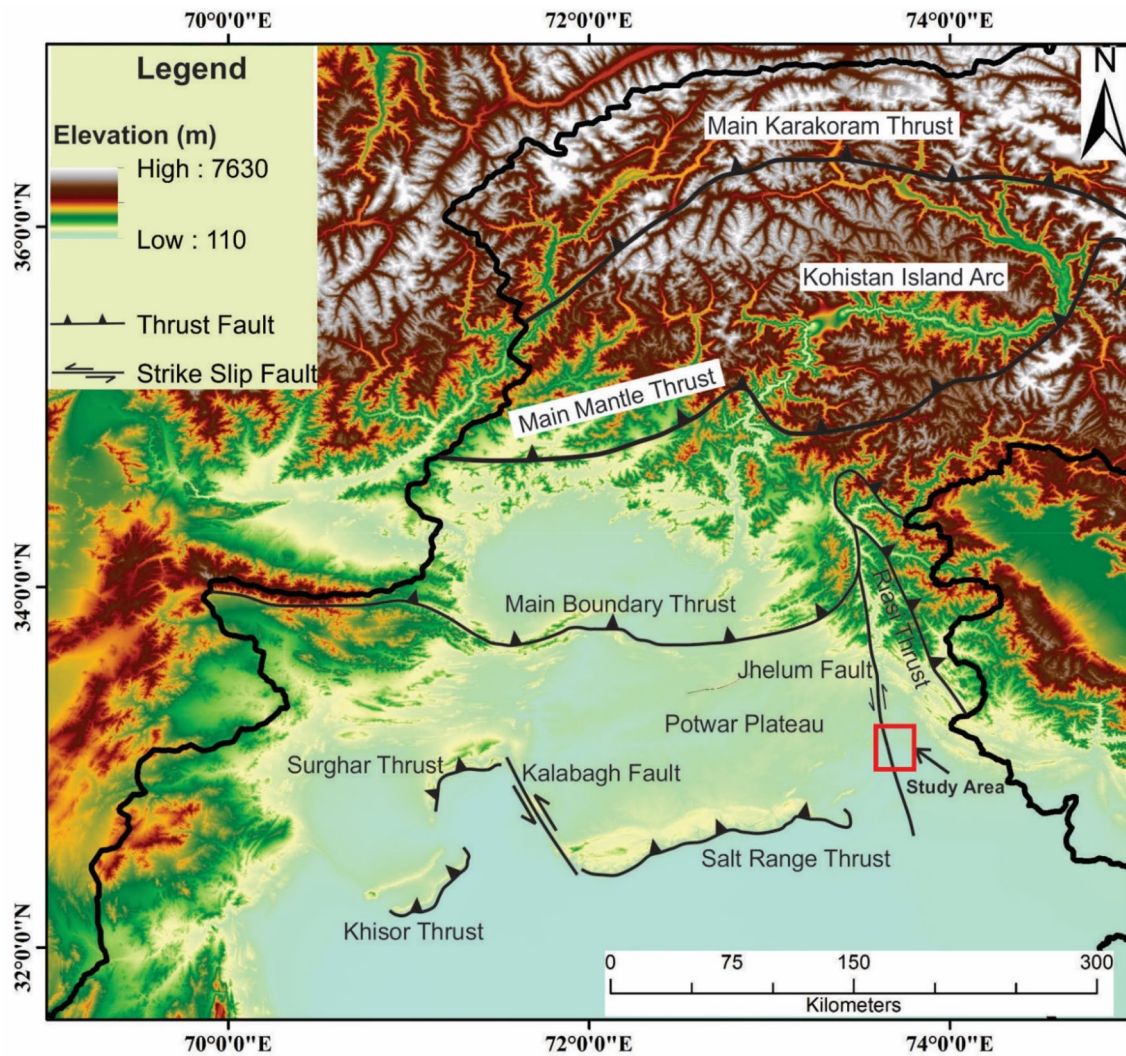

Fig. 3 Google Earth image showing tectonic boundaries of Indo-Eurasian collisional zone (after Qayyum et al. 1996)

**Fig. 4** DEM showing tectonic boundaries of North Pakistan (after Kazmi and Rana 1982)

rocks and sedimentary units was given by Coward et al. (1988). They divided Himalayas in the north Pakistan into two major zones, those having igneous and metamorphic rocks are named as Internal Himalayas while those having sedimentary rocks are given the name as External Himalayas. We are using the recent classification of Yin (2006) that classified Himalayas into four distinct geological domains which, (1) Tethyan Himalaya (2) Higher Himalaya (3) Lower Himalaya (4) Sub-Himalaya.

Local tectonics

The study area lies at the southern part of Hazara-Kashmir Syntaxis (HKS) (Fig. 5). This syntaxis is a part of Himalayas and was first discussed in detail by Wadia (1931), who called it as the Northwest Himalayan Syntaxis. This bend of northwest Himalayas is surrounded by a number of faults (Fig. 5).

The two prominent faults exposed at the apex of HKS are Panjal Thrust (MCT of DiPietro and Pogue 2004) and MBT. These faults are post-metamorphic with low-grade and truncate various rock units in their footwall blocks (Bossart et al. 1988). The Panjal Thrust is considered to be the eastern and western continuation of Khairabad Thrust and MCT, respectively (DiPietro and Pogue 2004). However, the MCT in central Himalayas is post-metamorphic and is older than the Panjal-Khairabad Fault. The Balakot Shear Zone forms as a result of an active tear fault (Balakot Fault) that discriminates the HKS in the west from western Himalayas (Kazmi 1979). This fault merges with a strike-slip system known as Jhelum-Balakot Fault (Fig. 5). The Batal Fault seems to be the extension of Balakot Fault and was active during metamorphism in Eocene time (Greco et al. 1989), but the Balakot Fault is younger than the Batal Fault because it cuts the regional foliation as well as the Panjal and Murree

Fig. 5 DEM showing major faults in the surrounding of Hazara-Kashmir Syntaxis (HKS) (from Monalisa and Khwaja 2005)
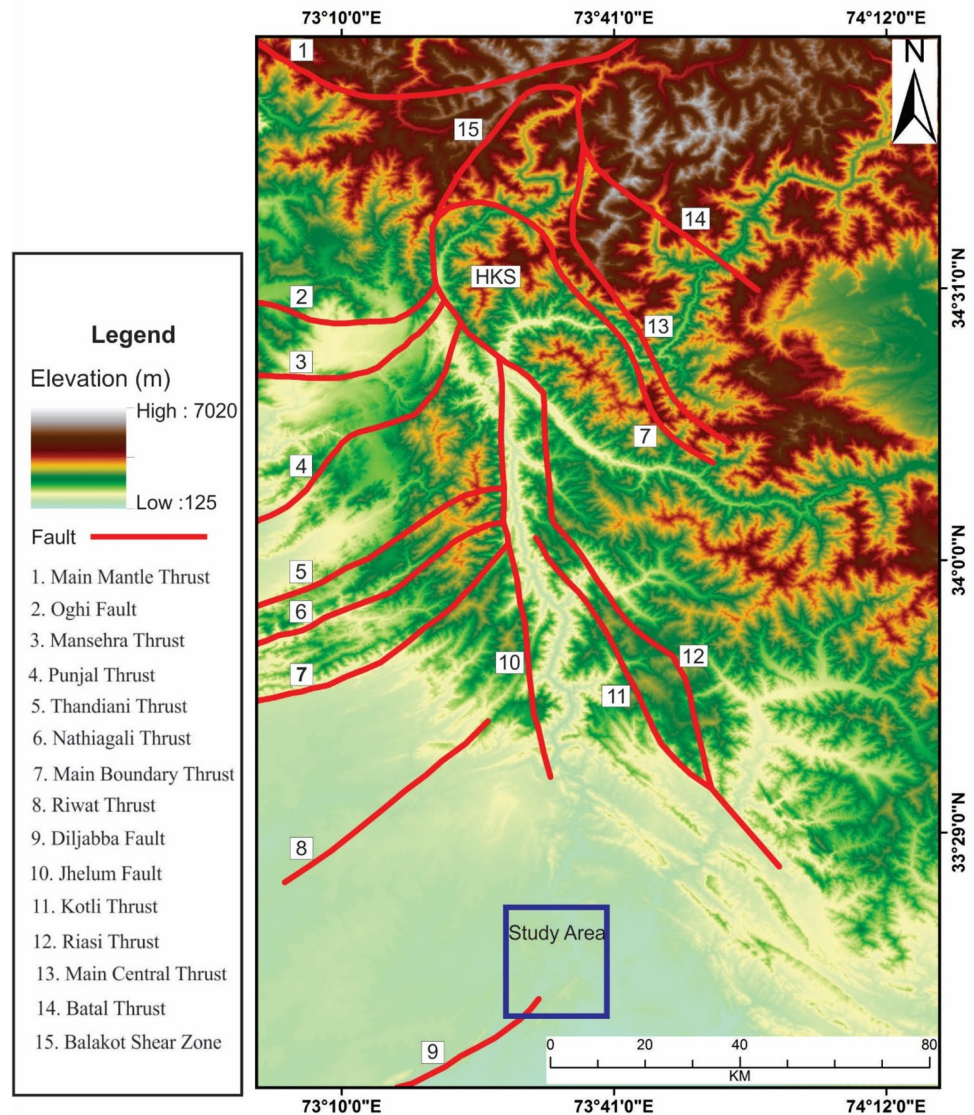
Thrusts (DiPietro and Pogue 2004). The NathiaGali Thrust is the eastern extension of Cherat and Hisartang Thrusts that are present in the lesser Himalayas of Pakistan towards the north of MBT (DiPietro and Pogue 2004). The Riasi Fault trending NNW present in the vicinity of the study area (Baig and Lawrence 1987) and meets with the Jhelum Fault in Muzaffarabad.
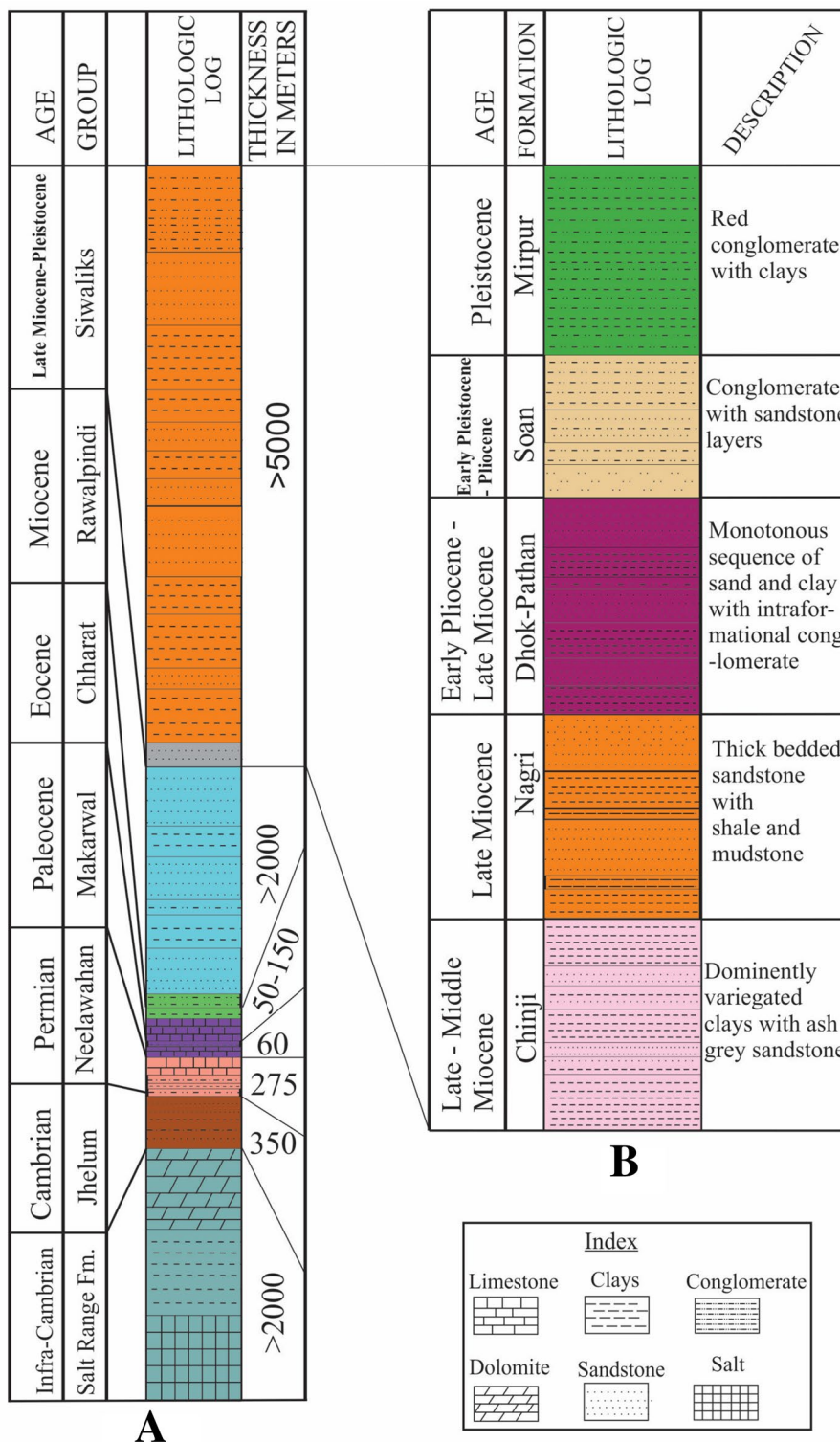
Stratigraphy of the area

The study area lies at the boundary between Eastern Potwar Plateau (EPP) and Hazara- Kashmir Syntaxis (HKS). The Jhelum River cuts the rocks in the middle from north to south so that the area covers both the successions of EPP as well as southern part of HKS (Figs. 8 and 9). The stratigraphy of the mapped area consists entirely of molasse sediments especially Siwaliks of the Sub-Himalayas. The

rocks exposed in the area are sedimentary and ranging in age from Miocene to recent which includes Chinji Formation, Nagri Formation, Dhok-Pathan Formation, Soan Formation, Mirpur Formation and Quaternary Alluvium (Figs. 6 and 7).

Materials and methods

Reconnaissance study of the area was done by using computer-based software Arc-GIS 10.2.2 and Google Earth along with available satellite images at USGS website. The map of Geological Survey of Pakistan (sheet No. 43G/11) was used as a base map for the understanding the stratigraphic sequence of the rocks in the area. Methodology comprised of geological fieldwork and subsequently the Lab work. First, the detailed geological fieldwork was carried out in two different parts. Main field trip was conducted in May,

Fig. 6 **A** Generalised stratigraphic column of Eastern Potwar Plateau/Salt Range (after Pennock et al. 1989) and **B** stratigraphic column of the study area (Formation names after Akhtar et al. 2004)

2016 for five days in order to familiar with the stratigraphy and surface structural trend of the area. The following field trip was conducted in September, 2016 for five days in order to collect data of outcrop structural trend for the preparation of a geological map and structural cross sections, where field strike/dip data were collected through Brunton compass and GPS was used to collect the spatial (latitude/longitude) data on contacts of different formations. Metalled and unmetalled roads and small streams were used as tracks for across the structural trend of area.
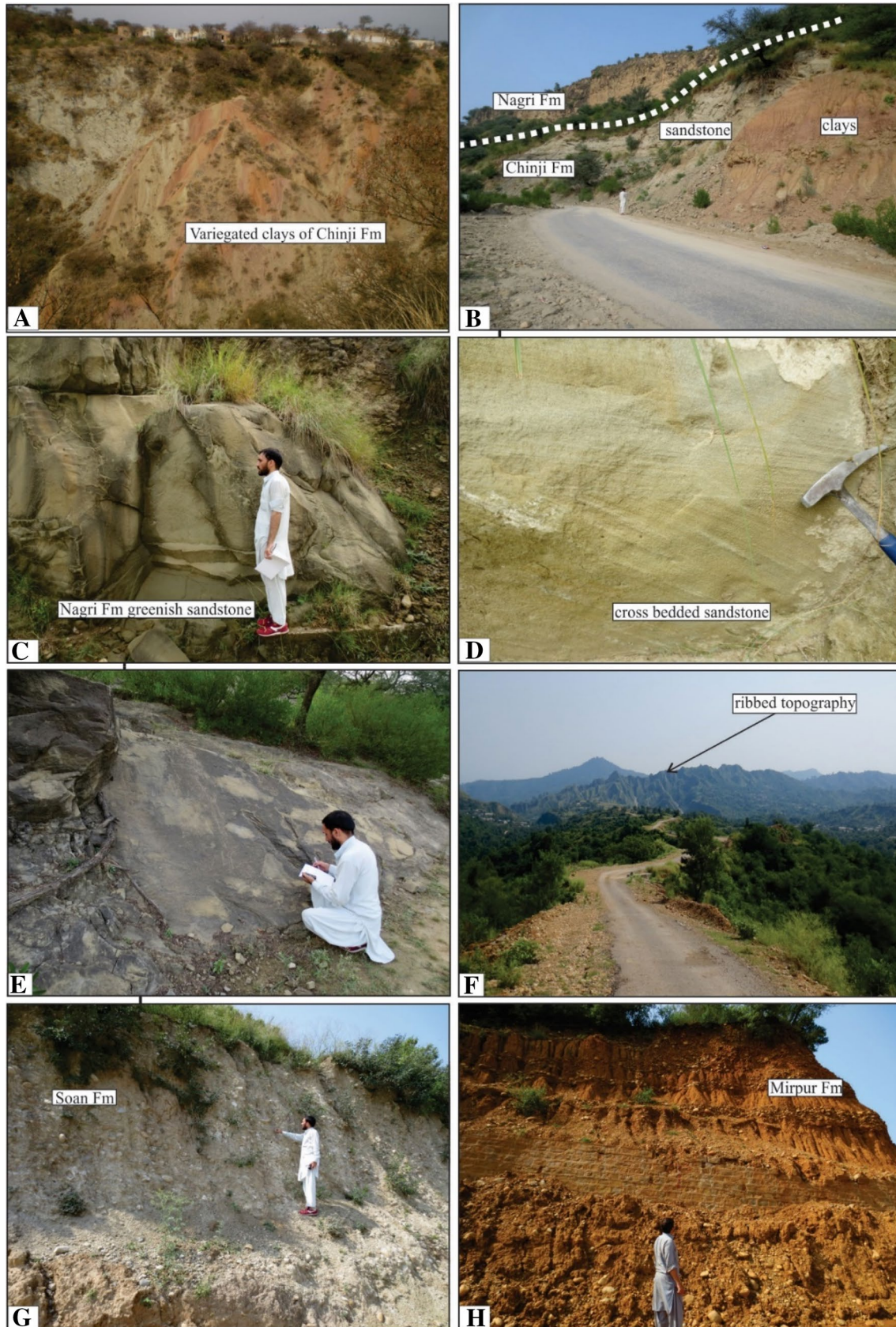
Fig. 7 Chinji Formation (**a**, **b**), Nagri Formation (**c**, **d**), Dhok-Pathan Formation (**e**, **f**), Soan Formation (**g**) and Mirpur Formation (**h**)

Fig. 8 Landsat-8 Image showing major structures in the study area
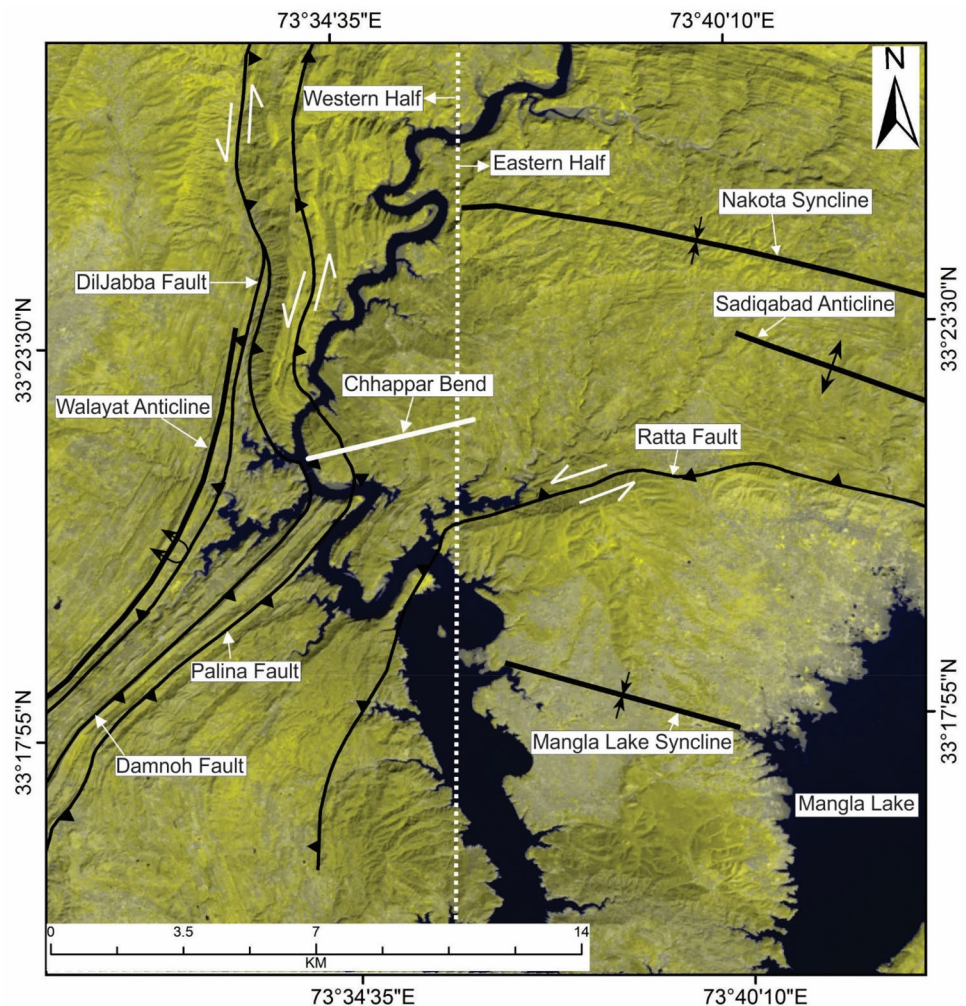
Secondly, the laboratory work was divided into two segments, i.e. preparation of geological map and geological cross sections as followed by Yaseen et al. 2021a, b in his latest work. Geological map of the area at scale of 1:25,000 was constructed in the Geographic Information Systems (GIS) software 10.2.2 (a modern tool for geological mapping) by using satellite image, geological field data and base map of Geological Survey of Pakistan. Cross sections were generated in order to know the subsurface behaviour of various structures present in the area. These cross sections were drawn to cover most of the structures present in the area. Pennock et al 1989 and the data of Missakeswal-01 well were used for the thickness of the subsurface lithology in the study area. The geological map prepared in the GIS software along with the DEM was brought into the MOVE software for preparation of geological cross sections. Horizons were created through "create horizon" and "kink method" present in the model building window. Similarly, "create fault" was used for faults. After the preparation of deformed state cross sections, they were restored in order to find the shortening in these cross sections as well as in the mapped area. Move on

fault algorithm in 2D MOVE was used to restore the faults in the cross sections. The "fault parallel flow" method present in the 2D Module was used for the restoration of faults as recently followed by Yaseen et al. 2021a, b and Ishaq et al. 2021. After that "flexural slip method" was used for the unfolding of the cross sections in 2D module of MOVE software. All the cross section work was carried out in 2D kinematic module of MOVE software. Afterwards, the cross sections are transformed to 3D module of the MOVE software to show the third dimensional path of the sequences present in the area.

Structural framework

North–south-oriented network of faults control the structural fabric of the study area. Along these faults, the whole rock package has drifted westwards over the Potwar Basin, with few back thrusts. This north–south fault controlled lineament is very persistent along its map extension which proves that these faults are regional in scale. This
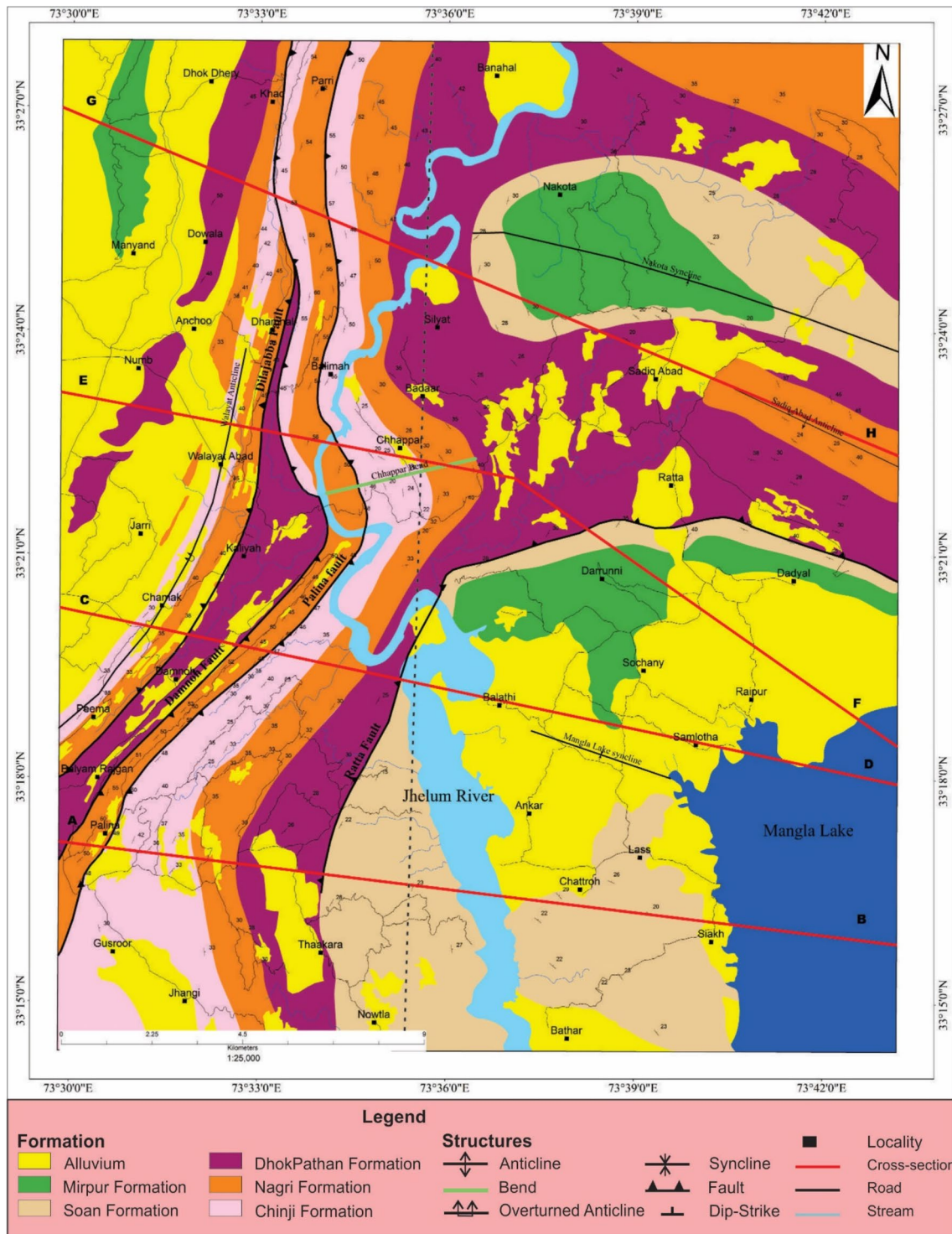
Fig. 9 Geological map of the study area

persistent lineament also works as a boundary between two basins where Potwar Basin lies towards west and Kashmir Basin towards east. This fault zone marks the intensely deformed strata mostly dipping towards east. While on either sides of this intensely deformed zone, the rocks are folded as broad series of anticlines and synclines having intact structural closure. The structures present at surface and subsurface of the study area are discussed as follows.

Surface structures

The mapped area can be divided by dotted line into the Eastern Half and the Western Half on the basis of structural style. Both the halves occupy the recent molasse sediments (sands and clays) without any single carbonate exposure. All the faults present in the area are thrusted within this monotonous sequence of cyclic fluvial sediments and seem to have more lateral (horizontal) throw than vertical throw. The north–south-oriented faults present within the study area extendable along their strikes outside the study area in both north and south directions which puts them in the category of regional faults. These regional faults have not done much with their up-dip-slip component of displacement because they run within the molasse sediments, which prove their dominant strike-slip component vector and can easily be attributed to the transpression. The surface expression of the area appears that the stiff unit of lithologies like sandstone and conglomerate form ridges while comparatively loose sediments shales form valleys in the area. The geology of these rocks is mainly controlled by the north–south as well as east–west shortening. Most of the faults are north–south tending having strike slip along with reverse-slip component. The Diljabba Fault is the main back thrust in the area. The folds present in the area are of various categories. The complete description of the surface structures present in the map is given below.

Eastern half

It covers all the eastern part of the study area extended from Banahal in the north to Bathar in the south (Figs. 8, 9). The major structures present in this part are two synclines, one anticline and one fault which are described as follows:

Mangla Lake Syncline is a broad and open syncline which lies to the southern part of eastern half. Although it does not shows a clear synclinal fold axis due to alluvium cover in its core but on the either limbs is covered by stratigraphically older Soan Formation containing younger Mirpur Conglomerates in its core. Mangla Lake also covers a part of this syncline. The **Nakota Syncline** is a wide synclinal fold present in the north of the Eastern Half. The Mirpur Formation is present in its core while the Soan and Dhok-Pathan Formations surround it in the periphery. The Dhok-Pathan Formation surrounding Nakota Syncline fills most part of the upper Eastern Half. The **Sadiqabad Anticline** is a northwest-southeast trending anticline exposing Nagri Formation in its core (Figs. 8, 10). The fold plunged towards northwest direction where the Nagri Formation plunges down and Dhok-Pathan Formation covers the valley. The southern limb of this fold is thrusted over the Mangla Lake Syncline. The **Ratta Fault** is a west verging thrust fault which juxtaposes Dhok-Pathan Formation against Soan Formation (Figs. 8, 10). As mentioned earlier, the area consists of molasse sediments in which stratigraphic terminations are complicated to find, that is why only structural terminations in the form of discordant bedding relationship between Dhok-Pathan and Soan formations are evident to mark Ratta Fault. The Ratta Fault in the Eastern Half has east–west trending but it changes to north–south direction while moving towards Western Half.

Western half

This half occupies the western part of the mapped area from north to south. This half consists of laterally extended ridges trending mostly in the north–south or northeast–southwest directions. The key structures mapped in this half of the study area are discussed ahead. The **Chhappar Bend** is an oroclinal structure mapped in the middle of the map near Chhappar Village (Figs. 8, 9). It reflects the connection between the eastern and western half and accommodates the shortening caused by both north–south compression as well as east–west transpression. The Chinji Formation lies in the middle of the bend bounded by Nagri Formation on either side. The **Walayat Anticline** is an elongated structure and extended in the north–south direction in the form of an overturned fold. It occupied Chinji Formation in its core and Nagri Formation on limbs (Figs. 8, 9). The beds on both limbs of the fold dip towards west in the same direction. This sharp overturning of the beds towards west shows the association of this anticline with the east verging, west dipping Diljabba Fault. The **Diljabba Fault** is the main back thrust which enters the study area in the southwestern corner and runs towards north where it merges in the Damnoh Fault near Dhamnal Village (Figs. 8, 9). It is a northeast–southwest trending fault which thrusts the Nagri Formation over the Dhok-Pathan Formation. The eastward vergence of this classifies it as the major back thrust within the study area. The **Damnoh Fault** runs from southwest to north where it bends along the Chhappar bend. It is a west verging, east dipping forethrust. It juxtaposes Nagri Formation over Dhok-Pathan Formation in the southern part of Western Half while moving towards north it brings Chinji Formation over the Dhok-Pathan Formation which shows that the up-dip slip component along this fault increases towards north (Figs. 8, 10). The **Palina Fault** is a continuous fault running from north to south having a bend in its trend as passes from Chhappar bend like Damnoh Fault. It is also a west verging, east dipping forethrust which places the older Chinji Formation over the Nagri Formation in the hanging wall (Figs. 8, 10). The network of all these faults reflects that there is a kind of positive flower structure which shows insignificant up-dip slip component as compared to its significant strike-slip component but more of a lateral displacement because all faults are very continuous from
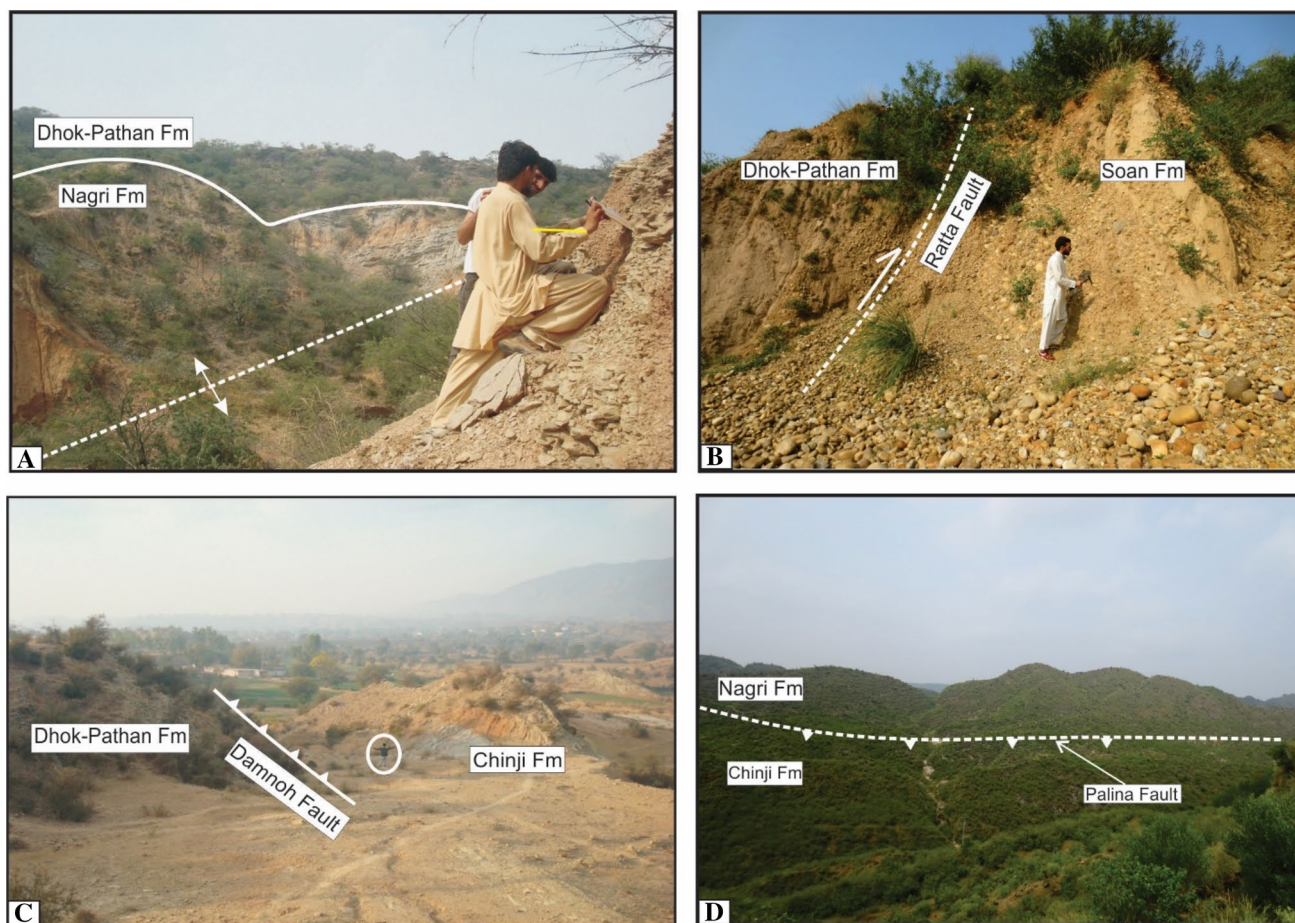
Fig. 10 A Northeast looking view of Sadiqabad Anticline, **B** East looking view of Ratta Fault, **C** East looking view of Damnoh Fault and **D** West looking view of the Palina Fault

north to south but do not expose the strata older than Chinji Formation.

Description detail of geological cross sections

Four geological cross sections constructed from south to north direction are AB, CD, EF and GH. All the cross sections are almost east–west oriented and are approximately along and across the structural trend of both halves of the mapped area to the trend of regional structural fabric. During the interpretation of these cross sections, an average depth of −6000 m has been contacted. The overall thickness of the package taken in this study reached 6000 m to 7000 m which includes the Mirpur and Soan formations at the top while Salt Range Formation at the bottom (Missakeswal-01 exploratory well).

Cross section AB marks the southernmost part of the map area and is east–west oriented (Fig. 11). In the western part of the section AB, a number of faults are present which merge in the subsurface to form a positive flower structure. In the eastern part of the section AB, Mangla Lake Syncline

is present in which Mirpur Formation lies in the core. This syncline is an open structure of 12 km width and having several kms east–west extension. This broad syncline transforms into a very sliced anticline towards the west of the cross section.

Cross section CD lies next to the section AB and is also oriented in east–west direction (Fig. 11). In the western part of the section, Walayat Anticline is present in the form of an overturned fold. Next to this anticline, Diljabba Fault which is a back-thrust juxtaposes the Nagri Formation over Dhok-Pathan Formation. Damnoh Fault also brings the Nagri Formation over Dhok-Pathan Formation having vergence opposite to that of Diljabba Fault and form a triangular zone. Relatively more movement has taken place along the Damnoh and Palina Faults as compared to Ratta Fault which overlie the Dhok-Pathan Formation over Soan Formation. The Eastern Half of section CD is again cover by the Mangla Lake Syncline. Cross section EF lies further towards north and is oriented in WNW–ESE direction (Fig. 11). This section has almost the same structures as present in the cross section CD. The Diljabba back thrust shows a little gentle
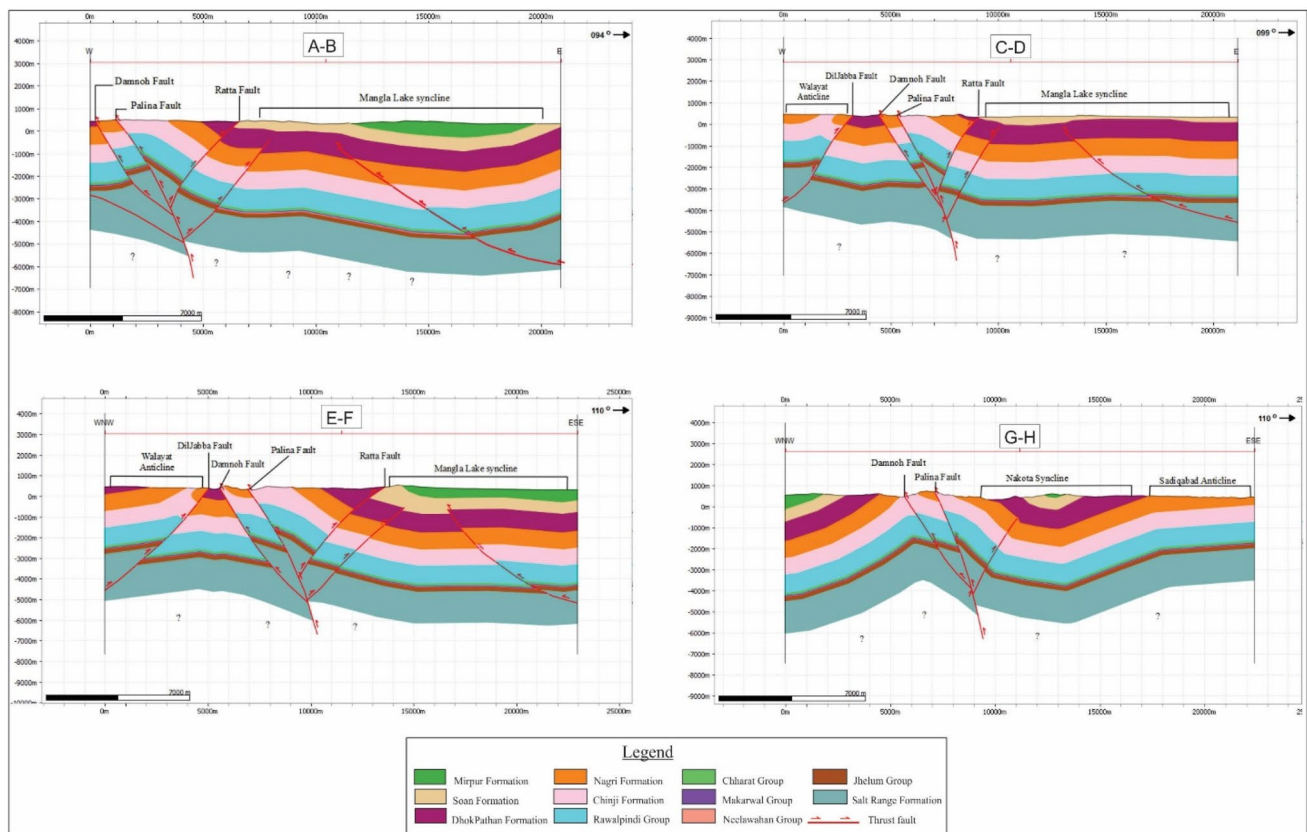
Fig. 11 Deformed state of cross section A–B, C–D, E–F and G–H

behaviour in this section. The displacement along Damnoh and Palina Fault increases.

Cross section GH marks the northern limit of the map area. It is also oriented WNW–ESE, rather oblique to the structural trend of the Western Half (Fig. 11). In the eastern part, the section is drawn parallel to the axis of the Sadiqabad Anticline and shows the plunge of this anticline where it transforms into a syncline known as Nakota Syncline in which Dhok-Pathan Formation lies in the core. These anticlinal and synclinal structures present in the eastern part trending almost perpendicular to the strata present in the western part. This contrasting behaviour in the trend of the structures is yet another evidence of the presence of some lateral movement in the area.

All the cross sections show a positive flower structure in the Western Half which indicates the presence of strike-slip movement in the area. This movement is not provided by a single strike-slip fault rather it points towards the presence of a zone in which all the faults facilitate the lateral movement in the area. Therefore, Jhelum Fault is not a single linear fault but it is zone along which many faults facilitate the deformation of rocks. These faults have a little stratigraphic throw and longer surface exposure proving more lateral throw. These faults converge at an average depth of

−5000 m to −5500 m into a single fault plane and form a positive flower structure. The cross sections are not interpreted to the level of basement because of having lesser data and non-availability of seismic lines in the study area. So the sections are interpreted to the level of Salt Range Formation at the depth of almost 7000 m.

Restoration of geological cross sections

The cross sections are restored in the move software to find out the dip parallel shortening incurred due to the tectonic stresses (Fig. 12). The actual length measured for cross section AB is 20932 m while it increases to 22932 m when restored along faults and folds. The increase in length of the cross section is 2003 m which shows that increase is stored in deformed strata in the form of shortening. Thus, the shortening measured in the section line AB is 8.74%. The total length measured for cross section CD in deformed state is 21204 m. The length increases to 24115 m when it is restored through folds and faults. The difference in length stored in the form of shortening is 2911 m. The shortening of cross section CD is 12%. Similarly, the actual length of deformed cross section EF is 23040 m. After restoration, its length goes to 26974 m. The difference in the length of
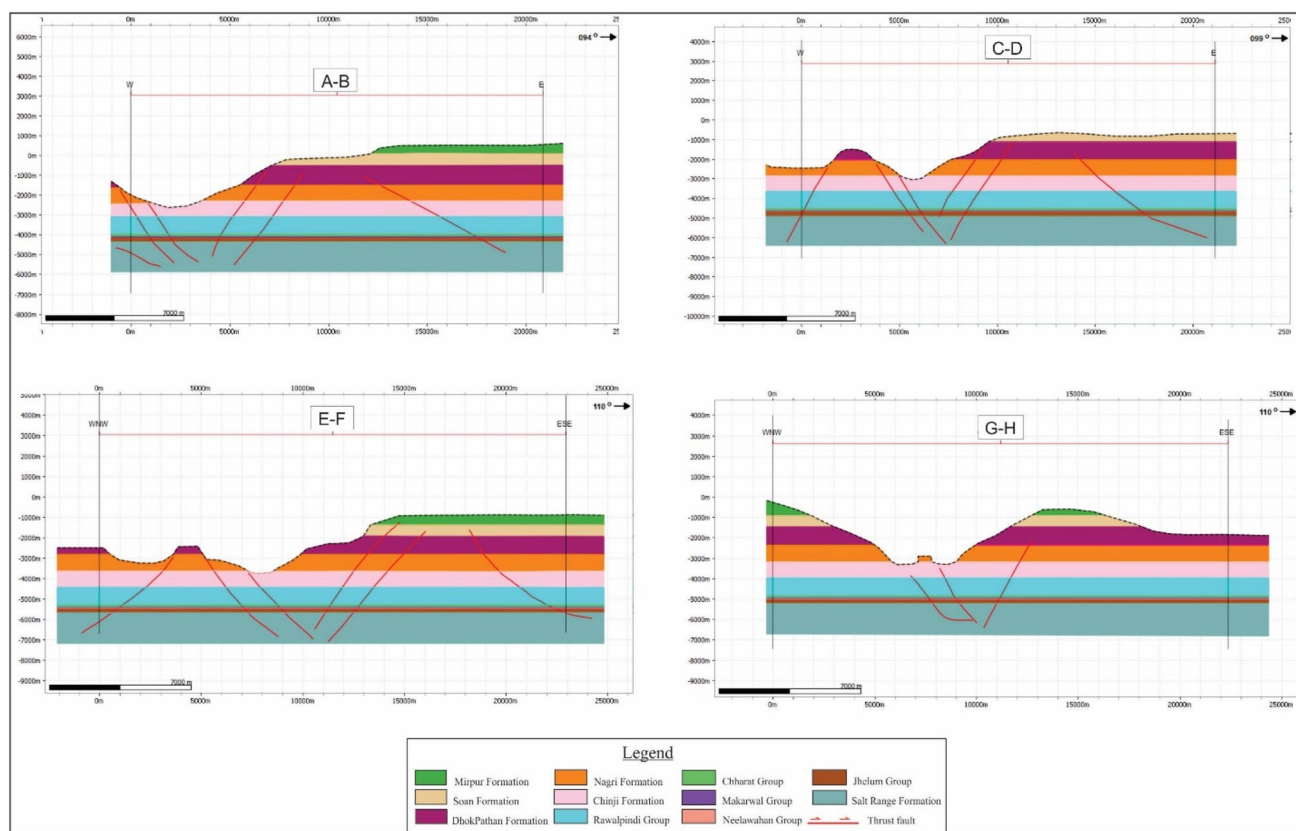
Fig. 12 Restored state of cross section A–B, C–D, E–F and G–H

deformed and restored cross section is 3934 m. The shortening in the section line EF is 14.5%. The shortening along this cross section is higher than the others, which can be attributed to the presence of Chhappar Bend along this section.

In cross section GH the actual length is 22478 m. The length of the cross section increases to 24765 m when it is restored. The length restored in this cross section is 2287 m. The shortening measured along this section is 9.3%. According to the shortening measured along the cross sections in this study shows that the area has got an average shortening of about 11.2%. It has been found through shortening percentages that the central part of the study area has undergone intense deformation as compared to the northern and southern parts.

## 3D Structural model of the study area

Geological cross sections in 2D represent the subsurface behaviour but there are a lot of changes going on between the adjacent cross sections. Therefore, in order to have a continuous picture of the transformation of structures from one configuration to another, the 3D modelling has been carried out for the study area. The surface map and subsurface cross sections are distributed and related in such a way to

get a closer picture of the area as described by Ishaq et al. 2021 (Fig. 13). In order to avoid confusion, only 3D models for the fault surfaces have been created because the faults are the major controlling factor in fabricating the shape and structure of the area (Fig. 13). All the faults and fault planes are drawn which point towards a positive flower structure. The fault planes of all the faults present in the area show convexity in its trend. It can be seen that the forethrusts have a very clear eastward convexity which indicate the presence of Chhappar Bend, while the back thrusts convex towards west direction. 3D models also show that the faults present in the area are very persistent and through going along the extension of surface exposure of the map. These faults are continuous along the north–south trend of overall structural fabric.

Results and discussion

Structural emplacement of Jhelum Fault (JF) and its effect on the surface and subsurface geology is the main concern of the present study. The area under investigation is a junction between southern part of Hazara-Kashmir Syntaxis and eastern part of Potwar Plateau, so the structural

Fig. 13 **A**, **B** and **C** showing the 3D models of the study area with different orientation in move window
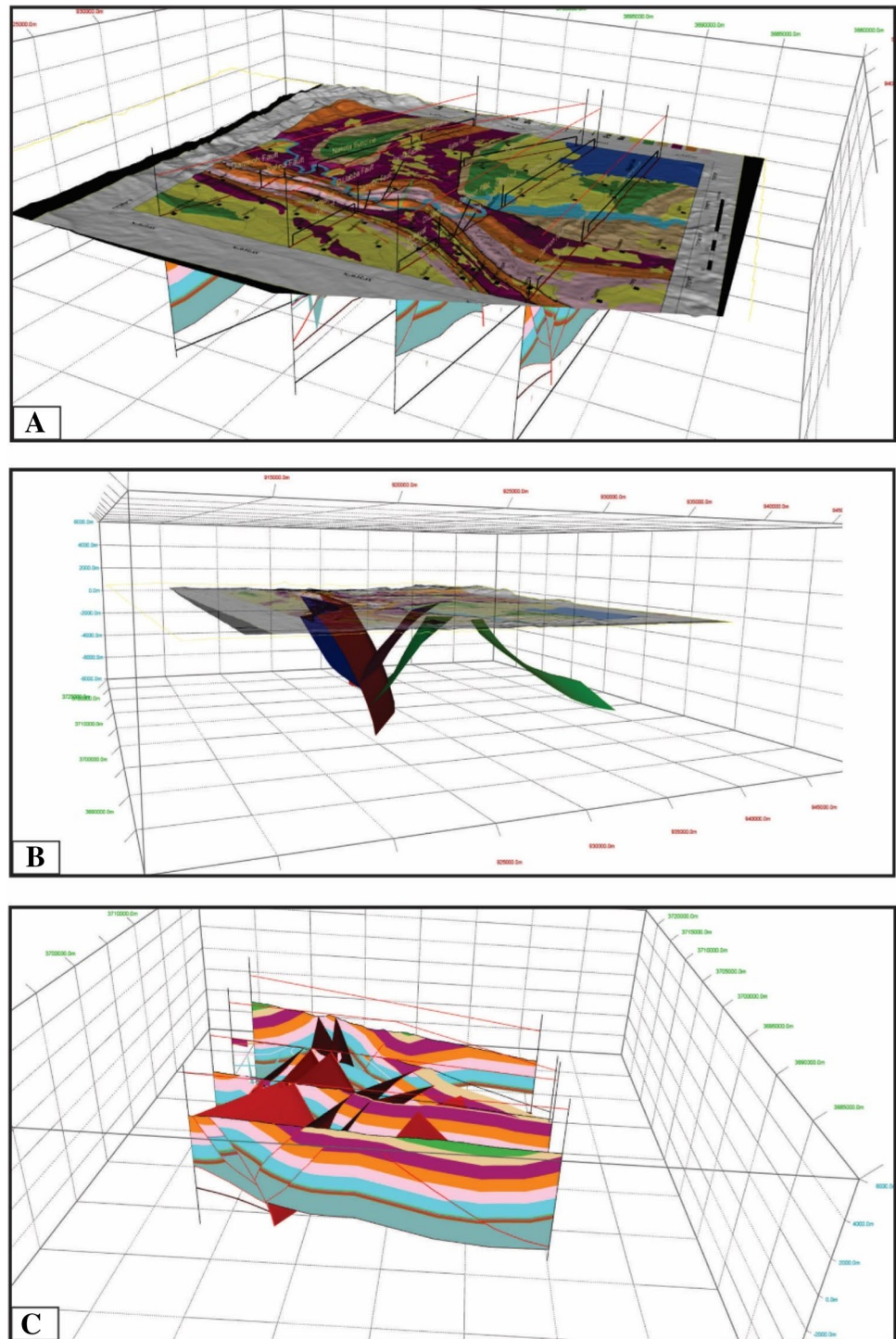
lineament present in the area has absorbed the behaviour of both the Hazara-Kashmir Syntaxis as well as the Pot-war Plateau. The structural description and surface extent of Jhelum Fault are provided by various researchers in the past. Jhelum Fault is a left-lateral strike-slip fault that extends from Muzaffarabad to Jhelum, following the linear trend of Jhelum River along the western margin of Hazara-Kashmir Syntaxis (Kazmi 1979, Fig. 1). Monalisa and Khawaja (2005) also described the nature of Jhelum Fault as a left-lateral strike-slip fault but they extend it from Muzaffarabad to Kahuta in their proposed regional tectonic model (Fig. 5). Both of the mentioned studies show that Jhelum Fault is a pure strike-slip fault but the research carried out by Iqbal et al. (2015) in the vicinity
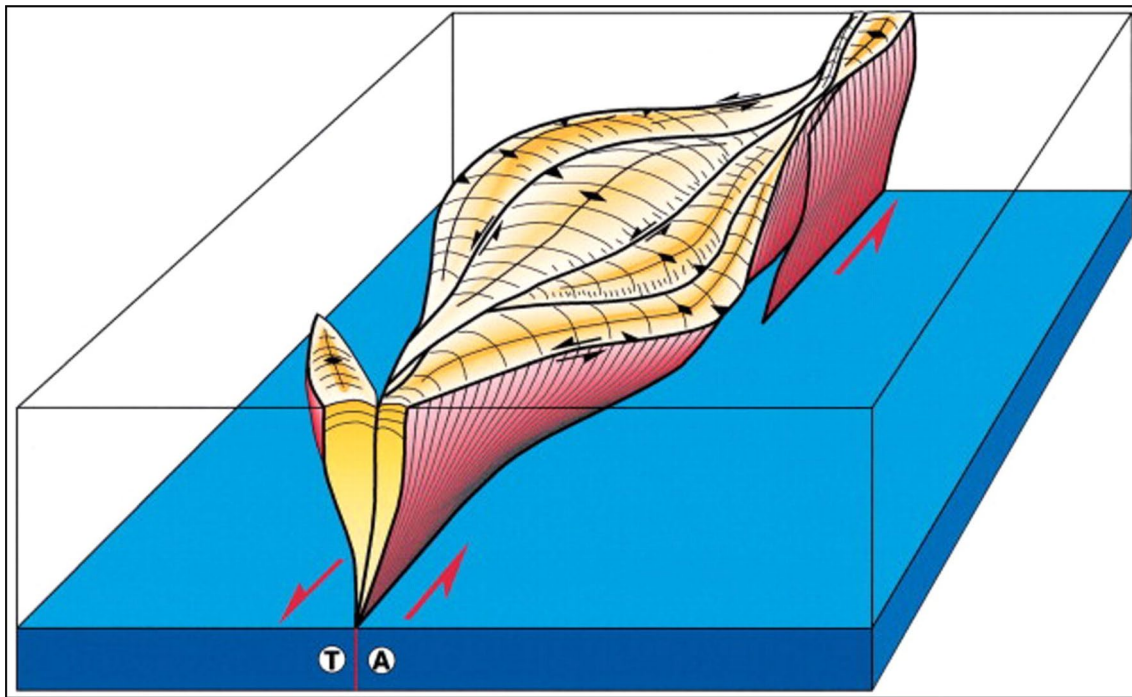
Fig. 14 Conceptual model of an ideal pop-up structure showing its 3D representation based on the results of analog modelling. T represents the baseplate moving towards the observer, and A shows the baseplate moving away from the observer (after McClay and Bonora 2001)

of the study area describes it as a sinistral fault with subordinate reverse motion.

The previous research work on the study area and its vicinity only describes the surface expression of the Jhelum Fault, while in the present study the surface expression of Jhelum Fault is modified and is projected into the subsurface using MOVE software. The surface and subsurface analysis of the study area shows that Jhelum Fault is a not a single lineament but rather a zone in which all the faults facilitate each other in lateral movement of the area and join in subsurface in the form positive flower structures. In order to clarify the structural behaviour of Jhelum Fault Zone and its relation to exposed structures, the area is divided into almost two equal halves, i.e. Eastern Half and Western Half. In the Eastern half NE–SW trending structures including faults and folds (Figs. 8, 9) could be the result of lateral ramp in the subsurface along which these structures dip towards east (Qayyum et al. 2015). But contrary to that the structures present in the Western Half trend in almost N–S direction, which is supposed to be the result of lateral movement along these faults. Faults present in the area join in the subsurface form a positive flower structure in the cross sections (Figs. 11, 12) as well as in 3D model (Fig. 13). These faults are nearly vertical dipping and uplift the area along its linear strand and form pop-up structures in the section view. According to McClay and Bonora (2001), those regions which show local uplifts, pop-up structures,

palm tree or positive flower structures as a result of compression at restraining stopovers indicated transpressional strike-slip faults (Fig. 14). On the basis above discussion, and the arrangement of structures present in the area it could be concluded that the area has undergone through initial phase of compressional deformation in the N–S direction which is followed by later phase of transpressional deformation in the E–W direction. The above results are based on the surface geological field data which are interpreted in MOVE software for subsurface analysis. In MOVE software, only the thrust component related to faults is restored while its strike-slip component which plays a major role in the deformation of the study area is beyond the scope of this study. The non-availability of the seismic and well data of the study area is also among the limitations for the accuracy of the model.

Conclusions

The conclusions of our research work are as follows:

- The map surface is clearly divided into two halves in which the structures are trending in north–south and east–west direction indicated the lateral movement of these structures along the Jhelum Fault Zone.

- The consistent through-going map extents of many faults in the study area prove that faults are playing major role in the tectonic fabrication of Jhelum Fault Zone.
- It is concluded that Jhelum Fault is not a single lineament but rather a zone in which several faults facilitate each other in the N-NE to S-SW directions.
- Geological cross sections are prepared and restored to the level of Salt Range Formation which show an average shortening of 11.2% in the Study Area.
- Positive flower structures, steep vertical faults and less shortening along the cross sections concluded that the area is undergone through transpressional deformation.
- Most of the faults in the area are of transpressional nature having dominant lateral component with relatively smaller push towards west on steeply east dipping faults.
- Pop-up structures are identified in the cross sections and are considered to be the potential zones for the hydrocarbon traps.

Declarations

Conflict of interest There is no conflict of interest in the research.

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