A Re-look on The Subsurface of Himalayan Foothills In View of New Acquisition And Reprocessing of Seismic Data

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ABSTRACT: Triangle zone in the Kangra re-entrant of Himalayan Foothills is the resultant of two oppositely hading thrusts, viz., Jawalamukhi/Gambhar thrust and the Deragopipur/Barsar back thrust. It is similar to many other triangle zones around the world and they are perfectly normal and common features of thrust fold belts. As many as six exploratory wells have been drilled around Jawalamukhi which have given indication of thermogenic gas with highly saline water. Geochemical analysis of the formation water indicates the presence of “oilfield brines” within Neogene sequence with a hydrogeological system. With the new seismic acquisition and the reprocessing of some of the key lines, the subsurface geometry of the triangle zone, as a whole, has been mapped for the first time. The Balh anticline which was earlier thought to be dying down at depth, appear to continue down to Tertiary-Pre-Tertiary unconformity. Triangle structure is continuing all along the length of Jawalamukhi and Barsar back thrust. The study suggests that all the deep exploratory wells are located on the flank of main triangle zone structure. The area merits a sustained exploration programme with tecno-economic considerations under NELP regulations. The exploration in triangle zone for deep as well as shallow gas/oil reservoirs is expected to result in the discovery of hydrocarbon in the Himalayan Foothills.

INTRODUCTION:

Jawalamukhi-Hamirpur-Ghumarwin area falls in the median tectonic belt of Kangra re-entrant of Himalayan Foothills (Fig.1). The belt is the resultant of two oppositely hading thrusts namely Jawalamukhi and Barsar back thrust (Fig.2). It is similar to many other triangle zones around the world such as triangle zone of Alberta foothills, Molasse basin of Switzerland, Carpathian Foothills of Romania, etc. Triangle zone are perfectly normal and common features of thrust fold belt of the world. Exploration activities were started around Jawalamukhi way back in 1956 by drilling a well near the Jawalamukhi temple. Non-commercial thermogenic gas encountered in the well was from very shallow sand of Lower Siwalik in the thrust sheet of Jawalamukhi thrust. Successive efforts to delineate this gas failed, as a number of holes drilled around Jawalamukhi did not encounter any commercial pool. The present study of the area is based on newly acquired seismic and reprocessing of some of the key lines. Due to successive failure in the triangle zone, the Jawalamukhi triangle zone of Himalayan foothills was treated as a part of the foothills whose hydrocarbon potential is poorer than the inner tectonic belt and the focus of exploration was shifted to Inner tectonic belt. Triangle zone in other parts of the world have been the site of many dry wildcat wells, particularly in the early days of exploration, but this did not dampen their enthusiasm to continue the exploration. Therefore, a need was felt to study the triangle as a whole and to integrate the entire available data to assess its hydrocarbon potential.
METHODOLOGY

Since full seismic imaging of the complicated structural geometry associated with fold and thrust deformation in the Himalayan foothills is difficult to produce, traditional methods of interpretation are found to be insufficient to achieve an accurate subsurface picture. A geometric model of the seismic reflections can be constructed by changing the reflection arrivals to depth by using the velocities from drilled wells. The depth model so constructed can be checked for its validation by using ray trace modeling. Zero offset synthetic seismic section can be generated by using computer aids. This synthetic data can be compared with the actual seismic for its validation. If both the data do not match then a reinterpretation of the actual seismic is carried out for generating new zero offset section. This process is carried out until a comparable synthetic data is achieved.

Triangle zone is adequately covered by seismic. Seismic data has been correlated by tying the drilled well data. A depth model (Fig 3) was prepared along a key line DD’ and ray tracing has been carried out by using GX-II software (Fig 4) and a zero offset synthetic section (Fig 5) was generated with several iterations to match with the actual seismic (Fig 6) to arrive at convincing and most acceptable model.

GEOLOGICAL ASPECTS OF THE JAWALAMUKHI – HAMIRPUR-GHUMARWIN- TRIANGLE ZONE

The Jawalamukhi – Hamirpur-Ghumarwin area is an integral part of the median tectonic belt of the Himalayan
Foothills in Himachal Pradesh, extending in an almost NW-SE alignment. This area has been referred to as a triangle zone, as it is bounded by two oppositely verging thrust, i.e., the east verging Jawalamukhi – Gambher thrust and the west verging Deragopipur-Barsar back thrust. Most important exposed feature in the area is Balh anticline which was mapped geologically by Talukdar et al (1959). The area has been under exploration but commercial discovery has eluded us so far. However, now there is a greater understanding of stratigraphic and structural complexities. The area looks promising once again and the testimony is the recent (July 2002) uncontrolled well activity at dry and abandoned well-2 wherein gas gushing out with saline water was observed. Some of the key features of the area are discussed below.

**Jawalamukhi thrust**

It is a low angle thrust with varying dip of 20° to 30°, in general, at the surface with homoclinal beds in the upthrown block compared to the complicated structure of the sub-thrust block. On the seismic line, it can be easily interpreted from the dipping events. On the surface it is long and prominent lineament in the area. The thrust is well marked and its topographic expression is a ridge trending NW-SE. It has resulted in the development of Jawalamukhi homocline / structural terrace. Hading north-east, it forms a terrace at shallow depth followed by a ramp. The terrace to the north of the thrust forms the overthrust block of Jawalamukhi thrust. Presence of Upper Dharamsala wedge in some of the wells of overthrust block indicates its large southwestward displacement.

**Gambhar thrust**

It is considered southeasterly continuation of the Jawalamukhi thrust and is also low angle 20° to 30° heading to northeast which has brought up the basal part of Lower Siwalik sediments over the Upper Siwalik in the subthrust, with a NNW-SSE trend. The thrust forms a prominent topographical feature all along its length.

**Deragopipur fault/thrust**

It is a high angle reverse fault/thrust heading southwest and is seen to emerge almost vertically. On the surface, it has been mapped as a long linear displacement zone.

**Barsar thrust**

It is enechelon/continuation of the Deragopipur thrust. In the outcrop, it runs almost NNW-SSE with very steep dips of 60° to 75° towards southwest. The thrust has brought up the Lower Siwalik to overlie the Upper and Middle Siwalik. The Barsar –Deragopipur back thrust extends for more than 250 kms.

**Johr fault**

It is an important fault within the Balh anticline. It was named by Boileau after Johar village where it is associated with saline spring and feeble gas shows. It is a high angle fault (45° to 55° dip) which makes steeply towards southeast. Various workers have also referred it to be as a thrust/zone of several thrusts as it brings Lower Siwalik rocks to override the higher horizons of Middle Siwalik Formation.

**Jawalamukhi Overthrust Block**

The over thrust block of the Jawalamukhi thrust essentially forms a gentle structural terrace which extends more
or less uniformly over long stretch forming the southmost limb of Lambergaon syncline. It exposes successively the Lower Siwalik and Middle Siwalik Formations with dips ranging from 20° to 40° towards NE near the thrust.

**Balh anticline**

It is prominent feature in the subthrust block of Jawalamukhi thrust and is observed on all the seismic lines passing across it. Geologically it was mapped by Talukdar et al (1959). It is essentially an asymmetric anticline limited by the Jawalamukhi thrust to NE and a synclinal axis (Balarru Syncline) to the SW, with a high angle reverse fault/thrust in the axial region—Johr fault and its associated fault system. The Balh anticlinal axis separates two limbs of the asymmetric Balh anticline, the SW limb being very steep to overturned in the central region of the structure and the NE limb having dips of the order of 25° to 60° to the NE, thus indicating that the axial plane dips to the NE.

**Changartalai anticline**

It is a doubly plunging asymmetric anticline developed between Jawalamukhi/Gambhar thrust and Barsar back thrust. The eastern limb of the anticline is gentle with dips increasing progressively towards the axis ranging from 10° to 20° and general direction is N40°E. In the core of anticline Middle Siwalik alterations are observed. The western limb is narrower than the eastern limb and is over ridden by the Barsar back thrust. The limb to the south of Changartalai is affected by Kallar fault.

**REPROCESSING OF THE OLD DATA**

During the course of the study some of the lines were reprocessed. As the data were processed in a conventional way, some of the lines did not show any significant improvement, but the line CC′ has come up with very good continuity of the reflections in the deeper part of the Tertiary strata and the geometry of the Balh anticline is very clearly seen.

**DISCUSSION ON SEISMIC DATA**

Almost entire triangle zone is covered seismically (Fig.3) though there are wide gaps at places. Seismic data in the triangle zone have been acquired under different investigations. Seismic lines pass through mainly Lower Siwalik and Middle Siwalik exposures in the outcrop which provide a good medium for the seismic energy penetration, but a few of the lines pass through the boulder patch of the conglomerate of the Upper Siwalik and they are the medium of poor energy transmission and so the data quality is poor in these parts. Some of the lines were reprocessed. Pre stack depth migration was also attempted on some of the lines. Unconformity surface (around 3 sec) divides each seismic section in two parts, i.e., a zone of discontinuous reflection from Tertiary strata and a zone of continuous reflections from Pre Tertiary strata. A high trend throughout the area has been mapped beneath the Upper and Middle Siwalik outcrops. The high trend is oriented in NW - SE in the subthrust of Jawalamukhi and Barsar back thrust. This zone of high trend can be referred to as triangle zone structure and can best be seen on lines DD′, AA′, BB′, CC′ and new line EE′ (Fig. 6-10). Earlier it was believed that the Balh anticline which is the main triangle zone structure, is dying down at depth (Singh et al., 1992) because of the fact, that there were no continuity of the events below 1 sec in most of the lines, but the reprocessing of the line CC, has changed the understanding of the structural picture. Reprocessing and new data have brought out the subsurface picture clearly. Triangle zone structure is continuing even below the Unconformity level which is more than 6 km deep.

**IDENTIFICATION OF PLAY**

One reflector within Lower Siwalik in the upthrust of Jawalamukhi thrust corresponding to the gas producing sand in well-5 and another in the subthrust of JMI thrust near the base of Lower Siwalik formation have been mapped. Isochron
maps of these reflectors (Fig 11&12) have been prepared. The structural geometry in the study area is controlled by Jawalamukhi thrust, its splays and the splay of Barsar back thrust/fault. Following two types of plays have been identified:

1) Hanging wall play and
2) Foot wall play.

**Hanging Wall play**

Structural geometry in the upthrown block is the resultant of propagation of ramp-flat trajectory of Jawalamukhi thrust. Isochron map corresponding to a horizon which has produced some gas in the well-5 from the Lower Siwalik formation shows that Jawalamukhi thrust has created two antiforms one near Hamirpur which can best be seen on line, DD’ and the other in the northwest of Ghumarwin. In addition to anticlinal reversals a number of thrust related closures against Jawalamukhi thrust have also emerged in the area (fig-12). No anticlinal reversal has been observed in any of the wells drilled in the triangle zone. Well -5 and Jawalamukhi...
temple fall on a thrust closure and the gas is continuously leaking through the Jawalamukhi thrust which is non-sealing in nature.

**Footwall Play**

Structural geometry in the footwall is the resultant of the propagation of Jawalamukhi and Barsar back thrust. One seismic horizon (Fig 12) near the base of Lower Siwalik formation has been correlated. Isochron map is suggestive of anticlinal reversal with several culminations throughout the length of the triangle zone. This high trend is oriented in NW-SE direction and it is in continuation of Balh anticline and continued down to the Bandla/Bilaspur limestone levels. This anticline is exposed at Balh but it is in concealed form in the southern part. Drinh fault has divided the anticline in two parts in the shallow zone. The high trend has been observed at Unconformity level also all through the entire triangle zone.

**ANALYSIS OF DRILLED WELLS**

Six exploratory, along with six structural wells have been drilled around Jawalamukhi and almost all the wells have shown gas shows, but only a couple of wells were penetrated in the Lower Dharamsala Formation. None of the wells has penetrated the main source rock, i.e., Subathu Formation. The gas is coming out with highly saline water. Geochemical analysis of the Formation water indicates the presence of “oilfield brines” within Neogene sequence with a hydro-geological system. The gas is leaking for the last several hundred years in the Jwalamukhi temple, which is suggestive of large size accumulations in the subsurface of the surrounding areas.

Well-5, which is falling on the eastern flank of the anticline has produced thermogenic gas from three horizons @ 43350 M$^3$, 10400 M$^3$ and 8150 M$^3$ per day. Isochron maps prepared near the base of Lower Siwalik in the subthrust of Jawalamukhi thrust and one in the hanging wall corresponding to the gas producing sand within the Lower Siwalik suggest all the wells are located at unfavorable locations. Reprocessed section CC' shows that well-7 was drilled in the western flank around 500m down from the crest and still it has produced some gas along with the saline water in large quantity (gas 624 M$^3$ and water 143 M$^3$ per day, water salinity 18.4 gm/Lt) from Dharamsala Formation which suggest that there may be large quantity accumulations. The deepest well -2 is far away from the actual axis. Well - 5 and 6 also fall on the eastern flank and are located 400 to 500m down.

**HYDROCARBON POTENTIAL**

Hydrocarbon potential of the Foothills has been established by the presence of surface seepages of oil and gases at various places in J&K and Himachal Pradesh, beside subsurface gas shows encountered in number of wells. Gas shows of non-commercial value were found in almost all the wells around Jawalamukhi area.

Hydrocarbon potential of the triangle zone has been analysed considering all the elements of a petroleum system, i.e., source rock, reservoir rocks, entrapment condition and the seal.

**SOURCE ROCK**

Surface samples of Pre-Tertiary Bilaspur/Bandla limestone which is the floor for the thick Cenozoic strata has exhibited varying TOC values (3.5 to 12.33 %) and can
contribute towards generation of hydrocarbons. Subathu group of rocks is the well recognized marine, fossiliferous source facies and considered to be the prime source rock for the hydrocarbon generation in the Himalayan Foothills. Though not encountered in any of the well, the outcrop samples exhibited much variation ranging from 0.0 to 7.20% (Agarwal et al, 1994) indicating poor to good organic matter richness. Palynological studies of Subathus have indicated the organic matter to be dominantly sapropelic-humic with well matured to over matured facies.

The basal Dharamsala sequence which is more than 1200 m thick in well-2 has indicated marginal to good levels of organic enrichment (TOC 0.62-4.69%). Pyrolysis has indicated marginal to good hydrocarbon generation potential with lipid rich organic matter (wet gas prone inter subordinate oil potential). These sediments have reached an early stage of maturation as indicated by Vro at 6140m to be 0.49 in well-2. Thermal modelling carried out by ONGC-BP has indicated depth of 4000-5000m for oil generation temperature (150°C). Oil generation commenced around 10.5 Ma (Late Miocene) during the deposition of upper part of Lower Siwalik.

In the extremely northern part of the triangle zone, the Lower Dharamsala sediments though having, in general, poor organic matter have exhibited fair richness in some of the intervals varying from 0.07-2.4% (average TOC 0.32%) which are immature (Tmax 419°C). However, TAI values of 2.5 to 2.75 indicate Dharamsala sediments to be mature which can generate gas. Carbon isotopic data for well-2 gas seepage inferred from 4031-4037m interval within Lower Dharamsala is given below:

- Methane: 89-93.7%, Ethane: 1.47-1.75%, Propane: 0.12-0.17% and Pentane: 0.02-0.3%

Besides, gas samples have indicated high Iodide content (9.51 ppm to 22.21 ppm) and Bromide 31 to 48 ppm are considered to be direct indicators of hydrocarbon.

Geochemical analysis of mudstones shows poor organic richness but poor potential due to the presence of inert organic matter (Dunn, 1991). In well-2 the organic carbon distribution (TOC) for the Lower Siwalik in the interval 500-2610 m ranges from 0.06 to 3.37%. Formation water samples analysed from the well -1 and well-2 falling within the triangle zone have indicated ‘oil field brines’ within the Neogene sequence in a hydrogeological regime. The presence of iodide and bromide in the waters proximates their association with the migration of gaseous hydrocarbons towards southernmost and westward direction along decollement planes and further migration along thrust conduits.

**RESERVOIR ROCK CHARACTERISTICS**

The Upper Dharamsala sandstones are considered to be very good reservoirs because these meanderbelt channel sandstones have been interpreted to be large, laterally accreting point bars.

In the Dharamsala group, the reservoirs are characterized by well developed channel sandstone of meanderbelt origin interconnected by channel stacking. Visual porosity observed in the field are fair to good. These sandstones are separated by overbank / abandonment claystone and the porosities estimated in well-2 range from 4 to 5%.

**ENTRAPMENT CONDITION**

Gaseous hydrocarbons are migrating through Jawalamukhi thrust conduits, partially charging the reservoirs (a thrust wedge) near Jawalamukhi and the accumulations are localized. The continued seepage taking place at Jawalamukhi temple indicates lack of effective trap being developed in this part. Isochron maps of the hanging and footwalls do not show any structural closure at any of the drilled location in the Jawalamukhi area. The entire triangle zone shows a high trend at shallow as well as at deeper level all through its length trending NW-SE, i.e., parallel to Jawalamukhi and Barsar back thrust. The high trend has been observed all through the thickness of Tertiary and extends further down in the Pre-Tertiary strata. Two types of play exist in the triangle zone, i.e., hanging wall play and footwall play. Isochron map of a reflector within Lower Siwalik formation corresponding to the gas producing sand at JMI-1 shows two culminations of anticlinal reversal near Hamirpur and north-west of Ghumarwin, which are best seen on seismic line DD’ and FF’, and hold very good potential at a very shallow depth for the entrapment of at least gaseous hydrocarbon. Sub thrust of Jawalamukhi thrust exhibits culmination of anticlinal reversal around Balh, Hamirpur, and North–West of Ghumarwin.

**CAP ROCKS**

No regional seal is reported in the area. However, within the Dharamsala group, genetically associated with the reservoir sandstones, deposited as isolated channels having limited areal extent, are the cap rocks present in the form of overbank/ channel abandonment floodplain deposits.
Potential for numerous stratigraphic traps do exist where sheets of meanderbelt fluvial channel sandstone exhibit updip truncation with local seal being provided by the overbank claystones (Sharma et al., 1997).

Effective seals are likely to be provided by the Lower Siwalik claystones developed as lacustrine/overbank deposits. Middle Siwalik Formation shows the best porosities among all the formations in the Tertiary strata but do not possess any effective seal.

LIMITATIONS AND CONSTRAINTS

Seismic imaging is poor in the shallower and deeper part of the Tertiary strata on some of the seismic lines. Only one line is available in the strike direction in the area except the southern part where one line parallel to strike and one oblique to the strike are available which has caused problems in correlation wherever the data quality is poor. There are also wide gaps even in dip orientation. The study has been carried out on time sections and the effect of time pull up in the footwall of Jawalamukhi thrust, if any, has not been considered. However, Pre stack depth migration (PSDM) carried out on one key line has not shown any viewable time pullup in the footwall of JMI thrust.

FINDINGS

1. Entire triangle zone in Kangra re-entrant has been mapped seismically for the first time.
2. A high trend all through the length of the triangle zone with axis trending NW-SE has been mapped seismically.
3. Several culminations of anticlinal reversals in the subthrust of Jawalamukhi thrust at all the levels in Tertiary and Pre-Tertiary strata appear to exist between Balh and Ghumarwin.
4. Two antiforms in the hanging wall of Jawalamukhi thrust have been mapped within the Lower Siwalik corresponding to gas producing sand at JMI-1.
5. All the wells drilled around Jawalamukhi fall on the flank of Balh anticline.
6. Reprocessing of line CC’ suggests that well-7 falls approximately 500m from the subsurface axis and therefore it is about 500 m structurally down.
7. The study suggests that despite no commercial discovery in the area, the area holds good hydrocarbon potential for further exploration.

ACKNOWLEDGEMENT

The authors express heartiest gratitude to GM-Basin Manager, Frontier Basins for encouraging to write this paper. Numerous discussions with Mr Jokhan Ram GM, KDMIPE helped clarifying some fundamental geological problems of this complex area. We warmly acknowledge the part of geological wisdom imparted by him.

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