Thermal Modelling and Hydrocarbon Generation History of the Kangra- Mandi Sub-basin of the Himalayan Foreland Basin, Himachal Pradesh, India*

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Abstract

A Tectono-stratigraphic model has been constructed based on the surface geology, seismic data and well data covering prospective Lambagroan syncline of approximately ≈8900 m(+) thick Tertiary sediments of the Kangra-Mandi sub-basin. Vitrinite data from Subathu and Dharamsala Formations has been calibrated to determine the maximum palaeo-temperature in conjecture with constructed tectono-stratigraphic model. Simulation with heat flow brings out 21.8°C/Km. as Palaeo-geothermal gradient. Simulation with kinetic model of Pepper and Corvi (1995) predicts the present petroleum system at advanced gas generation stage. The source beds of Subathu and Basal Dharamsala started generating liquid hydrocarbon at around 16 Ma – 14 Ma and 14 Ma -11 Ma respectively in the temperature range of 130°C - 140°C. Gas window has been attained for source beds at 9 Ma and 6 Ma in the temperature range of 160°C - 170°C. Total transformation (TR%) of Subathu and Basal Dharamsala predicted at 0.22 Ma are 94% and 86% respectively. Coevalness of tectonic elements and generation history indicates likely locales of hydrocarbon charging

Introduction

The Kangra-Mandi sub-basin forms a part of the western Himalayan Foreland basin and is located in Sub-Himalaya, Himachal Pradesh state, India (Figure 1).Tectonically this sub-basin is a recess bounded by Main Boundary Thrust (MBT) to the east, Himalayan Frontal Thrust (HFT) to the west and tectonic element known as Nahan-Solan Salient depicting an imbricate thrust system on the south. The maximum thickness of the Tertiary sediment fill reaches 8.9 Km in this para-autochthon.

Geochemical studies and well data indicate the sub-basin being prospective. A number of wells have been drilled in this sub-basin without penetrating the Tertiary base except for one on the western margin of basin. A few wells have produced small quantity of gaseous hydrocarbon.

The study primarily focuses on the reconstruction history of the hydrocarbon generation from 1D modelling studies. The prime inputs for this study are stratigraphic evolution and the temperature history of this part of the basin. The temperature history has been built up using the well data and VRo calibration with model. The depositional facies studies reveal that the Subathu Formation and the lower part of the Lower Dharamsala could be the hydrocarbon generation source potential sediments. Only a few wells have penetrated the source beds, vitrinite data available is limited which indicate later stage of maturity of gas generation.

To model the thermal and hydrocarbon generation history of the sub-basin vitrinite reflectance data has been calibrated to the strata of constructed tectono-stratigraphic model across the sub-basin using Barker and Pawlewicz (1986) equation to determine the maximum paleotemperatures corresponding to the maturity of the source beds. Different kinetics models were tested and the best model explaining the data of this sub-basin was chosen for simulation and predictions of the transformation of the kerogen.

Geology of the Kangra-Mandi Sub-Basin

During Late Paleocene to Middle Pleistocene, the Kangra-Mandi sub-basin had been filled by approximately 8.9 Km thick pile of sediments of marine to fluvial environment. The stratigraphy build-up is based on the litho-types, fossil assemblages, palaeo-magnetic study, heavy mineral assemblages etc. Varied litho-types, sand-shale ratio, heavy minerals, and studies on magneto-stratigraphy of the Siwalik Super Group have established the ages of different Units/Formations with minor discrepancies. However, there have been prolonged debates on ages of Subathu, Lower Dharamsala/Dagshai, and Upper Dharamsala/Kasauli Formations in the light of number of fission track studies. The fossil assemblages from Subathu Formation indicate an age of Late Paleocene to Middle Eocene. Detailed mapping by Batra (1989), Najman et al. (1993) showed that Dagshai Formation overlies Subathu Formation and the contact is relatively sharp, well defined, and no observable angular unconformity. The age of the base of Dagshai Formation could be placed in the rage of 28 Ma - 31 Ma (Najman et al., 2004). Age of the Dagshai and Kasauli Formations has been inferred by A. Yin (2006) as 20 Ma – 17 Ma and 17 Ma - 14.25 Ma respectively. A. K. Jain et al., 2009 inferred the age by detrital zircon fission track study of the oldest stratum in Subathu-sub-basin as 57 Ma - 41.5 Ma. A distinct unconformity spanning ~10 Ma between the Subathu and Dagshai Formations has been inferred in the basin. The stratigraphy adopted for the Siwalik Group is of S. K. Tandon (1991) based on the magnetic-polarity study. Figure 2 depicts the stratigraphy as worked out for the present study.

Subathu

Subathu unconformably overlies the Pre-tertiary namely Shali/Juansar and Simla group of rocks and comprises olive green and purple, oily looking gypseous shales with subordinate bands of limestone, sandstone and quartzite. Limestone is coquinite of broken oysters with Nummulites. Phosphatic nodules have been reported from green shales. Biostratigraphically, age of Subathu is Late Palaeocene to Early–Middle Eocene (Mathur, 1978). Najman et al., (2004) considered Subathu sediments as shallow marine environment deposits. Rare paleocurrent indicators (cross-beds) show NE directed flow (Najman et al.2004).

Dharamsala

The Dharamsala Group of Kangra-Mandi sub-basin has a near continuous sedimentary sequence which has been subdivided to Lower and Upper Dharamsala sub-groups. The Lower Dharamsala Sub-group is comprised of massive or finely laminated, mottled, maroon and green micaceous mudstones and siltstones. The preferred palaeocurrent direction is SSW (Najman et al., 2004). Lower section of the Upper Dharamsala is predominantly of varied color mudstone. Olive mudstones containing abundant leaf moulds and carbonaceous organic matter are common. The inferred flow direction is SW (Najman et al., 2004). The palaeocurrent data indicate that two drainage systems commonly occurred synchronously in the foreland basin (Burbank and Beck, 1991; Miall, 1995).

The Siwalik Group is divisible into three subgroups respectively the Lower, Middle, and Upper on the basis of lithostratigraphy (Karunakaran and Ranga Rao, 1979).

Lower Siwalik

Lower Siwalik rocks show facies variation over the areas of exposures in Himachal Himalaya. Lower Siwalik Subgroup rocks in the Jawalamukhi area consist of dominantly sandstone and claystone alternation. Contact between Upper Dharamsala and Lower Siwalik is normal. The Lower Siwalik subgroup varies in thickness from 1600 m thick in the Jawalamukhi area to 1900 m (Srikantia and Bhargava, 1998) in Paror-Sarkaghat area. Mammalian fauna and shells of Unio are found in this sequence. The age is Upper Miocene (17 Ma - 10.8 Ma).

Middle Siwalik

The Lower Siwalik Subgroup passes gradationally into Middle Siwalik. The rocks of this subgroup consist of dominantly sandstone of subgraywacke to arkosic nature, coarser, calcareous and micaceous with interbeds of earthy-red and silty clays. The thickness varies from 1400 m in Jawalmukhi area to 2000 m in Mandi area. Middle Siwalik Subgroup has yielded a rich collection of vertebrate fossils between Hamirpur and Haritalyangar (Prasad, 1970). The age of the Middle Siwalik is Pliocene (10.8 Ma - 5.22 Ma).

Upper Siwalik

The Upper Siwalik Subgroup dominantly consists of conglomerate facies in the upper part and alternations of sandstone, clay, and conglomerate in the lower part. The Upper Siwalik in this area is overlain by the still younger sediments i.e. Neogal Conglomerate and red clays of post – Upper Siwalik age representing the last phase of the Himalayan Orogeny. The Upper Siwalik attains maximum thickness of 2300 m in Bhakra Gorge and Janauri area where conglomerate facies becomes minor to negligible. It is mainly sandstone with silt. Further southward of Janauri the Upper Siwalik becomes highly argillaceous and is indicative of lacustrine origin. The age of the Upper Siwalik Subgroup is from Upper Pliocene (5.22 Ma) to Lower Pleistocene (0.22 Ma)

Prospectivity of the Sub-Basin

This area has generated interest of explorationists due to the presence of numerous surface gas seepages and an oil show. The drilling of a few wells has produced gas on testing though commercially non-viable. Subathu and Lower Dharamsala Formations are considered as prime source beds and have reached the maturity levels. Based on well data, maximum TOC determined from the basal Dharamsala is 4.69% (Kak et al., 1990, personal communication). EOM and Hydrogen Index (HI) study indicates source rich in lipid and of type IIIB/IIIA. %VRo of Subathu from surface sample from east of Hamirpur ranges from 0.84 - 1.88 (Tandon et al., 1998) and of Basal Dharamsala from Well-B (Figure 1) data is 1.22.

Geochemical analysis of the surface samples has revealed marginal to good source potential of Subathu and Dharamsala Formations (Max. TOC: 4.47%; M. S. Rana et al., 1989, personal communication). Palynological studies on these samples indicates that organic matter was mainly amorphous, algal-sapropelic, and humic–sapropelic in nature with TAI ranging from 2.27 to 3.0^{+} showing adequate maturity. As per palynological studies, Subathu is considered as a good hydrocarbon generating source with maturity. Adsorbed, free gas analysis and Iodine Surveys indicated anomalies of interest in this sub-basin.

Model Building

Tectonostratigraphic Model

The Tectonostratigraphic Model presented here is based on the surface geology, seismic data, and well data. A transect from west of Himalayan Frontal Thrust to Trans-Main Boundary Thrust and covering the Lamagroan Syncline has been constructed. The stratigraphy evolved at the deepest single point being considered for modelling is given in Table 1.

Calibration

The temperature data available from the wells represent the present geothermal gradient palaeo-geothermal gradient has been simulated and validated using vitrinite reflectance data set and finally calibrated with stratigraphy.

Vitrinite Reflectance and Temperature Data

The temperature data of the Well A and deepest well, Well-B, indicate present geothermal gradient as 21.2°C/Km and 19.3°C/Km respectively. %VRo data available is very scanty. Two %VRo values from wells Well-B and Well-C and three VRo values from the surface samples (Tandon et al., 1998 and Najman et al., 2004) forms the basic data for both Kangra-Mandi sub-basin. This vitrinite reflectance (%VRo) data has been displayed in Table 2. Since the depth of occurrence of studied samples differ, the %VRo data is required to be calibrated with the stratigraphic model. An attempt has been made to convert the Vitrinite Reflectance data to the actual depth of occurrence using the Barker and Pawlewics (1986) equation- " In (Ro) = 0.0096(T)-1.4 where Ro is Vitrinite Reflectance and T is maximum temperature in °C. Stratigraphy of the model and modified geothermal gradient is based on Heat Flow Data applied. The variation in the depth of occurrence for the same Vitrinite Reflectance values as per varying geothermal gradient for Kangra-Mandi is displayed in Table 3.

Heat Flow

Available temperature data of drilled wells indicate that the gradient varies a lot in the section below 2500 m. An average gradient of 25°C/Km was first considered and tested with the depth of occurrence of %VRo of 1.22 at well depth 6404 m occurring in the undisturbed sub-thrust of Jhor Fault. With this gradient and average surface temperature of 22°C - 23°C the palaeo-depth of %VRo of 1.22 comes to be 5780 m which is shallower than the present depth of occurrence. A temperature gradient of 22.6°C/Km explains the occurrence of maximum temperature (166.5°C) derived from Barker and Pawlewics (1986) equation at around 6394 m which is close to the actual depth of %VRo (6404 m). Hence, to start the simulation, the geothermal gradient 22.6°C /Km is chosen.

Simulating curves on temperature and Vitrinite Reflectance data reveals that the palaeo-geothermal gradients 22.6°C/Km, 22.3°C/Km, and 22.0°C/Km considered are still on the higher side. A palaeo-geothermal gradient 21.8°C/Km was attempted (Figure 2) and found to be most satisfying with the temperature and Vitrinite data rectified as per this gradient.

Transformation Ratios

Kinetic Model

In the absence of any workable kinetics of the present study area, many kinetics (models) have been tested and corroborated with the type of source, temperature, and hydrocarbon shows in the study area (Kroeger et al, 2008). Adopted kinetics (model) of Pepper and Corvi (1995) -T-IIIH predicted the petroleum system to have attained the advance stage of gas generation with TR%≈ 94% at 0.22 Ma which appears to corroborate with actual data of the area under study. Hence, this kinetics model is adopted for simulation and generation of maturity parameters.

Generation History and Transformation (TR%)

Kinetic model of Pepper and Corvi (1995) predicts the petroleum system, at present, at gaseous hydrocarbon stage of 5389 TTI value. Figure 3 and Figure 4 depict the TTI and Transformation Ratios (TR%) with respect to the threshold of the oil window, peak oil generation stage, and gas window for Basal Subathu (BS) and Basal Lower Dharamsala (BLD). Predicted significant events of hydrocarbon generation history of the Kangra-Mandi sub basin are shown in Table 4.

Discussion

The thick sequence of Tertiary sediments in the Lambagroan Low modelled as active kitchen area reveals a low geothermal gradient varying from 22°C/Km to 21.8°C/Km. The predictions of the maturity and transformation history reveal that advance maturation level of gas stage has been attained by the Basal Subathu and Basal Dharamsala source beds. The maturity history indicates that source rock started generating oil during early middle Miocene time (16 Ma -14 Ma) and reached peak oil generation stage at ~10 Ma (late middle Miocene). There seems to be an increase in geothermal gradient after 14 Ma which may be due to fast subsidence during deposition of Lower Siwaliks sediment and/or tectonic activity. Considering the ages of the tectonic elements coevalness with generation history of hydrocarbons in the kitchen area emerges. The generation of hydrocarbons started in the kitchen area when the Main Central Thrust (MCT) was in its later stage of formation. The age of the MCT is constrained to be 22 Ma - 14Ma. The structures falling in the eastern part of the generating area up to the MCT might have got charged. Besides this, charging can take place in the rising flank of the foredeep margins to the west. However, the charged structures to the east have been further affected by the continuing tectonic activities and higher geo-thermal regime.

Peak oil generation of Basal Subathu and Basal Lower Dharamsala during late middle Miocene (11 Ma – 10 Ma) is coeval with formation of Main Boundary Thrust (MBT) and subsequent Jogindernagar Thrust. Thus, the best locales for hydrocarbon charging are the structures in the sub-thrust of MBT and Jogindernagar Thrust. Structures generated after 6 Ma are expected to be charged with gaseous hydrocarbons. Structures in the sub-thrust of Palampur Thrust (age ≈ 5 Ma) are considered the best locales for charging of gaseous hydrocarbons.

The tested gas pool in Lower Siwalik in the upthrust of Jawalamukhi Thrust is assumed, based on analogy as discussed under structure earlier, to have initiated during upper Pliocene times (2 Ma). Transformations, as per our model, of Subathu and Lower Dharamsala Formations are predicted to be 88% and 81% at burial depths of 8300 m and 7650 m respectively. Hence, it may be safely inferred that the Lower Siwalik gas sand pools are either charged on further continuing maturation and transformation of the left over source potential or connected to and remobilised from the matured charged structures located towards hinterland direction.

Modelling predicts that lower part of the Upper Dharamsala Formation attained oil window maturity level during early Pliocene (5 Ma) times at burial depth of 5100 m. The presence of liquid hydrocarbon in the upper part of Upper Dharamsala Formation in the well-A corroborates the prediction. Dutta and Samanta (2005) indicated Subathu and Lower Dharamsala maturity at 10 Ma and Lower Siwalik also in oil window at 3 Ma considering 21ºC/Km geothermal gradient.

Conclusions

The best and most likely locales of hydrocarbon charge inferred from the study are:

- Towards hinterland in the sub-thrust of Palampur Thrust,

- Structures formed before 2 Ma to the west of the generation locale and
- Younger structures getting connected with charged structures at greater depths may be of interest also.

A better understanding of the timing of all available entrapment conditions with proper seal is of prime importance.

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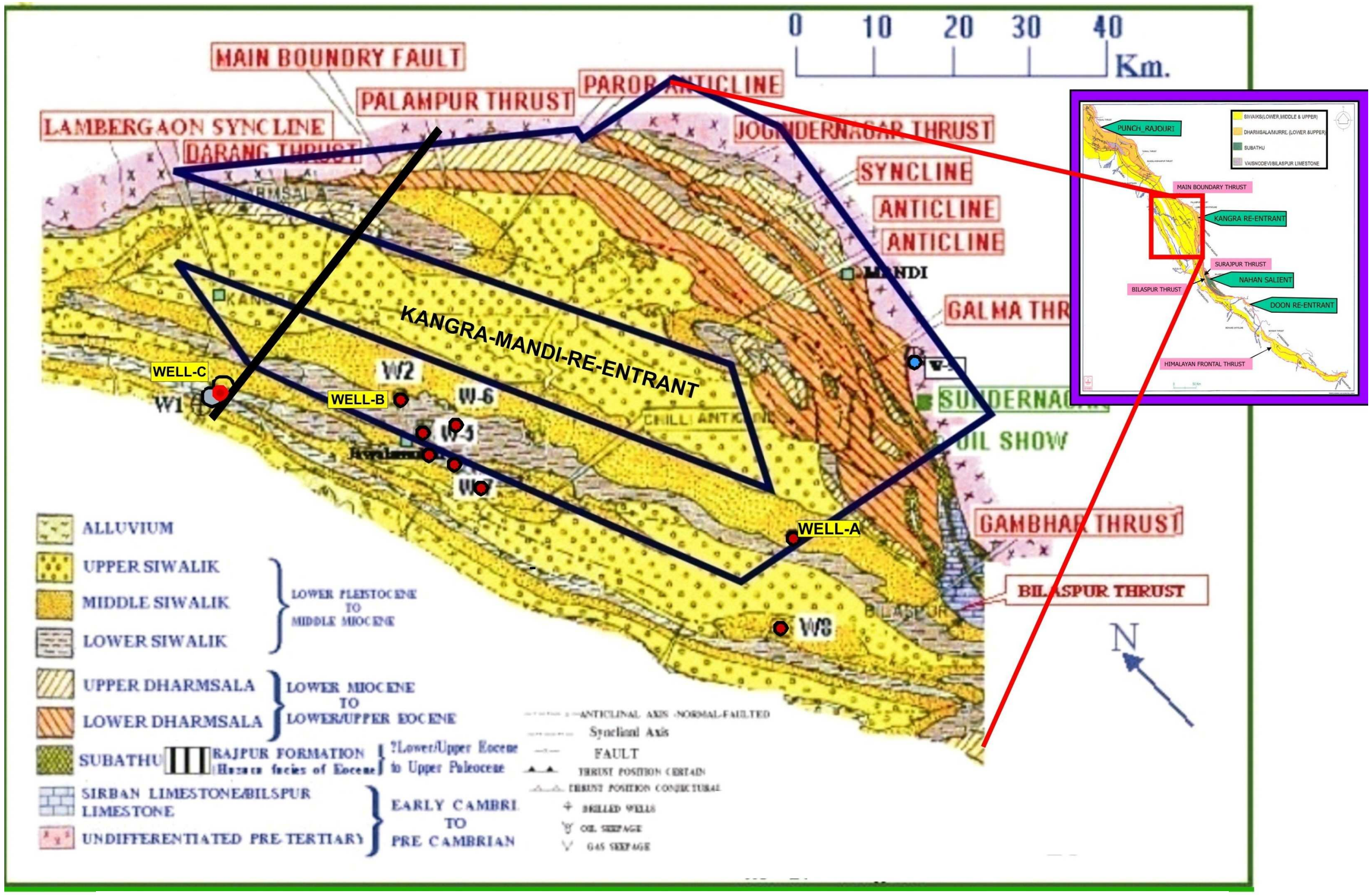

Figure 1. Geological Map and Location of Kangra-Mandi Sub-basin in Himalayan Foothills.

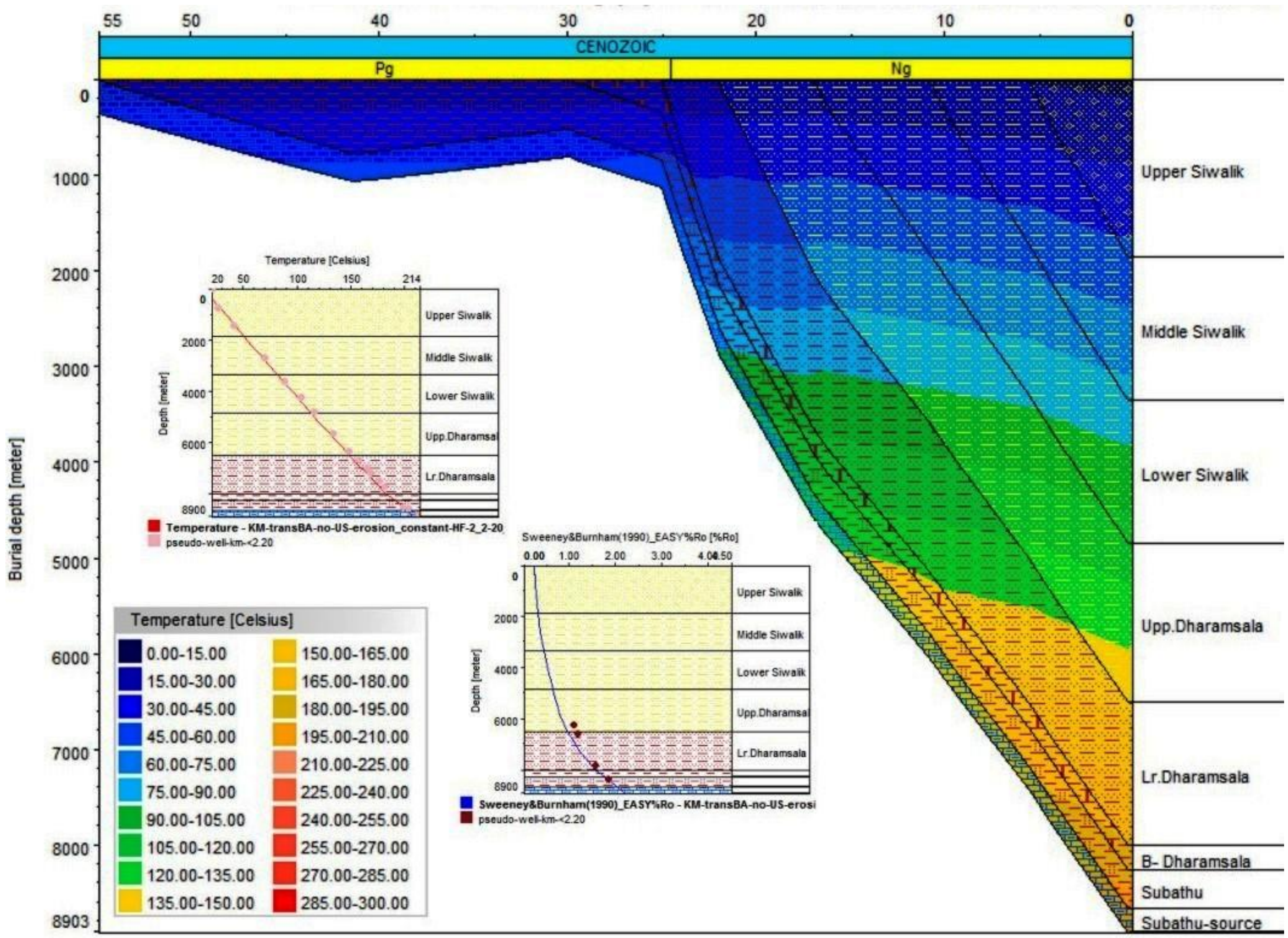

Figure 2. Simulation of temperature and Vitrinite reflectance with constant HF48mW/M2.

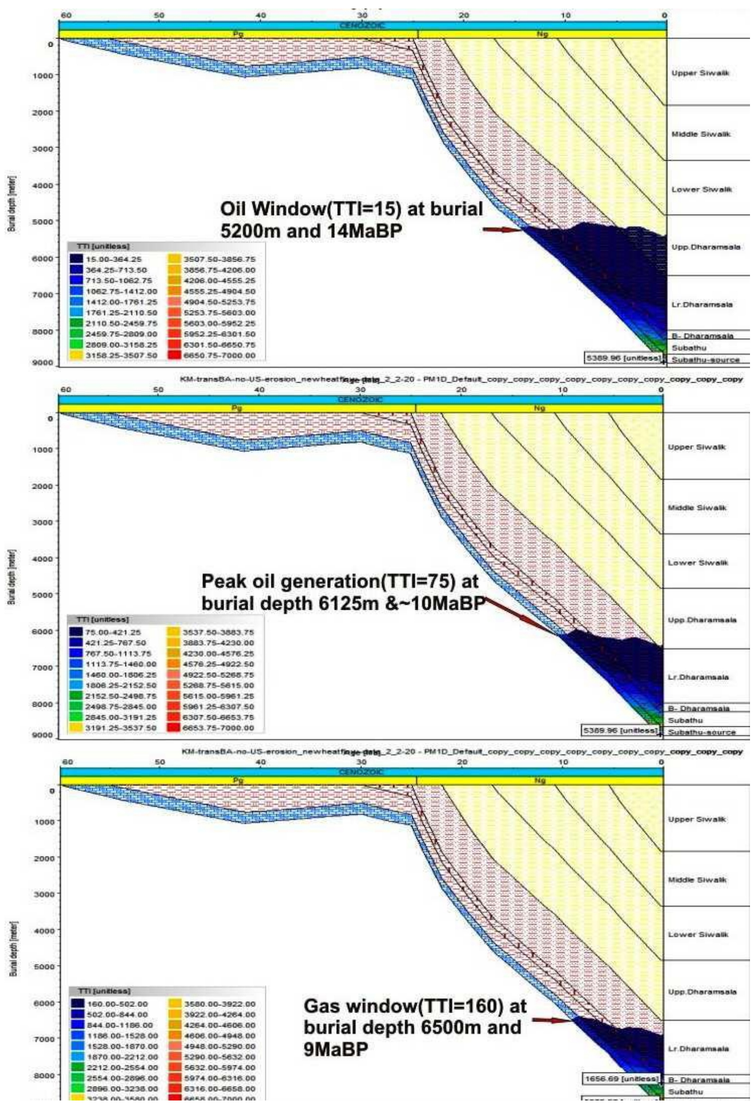

Figure 3. Timing, burial depth and TTI at Oil, Peak Oil and Gas Windows.

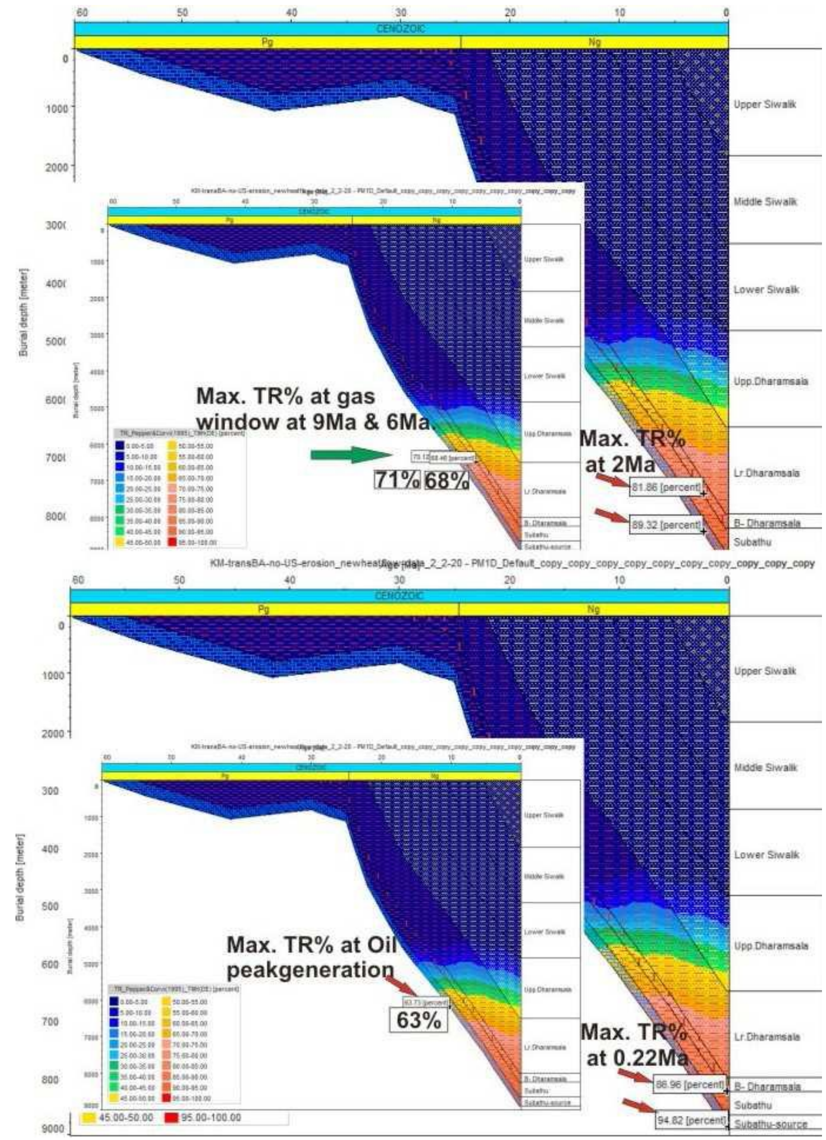

Figure 4. TR% at Peak Oil and Gas Windows.

POINT	GROUP	SUBGROUP	FORMATIOM	GEOLOGICAL AGE	STAGE	DEPTH (M) WITH (ORIGINAL THICKNESS)	THICKNESS ERODED	AGE* (Ma)
TB-B	SIWALIK	UPP.SIWALIK		EARLY PLIOCENE - MID. PLIESTOCENE	ZANCLEAN- LATE EARLY PLIESTOCENE	0-1850 (1850)	600	5.22-0.22
		MID.SIWALIK		EARLY UPP.MIOCENE- EARLY PLIOCENE	EARLY TORTONIAN - ZANCLEAN	1850-3350 (1500)	NIL	10.8-5.22
		LR.SIWALIK		LATE LR.MIOCENE- EARLY UPP.MIOCENE	MID.BURDIGALIAN- EARLY TORTONIAN	3350-4850 (1500)	NIL	17.0-10.8
	SEMERI / DHARAMSALAS		KASAULI / UPP. DHARAMSALA	LR.MIOCENE- LATE LR.MIOCENE	AQUITANIAN- MID.BURDIGALIAN	4850-6450 (1600)	NIL	22.0-17.0
			DAGSHAI / LOWER DHARAMSALA	LATE OLIGOCENE- LR.MIOCENE	LATE RUPELIAN- AQUITANIAN	6450-8250 (1800)	NIL	30.0-22.0
			UNCONFORMITY					42.5-30.0
			SUBATHU	LATE PALEOCENE- UPP.MID.EOCENE	LATE LUTETIAN- SELANDIAN	8250-9090 (840)	190	60.0-42.5

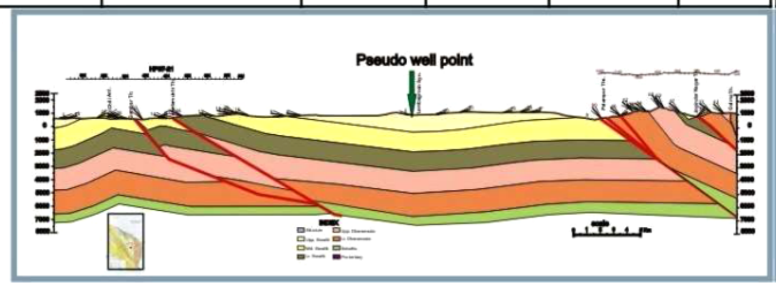

Table 1. Stratigraphy of the pseudo well point with Seismo-Geological Cross-Section (a part of transect-B across the thrust-fold belt).

VRO	SOURCE OF DATA
0.54	**Janauri #1 well depth 2258m (Lower Siwaliks)**
0.48	**well depth 61404m (Basal -Lower Dharamsala)**
1.13	**Surface Sample (Kasauli Form. ; Najman)**
1.22	**well depth 6404m (Basal -Lower Dharamsala)**
1.6	**Surface Sample (Dagshai Form. ; Najman)**
1.84-1.88	**surface sample from Subathu , east of Hamirpur (Tandon et al.1998)**

Table 2. Vitrinite Refrectance (%VRo) Data.

VRO	MAX.TEMP (°C)	Average surface temperature:22°C				
		2.18°C/ 100M	2.20°C/ 100M	2.23°C/ 100M	2.26°C/ 100M	Temp/Actual depth of occurrence
1.13	158.6	6266	6209	6125	6044	Surface Sample (Kasauli Form. Najman)
1.22	166.5	6628	6568	6480	6394	well depth 6404m (Basal Lower Dharamsala)
1.6	194.8	7926	7854	7749	7646	Surface Sample (Dagshai Form.Najman)
1.84-1.88	211.6	8697	8618	8502	8389	surface sample from Subathu , east of Hamirpur (Tandon et al.1998)

Table 3. Chart depicting the maximum temperature based on equation and their depth of occurrence at variable temperature gradients for Kangra-Mandi area.

S/ Rock	OIL WINDOW; TTI=15				PEAK OIL WINDOW; TTI=75				GAS WINDOW; TTI=160				Max. TR(%) /TTI	Remarks
	AGE (Ma)	DEPTH (M)	TEMP (°c)	TR %	AGE (Ma)	DEPTH (M)	TEMP	TR%	AGE (Ma)	DEPTH (M)	TEMP	TR %		
BS	16Ma-14Ma	4800M-5300M	130-140	≈19	11Ma-10Ma	5750M - 6150M	150-160	63-68	10Ma -9Ma	6250 – 6500	160-170	≈71	94/ 5389	6% yet to transformed
BLD	14Ma-11Ma	4650M-5250M	125-140	≈17	8Ma	5875M	150-160	≈57	7Ma - 6Ma	6250 - 6500	160-170	≈68	86/ 1656	14% yet to transformed

Table 4. Significant events of hydrocarbon generation history of the Kangra-Mandi sub-basin.