Impact of Indo-Pakistan and Eurasian Plates Collision in the Sulaiman Fold Belt, Pakistan*

Muhammad Iqbal[1] and Moin Raza Khan[1]

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[1]Exploration, Pakistan Petroleum Limited, Karachi, Sindh, Pakistan (d_iqbal@ppl.com.pk)

Abstract

The Sulaiman Fold Belt has a complex tectonic setting as it is located in the collision zone of Indo-Pakistan and Eurasian plates with the left-lateral Chaman fault in the west and the Himalayan fault and thrust system in the north. The Indian Shield, with pre-Cambrian basement rocks, is exposed in the east.

The Himalayan chain is primarily resulting from the north-south collision of the Indo-Pakistan and Afghan Block (Eurasian) plates. The resulting consuming margin extends from Pakistan through India, Nepal and Myanmar. To the west of this collision zone, a consuming boundary is present between the Arabian and Persian plates. During the collision process, the sedimentary overburden detached from the crystalline basement of the Indian Shield. The sea floor of Neo-Tethys is preserved as Bela-Waziristan Ophiolite Zone.

In Pakistan, the oblique collision of Indo-Pakistan and the Eurasian plates led to the formation of Kirthar-Sulaiman fold belt involving Mesozoic through Cenozoic sediments. The colliding converging plates have strongly deformed the sediments deposited on the shelf and frontal part of Indo-Pakistan Plate. Subsequently due to strong orogenic events marine sedimentation changed to terrestrial one followed by more than 3,500 m thick coarse grained fluvial sediments of the Siwalik Group deposited in the Indus Foredeep, which is considered as a hydrocarbon kitchen area.

This paper discusses different concepts about the tectonics of the eastern Sulaiman Fold Belt, Pakistan which was previously interpreted in terms of thin-skinned and strike-slip / wrench tectonics. Present work is based on interpretation of satellite images and geological fieldwork, which concludes that area under discussion, has been developed as a “Positive-Flower Structure” due to left-lateral strike-slip movement in the basement of the Indo-Pakistan Plate. In the overlying sediments its impact can be substantiated only after the deposition of the Upper Siwaliks that is not more than 0.7 million years old.

Introduction

A simplified tectonic map of the Himalayas and Tibetan Plateau formed due to the collision of Indo-Pakistan Plate and Eurasian Plate is given in Figure 1. The Sulaiman-Kirthar ranges are part of the western Himalayas in Pakistan and show measureable impact of the collision process, which has been analysed in the eastern frontal part of the Sulaiman Fold Belt particularly in the Zindapir Anticlinorium (ZPA).

Stratigraphy

The regional stratigraphic succession (Table 1) shows marine carbonate and clastic strata dominate the basal part and fluviatile of Himalayan provenance in the upper part. During the Oligocene a hiatus prevailed. The Lower Miocene begins with the Nari Formation, a near-shore flood-plain deposit. The molasse facies deposited in front of the rising Himalayas since the Middle Miocene. Siwaliks are divided into massive Lower Siwalik sandstones, Middle Siwaliks mainly sandstone and Upper Siwaliks. The latter are a local development of massive, weakly consolidated conglomerates. The main pebble component is limestone from Cretaceous and Jurassic rocks of the Sulaiman Anticlinorium. The age of the Upper Siwaliks could be around 700,000 years. They wedge out towards the Indus floodplain and once have been covering the area occupied by today’s Zindapir Anticlinorium (ZPA). Above the Upper Siwaliks follow two terraces forming the core of the large Barthi Syncline. The older terrace (T1) has a high content of Pab Sandstone pebbles, which are covered by dark desert varnish. They were also found on the crest of the Afiband and Rhodo anticlines between 450 m and 600 m above mean sea level. They must have covered the area of the ZPA as well. Only the next younger terrace (T2) found the ZPR already as an obstacle. Lignite fragments found during this study indicate an age of 11,750 to 11,500 years. Only then the existence of the up-rising Zindapir Anticlinorium could be manifested in the overlying sediments.

Tectonic Concepts

Following concepts have been presented for the structural evolution of the western Himalayas in Pakistan.

1. Thin-skinned tectonics - Passive Roof Duplexes (Banks and Warburton, 1986, Humayon et al., 1991, Jadoon, 1991 and 1994).
2. Strike-slip Tectonics- Inversion tectonics (Bannert et al., 1992, 1995, Coward, 1994, Iqbal and Helmcke, 2004, Ali et al., 1996. Iqbal, 2004, 2008, Farrukh and Peressen, 2009).

According to thin-skinned concept the sedimentary strata detached from the basement along a floor thrust in Paleozoic salt and a roof-thrust in Cretaceous Sembar Formation and duplexes developed in between in older sequences. A back-thrust arises from the foreland that carries a thrust sheet towards the hinterland (passive roof duplex) for several kilometers. As a result the strata are elevated from the regional due to duplex geometry.
The strike slip concept considers that the collision and oblique convergence of the IPP and AB resulted strike-slip faults in the basement beneath the present day IPP. These basement faults branching out and giving rise to opposite verging geometry as positive flower structure. The structures of the frontal part of the mountain belt (Sulaiman Range) develop as strike-slip positive flower structure and the ZPR is evidence.

Geological Setting of the Sulaiman Range, Pakistan

The main structures of Pakistan are given in Figure 2. The area of our interest, the Sulaiman Range, is dominated by rocks of Triassic through Cenozoic. These rocks are tightly folded, uplifted and faulted. The Zindapir Anticlinorium is a major structure forming the eastern mountain front. It comprises of en echelon folds named Dhodak, Rhodo, Afiband and Zindapir anticlines (Figure 3). The Barthi Syncline, in the W filled with Siwaliks, is structurally a part of ZPA.

In the Sulaiman Range strongly deformed shelf sediments of the IPP, that has detached from the crystalline basement of the Indian Shield, are exposed. The ophiolitic sea floor (Neo-Tethyan) rocks which are part of the IPP occur as Bela-Muslim Bagh-Waziristan Ophiolite Zone (Figure 2). The IPP and Eurasian plates convergence featured first an oblique collision (Paleocene - Eocene, 65-55 ma) followed by a head-on collision and anticlockwise rotation of the main body of the IPP (Eocene - Early Miocene, 55-20 ma) and basin formation (Early Miocene-Present, 20 ma to present). The sediments of the Indus Basin were folded and rotated under the influence of the plate collision in the Early Tertiary and developed its present geometry. The structural fabric is analysed to assess the nature of deformation i.e. thin-skinned versus strike-slip tectonics.

Impact of Collision Tectonic in the Zinidapir Anticlinorium

The main axis of the ZPA is N-S trending with swing to the W on both ends. NE-SW and NW-SE diagonal faults also occur. The eastern flank of the ZPA is highly tectonised and developed tightly cored secondary anticlines with fold axes oblique to the fold axis of the main ZPA. Dip variation and overturning in the incompetent strata along the strike is common. Strike parallel, shear faults with outward opposite verging geometry is dominating along the flanks of the ZPA. A consistent west verging thrust observed in Eocene Sirki Shale and Pirkoh members at the E flank of Dhodak anticline of ZPA (Figure 4) and a box fold at the northern plunge of Rhodo anticline of ZPA (Figure 5).

The regional west verging fault in Eocene strata along the eastern flank of the main ZPA was named Sanghar Lahar Back Thrust (SLBT). At the east flank of Afiband anticline another east facing fault develops in younger Eocene Pirkoh member. Likewise a regional west verging fold and thrust with breccias in Habib Rahi member occurs at the west flank of Afiband anticline (ZPA). Occurrences of such outward facing box folds on both flanks suggest a shallow basal detachment of SLBT. The paralleling of Afiband fold axes and opposite vergence on the east and west flanks have interpreted as indications of an initial positive flower structure.

Interpretation of Rhodo anticline shows steep, outward verging thrusts and east and west verging basement rooted faults (Figure 6). Likewise Afiband anticline shows comparable fault system (Figure 7). It indicates upward splaying fault branches with a reverse separation which are considered as manifestation of “flower structures” and the near surface expression of an upward spreading fault zone.

At Zindapir anticline Proper, SLBT has formed a high angle reverse fault. The split of the main fold axis, east verging folds and high angle fault was investigated. At Rikayni Nala, overturning in the eastern limb of the ZPA occurs in Ghazij Shale. It indicates branching out of Eocene sequence near to the surface (Figure 8). A reverse fault was also investigated at its E flank (Figure 9) at Sori Nala. It has similarity with faults of the Rhodo and Afiband structures and suggests comparable deformation.

At Vidor Nadi again overturning occurred. The ductile Ghazij Shale caused the sediments to flow towards the flank of the fold and is giving rise to opposite verging fold (Figure 10). Southwest of Rakhi Munh (Figure 11), the plunge of ZPA interrupts the already deposited terraces T1 and T2, and drainage pattern. Upper Siwalik beds pierce the terrace deposits thus changing the depositional pattern. Since the age of the terrace T2 could be determined as being approximately 11,000 years it is a proof for the ongoing southward extension of ZPA.

Tectonic Set Up of the Barthi Syncline and its Contact with the Sulaiman Anticlinorium

The Sulaiman Anticlinorium is standing about 3,300 m amsl (the highest peak Takht-i-Sulaimani).The cause of this sudden increase in height within a short distance is note worthy. Barthi Syncline filled with more than 2,000 m thick Siwaliks is tectonically an undisturbed structure and without any faulted contacts on its both flanks. At the foothills of Sulaiman Anticlinorium near Thak village a back-thrust was found in the east limb of the main Sulaiman Anticlinorium where a detachment occurs in Eocene Habib Rahi (0550/250) Limestone (Platy Limestone) (Figure 12) and there is increase in stratigraphic thickness.

It is considered that the underlying Ghazij Shale caused the detachment that break the Habib Rahi Limestone (HRL) and filling the gap with breccias. The hanging, detached part of the HRL, reaches to the peak of the folds of Sulaiman Anticlinorium and rests as klippen (Passive roof thrust). The Ghazij Shale serves as the upper incompetent detachment horizon. The occurrence of a prominent syncline of HRL in the west of the main ridge of the Sulaiman Anticlinorium is most likely an erosional remnant of a passive roof thrust (Figure 13). The Ghazij Shale is pushed eastward against the Barthi Syncline by the up-warping and strongly compressed Sulaiman Basement Anticlinorium (SBF).

It is considered that a major fault system separated the Sulaiman Anticlinorium from the Barthi Syncline and the Zindapir Anticlinorium. This fault system is considered the surface expression of the Sulaiman Basement Fault (Bannert et al., 1992). It reflects a drastic change in structural style compared to the structural style of the ZPA. This led to the conclusion that variation in structural style of the Zindapir Anticlinorium is assumed to owe its origin from the SBF strike-slip system. This is the main reason for Sulaiman Anticlinorium being much higher than its surrounding features.

Discussion

Review of the geological observations has been focused on the nature of structures associated with thin-skinned or strike-slip tectonics. Sufficient evidence suggests that the ZPA is an early positive flower-structure. In the northern anticlines (Rhodo and Afiband) seismic lines clearly show the opposite inward dipping faults, which serve as shear planes to allow the central part of the anticlines to move upward. Similarly, auxiliary, inward dipping faults have been found along the east flank of ZPA. On the western flank of Afiband anticline comparable features have been found. No foreland facing thrusts are known from this region. But a regional back-thrust (SLBT) is a steady feature along the entire east flank of the ZPA. In places, the thrust is reaching back for nearly one kilometer over the autochthonous rocks of the ZPA.

Coward (1994 fig.14.26) showed a simplified example from the Sulaiman and Kirthar Ranges in Pakistan, which represents the wedge of a thrust fold-belt. The section shows a layer of sediments gently folded, thrusted and uplifted to form a mountain front monocline against the foreland basin. No thrusts emerged into the foreland basin and all the shortening within the thrust-fold belt has to be transferred onto a back-thrust beneath the frontal monocline. (Coward, 1994; fig.14.27b) model assumes that much of the uplift beneath the thrust-fold belt is a result of shortening of a sedimentary basin and expulsion of sediments. It is not necessary to assume a lower detachment from the basement to continue back beneath the hinterland of the thrust fold belt.

The thin-skinned model (Coward, 1994; fig.14.27a), assumes that the uplift of the thrust -fold is a result of thrust imbrication at depth. As the shortening within this deep-level imbricate / duplex zone far exceeds the shortening seen in the upper layers of the thrust fold belt, a passive- roof back thrust has to be postulated beneath the upper layers of the thrust-fold zone. As the basement is not imbricated by the thin-skinned thrusts, it must continue x kilometres back beneath the hinterland of the thrust fold belt, where x is the shortening on the imbricate / duplex zone. In the case of thin-skinned deformation a major upper detachment horizon needs to be identified. It could accommodate a back-thrust. Humayon et al. (1991) in the Zindapir area assumed the Cretaceous Sembar Formation as detachment layer; however, the available seismic data from Rhodo and Afiband anticlines do not reveal any increased thickness of the Cretaceous rocks, which could support this assumption.

Coward (1994) is of the opinion that examples of reverse faults and folds which have been interpreted as thin-skinned thrusts i.e. parts of Apennines of Italy, the Zagros Ranges in Iraq and western Iran (Treloar et al., 1992) and the Kirthar, Sulaiman and Kohat ranges in Pakistan, may warrant re-interpretation as thick-skinned inversion structures.

Treloar et al. (1992) assumed the ZPA as a result of inversion tectonics. They question whether the Indian Plate contained important pre-existing structures, which controlled later structural development of this region. They conclude early sinistral displacements, rather than being accommodated within a single fault along the plate margin, were distributed across a wide zone (200 km) of crustal scale strike-slip structures, all related to deformation along the lateral margin of the Indian Plate". This is in accordance with the segmentation of the western Indian Plate along north-south basement faults during the oblique plate collision (Bannert et al., 1992). The tremendous force of the collision segmented the basement of the IPP regardless of any pre-existing faults.

The presence of Pre Mesozoic salt as assumed by previous workers for duplexes and lower detachment (Humayon et al., 1991) is neither discernible on any seismic lines, nor reported from any well. Likewise no drastic increase in thickness which is require for staking in upper detachment in the Sembar Formation, is reported from wells in ZPA so the roof thrust is in question and the thin-skinned tectonic concept does not apply for the ZPA.

Pivnik et al. (1998) suggested that the Kohat Plateau, in the northern Pakistan has undergone transpressional deformation expressed as highly oblique reverse faults with considerable strike-slip components, positive flower structures, and basement involved deformation. The strike-slip faults affecting structural genesis in the area have relatively short lateral displacement and there are no major transcurrent faults such as Chaman and San Andreas faults, which produce quantifiable piercing points and explicit offsets. The faults in the Kohat area are poorly constrained but are estimated to range from several to tens of kilometres. These faults are not recognizable at the surface as strike-slip faults, but originate deep-seated in the basement, and manifested by complex cored anticlines in shallow stratigraphic sections through vertical movement, rotation, and ejection. Pivnik et al. (1998) analysed well and seismic data from Tolanj Well in Kohat area suggested that in incompetent Eocene evaporite sequence the deep-seated high angle reverse faults become shallow near the surface. Near surface shallowing, high angle, reverse faults have been termed "positive flower structure or "palm tree structures" (Sylvester, 1984) common in terrains subjected to oblique compression, or transprsession. Previously thin-skinned tectonics was considered instrumental in structural deformation in the Kohat area, Pakistan.

Basement involved tectonics with strike-slip faults from the Unita Mountains of Colorado and Utah has been described by Cook (1978). Searle (1994) analysed the structures of the Palmyrides of Syria and concluded that the occurrence of Triassic salt resulted in box folding and flower-structures associated with inward-dipping reverse folds. Other comparable folds in sedimentary rocks have been published by Meer and Jen (1996) from Ronda in Spain. Deformation of the Zindapir Anticlinorium is comparable in several aspects to the mentioned cases. Therefore, it is considered that the Zindapir Anticlinorium is the result of deep seated basement strike-slip tectonics. The synthesis of earthquake data from the region, field observations and analogous structures reported elsewhere, the Positive Flower Structure model is proposed for the structural deformation of the Zindapir Anticlinorium (Figure 14).

The continuous SLBT along the east flank of the ZPA suggests that the entire ZPA undergoes a comparable deformation. Occasional strike-slip movements can be attributed to the curvilinear nature of the ZPA. They can be observed in several places of the southern parts of the structure. The boundary zone to the Sulaiman Anticlinorium which is included in this study is separated from the ZPA by Barthi Syncline. A detachment and klippen pattern occurring in HRL of the western flank of Barthi Syncline was observed in the field. The base of the Barthi Syncline overrides to the east the frontal part of the Sulaiman Anticlinorium along a back-thrust.

The age of the deformation and uplift of the ZPA is very young. There are two salient observations in support. At the southern tip of the ZPA, the distribution of the terraces T1 and T2 from the foothills of the Sulaiman Anticlinorium towards the Indus River is interrupted by the anticlinal fold of the ZPA (Figure 11). On Rhodo and Afiband anticlines remnants of T1 have been observed, indicating that before T2 deposition (11,970 a and 1,130 a) there was no surface indication of the uprising ZPA.

In the eastern flank of the Zindapir Anticline Proper (Belab Nala), the tilted T1 is located on rather steeply dipping Siwaliks and is partly fractured by steep faults. Clastic dykes in the lower reaches of Sanghar Lahar (9) infer paleo-earthquakes (26, 27) that occurred during sedimentation of the Middle Siwaliks.

Conclusions

There is a difference in opinion of the nature of ZPA. One group of geologists adheres to the concept of thin-skinned tectonics that requires regional detachment horizons and back-thrusting of tens of kilometers. The other group of geologists give evidences of basement related regional faults that deformed the overlying sediments. These faults developed during Tertiary collision.

This study concludes that:

1. In the Zindapir Anticlinorium (ZPA) the deformation is connected with the sinistral Sulaiman Basement Fault, which induced a flower-structure in the overlying sediments of the Indo-Pakistan Plate (IPP). Since the hard collision of the IPP and the Eurasian plates is rather young, the resulting basement faults are likewise very young. The flower-structure is regarded to be in its initial phase, since prior to 11,000 years it had no surface effect on the sedimentation.
2. The structures on the entire eastern frontal part of the Sulaiman Range from south to the most north part have formed by left lateral strike-slip movement whereas the main Sulaiman Foldbelt has formed due to thin skinned tectonics and an offshoot of regional strike slip tectonics.
3. A basement induced strike-slip tectonic, which develops due to the oblique convergence of IPP and Eurasian plates in Cenozoic time, is responsible in the generation of the ZPA flower-structure.
4. The Sulaiman and the Zindapir anticlonoria and intervening Barthi Synclines share similar geology but the former one has different tectonic style than the latter ones and Barthi Syncline is the part of the ZPA.

Acknowledgements

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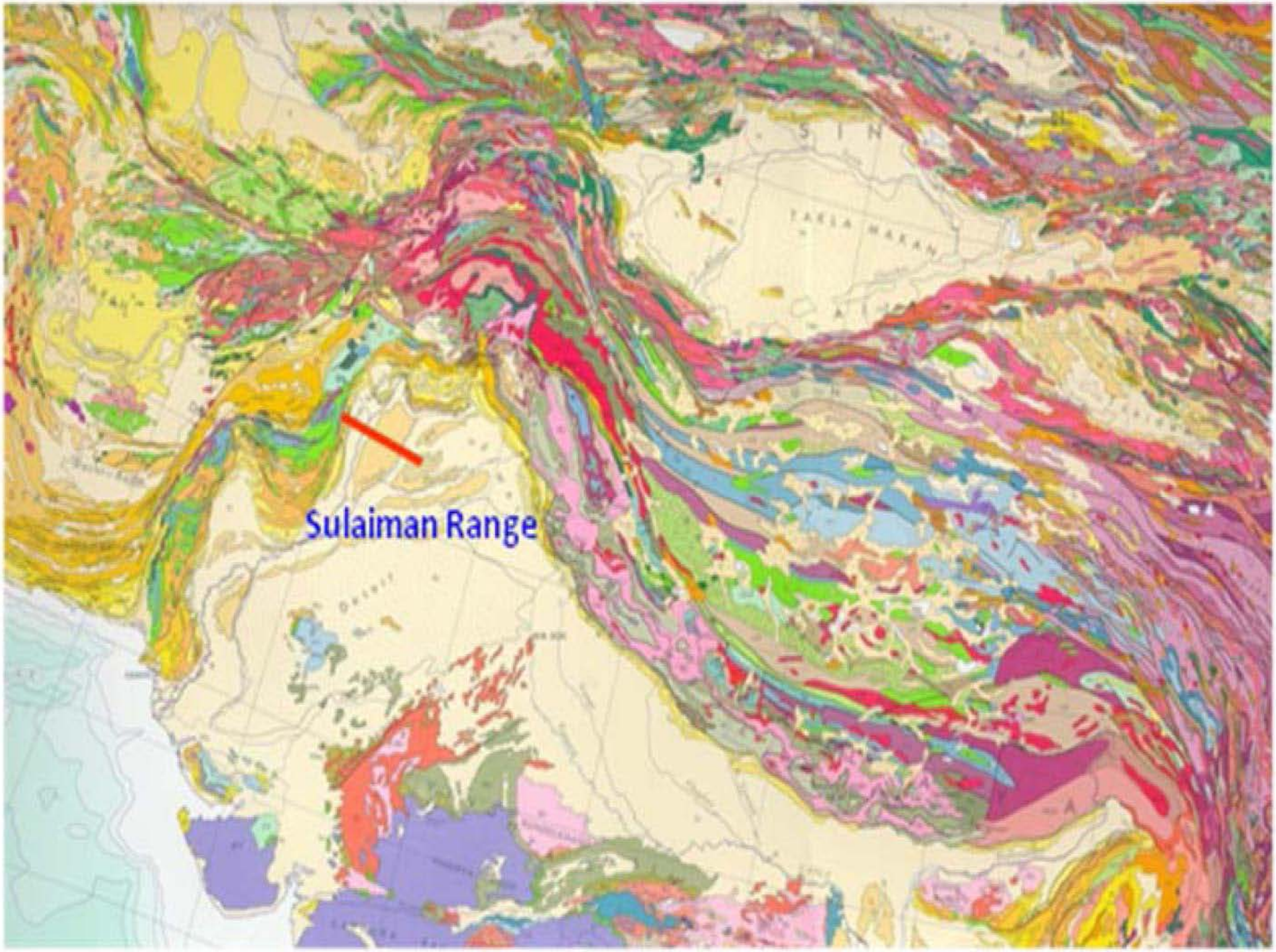
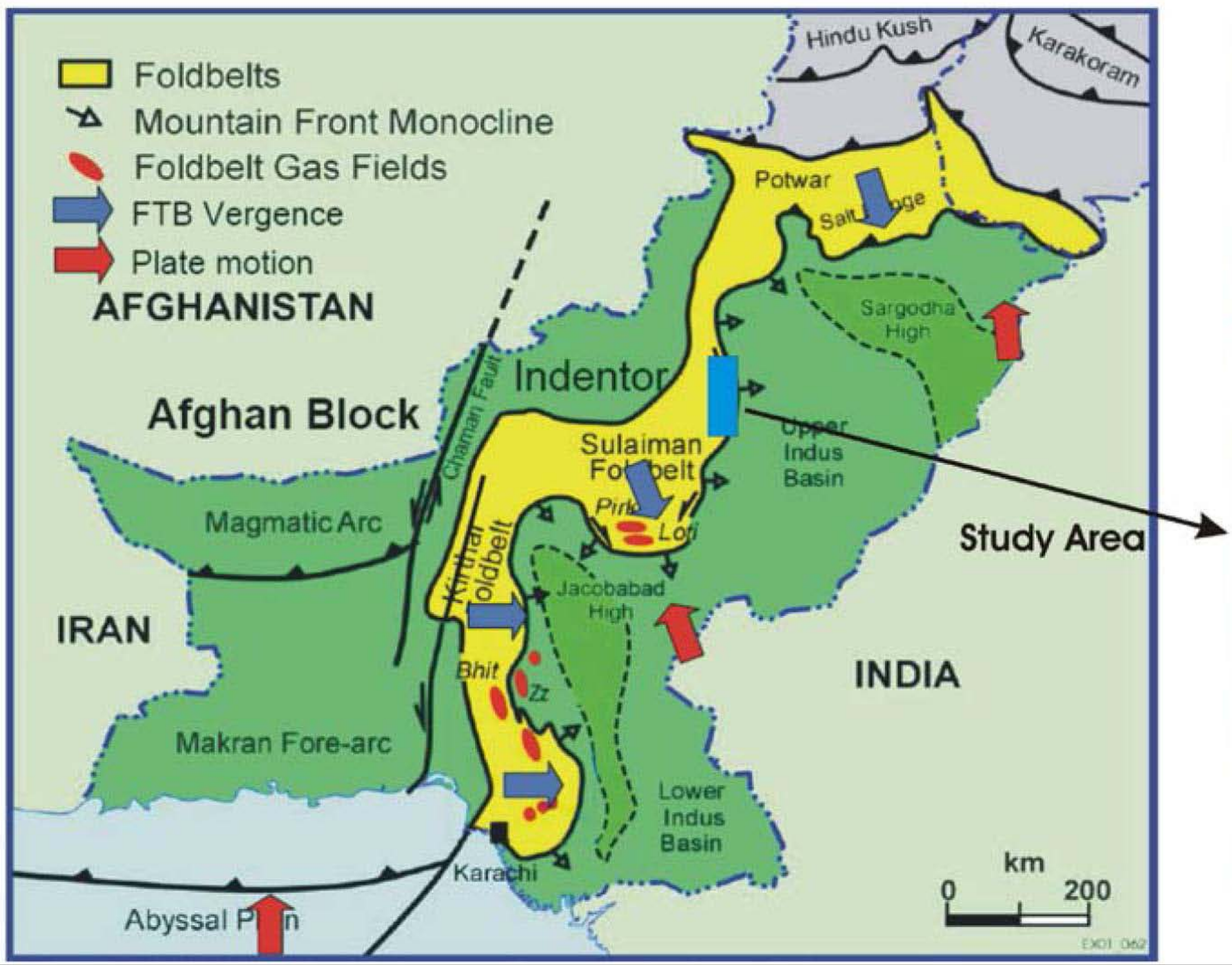


Figure 1. The collision of Indo-Pakistan and Eurasian Plates resulted the underplating of the Indo-Pakistan Plate and upheaval of Himalayas and Tibetan Plateau. The Sulaiman-Kirtahr Fold Belt (SKFB) drapes over the IPP.



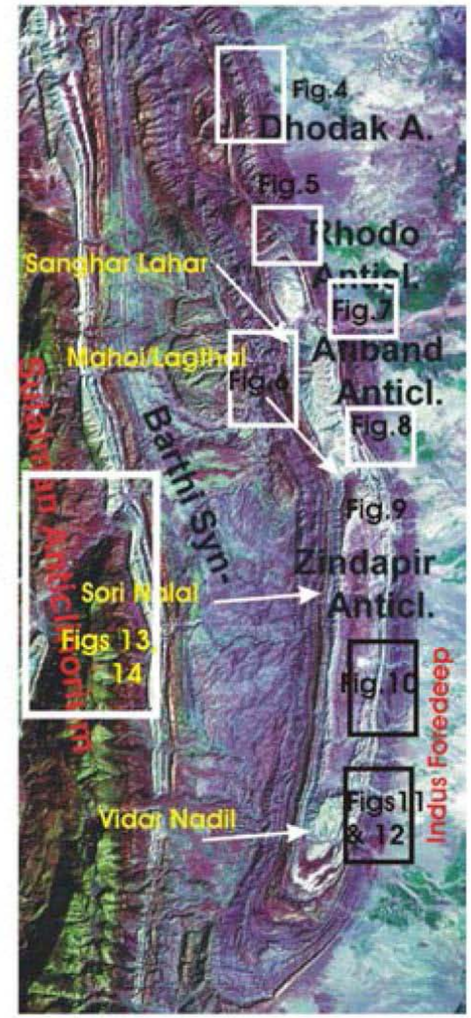


Figure 2. Tectonic map showing major structural elements of Pakistan.

Figure 3. Satellite Image of the Zindapir Anticlinorium (ZPA), Sulaiman Fold Belt (Study Area) and location of figures referred in text.

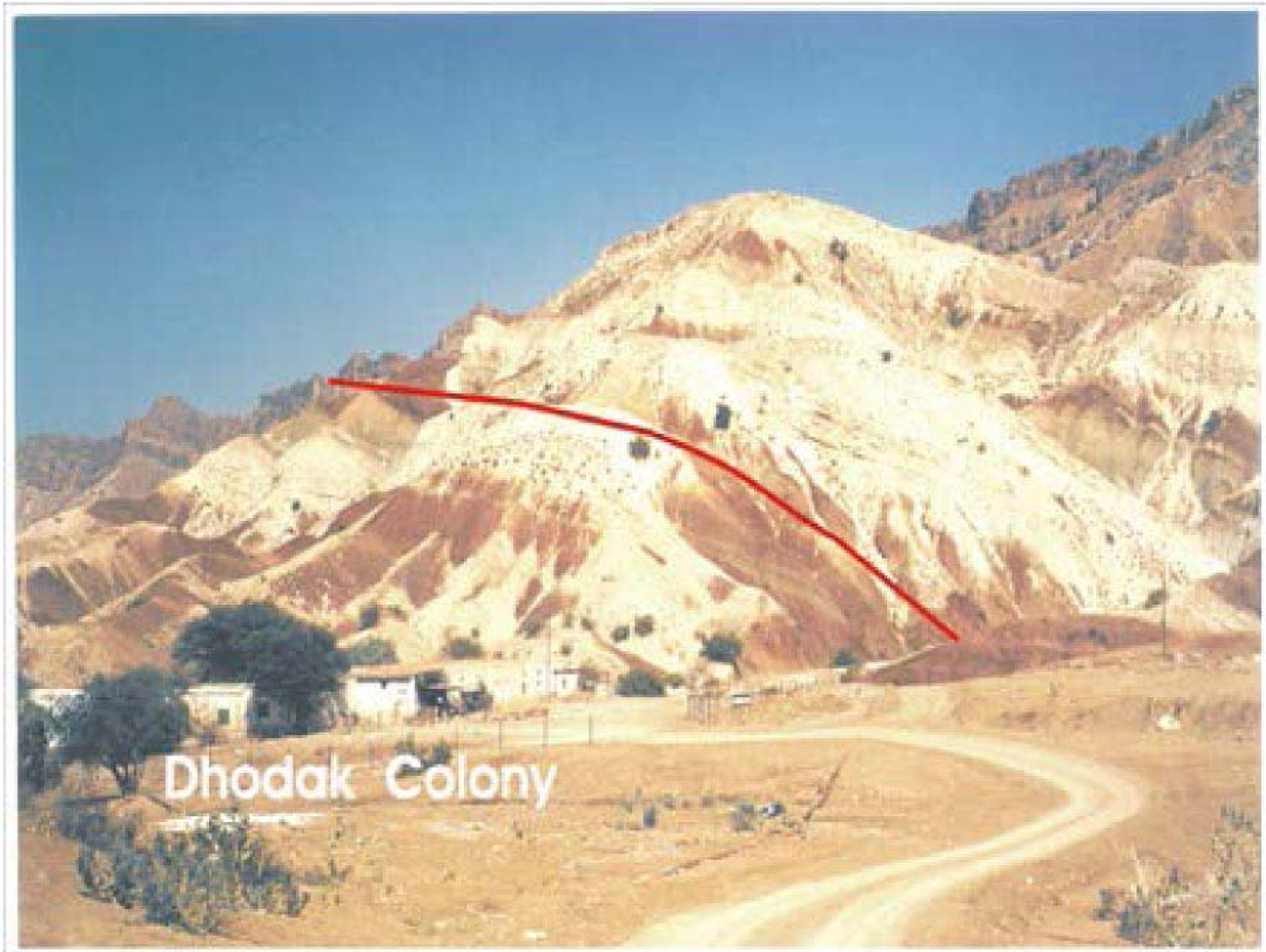


Figure 4. View to the north, the east flank of Dhodak anticline with repeated Eocene Sirki Shale Pirkoh member (white). Trace of SLBT is marked (red).

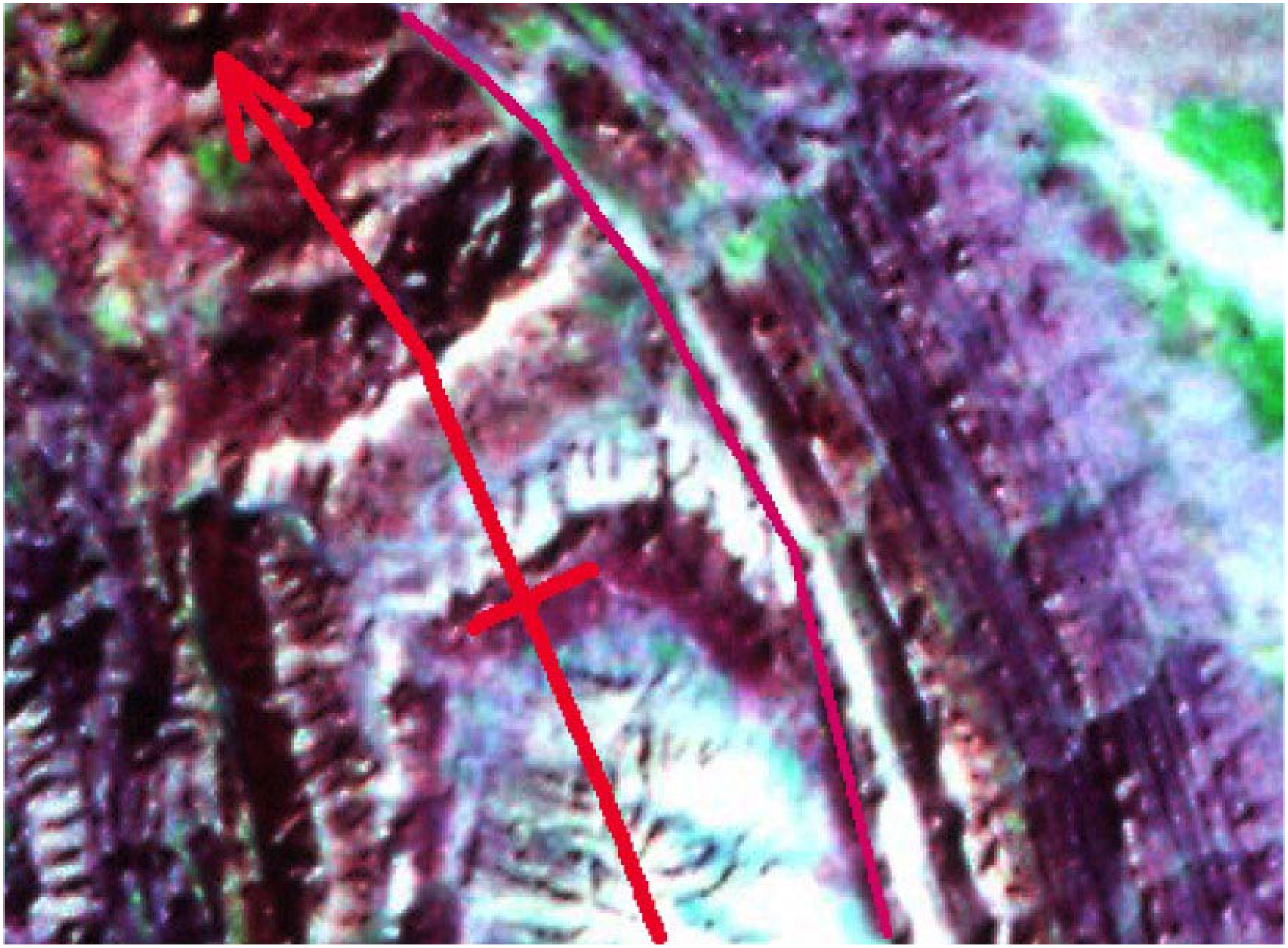


Figure 5. The box-fold structure of the northern tip of Rhodo anticline. In magenta the trace of SLBT is marked. The width of the picture corresponds to 5 km.

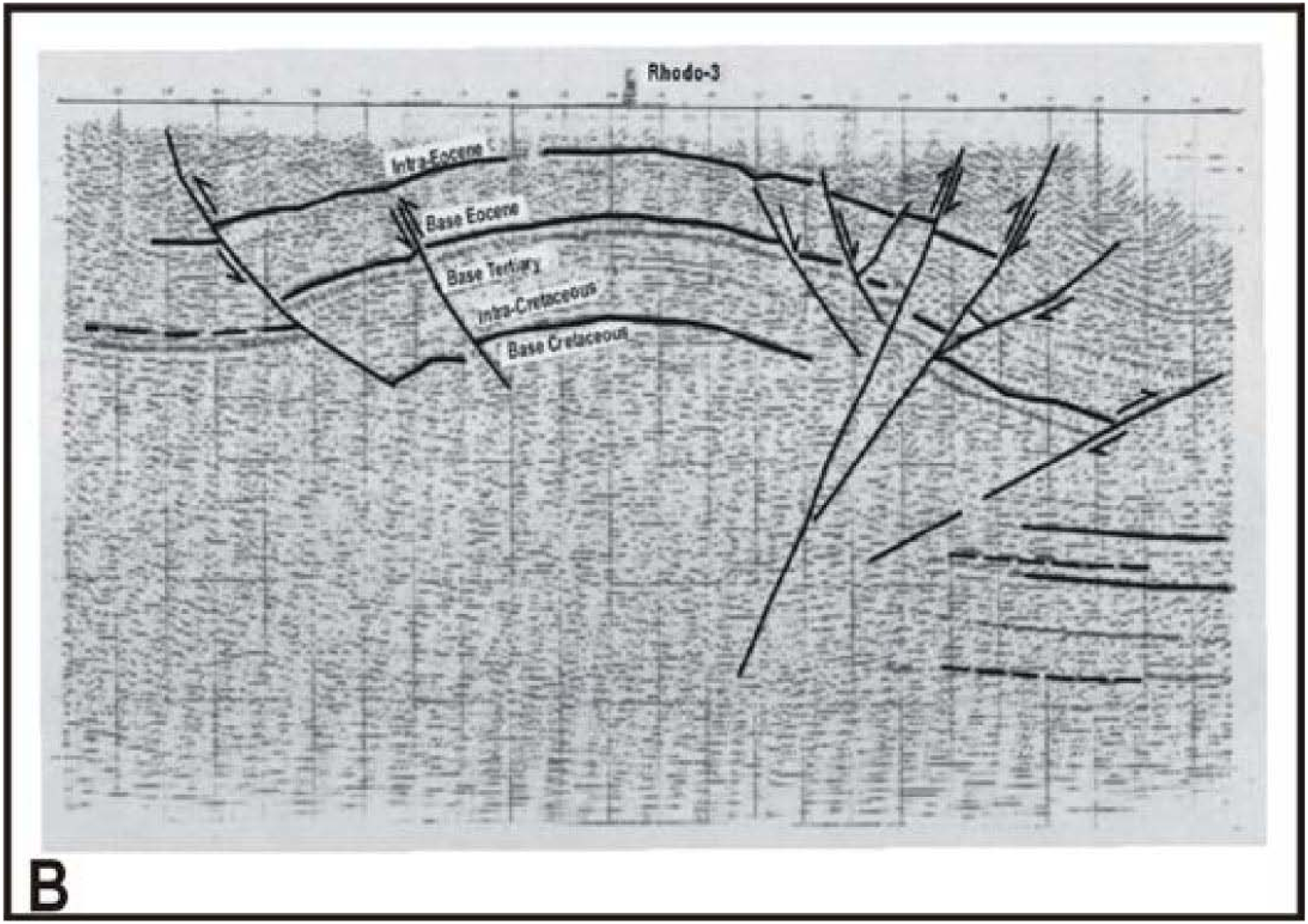


Figure 6. An E-W dip line (845-SK-29) across Rhodo anticline (1988).

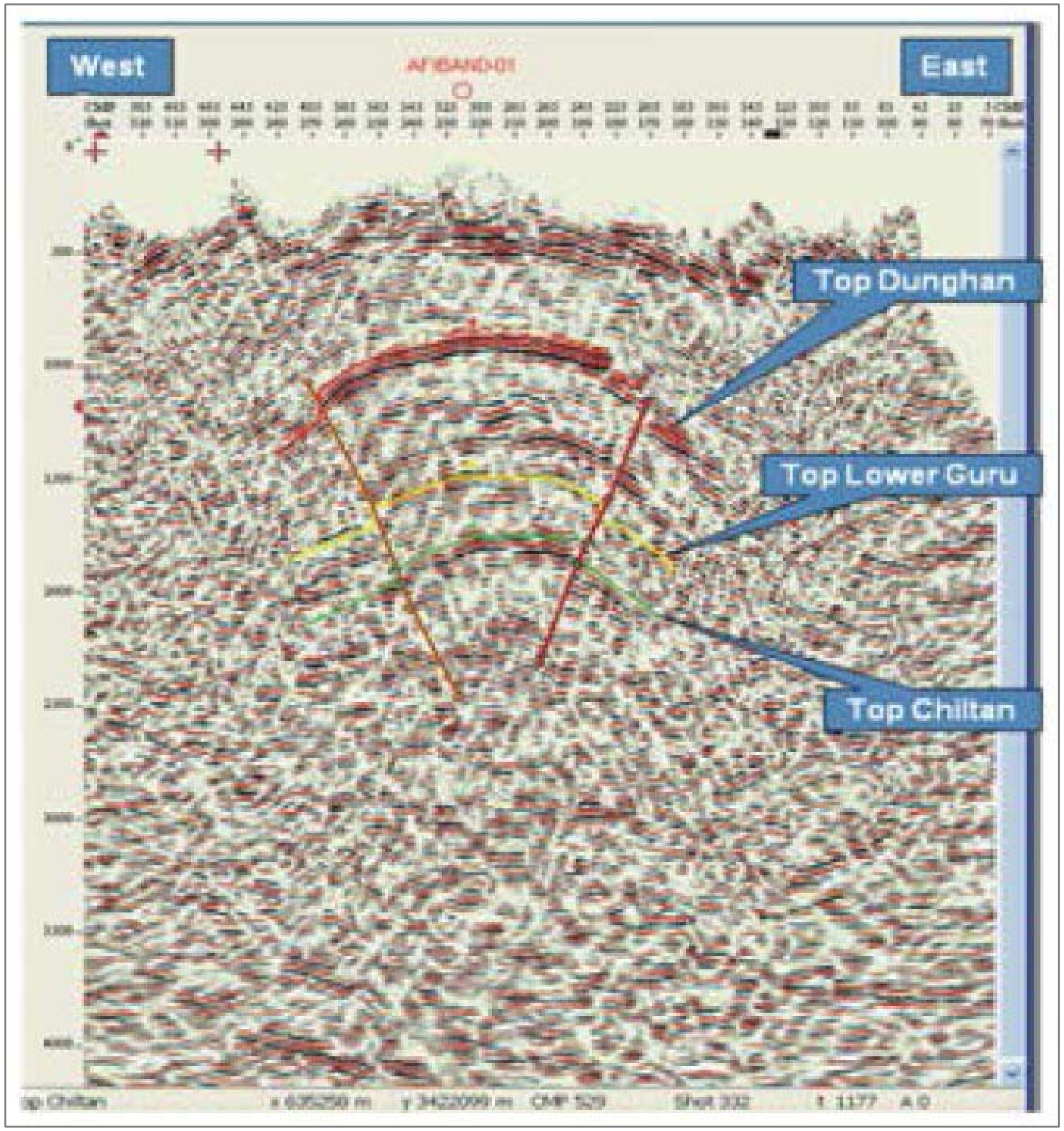


Figure 7. Dip line for Afiband anticline showing opposite verging thrust geometry (2010).

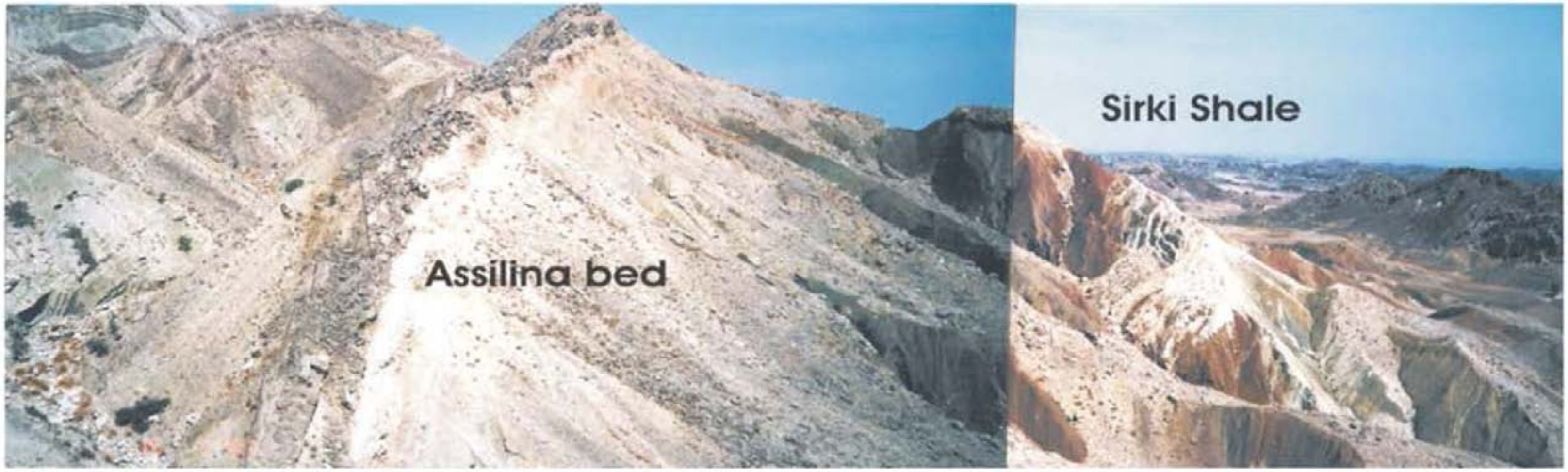


Figure 8. View from S at the E flank of ZPR at Rikayani Nala shows overturning (Assilina bed showing west dip instead of east).

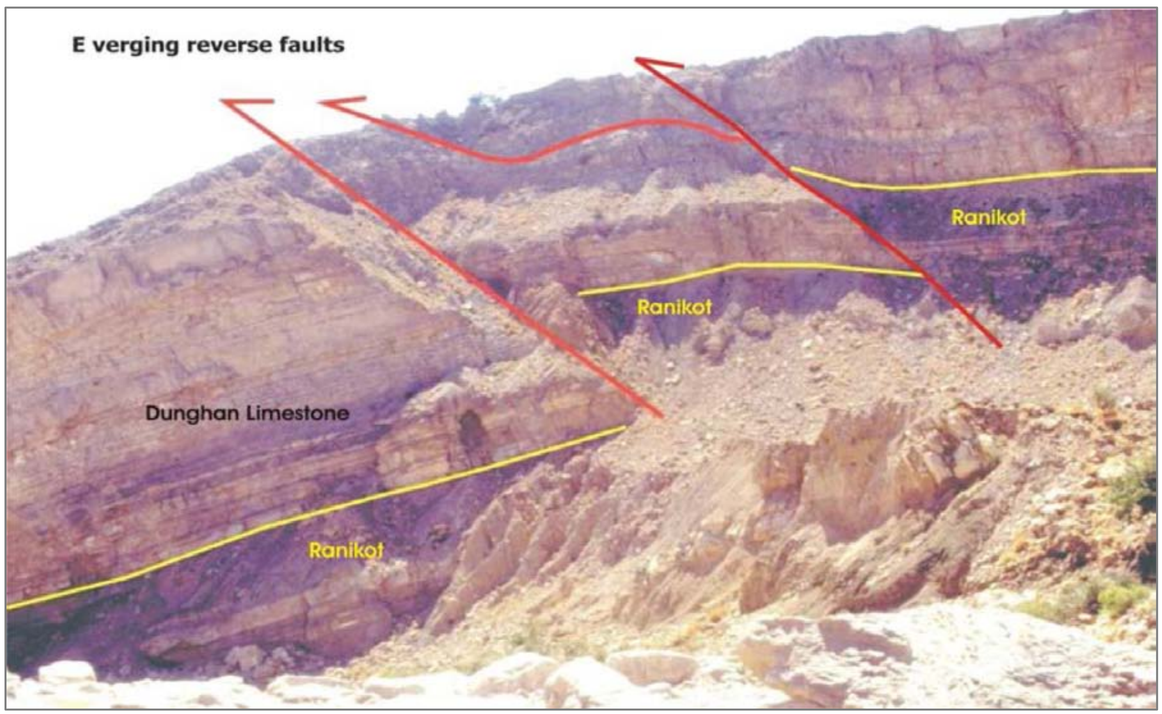


Figure 9. East facing reverse faults (red) at the east flank of the ZPA at Sori Nala.

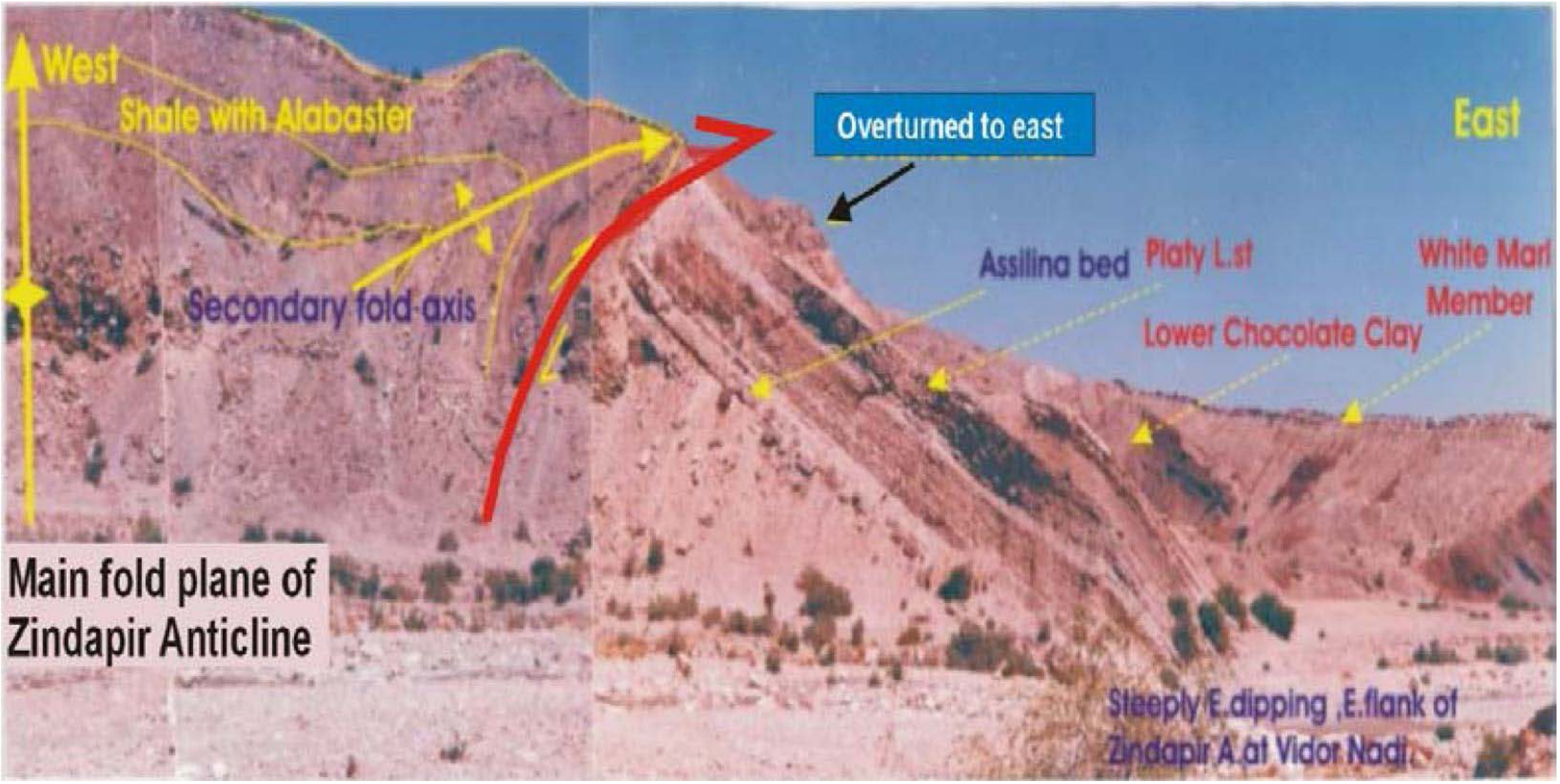


Figure 10. East flank of the ZPA with an east facing fault at Vidor Nadi in Ghazij Shale.

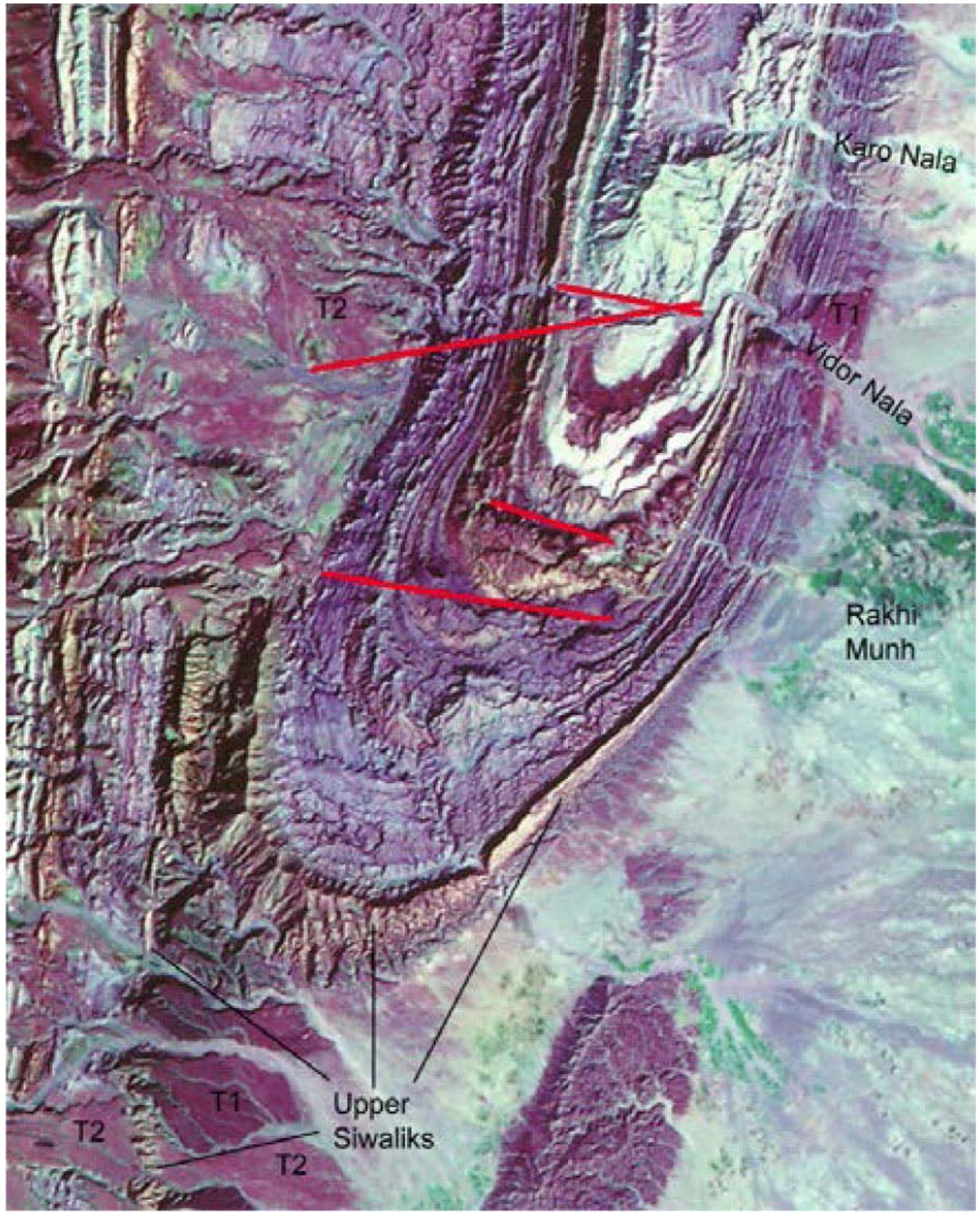


Figure 11. The ongoing uplift and folding of ZPA southern tip destroys former terrace. T2 fan deposits in upper left corner are disconnected from Indus River in the E by the rising anticline. T2 = younger terrace - T1 = older terrace. Red lines indicate vertical faults, down-throw to the N.

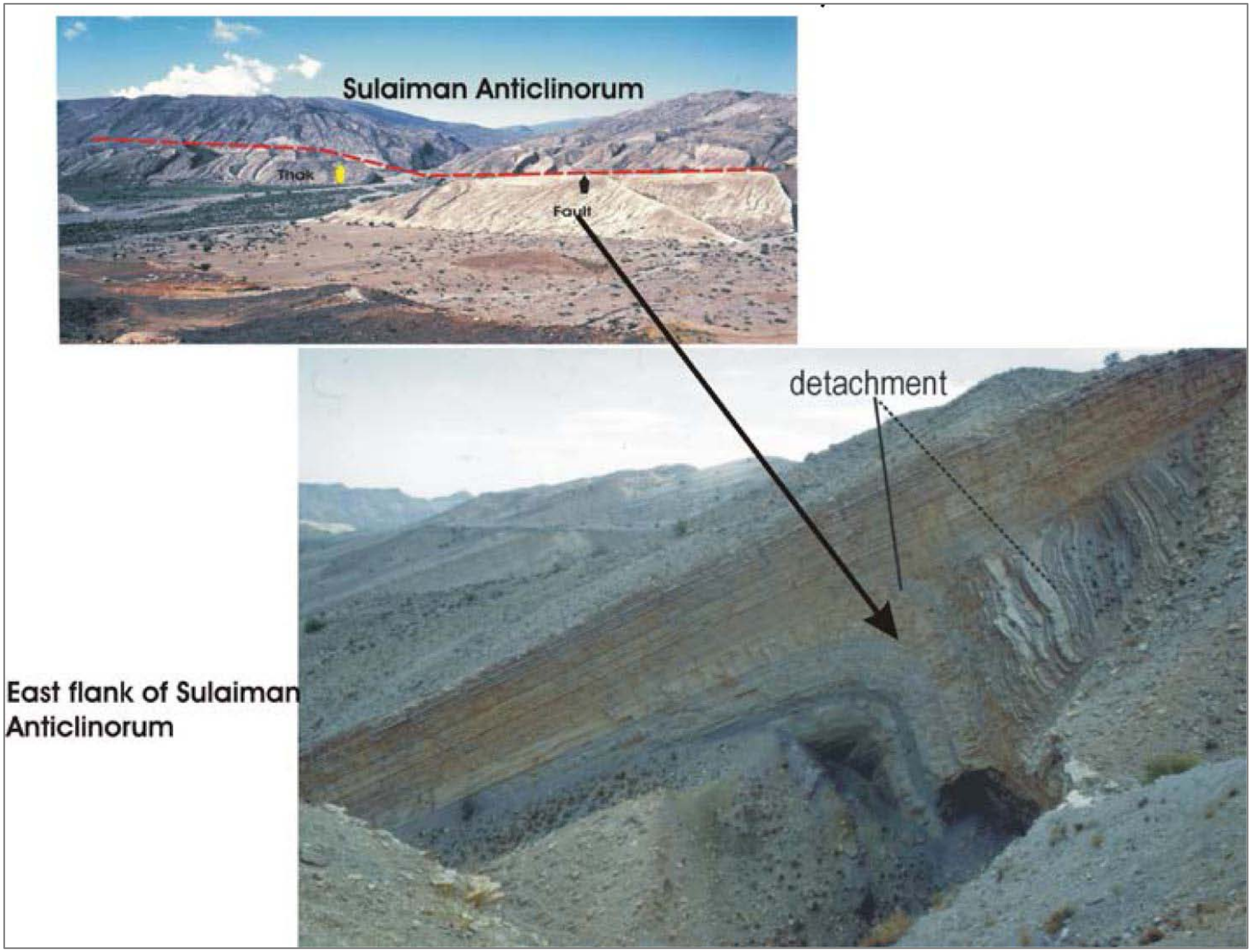


Figure 12. The split of Habib Rahi limestone (HRL) member near Thak, west of Barthi Syncline

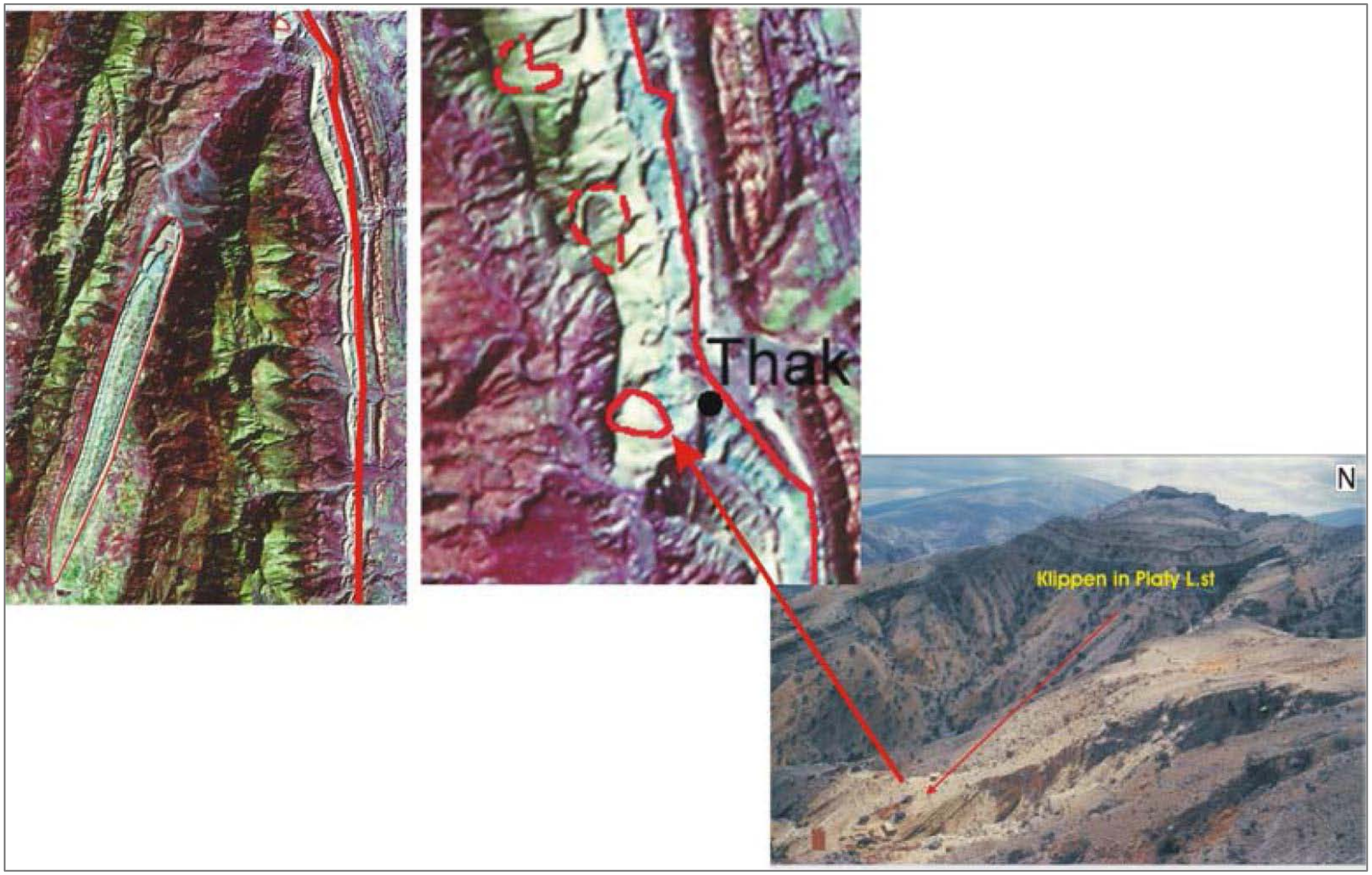


Figure 13. East flank of the Sulaiman Anticlinorium. Bottom right. The Klippen of Thak in the west of Barthi Syncline. The klippen of HRL (Platy limestone) was thrust from the east on the east-dipping Ghazij Shale and Dunghan Limestone underlying them. Middle and top west: The klippen (left) and two synclines (cream colour of western photo) are attributed to be due to the passive roof, which was initiated in Ghazij Shale and Habib Rahi limestone along the red line in the east.

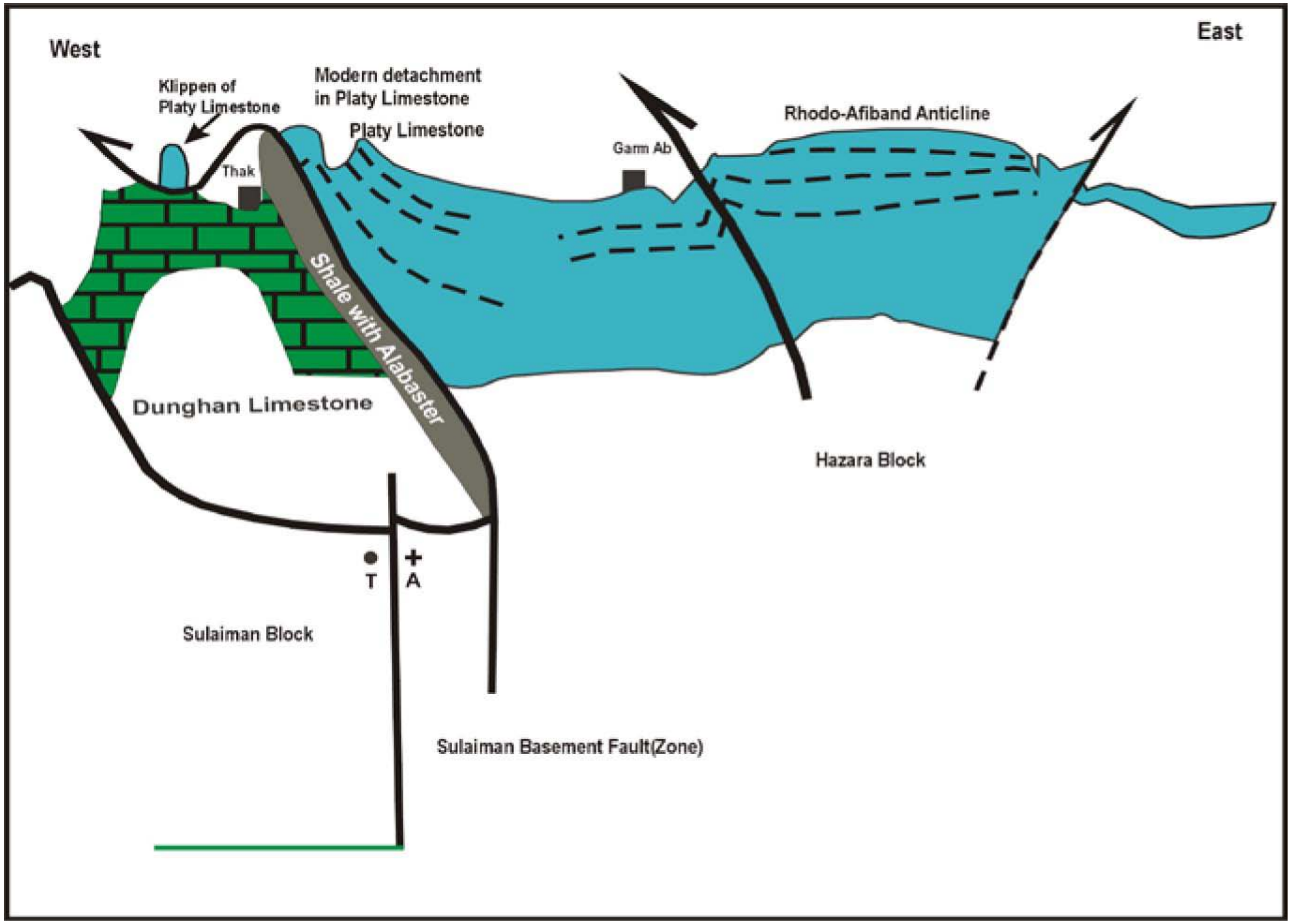


Figure 14. The proposed positive flower structure pattern develops in the Zindapir Anticlinoriums above the Sulaiman Basement Fault.

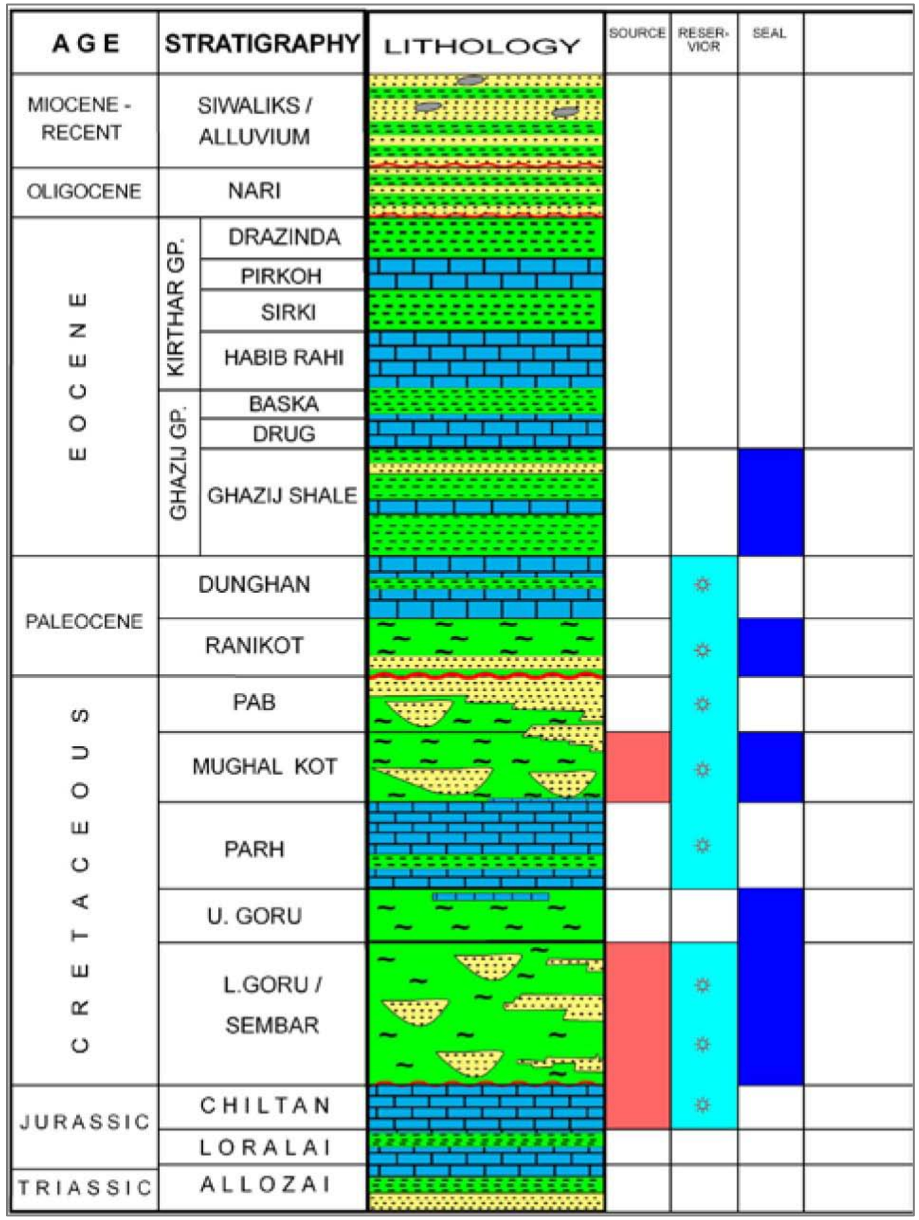


Table 1. Generalized stratigraphy of the Sulaiman Range and Elements of Petroleum System.