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Identification of new plays and prospects with integrated geoscientific approach in North-West Himalaya, a geologically complex and challenging frontier area

Abstract

In view of hydrocarbon exploration, North-West Himalaya is one the most important category-III frontier areas having challenges and complex geological set up. Heim and Gansser geologically divided Himalaya into four geographic belts from South to North i.e. sub-Himalaya, Lesser Himalaya, Higher Himalaya and Tethyan Himalaya separated from one another by regional thrusts. Exploration in the North-West Himalaya, so far, is confined to sub-Himalaya where a Tertiary petroleum system has been established with Eocene Subathu shale as source, Oligocene-Miocene Dharamsala-Lower Siwalik as reservoirs and regionally extensive clay/shales in Dharamsala and Siwalik as cap. Besides, Subathu as a source rock, resource supplement from Proterozoic Bilaspur Limestone is also envisaged as a feed to Tertiary petroleum system. Presence of several structural traps and stratigraphic traps act as favorable locales for hydrocarbons entrapment in this fold thrust belt. Several geoscientific investigations have been attempted to explore hydrocarbon in diverse geological set up like up-thrust structures, large anticlines, triangle zone, anticlines near frontal thrust, imbricated schuppen zone and structures beyond Main Boundary Thrust (MBT) etc. still commercial success is awaited. The multifaceted complexity and challenges in fold-thrust belt can be overcome through integration of various geoscientific data such as geological, geophysical, geochemical, remote sensing and well data etc. through Geographic Information System (GIS) platform. Systematic amalgamation of these various geoscientific datasets can lead to identification of new plays and prospects in this area. Thus the scope of the paper is to describe the necessity of various datasets and their proper integration in understanding of a complex-fold thrust belt where the quality of the data is poor and number of wells is very less. Thus, a multifaceted approach will always be useful during seismic data interpretation to visualize the geological model in an area of 2D data sets.

Introduction

The experiences gathered from intensive exploratory efforts in the Himalayan Foothills Belt suggest that the hydrocarbon plays for this area are potentially both stratigraphy and structure related. It being part of a frontal fold thrust belt system; obviously there are a variety of structural plays available that are related to a compressional stress regime. Principal stress direction being mainly NE-SW, most of the structures trend in the NW-SE alignment, and include both folds and faults/thrusts, thereby giving rise to four-way anticlinal fold closures and sometimes three-way closures bounded by sealing faults. Duplex structures and triangle zone structures have also been envisaged in this region. Towards the foreland, most of the structures are open folds and broad crested anticlines. The hinterland side, however, contains tighter folds and sharp crested closures elongated in the NW-SE trend. Stratigraphically, the presence of sandstone lenses within thick claystone bands, stacked fluvial channel sandstones, lateral facies variations, etc. are also envisaged. In addition, strati-structural plays, related to regional and local unconformities and favourable sand-shale juxtapositions are also possible plays and habitat for hydrocarbon in this area.

The hydrocarbon potentiality in NW Himalaya has been governed by the deposition of Proterozoic Bilaspur Limestone at the base, Upper Paleocene to Middle Eocene Subathu shale-subsidiary limestone-carbonaceous shale, coal, Dharamsala sandstone/claystone formation, sandstone/claystone deposits of Siwalik Formation up to the recent age. In this entire depositional setup from Proterozoic to Recent there is no dearth of potential source, reservoir, entrapment and burial depth in Himalayan Foothills.

Efforts of exploration in Himalayan Fold -Thrust belt

So far, the exploration in North-West Himalaya is confined to sub-Himalaya only around the places where oil/gas seepages are reported. Jawalamukhi, a prominent place is one of these seepage areas where burning of gases are reported from time immemorial. Thus Jawalamukhi area was the initial area of focus by the explorationists of ONGC and a number of wells were drilled in the up-thrust belt of the Jawalamukhi Thrust. Some of the wells in Jawalamukhi area exhibited optimistic results with gas show in Upper and Lower Dharamsala and in Lower Siwalik formations ([2]Arya et al., 2017*)*.

Later on exploration efforts shifted to few anticlines near Himalayan Frontal Thrust (HFT) like Janauri anticline, Mohand anticline. Gas show was observed in Dharamsala Formation during drilling in one of the wells at Janauri structure. Another well at Janauri and one well at Mohand were dry and abandoned. In the Punjab plains no oil and gas show was observed in wells drilled at Zira and Adampur. In well near Hoshiarpur, oil and gas show was observed during drilling in Dharamsala Formation only.

After that the exploration focus shifted to the Triangle zone, a zone that is created due to compression in between fore thrust and back thrust. Many structures likes Balh, Changartalai and bottom part of Jawalamukhi-I were drilled in this set up. In Balh well, gas was flowed from Lower Dharamsala and during drilling gas cut mud was observed from Upper Dharamsala Formation. In Changartalai well specky Golden Yellow Fluorescence and positive cut was observed in cuttings and core in Upper Dharamsala.

After no commercial discovery through up-thrust structure of Jawalamukhi Thrust a few large anticlines like Hamirpur anticline, Surin-Mastgarh anticline etc. were explored. In Surinsar, two wells were drilled in Surin-Mastgarh anticline but no indication was observed whereas oil show was observed from Hamirpur-A well.

Two wells were drilled in Karewa basin (Kashmir valley) near Narbal and Chattargam area to explore potentiality of Lower Karewa but the results were not encouraging.

A few wells were also drilled in the Nahan salient where distance between MBT and HFT is narrow resulting into a zone of imbricated schuppen belt that brings deeper facies near to the surface compared to other areas of the fold thrust belt. Few wells like Kasauli, Ramsahar and Cheri were drilled in this set up but no fruitful result was achieved.

A well was also drilled beyond MBT near Sundernagar area to probe sub-thrust of MBT (Tertiary prospect drilling through Lesser Himalayan low-grade metamorphic rocks) but that was not successful.

Thus several structures and geological set up in sub-Himalaya i.e. up-thrust belt, surface exposed large anticlines, triangle zone, anticlines near Himalayan Frontal Thrust, structures in imbricated schuppen belt, structures beyond MBT, Karewa basin and in the Punjab plains have been explored for the last sixty years. During this phase, thirty-four wells have been drilled in this sector, where three wells at Jawalamukhi sector and one well at triangle zone produced gas and many wells showed indication of gases during drilling, though any commercial discovery is yet to be established. Here in this paper few new prospects/plays other than so far explored prospects/plays (like upthrust of Jawalamukhi prospect) have been discussed. Efforts through churning of available data and detailed analysis are required for commercial outlook (**Figure 1**).

Integrated geoscientific approach to overcome challenges of exploration

Hydrocarbon exploration is a systematic analytical procedure of various geoscientific surveys such as geological, geophysical, geochemical etc. All these geoscientific methods help to investigate origin, occurrence, migration, trapping of hydrocarbon and finally successful integration leads to hydrocarbon exploration. Incorporation of all available geoscientific data is indispensable to understand the complexity in fold-thrust belt. In a fold-thrust belt like Himalaya, due to enormous thrusting and folding older strata have been thrusted over the younger strata resulting repetition of sedimentary beds, which causes deterioration of seismic imaging in this sector. In some of the places imaging in the sub-thrust layers is improper where the high velocity layer over rides above low velocity layer because of thrusting. Thus simply interpretation of seismic datasets may not always provide true pictures of the sub-surface structures and integration of various geo-scientific datasets are essential to assimilate in this purpose.

As far as geological survey is concerned, the area is systematically covered through semi-detailed geological mapping (**Figure 2**). A number of gravity-magnetic stations covering the wide area of sub-Himalaya are useful to delineate the basinal dip. The area is also covered by seismic surveys (**Figure 3**) since inception of both refraction and reflections seismic data have been acquired to identify sub-surface architectural setup in this belt. Reprocessing of some of this seismic data showed improvements over the earlier processed/re-processed lines (**Figure 4**) that helped to delineate a number of prospects. Simultaneously geochemical studies (**Figure 5**) have been carried out for investigating the nature of source rock and its potential for producing hydrocarbons. Based on the geochemical data it is possible to comprehend chemical composition of oil/ gas from seepage observed during drilling that explains the migration nature of the entrapped hydrocarbon. Many wells have been drilled in this area, with the deepest well penetrating more than 6000m in Jawalamukhi area. This vast wealth of G&G data acquired through drilling of wells has provided an insight into sub-surface strati-structural disposition and forms the basis for exploration strategies. Advancement of new structural modeling (**Figure 6**) software like MOVE^{TM} is also being used to model complex sub-surface geometry like fault bend fold, duplex structures etc. ([5]Dutta.T et al., 2017). Analogy with the eastern part of petroliferous Potwar plateau (**Figure 7**) is also being used to understand petroleum system of the NW Himalaya. Use of Google earth images (**Figure 7**) is also very advantageous to delineate regional thrusts and large structures in NW Himalaya. Remote sensing and GIS based studies are widely being used to delineate faults and lineaments (**Figure 8**) in near surface condition and useful for identifying shallow prospects. Moreover, aerial photography and satellite images have become an integral part of petroleum exploration in the North-West Himalayan fold thrust belt. Data integration through Geographic Information System (GIS) (**Figure 9 and Figure 10**) is the final stage to collate the geoscientific data for effective analysis in exploration. Remotely sensed surface lineament data, together with variety of G&G datasets can be properly managed, retrieved, displayed and maintained through GIS. Thus, thorough integration of various geo-scientific datasets assists to understand and visualize the complex nature of Himalayan fold thrust belt in an easy way where the seismic imaging are generally of poor quality.

Integration of data through GIS and validity in MOVE platform

During seismic data interpretation it is a mandatory requirement for all geo-scientists to examine the legacy works carried out in any particular area. There may be various versions/ various field season maps for any area. Using GIS platform one can efficiently integrate the available datasets. A geo-scientist has a greater role in bringing all the spatial datasets/maps in one platform, which can be carried out, through the help of GIS. Integrating through superimposition can help to bring out various leads. The use of spatial datasets likes maps; toposheets in various scales and in resolution with different themes can be obtained from GIS. Updation of all legacy maps with the availability of more information and datasets can be carried out. GIS has the ability to separate great quantities of information into layers and can explore each layer with a powerful suite of analytical tools, and then combine the layered information to use it in an integrated fashion and that makes the GIS a powerful and effective decision-support tool. Different thematic layers like (faults, culture data, well data, geochemistry data etc.) can be created in GIS from available maps. We can give various kinds of queries like what exists at a particular location? (i.e. at any lat, long) and GIS is able describe the features of that location. Queries like where can specific features be found, for example, any area having dip more than 50° and less than it can be separated. Queries like trends or what has changed over time can also be found out through analytical tool in GIS. Thus the need for a software that can do all of these can bring paradigm shift from manual spatial database management to digital spatial database management.

Areas like Himalayan fold and thrust belt where the data quality is poor and the sub-surface seismic sections show many thrusts involved then an obvious question arises in our mind about the validity of our interpretation. Then the role of structural modeling software, which can work on the database of GIS, is required. Restoration is a fundamental test of the validity of the interpretation where we try to return into a restorable section to its pre- deformation geometry. If a section is not restorable, it is geologically not possible. In case of sequential restoration, intermediate stages between fully deformed and fully restored which provides insights into the structural evolution. In areas of sparse data, multiple valid structural models can exist and no unique solution can be achieved to a particular structural problem. The restoration technique helps to validate structural interpretation, determine structural evolution and make predictions about structures that are not imaged. To validate any structural model we prior need structural data sets to validate our model.

Structural data requirement for modeling in MOVE^{TM} can be integrated in GIS platform and can be called whenever they are required. Organization and visualization of geospatial data, including field data and cross sections can be integrated when they are properly arranged in GIS platform.

Identification of new plays and prospects

In recent times an oil show at Sehl village, Himachal Pradesh, has been discovered in the *inner part of inner tectonic belt* (at the up-thrust of Galma Thrust). Analysis of the water sample indicates presence of higher hydrocarbon and samples of the shallow Subathu shows good TOC. Moreover, oil show at Chowmukha and good TOC in surface samples in Mera-Masit >4% also indicate the area deserves attention for hydrocarbon exploration. In the inner belt of the area, the newly reprocessed seismic lines clearly reveal that the Subathu and Bilaspur Limestone formations are brought up to shallow depths especially in the up-thrust of Palampur Thrust, Galma Thrust, Jogindernagar Thrust and Kathiari Thrust and also validated by the surface geological evidences.

The deeper formation like Bilspur Limestone has been taken up to the shallower level in the upthrust block by deep seated thrusts like Palampur Thruts, Galma Thrust, Jogindernagar Thrust etc. and by other associated faults/thrusts, which may acted as the primary conduit for migration of the generated hydrocarbons in deeper sources. The area being part of a foreland fold thrust belt, presence of other smaller interlinking faults is also expected. Abundant vertical fractures and open fractures are observed in the XRMI logs in Jawalamukhi area. Thus vertical migration is another phenomenon that is likely to have occurred in this area. Presence of numerous fractures and joints associated with the hanging wall unit is likely to have influenced hydrocarbon migration and charging within the available shallow Tertiary entrapments.

These formations have been studied in detail and their possible extents in the sub-surface have been mapped. This sector, hitherto unexplored through exploratory drilling promises to give not only valuable insights into the sub-surface nature and behavior of the elusive Subathu and Bilaspur formations in the Kangra Recess but also may yield hydrocarbons. In view of the above, one prospect in the inner belt of Kangra Recess was released to examine the prospectivity of the Bilaspur Limestone and Subathu formations as up-thrust play ([3]Arya et al., 2015*)*.

In deformed seismo-geological section a *prominent low* can be observed near Una-Kalka area and the trend can be validated by the regional gravity data. After restoration, the remnants of the low exist, which implies presence of an existing low before deformation due to HFT. The low can be visible even after the splay of MBT is restored which means a low existed even before the deformation of MBT. Presence of source rock like Subathu and Bilaspur Limestone within the low may act as a kitchen for hydrocarbon generation for adjoining structures.

A *deeper prospect* at the regional unconformity level can be mapped with good degree of confidence. A high trend can be seen along NW-SE in between Triangle Zone. A four-way closure with an area of about 160 sq. km has been identified as Prospect.

Sub-thrust prospects have not been explored so far in Himalayan Foothills and can be potential areas for future exploration. Recent understanding indicates long distance gas migration from the inner part of the Kangra Recess to the Jawalamukhi play and it appears that the Jawalamukhi is a secondary accumulation that gets charged by hydrocarbons migrating up-dip from deeper ‘primary’ reservoirs ([1]Arya et al., 2015). Thus this increases the chance of an in-situ new prospect at the sub-thrust level of the Palampur Thrust. Sub-thrust structures are generally less disturbed due to less effect of thrusting compared to the up-thrust and have better chance of preservation of primary reservoir (**Figure 11**). Recent structural modeling in Kangra Recess shows the presence of sub-surface highs near sub-thrusts of Jawalamukhi Thrust, Palampur Thrust, Jogindernagar Thrust and Galma Thrust. These sub-surface highs appear to have come into existence at a very early stage of deformation in this area. Presence of source rock Subathu and Bilaspur Limestone within these structures also indicates presence of a petroleum system. Amplitudes are also supporting AVO anomaly within this structure.

Some recently reprocessed seismic data have brought out a few high amplitude anomalous events (Direct Hydrocarbon Indicator) within Lower Siwalik Formation in the up-thrust of Dhorian Fault as *shallow level prospect*. The structure merges gradually with a major prominent syncline known as Lambagraon Syncline towards North-East intervening with some highs and lows all through the study area. Two cross faults namely CF2 and CF3 in the North and South further delimits this structure. These cross faults along with main Dhorian Fault have been responsible to favorably create an anticlinal structure with a four-way closure. It being close to CF2 and CF3 faults with the Lambagraon Syncline as kitchen for this area, the role of these cross faults for providing hydrocarbon pathway cannot be ruled out (**Figure 11**). Clays present in Siwalik Formation may provide effective seal on the structure ([4]Arya et al., 2015*)*.

Palaeozoic-Mesozoic plays can be explored in the least explored Karewa Basin. This basin has developed as a piggyback basin on top of the uplifted Paleozoic-Mesozoic sequences floored by the Kashmir Nappe. Presence of numerous surface gas shows and carbonaceous matter in the form of peat and lignite of Pakharpur Formation enhances the chances of a suitable source rock in the sub-surface. The Paleozoic-Mesozoic rocks surrounding it have Tethyan affinity and therefore have greater prospectivity from hydrocarbon exploration point of view (**Figure 12**).

Tethyan Basin lying in the North of Higher Himalayan Crystalline Zone (HHCZ) and South of Indus Tsangpo Suture Zone (ITSZ) can be a potential candidate for hydrocarbon exploration. Presence of thick (~12 km clastics and carbonates sedimentary section) ranging from Precambrian to Eocene enhances the possibilities of presence of an active petroleum system. A thick Palaeozoic-Mesozoic sedimentary column at Spiti in the south and Zanskar in the north is correlatable with adjacent hydrocarbon bearing Kohat-Potwar hydrocarbon province in Pakistan. In Tethyan Basin Gungri Formation (Permian) and Spiti shale can be considered as source, Triassic-Jurassic clastics (Giumal sandstones) and carbonates can act as reservoir rocks and large anticlines, fault related combination traps; stratigraphic plays may act as entrapment system. Chikkim Shale may act as effective seal.

Challenges in exploration

Exploration is really a challenge in a fold and thrust belt all over the world. Complex geology has always been a problem in this sector. Due to thrusting and folding older sediments have been thrusted over the younger sediments. Repetition of sedimentary beds along with thrusting and folding deteriorates seismic imaging in this sector. Sometimes the imaging in the sub-thrust layers is improper where the high velocity layer over rides above low velocity layer because of thrusting of beds. The area has a very high elevation along with uneven topography manifested as hills and valleys which makes the area logistically very difficult. In some places road approaches are absent or difficult to make due to rugged topography for most of the exploratory prospects. In the North-West Himalaya especially in the Jammu and Kashmir sector few prospects have been identified in the Poonch and Rajauri area. Moreover for drilling a location a favorable land dimension of 120m x 120m is required, but due uneven topography and steep slope, preparation of drill site is an issue for exploration.

Conclusion

Several structures and geological set up in sub-Himalaya i.e. up-thrust belt of Jawalamukhi area, large anticlines, triangle zone, anticlines near frontal thrust, imbricated schuppen zone, structures beyond MBT, Karewa Basin and in the Punjab plains have been explored since last sixty years but commercial finds are yet to be discovered.

In the advent of new software and scientific techniques, incorporation of various geoscientific data such as geological, geophysical, geochemical, remote sensing and well data etc. through GIS platform has become an integral part to understand the complexity of a fold and thrust belt. GIS platform made it very easy in generating, updating, integrating, analyzing, interpreting and communicating effectively and more importantly very swiftly.

In areas of sparse data where multiple valid structural models exist, no unique solution can be achieved in any structural problem. This kind of imperfection in seismic interpretation can be minimized through structural restoration. Structural restoration technique helps to validate structural interpretation, determine structural evolution and make predictions about structures that are not imaged. In Move, data organization and visualization of geospatial data, including field data and cross sections can be integrated when they are properly arranged in GIS platform.

The successful integration has lead to identification of many prospects like Palaeozoic Mesozoic plays in sub Himalaya, Karewa Basin and in Tethyan Basin with the analogy of nearby petroliferous Potwar plateau can lead to new prospects. New plays and prospects may be identified in inner part of inner tectonic belt, highs within Kalka-Una low, deeper prospect at unconformity level, sub-thrust prospects below Palampur Thrust and shallow prospect at the up-thrust of Dhorian Fault.

The integration become more challenging due to presence of complex geology, poor imaging, repetition of sedimentary beds by thrusting, over riding of high velocity layer above low velocity layer, high elevation, logistics difficulty, absence of approach road, security issues and unavailability of required flat land dimension are the major challenges in exploration in Himalayan fold thrust belt.

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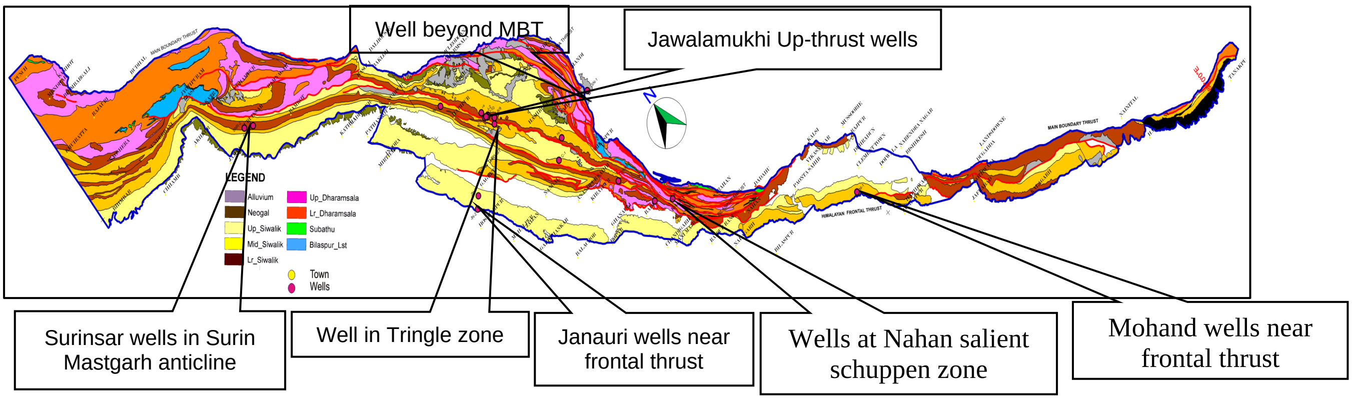


Figure-1: Geological map of North-West Himalaya showing various drilled location in last sixty years

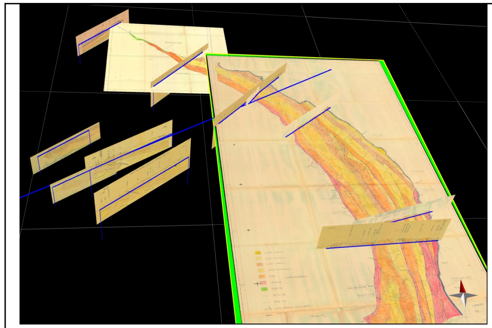


Figure 2: Geological map and cross section by various workers in HF

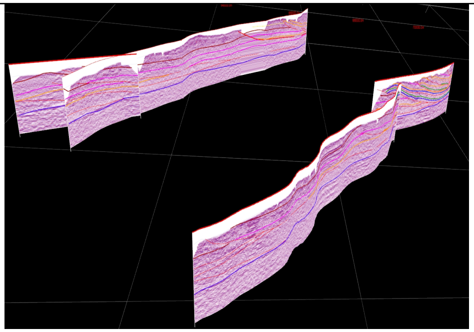


Figure 3: Seismic survey in the area

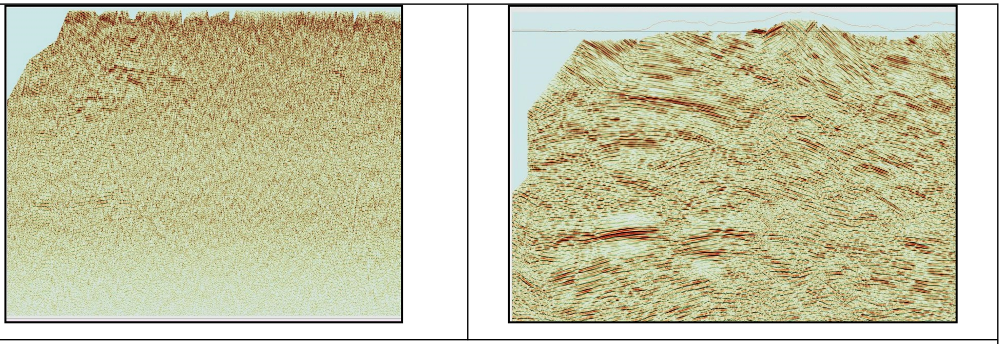
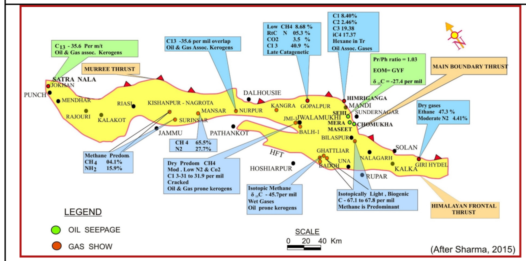


Figure 4: Improvement of seismic data through reprocessing



(After Sharma, 2015)

Figure 5: Geochemical data in HF area

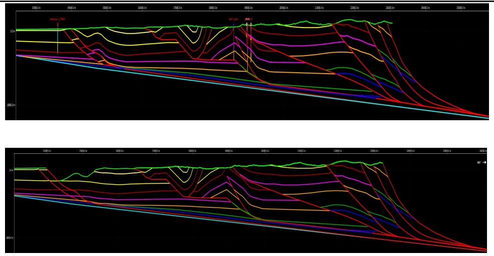


Figure 6: Structural modeling in MOVE^{TM}

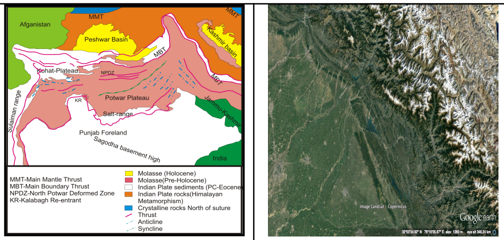


Figure 7: Correlation through analogous basin and Traces of MBT (Yellow) and HFT (White) can be inferred from google image through variation of shades

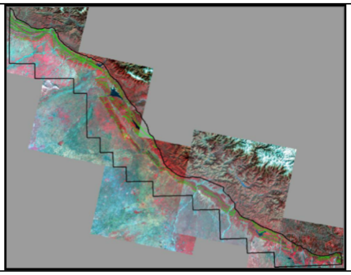


Figure 8: Remote sensing data of the area

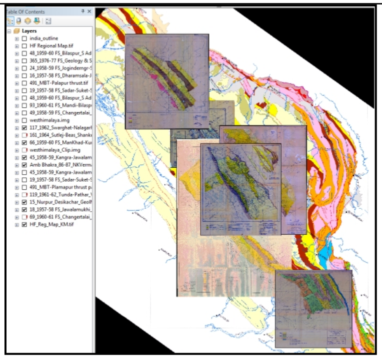


Figure 9: Integration of various data in GIS platform

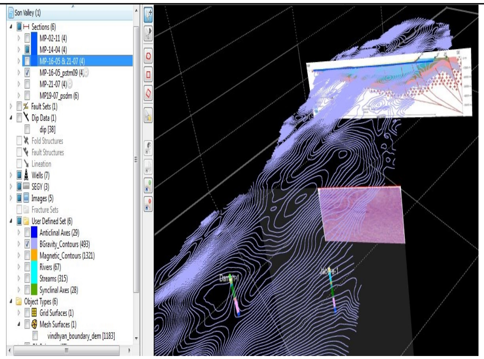


Figure 10: Integration of various data in MOVE^{TM} for better understanding in

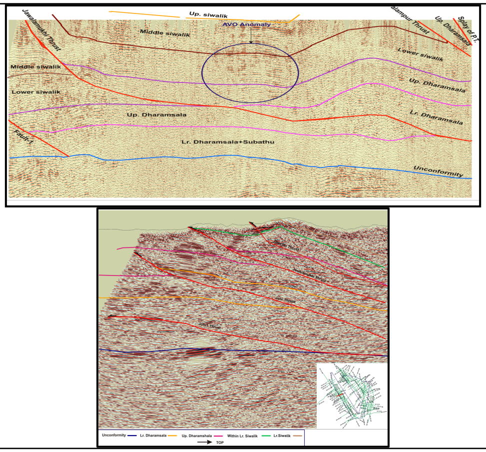


Figure 11: Sub-thrust prospects and Dhorian prospect, a shallow prospect (green horizon)

Figure-12: Palaeozoic-Mesozoic Prospects in Karewa Basin

	interpretation		