Restoration of thrusts to provide an insight into structural evolution in North-West Sub-Himalaya

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Abstract

Sequential restoration of seismo-geological model is a common practice in fold and thrust belt to know the kinematics of thrusting and evolution of structures through time. Restoration of two such regional profiles in Kangra-Mandi area of Himachal Pradesh covering from Main Boundary Thrust (MBT) to Himalayan Frontal Thrust (HFT) illustrates around 29% and 35% shortening respectively. A few structures came into existence near Balh, Changartalai, Hamirpur and towards hinterland area during sequential restoration. Occurrences of hydrocarbon shows in these structures during drilling also indicate importance of these structures as hydrocarbon locales. Moreover the study reveals that some of the thrusting events and its related structurization are likely to have come into existence during or before the expulsion of hydrocarbons and stand a good possibility in entrapment mechanism. Gentle structure in the sub-thrust of Drang Thrust, Palampur Thrust and Splay of MBT may hold primary reservoirs within Subathu Formation. The study also suggests that an up-gradation of the well top of Upper Dharamsala is required in well JMI-G as around 2933m thick Lower Siwalik was drilled at the up thrust of Jawalamukhi Thrust, which appear anomalous when compared with the nearby drilled wells in this area. A proper structural modeling is also useful to identify the nature of thrusts i.e. whether it is deep seated or shallow, amount of shortening and related up-liftments, volume of erosion of different rock types etc. Moreover structural model helps in validation of sub-surface buried faults, which can control surface morphotectonic features.

Methodology

Structural modeling along two regional lines A-A' and B-B' (**Figure-1**) has been carried out in Kangra re-entrant area in Himachal Pradesh (H.P), India. The profile A-A' covers the seismic lines HP-AA-03 and HP-BB-02 and B-B' covers the seismic lines HP-CC-04 and HP-DD-02. Both of these seismic lines are chosen in such a way that it cover the region between MBT and HFT. For any realistic approximation of the sub-surface structure, an orientation analysis from the surface datasets is required to determine the trend of the major compressive/extensional stress. Usually the direction approximately parallel to the principal stress or the tectonic transport direction gives the actual geometry of sub-surface. Along such a section, measurements of initial and final line lengths, shortening and erosion estimation provides adequate results. Thus, in this area two profiles are drawn, oriented approximately in the NE-SW direction, which is perpendicular to the regional strike (major structural features, thrust traces and fold axes are oriented in NW-SE direction). Data gaps near HFT, Changartalai Anticline, Triangle zone and Jawalamukhi area are covered through the available geological maps and geological cross sections of the area. Gravity map has also been used to understand high and low axes within the area and to validate the model. Depth conversion was carried out through proper assignment of rock properties like formation type, age, thickness, porosity, top interface acoustic velocity (V_0), rate of change of velocity (k), depth coefficient, compaction curve etc. Depth model was calibrated with formation tops recorded at wells Balh-A, JMI-A, JMI-B, JMI-J, JMI-G, JNA-A, JNA-B, HSP-A, ADM-A and ZRA-A (for profile-1) and CHGT-A, HMR-A (for profile-2).

Results

Sequential restoration of Profile-1 (**Figure-2**)

i. HFT and HFT Splay restored

Bending on HFT has generated the fault bend fold on the hanging wall of HFT. The restoration of the thrust removes deformation (fault bend fold) on the up-thrust and shows the nature of Upper Siwalik erosional surface when restored. In deformed section a prominent low can be observed i.e. Una low and the low trend can also be validated by the regional gravity data. After restoration, the remnants of the low exist, which is indicative of presence of existing low before deformation due to HFT. The low in this area exists even after the splay of MBT is restored. Therefore it can be revealed that the presence of source rock Subathu within the low may act as a kitchen for adjoining structures (**Figure-3**).

ii. Barsar Back Thrust (BBT) restored

Restoration of Barsar back thrust removes the hanging wall deformation and restores Lower Siwalik, Middle Siwalik and Upper Siwalik erosional tops to the restored stage. The hollow space created by this process indicates erosion of Lower Siwalik, Middle Siwalik and Upper Siwalik during this stage.

Restoration of Barsar Back Thrust shows that a structure prevails at the up-thrust of Soan Thrust (Soan Anticline) at Lower Siwalik level (**Figure-4**).

iii. Soan Thrust restored

Removal of deformation along this thrust brings Middle Siwalik and Upper Siwalik erosional tops to the restored stage. Removal of deformation at the up-thrust of Soan Thrust reveals that Balh anticlinal structure came into existence during thrusting of Soan Thrust (present day Balh structure where high pressure gas was observed in well Balh-A @ 624 m3/day at a depth of 3616m-3610m in Lower Dharamsala and during drilling gas cut mud was observed at the depth of 2150m-2156m and 2955m-2961m in Upper Dharamsala. Presence of Subathu also indicates attendant petroleum system. Well JMI-G is also situated in this set up. During drilling of the well JMI-G fairly good gas shows were observed at depth about 1269m and 4024m (**Figure-5**).

iv. Johr Thrust restored

Ramp feature in up-thrust of Johr Thrust suggests that beginning of Balh structure commenced at this time, which culminated after thrusting of Soan Thrust. Restoration of Johr thrust removes the deformation at its up-thrust i.e. at Bilaspur limestone, Subathu, Lower Dharamsala, Upper Dharamsala, Lower Siwalik, and Middle Siwalik levels. The erosional gap that it creates indicates onset of Lower Siwalik erosion and continuation of Middle and Upper Siwalik erosion. During the stage of Johr Thrust restoration, an anticlinal structure can be seen at the up-thrust of Jawalamukhi Thrust at Upper Dharamsala level towards its leading edge and high also exists near the trailing edge at the sub-thrust of Drang Thrust (at Subathu and Lower Dharamsala levels) (**Figure-6**).

v. Jawalamukhi Thrust restored

Removal of deformation along this thrust brings erosional surfaces of Lower Siwalik, Middle Siwalik and Upper Siwalik tops to the restored stage. After restoration of Jawalamukhi thrust, a gentle high in its up-thrust existed at Bilaspur Limestone and Subathu levels. Thus it indicates the structure must be older than the deformation of caused due to Jawalamukhi Thrust. Presence of an older structure at Bilaspur Limestone and Subathu levels is important in hydrocarbon point of view (**Figure-7**) (*Arya et. al. 2017 and Arya et. al 2015*).

vi. Drang Thrust restored

Removal of deformation along this thrust brings erosional top of Middle Siwalik to the restored stage. After restoration of Drang thrust, a gentle high in its up-thrust existed at Subathu level. Thus it indicates the structure must be older than the deformation of caused due to Drang Thrust. Presence of an older structure at Subathu merits importance in hydrocarbon point of view (**Figure-8**).

vii. Palampur Thrust (PT) restored

Restoration of this thrust brings erosional tops of Lower Dharamsala and Upper Dharamsala formations upto restored stage. Restoration of PT reveals that before its genesis gentle structures existed to the East of PT in Bilaspur Limestone and Subathu levels (**Figure-8**).

viii. Splay of Main Boundary Thrust (MBT) restored

Restoration of this Thrust removes the hanging wall deformation and brings erosional top of Upper Dharamsala upto to the restored stage. Restoration of Splay of MBT reveals that before its genesis gentle structures existed to the East of Splay of MBT in Bilaspur Limestone and Subathu levels (**Figure-9**).

ix. Construction of eroded profile

In this stage, the erosional formation tops are constructed (indicated as dotted lines) whereas the bold lines indicate the result of the sequential restoration of present day deformed formations. Joining of bold lines and the dotted lines indicate the initial basinal condition. Though it is difficult to estimate the eroded volume of rock from a 2D line and can only estimate the amount of shortening in this process (**Figure-10**).

Sequential restoration of Profile-2 (**Figure-11**)

A similar sequential restoration for profile-2 (*Abstract vol., GSI, 2017, Indian Siwalik: Recent advances and future research*) was carried out by restoring younger to older thrusts like Himalayan Frontal Thrust, Lingur Thrust, Lunkhar Khad Thrust, Barsar Back Thrust, Kallar Back Thrust, Kallar Back Thrust splay, Jawalamukhi Thrust, Bhamla Thrust, Palampur Thrust, Jogindernagar Thrust and Galma Thrust. The result indicates before initiation of Jawalamukhi Thrust two broad structures were present at the foreland part of it near Changartalai and in Hamirpur areas. Wells CNGT-A and HMR-A are situated on these highs and oil-gas indications during drilling indicate hydrocarbon may be present within these structures. Presence of Bilaspur Limestone and Subathu (envisaged source rocks) indicates pre-Jawalamukhi Thrust structures with attendant petroleum system. After removal of deformation along Jawalamukhi Thrust a small anticlinal structure appears at Lower Dharamsala, Upper Dharamsala and Lower Siwalik levels which indicate formation of a folding prior to the thrusting of Jawalamukhi Thrust. Presence of gas in many drilled wells and surface gas shows in many places at the up-thrust of Jawalamukhi Thrust indicates presence of a petroleum system in sub-surface. During restoration of Bhamla Thrust, Palampur Thrust, Jogindernagar Thrust and Galma

Thrust also indicates evolution of small structure at Bilaspur Limestone, Subathu and Lower Dharamsala levels, which is a pointer towards existence of folding prior to the thrusting because of compression. These pre thrusting structures are important in hydrocarbon exploration point of view (**Figure-12 and 13**).

Up gradation of well top

Based on log analysis of well JMI-G, at the up-thrust of Jawalamukhi Thrust, a zone of Upper Dharamsala can be identified where increase of travel time (DT) and decrease in velocity can be observed (**Figure 14 and 15**). This observation also corroborates with the recently drilled well JMI-J where Upper Dharamsala is present. Log correlation of JMI-A, JMI-J and JMI-B (**Figure 16**) also suggests presence of Upper Dharamsala. Same log analysis also suggests the presence of Middle Siwalik at the sub-thrust of Jawalamukhi Thrust. Well Completion report of JMI-G suggests around 2933m of Lower Siwalik drilled in this well whereas in the nearby wells thickness of Lower Siwalik are as follows: JMI-A (1144 m), JMI-J (1317 m) and JMI-B (1353 m). Therefore when compared to the nearby wells the thickness of Lower Siwalik in JMI-G well appears anomalous. Structural modeling at the up-thrust and sub-thrust of Jawalamukhi area also suggest the same, hence, a zone of Upper Dharamsala in the up-thrust and Middle Siwalik in the sub-thrust are introduced in well JMI-G in the depth model. Now reviewed Lower Siwalik thickness is 1174m in well JMI-G at tandem with nearby wells of Jawalamukhi area (**Figure 17**).

Validation through morphotectonic features

A detailed morphotectonic analysis has been carried out for Himalayan Foothills (*Majumder et.al. 2016*) where a number of lineaments have been identified (**Figure 18**) based on tonal variations in processed remote sensing data. Presence of drainage anomalies like rectangular, rectilinear, drainage offsets, sinuosity variations, compressed meanders are useful to delineate micro-faults and lineaments. Geomorphic highs (**Figure 19**) can be identified by the anomaly in drainage characters (curved/peripheral drainage and radial drainage), which may indicate sub-surface structural highs (**Figure 20**). These geomorphic highs were validated in seismic sections as well as the restored sections of seismo-geological model (**Figure 21**).

Discussion

1. The process of restoration of profile-1 and 2 shows that the amount of shortening is around 29% and 35% respectively. The various crustal shortenings estimated in the western Himalaya (*Dubey et.al. 2001*) indicates shortening amounts from 22% to 71.3% (or 10.6–60 km) over a lateral distance of around 85 km and none of the tectonic models can explain such a rapid variation.

2. Restoration of Profile-1, where removal of deformation for HFT reveals the remnants of Una low which is indicative of presence of existing low before deformation due to HFT. This low in this area exists even after the splay of MBT is restored. It reveals that the presence of source rock within the low may act as a kitchen for adjoining structures. After Barsar Back Thrust restoration, it shows that structure prevails in the up-thrust of Soan Thrust (Soan Anticline) at Lower Siwalik level. Removal of deformation along Soan Thrust reveals a ramp at the up-thrust of Johr Thrust, which later culminates into Balh Anticline where high-pressure gas was observed. Presence of Subathu source rock within this structure also indicates presence of a petroleum system. Well JMI-G is also situated in this set up and continuous gas shows during drilling indicates towards available petroleum system. Restoration of Jawalamukhi Thrust, Drang Thrust, Palampur Thrust and splay of MBT shows that gentle structures existed at Bilaspur Limestone and in Subathu levels. Thus anticlinal structures at Bilaspur Limestone and Subathu levels towards the hinterland part (in sub-thrust of Drang Thrust, Palampur Thrust and Splay of MBT) require exploratory efforts through drilling of these sub-thrust structures, which may lead to hydrocarbon exploration.

3. Restoration of Profile-2 indicates two highs were present before the formation of Jawalamukhi Thrust near Changartali area and in Hamirpur area. Even though these highs were preserved upto the sequential restoration of the oldest thrust (MBT). These highs only disappear only at the time of restoration of decollement. Presence of traces of liquid hydrocarbon in well HMR-A and specky GYF positive cut in well CNGT-A in Upper Dharamsala indicates presence of proven petroleum system. Restoration of the Jawalamukhi Thrust indicates appearance of anticlinal structure at Lower Dharamsala and Upper Dharamsala levels in the hanging wall of Jawalamukhi Thrust. Presence of many gas indication wells at the up-thrust of Jawalamukhi Thrust and source rock i.e. Bilaspur Limestone and Subathu formations within these structures indicate the structure has hydrocarbon charge. GME model of the area indicates Subathu and Lower Dharamsala level entered into gas window in 9 Ma and 6 Ma respectively. Gas generation from Subathu and Lower Dharamsala post-date the age of Jawalamukhi Thrust, thus a possibility of gas entrapment due to Jawalamukhi Thrust is expected.

4. Based on log analysis, structural modeling and clues taken from the nearby wells a zone of Upper Dharamsala and Middle Siwalik may be introduced in the well JMI-G.

5. Based on GIS and Remote sensing observations geomorphic highs were identified. These geomorphic highs were validated when seismo-geological models are restored.

Conclusion

- Kinematics analysis revealed shortening of 29% and 35% during thrusting in Profile-1 and Profile- 2 respectively.
- Restoration threw light on the genesis of some structures like Balh, Changartalai and Hamirpur highs. Occurrence of hydrocarbon shows in these structures also indicates presence of petroleum system.
- Gentle structure in sub-thrust of Drang Thrust, Palampur Thrust and Splay of MBT may hold promise of primary reservoirs within shales of Subathu Formation.
- Based on GIS and Remote sensing studies identified geomorphic highs have been validated during restoration of seismo-geological model.
- To get comprehensive idea about Himalayan orogeny, a profile spanning from HFT to ITSZ can be used to restore the deformations caused by MCT, STD and ITSZ, but it demands seismic data beyond MBT.
- Long offset seismic data with basement imaging (PSDM) may illuminate decollement with sedimentary strata and long distance transportation of sediments riding over hanging walls of different thrusts.
- Robust velocity model for time- depth conversion of model requires adequate number of wells in each tectonic unit.

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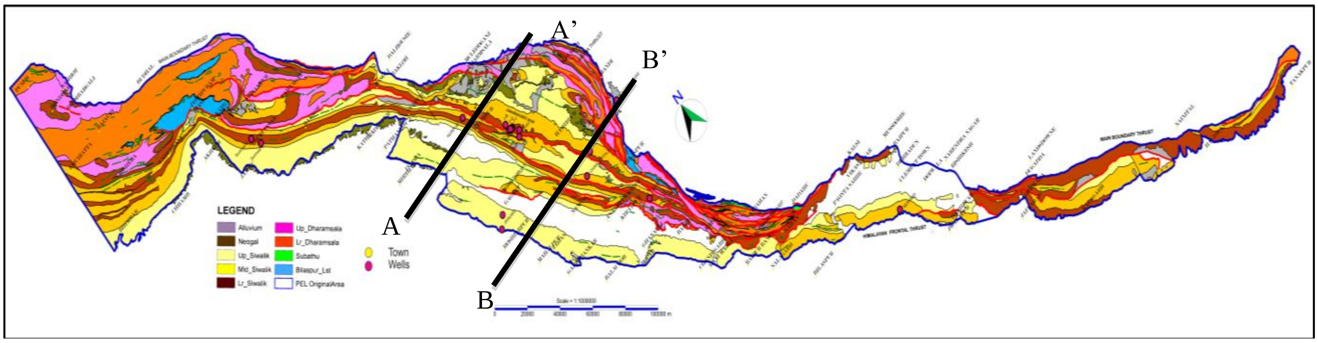

Figure-1: Regional geological map of the area and the profiles A-A' and B-B'

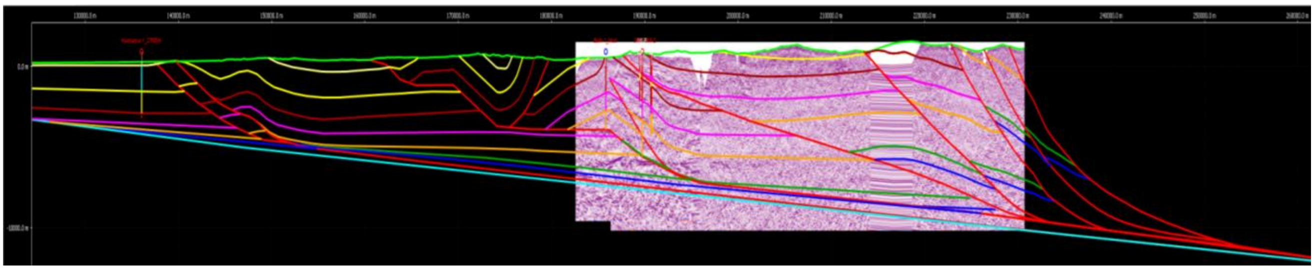

Figure-2: Deformed geometry: Present day section (Profile-1)

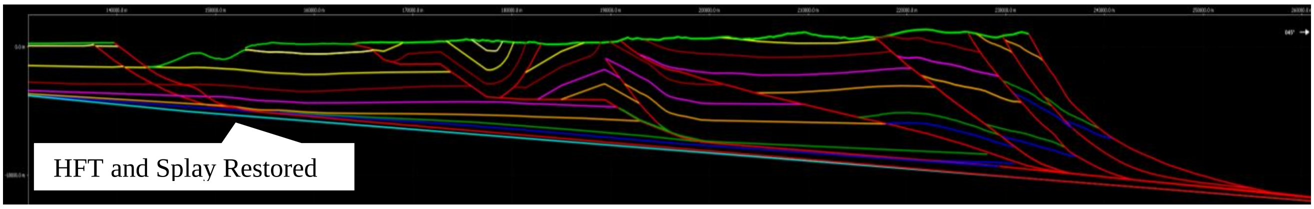

Figure-3: HFT restored

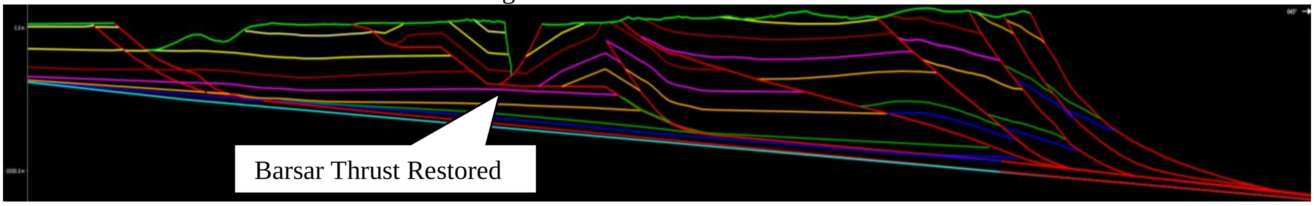

Figure-4: Barsar Back Thrust restored

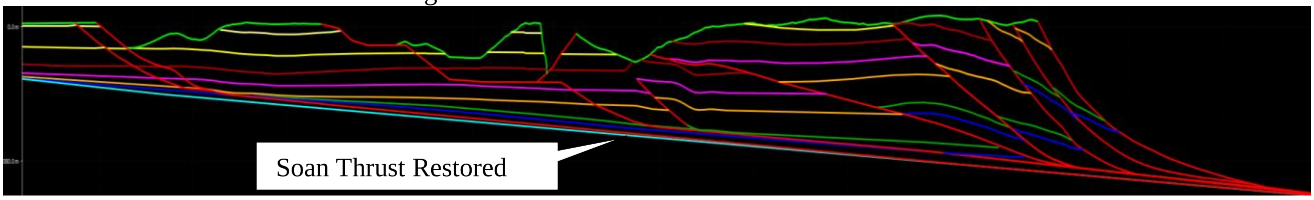

Figure-5: Soan Thrust restored

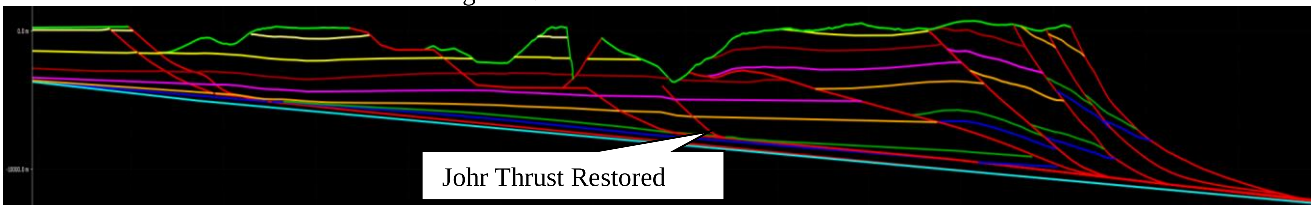

Figure-6: Johr Thrust restored

Figure-7: Jawalamukhi Thrust restored

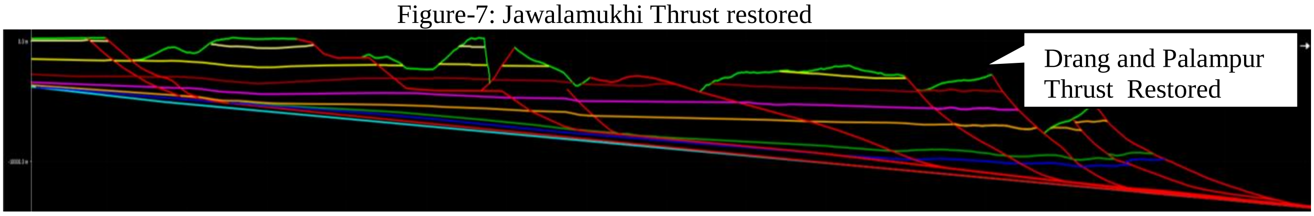

Figure-8: Drang Thrust and MBT Palampur Thrust restored

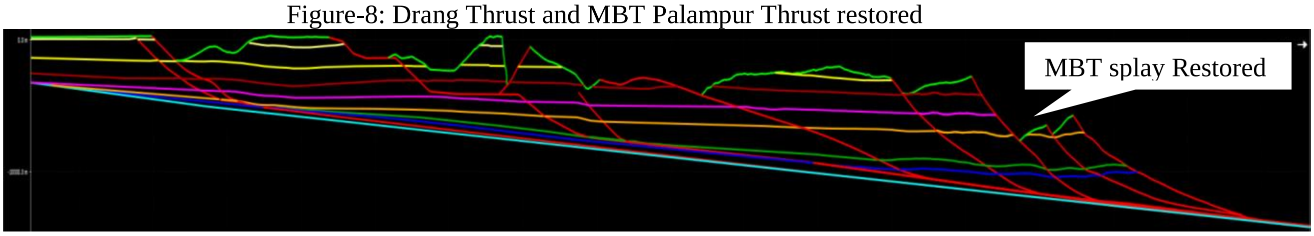

Figure-9: MBT splay restored

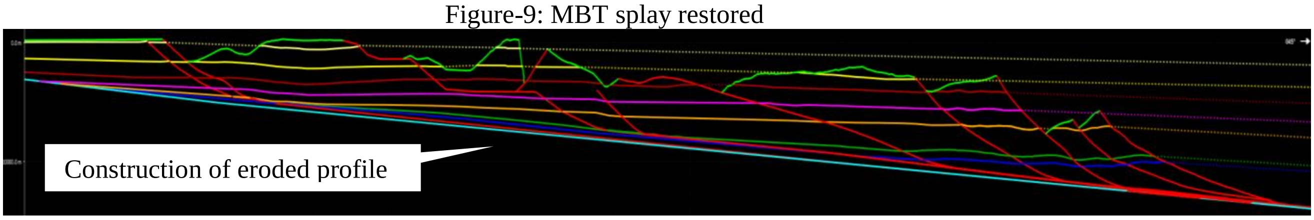

Figure-10: Construction of Eroded profile

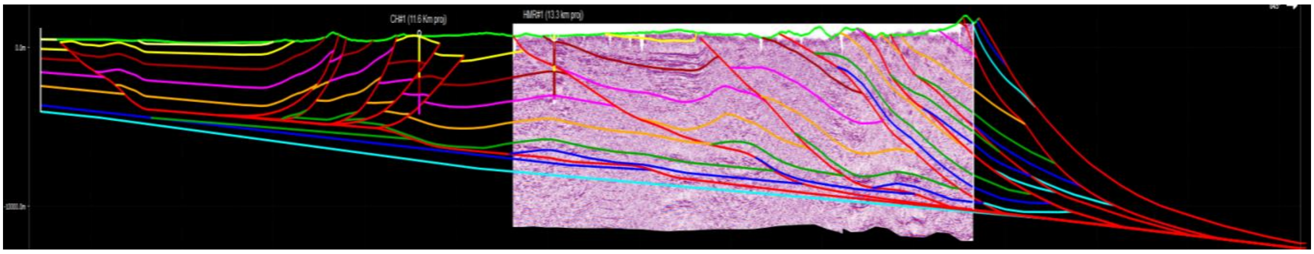

Figure-11: Deformed geometry: Present day section (Profile-2)

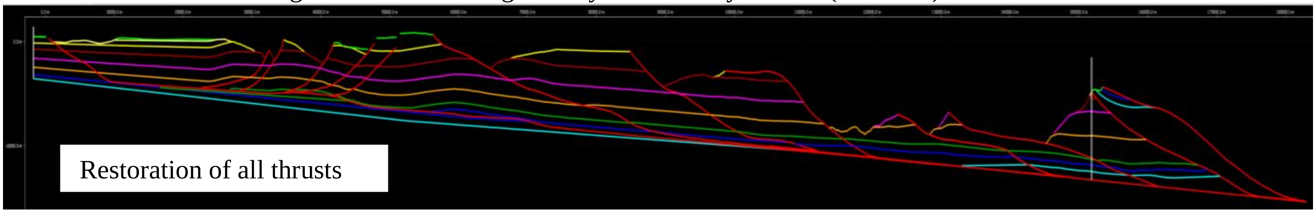

Figure-12: Restoration of all the thrusts from foreland to hinterland indicates two broad anticlines near foreland and a few highs at Bilaspur, Subathu levels near hinterland

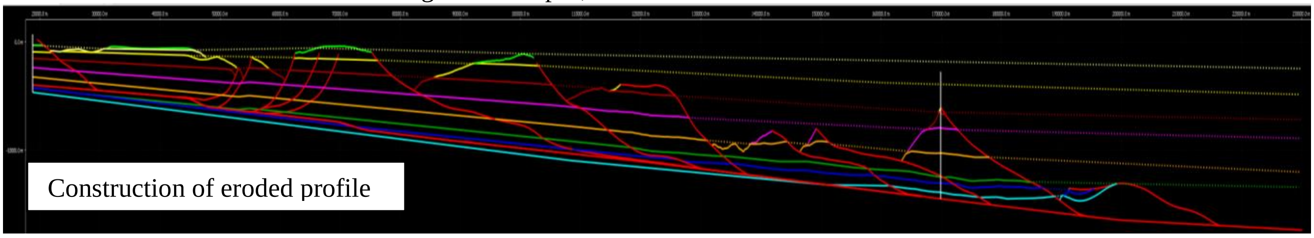

Figure-13: Construction of eroded profile

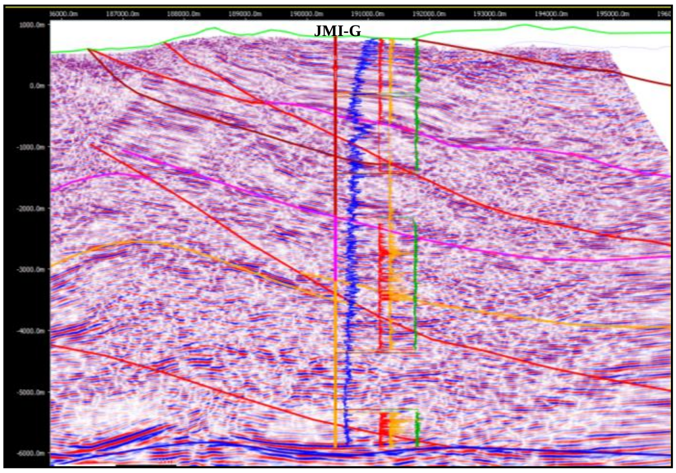

Figure-14: Log curves of well JMI-G (DT-Blue, LLD-Red, LLS-Orange and Gamma-Green) showing DT increasing

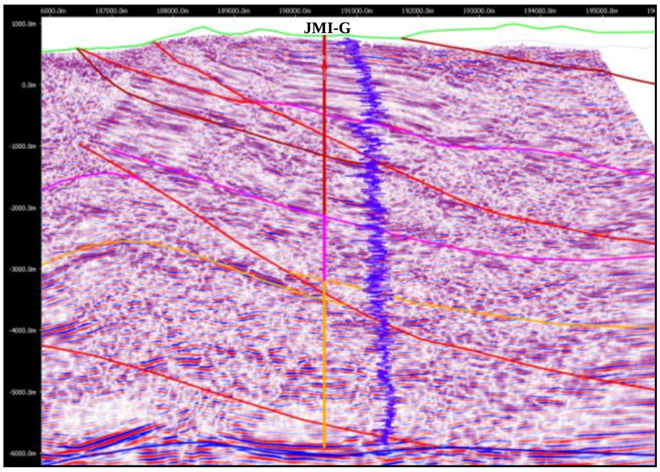

Figure-15: Velocity log of well JMI-G showing a deceasing trend at the top of Upper Dharamsala

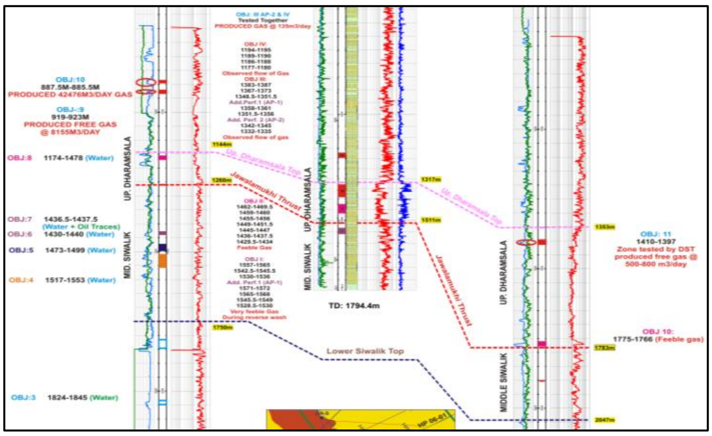

Figure-16: Log correlation of JMI-A, JMI-J and JMI-B showing Upper Dharamsala horizon at the up thrust of Jawalamukhi Thrust

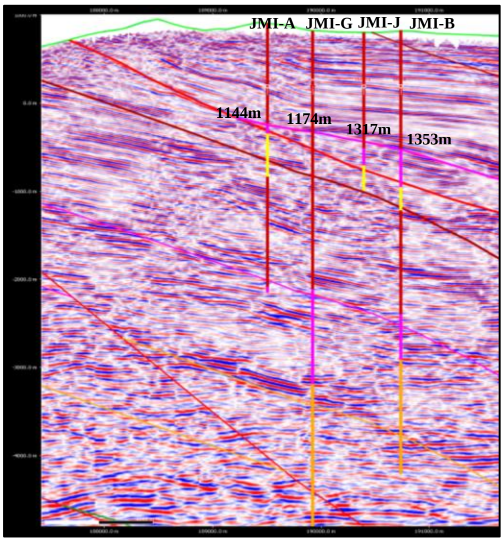

Figure-17: Well tie in the depth section (JMI-A, JMI-G, JMI-J and JMI-B)

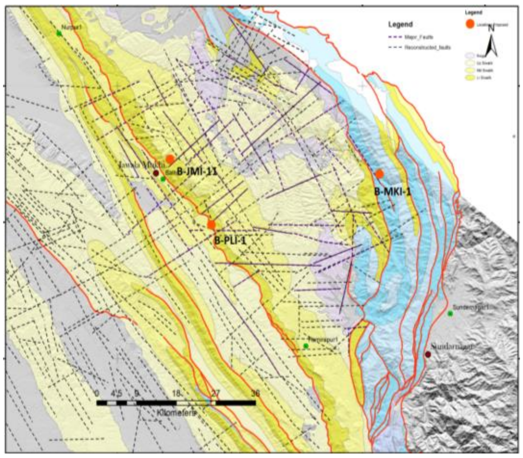

Figure 18: Lineaments and probable faults in Morphotectonic map (*Majumder et. al 2016*)

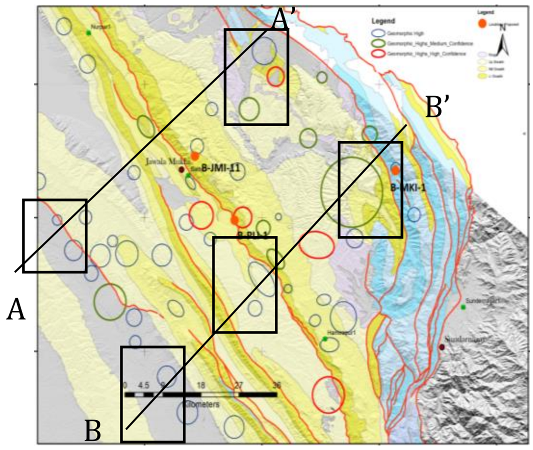

Figure 19: Morphotectonic map of the area showing geomorphic highs (*Majumder et.al 2016*)

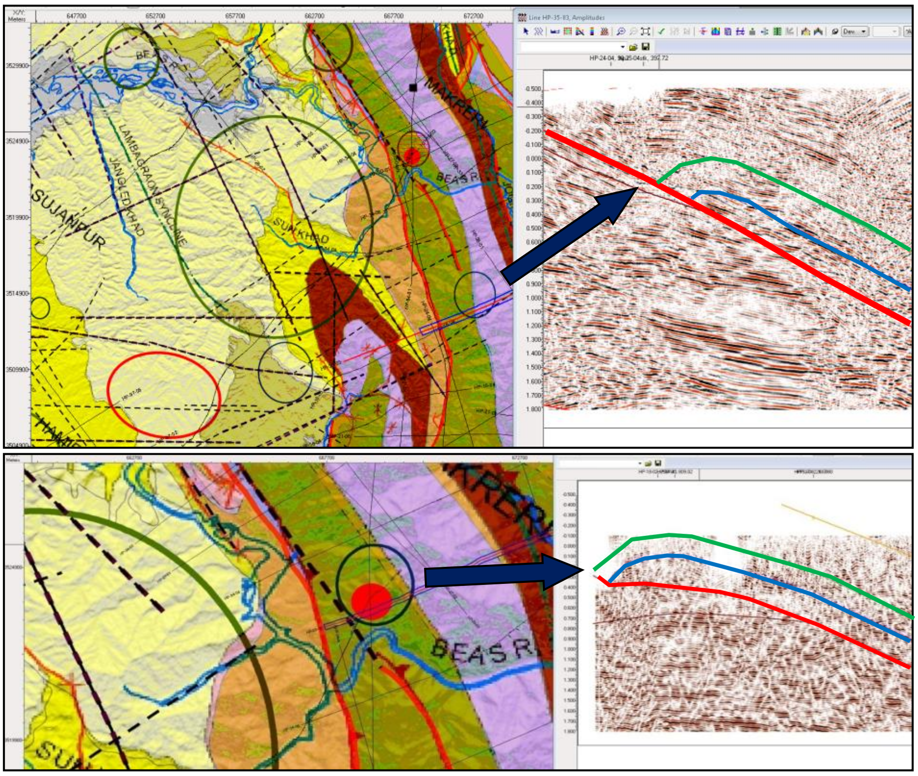

Figure-20: Evidences of geomorphic highs in sub-surface seismic data of the area

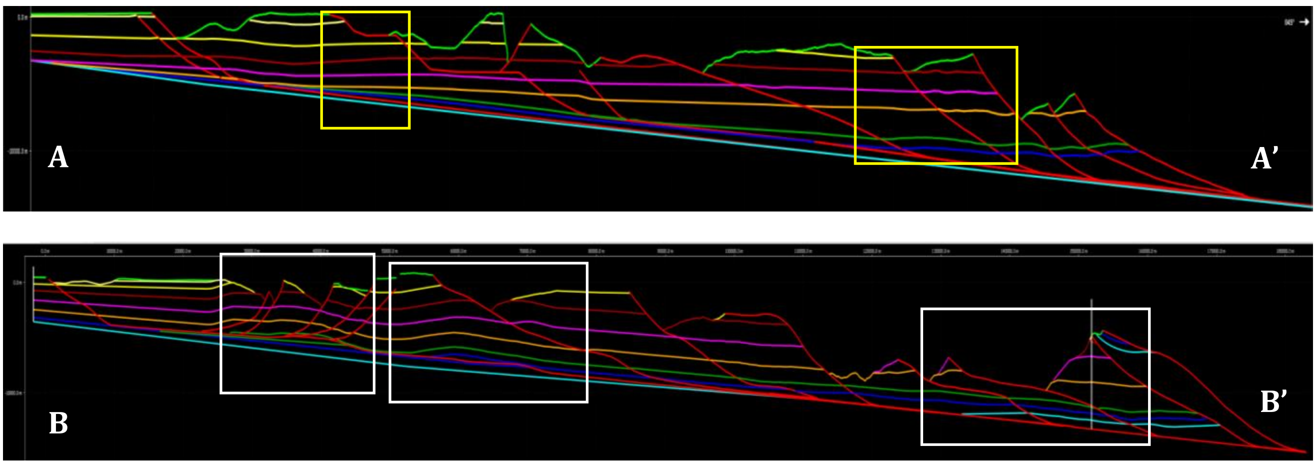

Figure 21: Some of the geomorphic highs can be correlated with the sub-surface highs after sequential restoration of both the profiles