SOURCE ROCK EVALUATION FOR HYDROCARBON GENERATION POTENTIAL OF SUBATHU SUB-BASIN, LESSER HIMALAYAS

Submitted By

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CHAPTER 1- INTRODUCTION, OBJECTIVE AND METHODOLOGY

1.1 INTRODUCTION

“Mountain belts created by continent-continent collision are perhaps the most dominant geological features of the surface of the Earth” - Dewey & Burke (1973). The Appalachians in North America, the Urals of central Eurasia, and the Qinling-Dabie-Shandong of central-eastern Asia are a few examples to corroborate this. Over the years geoscientists and geologists have researched the genesis of these orogenic systems establishing that the continent-continent collision is the most efficient process impacting the geologic and biologic evolution of the Earth. The youngest and the most fascinating mountain ranges formed due to such continent - continent collision on Earth is the Great Himalayan system. This orogenic system was created due to the India-Asia collision dating 60–50 Ma. This is a significant part of the greater Himalayan-Alpine system which extends from the Mediterranean Sea in the west to the Sumatra Arc of Indonesia covering over 7000 km. This extraordinarily long and complex belt of the Himalayan system was formed by the closure of the Tethys ocean with in the collision zone dating back to the Paleozoic. The collision processes result in the formation of a variety of geologic features such as large-scale thrusts, strike-slip and normal fault systems (Yin et al. 1994), leuco-granite magmatism (Harrison et al. 1998), regional metamorphism and continental & intercontinental –margin ocean basins. The formation of the Himalayan Foreland Basin is directly linked with the intercontinental collision. This basin comprises thick succession of marine to continental beds and its sediments portray the collisional history and the Tethyan withdrawal. The huge tectonic loading resulted due to the intercontinental collision and the subsequent Intrusion of ocean waters in to the depression zone resulted in formation of the foreland basin.

1.1.1 HIMALAYAN FORELAND BASIN - SEDIMENTATION

A unique and geologically significant development in the Foreland-basin succession was the complete reversal of drainage during the Early Paleocene time. The rivers draining the northern part of Peninsular India flowed in the northward and north-westward directions for more than 2000 Ma. The formation of foreland basin and the upheaval of the Himalayan region resulted in a reversal of the pattern of palaeocurrents and sediment dispersal. After the formation of the foreland Basin, rivers started draining the newly formed Himalayan highlands and flowing southwards in the central sector (Srivastava and Casshyap, 1983) and eastwards in the Pakistan sector (Waheed and Wells, 1990).

The final withdrawal of the sea from the Himalayan province was another significant development which resulted in the beginning of the fluvial sedimentation. The Late Paleocene–Middle Eocene Subathu succession that represents the nascent phase of the foreland basin in the northwestern sub-

Himalaya has preserved distinct episodes of withdrawal of the Tethys Sea during the India–Asia convergence and the onset of continental setting. The age of fluvial sedimentation is dated at about 31 Ma - on the basis of fission-track dating of detrital zircon and monazite from the basal Dagshai succession (Najman et al., 1993, 1994). The denudation forced the Himalayan province to rise up as a highland. The erosion due to the withdrawal resulted in the generation of enormous volumes of detritus; these detritus were carried by the rivers before draining them into the Sirmaur Basin. The Tethys Sea retreated progressively, due to the formation of huge delta at the river mouth resulting in creation of huge floodplains (Waheed and Wells, 1990; Valdiya, 1998).

The Himalayan Foreland Basin (HFB) was developed in front of an active orogenic belt similar to other collision-related foreland basins. The lithospheric subsidence induced by topographic load of the hanging wall and the sedimentary load in the basin facilitated its development. The sedimentary fill of the Foreland basin depicts the interaction between growth of the thrust wedge, isostatic adjustment of the cratonic lithosphere due to thrust loading and the resultant basinal subsidence.

The development of sedimentary successions in the foreland basin is related to the lithographic subsidence. On deeper analysis, the sedimentation pattern reveals two prominent changes at 10 and 5 Ma in the Siwalik succession of the Foreland basin. These changes are related to the deformation created along the Main Central Thrust and Main Boundary Thrust. The first change dating between 11 and 9 Ma records thick, multistoried, grey sheet sandstone over mudstone-dominated succession. The second change recorded between 6 and 5 Ma reveals extensive and thick conglomerates. Fluvial architecture suggests presence of broad catchment area probably created by a large river network with high sediment flux. This could be the result of tectonically raised high relief and/or high intensity rainfall due to major climatic changes. The resultant basin was quite shallow, and its shores were agitated by waves and currents; it became the site of marine sedimentation. The oolites and pisolites, and certain sedimentary structures in the basal horizons substantiate the same. The basin has presence of variety of algae, bryozoans and foraminifers, gastropods, lamellibranchs and echinoids. South-west of Shimla in the Gambhar valley (Himachal Pradesh), the Early Paleocene succession made up of pisolitic bauxite at the base and green-brown, purple and yellow shales with carbonaceous-phosphatic nodules, and characterized by foraminifers *Ranikothalia*, *Globigerina* and *Lockhartia conditi*, is known as the Kakara Formation (Srikantia and Bhargava, 1967; Juyal, and Mathur, 1990). In the Ganga valley in Garhwal, the Kakara has been described as the Singtali and the Bansi (Valdiya, 1980b). The Kakara is succeeded by the Subathu Formation, named after a town Subathu, south-west of Shimla by Medlicott (1865). It represents a lagoonal deposit comprising carbonaceous shale, intercalated with oyster-bearing limestone and purple shale. The limestone contains foraminifers of the Late Thanetian (Upper Paleocene) to Lutetian (Middle Eocene) (Bhatia, 1982; Bhatia and Bhargava, 2006). Sedimentological and palaeontological studies have established its precise stratigraphic position

(Saluja et al., 1969; Raiverman and Raman, 1971; Raiverman, 1979; Mathur, 1969; Juyal and Mathur, 1992). In the Kalakot area in Jammu and Kashmir, it is represented by 4-5 m of breccia below a 6-10 mts thick horizon of bauxite. And at Salal an angular unconformity defines its base against the Proterozoic Jammu Limestone. The succession of the Kalakot-Salal belt indicates deposition of the Paleocene sediments in a fault-formed depression adjacent to a fore bulge in the peninsular shield (Singh and Andotra, 2000; Singh 2003). The presence of *Ranikothalia nuttali* in the basal beds indicates that it commenced in the Late Paleocene. In the Hazara and Potwar-Kohat regions in northern Pakistan, the Paleocene is represented by the Patala Shale and the Hangu Shale.

The rivers in the early stage laid down maroon and red sandstones, shales and mudstones in their floodplains and these sediments are represented by the Dagshai Formation. In the later stage, the sediments are grey lithic sandstone with subordinate mudstone deposited principally in their channels. The succession is represented by the Kasauli Formation (Raiverman and Raman, 1971). The Dagshai-Kasauli succession is a handiwork of a river system that flowed in the South East as well as South west directions in different parts of the basin (Srivastava and Casshyap, 1983). This combined Dagshai-Kasauli succession, also known as the Dharamsala Formation in western Himachal Pradesh, represents the filled or overfilled stage of the foreland basin sedimentation.

The Late Paleocene–Middle Eocene Subathu succession that represents the recent section of the foreland basin within the northwestern sub-Himalaya has preserved evidence of withdrawal of the Tethys Sea during the convergence and the onset of continental setting. Subathu sub-basin (Raiverman et al., 1983), the oldest foreland basin deposits consist of rocks deposited during period of initial contact, collision and suturing. Being marine, the rocks are consistent with deposition during the initial down warping stage of the foreland basin.

1.2 DETAILS ABOUT THE STUDY AREA

The Himalayas were formed once the Tethys ocean, that had been subducting below the continent, closed, resulting in India - Asia collision. Microplates and island arcs were sandwiched between the continents. The transpressional boundaries which are the eastern and western lateral margins of India – Asia contact zone was formed as India continued its movement north into Asia. These transgressional margins are outlined by accretionary prisms (the Makran and thus the Indo–Burman ranges) and strike slip faults that form the boundaries between the continents. The Himalayas stretch over 2400 km between the Namche Barwa syntaxis in Tibet and the Nanga Parbat syntaxis in Pakistan. The frontal part of the 2400km long NE to SW and 200-300km wide north to south are sub-divided into

1. The Tibetan or the Tethyan Himalaya is underlain by rocks dating from Proterozoic to Late Cretaceous and Eocene dominated by platform deposits of carbonate, quartzite and shale of shallow water origin.
2. The Central or the Higher or the Greater Himalaya composed of highly deformed and metamorphosed rocks of Precambrian age.

3. The Middle or the Lesser Himalaya, with a sequence of Upper Proterozoic to Lower Paleozoic sedimentary rocks &
4. The Outer or the Sub-Himalaya consisting of Tertiary sedimentary rocks deposited in front of the rising mountain front.

Each of lithotectonic units are bound on either side by longitudinally continuous and supposedly intercontinental thrust, such as

a. Main Frontal Trust (MFT)
b. Main Boundary Thrust (MBT)
c. Main Central Trust (MCT)
d. Tethyan shear Zone (TSZ) and
e. Indus-Tsangpo Suture Zone (ITSZ).

The collision of the Indian Plate with the Asian Plate and the eventual withdrawal of the NeoTethys Sea created the foreland basin and the Sub-Himalayan Palaeogene succession accumulated in a foreland basin between the two plates. The most commonly quoted age of collision, 55–50 Ma, is taken from a variety of data including Paleomagnetic methods which show the Indian plate velocity to have decreased rapidly around this time (Patrait and Achache, 1984; Klootwijk et al., 1992), the time of cessation of marine facies and development of flexure related unconformities in the suture zone and Tethys Himalaya (Garzanti et al., 1987).

The sub-Himalayan foreland extends from the Brahmaputra Valley in the northeast to the Potwar Plateau and the Bannu Plains in the northwest, and lies between the Main Boundary Thrust (MBT) in the north and the Himalayan

Frontal Thrust (HFT) in the south. Sub-surface studies have indicated its southern extension beyond the HFT. It is unique as it records distinct episodes of withdrawal of the Tethys Sea during India-Asia convergence and the onset of continental sedimentation as a consequence of initial contact. Numerous reaches in this area has proved existence of plethora of information on pre-collisional, collisional and post-collisional histories of the Tethyan closure. It has great potential for information on wider consequences of collision including paleontological, sedimentological, geochemical, tectonic, palaeoclimatic, orographic and sea level changes that need to be recorded and interpreted in terms of geodynamic models. Its evolutionary history witnessed three main phases

- Nascent phase with the paralic sediments in which black shales with coal seams, ironstone and phosphorite, and marine fossiliferous shales, siltstones and limestone (Late Paleocene-Middle Eocene Subathu Group) deposited at a slow sedimentation rate.
- Middle phase when the first clastic sediments (Late Eocene-Early Miocene Dagshai and Kasauli formations and their coevals) deposited at a moderate rate as a result of the initiation of uplift.
- Last phase when molassic sediments (Miocene-Pleistocene Siwalik Group) accumulated at higher rates.

Sediments eroded from the mountain belt have been deposited in the marine depositional environments of remnant ocean basins and deep sea fans, and in sedimentary basins on land of which the major depocentres are the foreland basin and suture zone. The suture zone marks the contact between the continents of

India and Asia. Continental collision resulted in the evolution of the marine forearc to an intermontane setting. Most information on the suture zone molasse has been gathered from its western end, in Ladakh, with more recent studies encompassing the eastern region in south Tibet.

The area of interest, the Subathu basin is predominantly dispersed along the Lesser Himalayas. The systematic geological surveys of the, foothills were conducted in the last century by Medlicott (1864), Theobald (1881), Oldham (1883) and Middlemiss (1890). Wadia (I928), Auden (1934) and several other geologists of the Geological Survey of India mapped the Tertiary sediments of the foothill belt.

1.3 NECESSITY FOR FURTHER STUDY

Although lots of studies have been carried out on the Himalayas, lot of questions and queries are remaining for suitable answer. There are hydrocarbons seepages found in the sub-basin but till now commercial hydrocarbon source is elusive. The following queries were attempted to answer through this thesis.

- Identify the source rock for the seepages reported and hydrocarbon accumulations. What is the original source of Hydrocarbon?
- Hydrocarbon seepages have been reported but still to explore and understand the entrapment mechanism of the study area
- Distribution and percentage of total available organic matter in the identified source rock.

1.4 OBJECTIVES

The areas which are part of the Subathu sub-basin in the Lesser Himalayas identified for this research are Nilkanth, Bidasini and Dogadda in Uttarakhand state and Subathu, Dharampur in Himachal Pradesh, depicted in the **Figure 1.1**. We found interesting outcrops of Subathu, Dagshai, Kasauli, Dharamsala, Krol & Infra Krol formations in the study area.

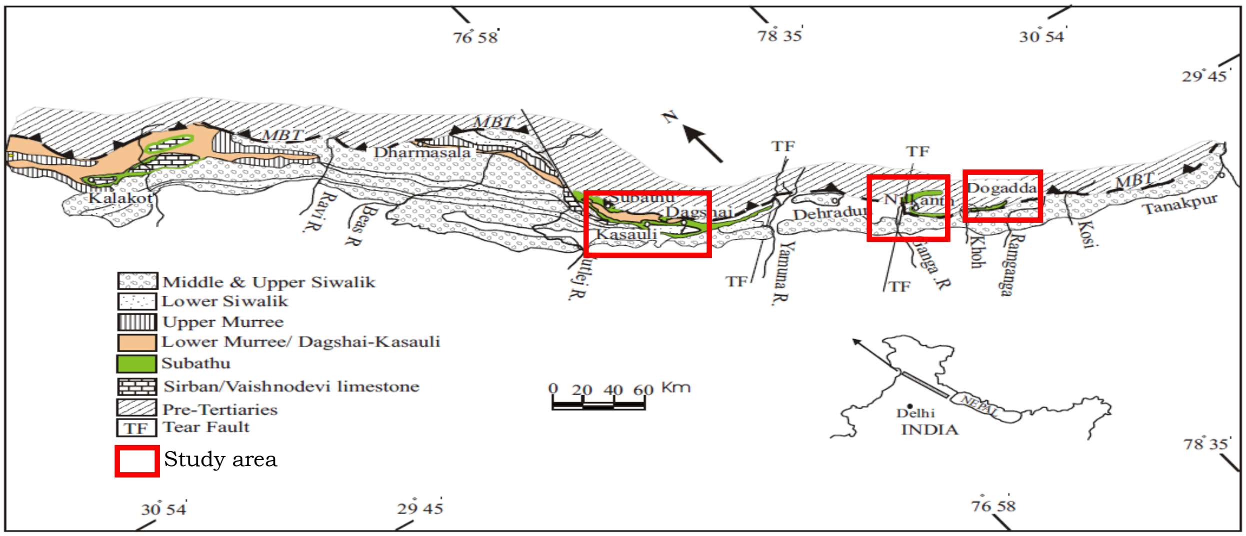


FIGURE 1.1: Outcrop distribution of Subathu rocks, modified after Karunakaran and Ranga Rao (1976)

The main objectives of the work finalized based on the recommendation of the assessment panel during Synopsis stage are

- To understand the Palaeobiology and Biostratigraphy of the Subathu Formation.
- Organic matter Maturation and TAI (Thermal Alteration Index).
- Organic Geochemistry for source rock evaluation.

1.5 METHODOLOGY

Methodology is the process to arrive at the desired result of any problem with useful combination of tools and data sets. The methodology used to analyze the rocks and identify the source rock for the Himalayan hydrocarbon consists of two parts:

- Field Studies / Excursions
- Laboratory Methods

The scope of the field studies cover detail outcrop observation in the field and collect samples for laboratory analysis. Existing literature study was carried out to understand field information (locations, geological maps, lithology etc), related to the study area. The sample collection , traverse mapping are carried out using tools like GPS, hammer, chisel, brunton compass, measuring tape, Abney level, camera etc. The location identification was done with the help of Survey of India Toposheets - 53F/1 (Dharampur, Kalka, Kheel ka more, Kumarhatti, Salon), 53B/13 (Kasauli, Koshaliya river, Subathu), 53J/4 (Nilkanth, Bidasani, Dogadda), and were used for identifying the location of the traverse points.

The activities carried out in the laboratory environment are analysis of micro fossils, preparation of micro fossils by acid maceration, geochemical analysis and Total Organic Content (TOC) measurement. The analysis results and field data were used to prepare detailed lithologs. Schematic diagrams have been prepared using the available data and data collected during field studies.

The following work sequences were carried out to complete the research objective:

- Literature review from published and unpublished literature.
- Traverse Mapping analyzing outcrops, major fold and fault structures, and collection of outcrop samples of Subathu formation
  - Data Collection through field work – Traverse mapping & outcrop Sample collection from Nilkanth, Bidasani, Kumarhatti, Dharampur, Subathu, Koshaliya and Kuthar rivers.
- Geological setting of Subathu
- Paleontological studies of the study area.
- Maceration & Thermal alteration Index analysis
- Geochemical study for organic maturation.

The following write up provides a detailed description of the methodologies adopted for completing the research objectives and documenting the same.

1.5.1 FIELD STUDIES / TRAVERSE

The field study, mapping, outcrop studies and outcrop sample collections were carried out in the following areas.

- Nilkanth
- Bidasini
- Subathu Cantonment
- Kheel-ka-more
- Kumarhatti
- Dharampur
- Lower Koshaliya River Section

- Upper Koshaliya River Section
- Kuthar River Section, Subathu
- Kasauli road sections

The field study and analysis indicate reasonable evidence of Hydrocarbon content. The samples from these locations were analyzed for Hydrocarbon content and the results are leaning towards affirmative conclusions.

1.5.2 LABORATORY METHODS

1.5.2.1 Thin Sections

Thin sections of Sandstone, Limestone, and Shale were prepared in the section preparation lab. These thin sections are useful for the identification of rocks, minerals and microfossils. The samples were broken into small pieces (approximately 2 cm × 2 cm). The hardened samples were then polished over a piece of glass by using 220, 400, 800 and finally 1000 mesh carborundum powders. The polished smooth surface was then mounted on a glass slide using cold-setting resin (R.I.>1.54). The final thickness of the sections was reduced close to 30 micron and the sections were then covered by a transparent cover slip and numbered.

1.5.2.2 Photo Documentation

Photo Documentation was carried out using three different microscopes.

Stereoscopic Microscopy: The stereo or dissecting microscope is an optical variant designed for low magnification observation or a sample using incident light illumination rather than trans-illumination. It uses two separate optical paths with two objects and eyepieces to provide slightly different viewing angles to the left and right eyes. This arrangement enables the microscope to produce three-dimensional visualization of the sample being examined.

Light Microscope: Optical or light microscopy involves passing visible light transmitted through or reflected from the sample through a single or multiple lenses to allow a magnified view of the sample. The resulting image can be imaged on a photographic plate or captured digitally and can be detected directly by the eye. Nikon Eclipse 80i used for magnifying microfossils in Palynological slides by passing visible light transmitted through the samples.

Scanning Electron Microscope (SEM) - A scanning electron microscope (SEM) is a type of electron microscope that images a sample by scanning it with a beam of electrons in a raster scan pattern. The electrons interact with the atoms in the sample, producing signals that contain information about the electrical conductivity of the sample, its composition and surface topography.

Sample Preparation- All samples fit in the specimen chamber and are generally mounted rigidly on a specimen holder called a specimen stub, 13mm radius aluminum stubs used in the study. For conventional imaging in the Scanning Electron Microscope, specimens must be electrically conductive to the least at the surface and electrically grounded to prevent the accumulation of electrostatic charge at the surface. Therefore nonconductive specimens usually coated with an ultrathin coating of electrically conducting material, either by low-vacuum sputter coating or by high-vacuum evaporation. Gold/palladium alloy are the common conductive materials used for specimen coating. The thickness of coating lay between 100 A°– 300 A°. Polaron sputter coater used for coating.

1.5.2.3 Maceration

Maceration or Acid Maceration is a technique to extract Insoluble organic microfossils from a surrounding rock matrix like siliciclastic rocks, carbonaceous siltstone and shale using acid. The following steps are used to extract acritarchs from the rocks: cleaning, disaggregation, removal of carbonates, removal of silicates, removal of fluorides, oxidation, filtration, and slide preparation, and are summarized in Figure 1.2.

<u>Cleaning and disaggregation:</u>

Samples were cleaned externally by scrubbed with a stiff brush to remove mud. In such cases, the elimination of possible surface contamination was ensured by careful washing of the samples. They were placed in the container to be used for acid digestion, and washed with hot, running tap water until the decanted water ran clear. The sample was then washed two or three times using distilled water.

Violent crushing methods are avoided to prevent fragmentation of large size (> 500 µm) acritarchs. Both Burzin (1990) and Butterfield et al. (1994) pointed out that bedding-parallel thin sections revealed concentrations of fossils, and concluded that much of the fragmentation resulted from extraction methods.

Disaggregation is least destructive method of sample catching. Fissile shales were split along bedding surfaces using fingernails or a knife blade. Samples that required additional fragmentation were soaked in hot water to promote expansion along the partings. Alternate wetting and drying could break-up even well-consolidated samples.

If above techniques fail to disaggregate then crush the sample either in a mortar and pestle or by using a hammer and a metal plate (Phipps and Playford, 1984). The diameters of such crushed samples were approximately 5 millimeters. Typically the size of sample is larger than that one normally used for Palynological preparation, but reduces the risk of damaging larger acritarchs. Fragmented samples were then washed several times with distilled water.

Carbonate removal

Carbonate was removed by hydrochloric acid (HCl) treatment to prevent the formation of insoluble calcium and magnesium fluorides during the Hydrofluoric acid (HF) procedure. HCl treatment was carried out in the same plastic screw-topped container later used for Hydrofluoric acid digestion. A few milliliters (mL) of dilute (about 10% of the stock solution) HCl was added to the sample to test the strength of the reaction. Samples that showed little or no reaction were treated directly with about 100 mL of 32% HCl. Samples that showed reaction was treated with gradually increasing quantities and strength of HCl until the reaction ceased. Samples were left in dilute acid for about 24 hours, and then tested again with fresh acid to check whether the reaction had ceased. The acid treatment was repeated until no further reaction was observed. The sample was then washed to near neutrality with distilled H2O by settling and decanting after each wash (at least four washes were usually required). The solution was left slightly acidic so that any possible carbonates, precipitated when HF dissolved the silicates, would be dissolved by the residual HCl, reducing the formation of fluorides.

Fluoride removal

Gentle boiling with HCl was used to remove any precipitates that had formed during the HF processing. The decanted sample was transferred to a 500 mL, 25 mm-diameter, plastic screw-top test tube with a conical bottom. About 250 mL of 32% hydrochloric acid was added to the sample, and the contents were raised to boiling point as gently as possible by placing the tube in a beaker of water on a hotplate. Boiling was continued until the greyish, gel-like fluorides get dissolved. The sample was allowed to cool, and was then decanted, washed, and allowed to settle. The process was repeated until the pH was neutral.

Kerogen mount

A Kerogen mount of the organic fraction was made at this stage as a record of the un-oxidized sample and to determine thermal maturation. It was also used to estimate how much oxidation might be required.

Oxidation

About 200 mL of concentrated HNO_3 was added to the decanted sample to oxidize dark-coloured organic matter, and in some cases to remove pyrite framboids or surface encrustations. The amount of oxidation required was pre-determined from the Kerogen mount or by microscopic examination of a few drops of macerate. Most samples required about 10 minutes of oxidation, but some required longer or shorter periods. Oxidation is stopped by the addition of distilled water, as soon as brown fumes were given off and the residue had changed color from black to a honey brown.

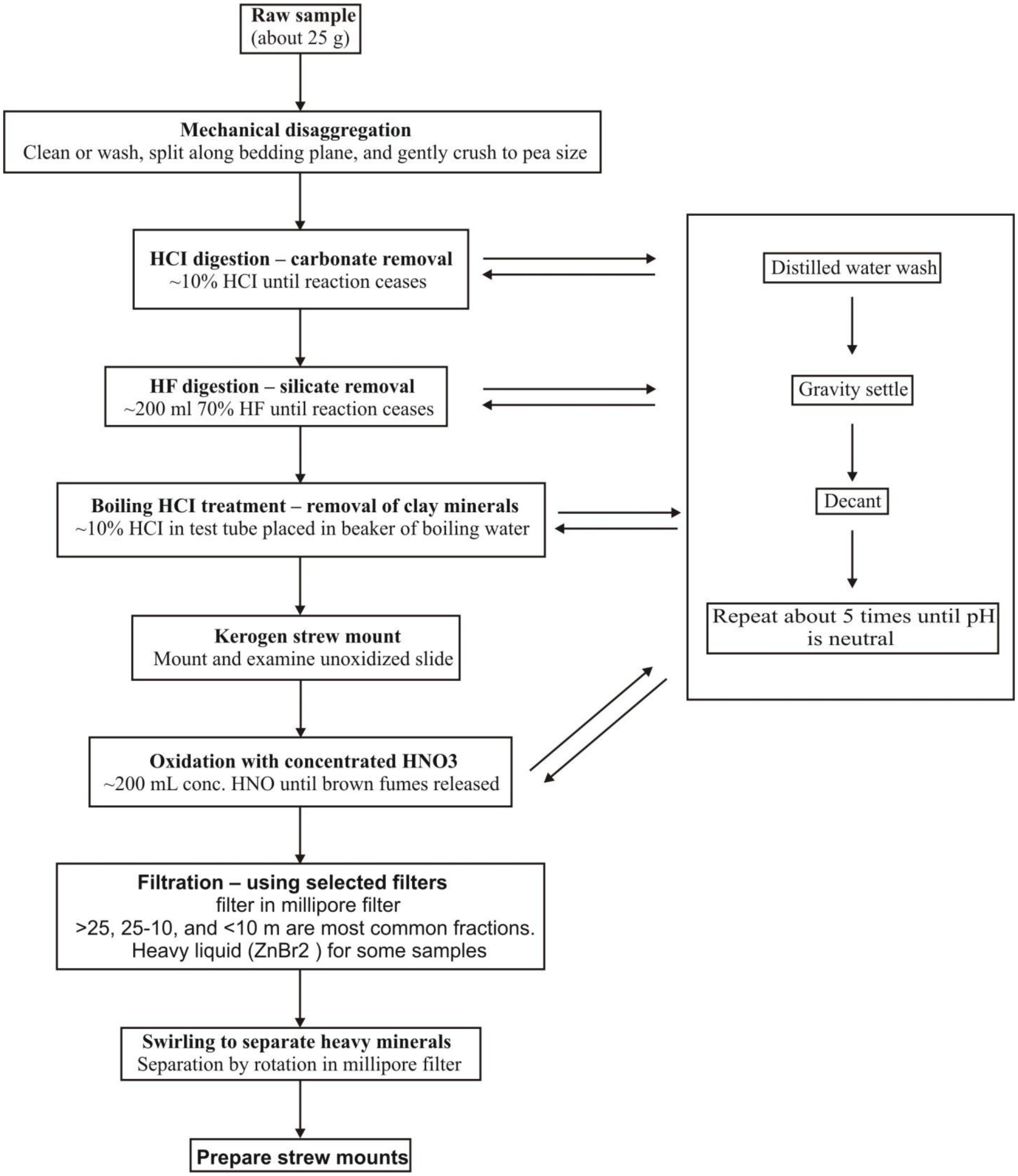


FIGURE 1.2 Flow chart showing steps for extracting Palynomorphs from Proterozoic samples (K. Grey, 1999)

Slide preparation

As for most Palynological preparations, residues were mounted on microscope slides using a transparent medium. Though a variety of substances are available but for permanent mounts an epoxide-based mounting medium that has a refractive index slightly higher or lower than that of sporopollenin (1.48) is preferred (Traverse, 1988). Although glycerin jelly has an appropriate refractive index (1.43), it is not really permanent; the jelly can dry up; or, if temperatures rise, the jelly melts and the specimens move around. The method outlined here is for Petropoxy 154, but other media such as Epotek 301 are also suitable, and are more appropriate if fluorescence studies are to be carried out because Petropoxy will fluoresce.

A cover slip was placed on a hotplate at a temperature of about 100°C. Two drops of a dispersing agent, 3% polyvinyl alcohol (PVA), were placed on the cover slip with a pipette. A few drops of residue were then added to the PVA and the mixture was gently spread over the surface of the cover slip with the pipette. A little extra distilled water was added to obtain the required dispersion and the residue was dried out slowly (at about 100°C). A drop of Petropoxy 154 was placed on a microscope slide, and the slide was warmed gently to drive off any bubbles in the resin. The coverslip was then inverted and lowered steadily onto the Petropoxy 154, allowing the resin to spread by capillary action. Excess resin and air bubbles were squeezed out from below the cover slip by gently pressing on the coverslip, and the prepared slide was placed on a hotplate at a temperature of 135° for 10–15 minutes to cure the resin. The cured slide was cleaned using a razor blade and ethanol. Surplus residue was stored in glass vials with a few drops of $CuSO_4$ added as a preservative, and the lid of the tube sealed with nail polish to prevent evaporation of the contents.

Contamination issues

The modified techniques reduced risk of contamination, which poses a problem in Proterozoic successions where specimens can be sparse and their taxonomy is poorly known. An indication of the extent of this problem was given in a discussion by Schopf (1992), and can be assessed from the comprehensive tables of micro-non fossils and micro-dubio fossils reported from the Proterozoic (Mendelson and Schopf, 1992). Although modern pollen and most Phanerozoic fossils can be recognized if they occur as contaminants, a variety of biogenic structures and other artifacts may be introduced during preparation procedures, and can be mistaken for bona fide fossils.

Contamination risks from airborne particles of organic matter and cross-contamination of samples are considerably reduced by using a minimum number of containers for each sample. Potential contaminants can be monitored if blanks (such as granite or other plutonic rocks) are processed at the same time as regular samples. Airborne particles can be collected by exposing cover slips with smears of mounting medium in the preparation area. Tap water and the various chemical reagents should be microscopically examined from time to time for potential contaminants. Results obtained from such studies indicate that great care is needed to ensure that only organisms of undoubted Proterozoic origin are included in systematic descriptions.

Measurement of Total Organic Carbon (TOC)

TOC (total organic carbon) measurements of black shale and carbonate samples were carried out at National Geophysical Research Institute, Hyderabad in their Geochemistry Department. The inorganic carbon fraction was removed first by treating the sample (about 50mg of homogenized and powdered to approximately 63 micron size) with drops of 50% HCl to remove its inorganic carbon content and kept in the oven overnight at 105°C. The dried, HCl treated samples were taken in the quartz boat and loaded into the furnace of the TOC analyzer for total organic carbon measurements. The model of TOC analyzer used is Solid Module 1000°C from Elementar Analysensysteme GmbH. Procedural blank and the soil standard (Boden Soil Standard, 4.1% TOC) was also analyzed in the similar way. The TOC released due to the chemical oxidation of the organic carbon is measured by the IR detector and expressed in weight %. The % RSD is ≤ 1%.Table 1.1 gives the operating conditions of the Solid Module.

TABLE 1.1: Technical specification of TOC

Technical Specification of TOC	
Carrier Gas	Zero Air
Carrier gas Flow	200 ml/min
Pressure	0.9 bar
External Standard	Boden Soil Standard
Max. Temperature	900°C
Run Time	18 mins

Principle & Instrumentation of TOC Analyzer:

The total organic carbon content analysis is based on the oxidative combustion of soil samples in the presence of platinum catalyst to form carbon dioxide and its subsequent determination with an Infrared detector. The total carbon determinations are carried out from the original sample while for TOC determination the sample is externally acidified and then dried before the analysis. Figure 1.3 shows the schematic diagram of Total Carbon Analyzer. The sample is combusted in a heated combustion reactor consisting of a pre and post combustion furnace. At lower temperature of 70°C, the purgable and inorganic carbon is removed with the carrier gas (zero air comprising of nitrogen and oxygen) and at higher temperature of 900°C, the non-purgable or the organic carbon is combusted in presence of oxygen and catalyst. The carbon containing combustion gases are oxidized to CO_2 in presence of post combustion catalyst (platinum on ceramic carrier). The reaction gas flows through a drying unit and a halogen absorption tube where unwanted compounds are withheld. The CO_2 obtained is measured in the Infra-red detector. The liquid TOC software converts the integral of the measuring signal into a respective concentration value with the help of a stored linear calibration (Elementar Solid Module 1000°C operating manual). The lower detection limit for approximately 2 μg C absolute is ~5 ppm C with 400 mg sample weight and the linear working range is up to 1.2 mg C absolute or 100%.The precision /standard deviation is ± 0.7 μg absolute or ≤ 1%, relative for the homogeneous test substances or standards.

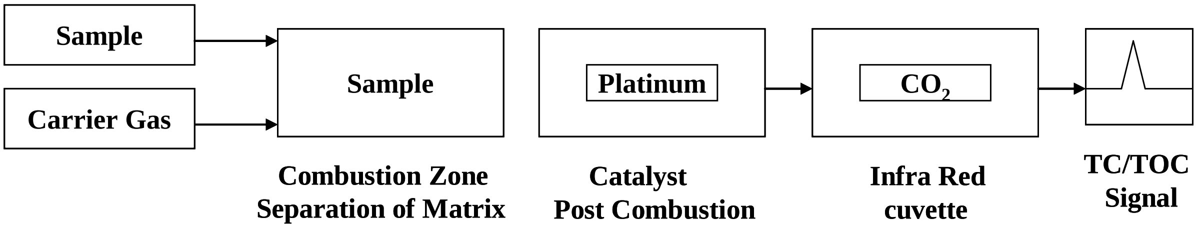


FIGURE 1.3: Schematic diagram of Total Organic Carbon analyzer.

Rock- Eval Pyrolysis:

The Rock Eval (RE) pyrolysis method consists of a programmed temperature heating (in a pyrolysis oven) in an inert atmosphere (helium) of a small sample (~100 mg) to quantitatively and selectively determine (1) the free hydrocarbons contained in the sample and (2) the hydrocarbon- and oxygen-containing compounds (CO_2) that are volatilized during the cracking of the un-extractable organic matter in the sample (Kerogen)

A Rock-Eval method is defined by:

- A temperature program
- Ranks of integration for surfaces recorded by the FID and the IR cells
- Parameters calculated after surfaces and peak temperatures.

Rock Eval Pyrolysis consists in estimating petroleum potential of rock samples by pyrolysis according to a programmed temperature pattern. Released hydrocarbons are monitored by a FID, forming the so-called peaks S1 (thermo-vaporized free hydrocarbons) and S2 (hydrocarbons from cracking of organic matter). The CO and CO_2 released during pyrolysis can be monitored in real time by an IR cell.

This complementary stage allows determination of Total Organic Carbon and Mineral Carbon content of samples. In this the bulk rock powder is taken ~60mg in bolt and put on Rock Eval -6 Turbo Complete analysis- Parallel Processes

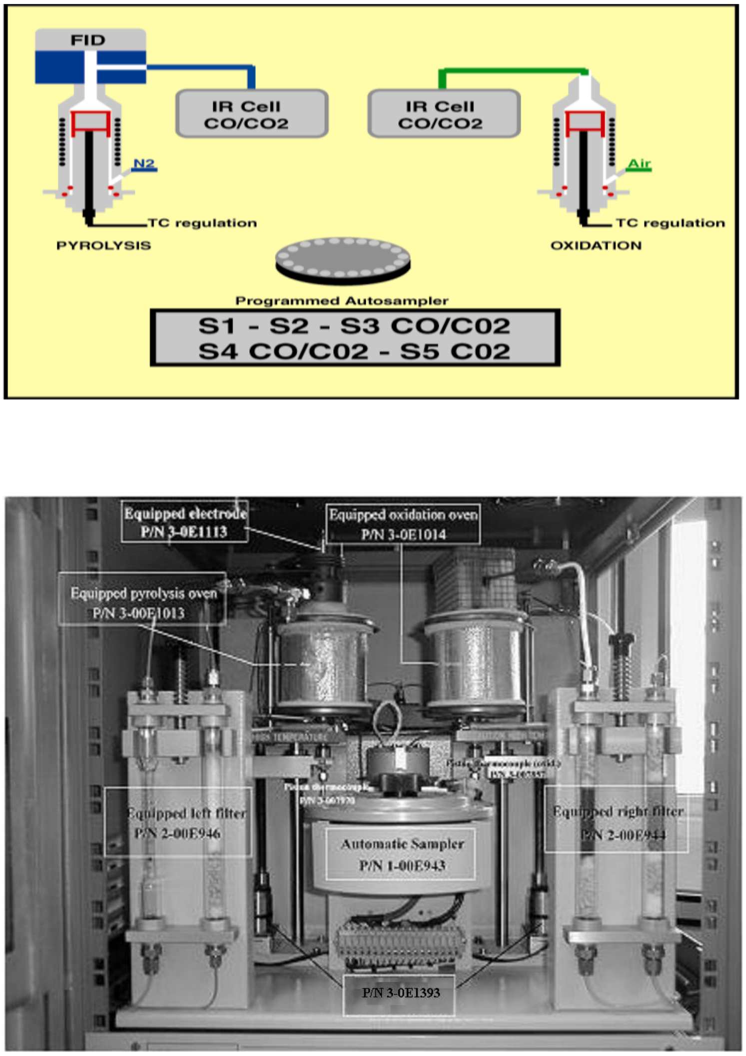


FIGURE 1.4 : Shows Rock Eval -6 Turbo Complete Analyses- Parallel Processes.

Analytical Methodology

The Rock Eval Pyrolysis instrument described in this study is RE6 (Turbo version), make of the Vinci Technologies. After obtaining a stable signal of all the detectors, the instrument was calibrated in standard mode using the IFP standard, (Tmax = 416°C; S2= 12.43). The samples were powdered homogenously and depending upon the organic matter content (about 50-70 mg of the shale and 10-20 mg of the coal); the samples were weighed in pre-oxidized crucibles. The shale/coal samples were run under analysis mode using the bulk rock method and basic cycle of RE 6. It is the bulk rock method used for screening of all types of samples and allows determination of the full set of available Rock-Eval parameters.

Temperature Program

It is the bulk rock method used for screening of all types of samples and allows determination of the full set of available Rock-Eval parameters (Table 1.2 and 1.3).The analysis plots are drawn as represented in Figures 1.5, 1.6 and 1.7

TABLE 1.2: Rock-Eval parameters

	Initial Temp °C	Final Temp °C	Rate °/min	Initial Step min	Final Step min	Extra Acquisition min
Pyrolysis	300	650	25	3	0	3
Oxidation	300	850	20	1	5	5

TABLE 1.3: Acquisition Parameters of RE6

Parameter	**Unit**	**Detector/ Oven**	**Name**
S1	mgHC/g rock	FID / Pyrolysis	Free Hydrocarbons
S2	mgHC/g rock	FID / Pyrolysis	Oil Potential
TpS2	°C	Pyrolysis TC(*)	Temperature for maximum of surface S2
S3	mgCO2/g rock	IR / Pyrolysis	CO2 from organic source
S3'	mgCO2/g rock CO2	IR / Pyrolysis	from mineral source
S3CO	mgCO/g rock	IR / Pyrolysis	CO2 from organic source
S3'CO	mgCO/g rock	IR / Pyrolysis	CO from organic and mineral sources
Tmax	°C	TpS2-ΔTmax(*)	Tmax
PI		S1/(S1+S2)	Production Index
PC	% weight	{[(S1+S2)x0.83]+[S3x12/44]+[(S3CO+S3'CO/2)x12/28]}/10	Pyrolysable Carbon org.
RC	% weight	RC CO+ RC CO_2	Residual Carbon org.
TOC	% weight	PC+RC	Total Organic Carbon
HI	Mg HC/g TOC	S2x100/TOC	Hydrogen Index
OI	mgCO2/g TOC	S3x100/TOC	Oxygen Index
OI CO	Mg CO/g TOC	S3COx100/TOC	Oxygen Index CO

Pyro Min C	% weight	{[S3’x12/44]+[(S3’CO/2) x12/28]}/10	Pyrolysis Mineral Carbon
Oxi Min C	% weight	[S5x12/44]/10	Oxidation Mineral Carbon
Min C	% weight	Pyro MinC + Oxi MinC	Mineral Carbon

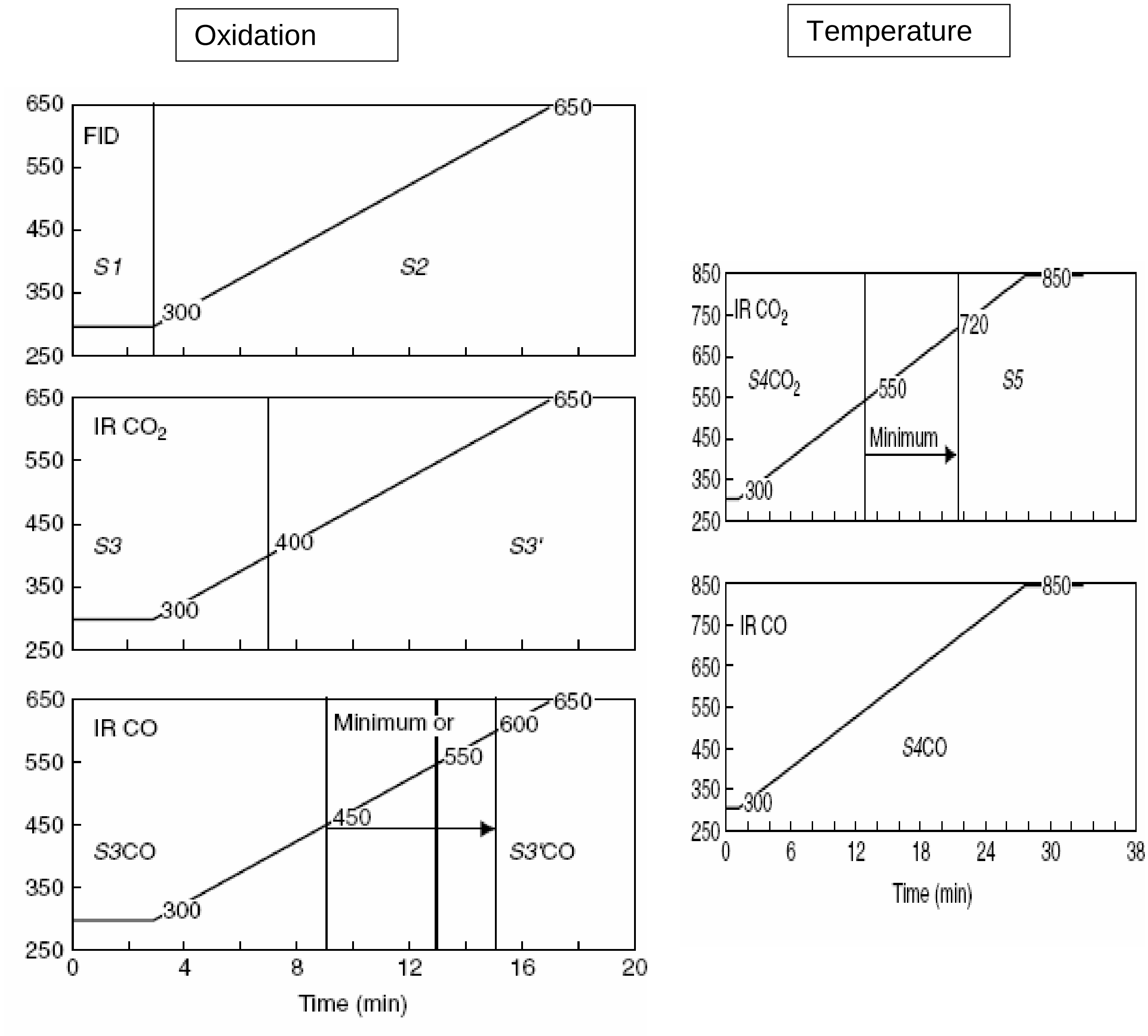


FIGURE 1.5: Conditions for integration of surfaces for RE 6 Oxidation

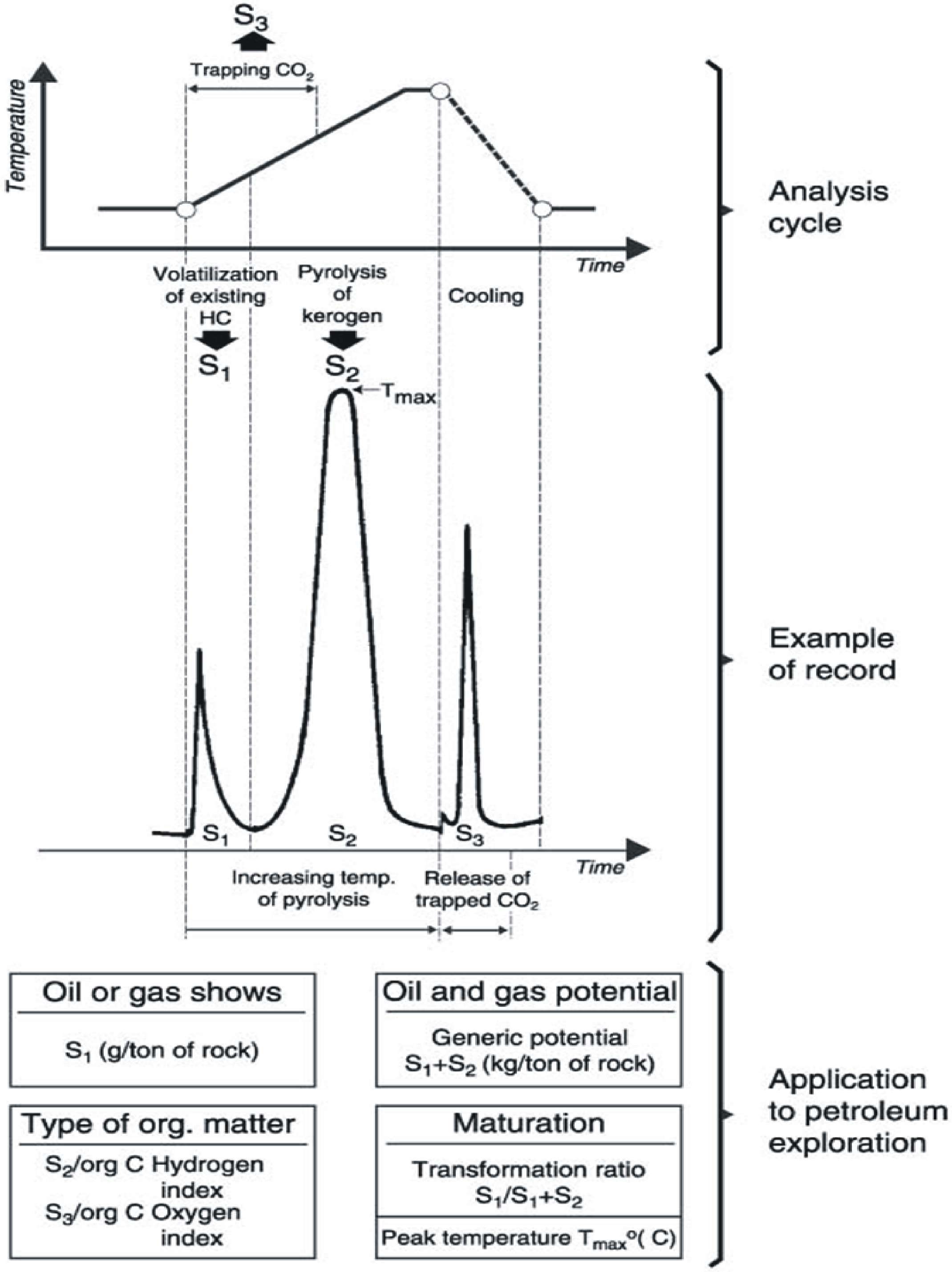


FIGURE 1.6: Indicative S1, S2, S3 plot

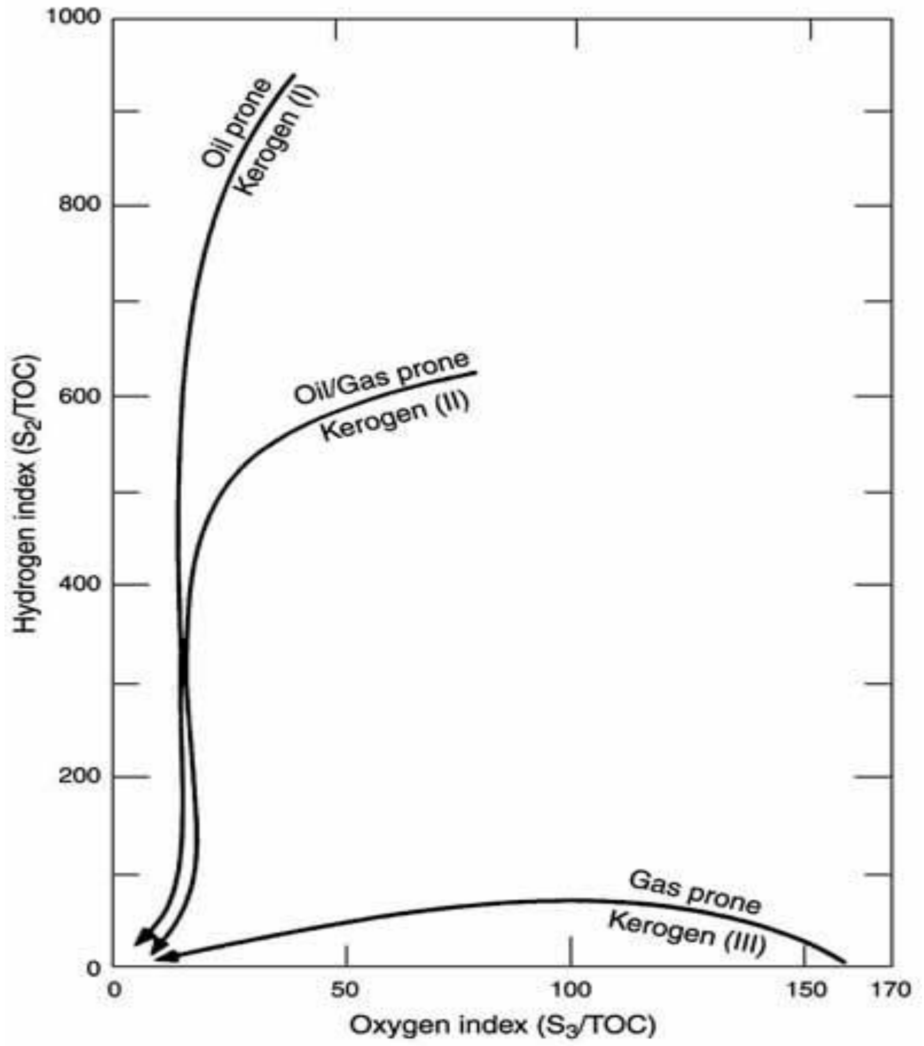


FIGURE 1.7: Indicative Hydrogen Index (HI) vs. Oxygen Index (OI) plot

1.5.2.4 GC-C- IRMS

Analytical Procedure

The $\delta^{13}C$ analyses of desorbed hydrocarbons is carried out using Gas Chromatograph-Combustion-Isotope Ratio Mass Spectrometer (GC-C-IRMS) which comprises of Agilent 6890 Gas Chromatograph coupled to a Finnigan-Delta Plus^{XP} Isotope Ratio Mass Spectrometer via a GC combustion III interface.

One ml of the adsorbed soil gas is injected into the Agilent 6890 GC injection port equipped with “Pora Plot Q” capillary column of length 25m and diameter 0.32 mm in split less mode with Helium as carrier gas at fixed oven temperature of 28°C. The chromatographically separated hydrocarbon gases after eluting from GC column enter a pre-oxidized Cu-Ni-Pt combustion reactor maintained at $960^{o}C$ where they get converted into carbon dioxide and water. The water is removed using Nafion membrane tube prior to their entry into the mass spectrometer. The purified CO_2 after combustion goes into the mass spectrometer for $^{13}C/^{12}C$ ratio measurement of the respective hydrocarbon. The GC-C-IRMS is calibrated with Natural Gas Standard (NGS-1) mixture using the ISODAT software. The $\delta^{13}C_1$ value in the sample is calculated with respect to the standard and reported relative to PeeDee Belemnite (PDB). The precision of the isotope analysis is ±0.5%

Principle and Instrumentation of GC-C-IRMS

Stable isotope mass spectrometers are widely used to determine the ratio of ^{13}C to ^{12}C in geological samples. The basic mass spectrometer comprises of the

- Ion source for fragmentation of sample molecule into ions and
- Mass analyzer for separating the ion beam according to the mass of the respective ions.

The sample and reference gases are carried into the ion source of the mass spectrometer through a stream of helium as carrier gas. With the advancement of hyphenated techniques, the separation power of gas chromatograph has been coupled to the mass spectrometer along with introduction of sample combustion interface into the gas chromatograph-isotope ratio mass spectrometer. The separated products of the sample mixture in the stream of helium at the output of the gas chromatograph are passed through an oxidation/reduction reactor and then introduced into the mass spectrometer for precise concentration determination. The open split-coupling device ensures that only a part of the sample/reference gas containing carrier gas is fed into the ion source of the MS. In this way, pulse injection of sample gas can be analyzed, reducing the volume constraints and sample size. Figure 1.8 shows the schematic diagram of GC-C-IRMS.

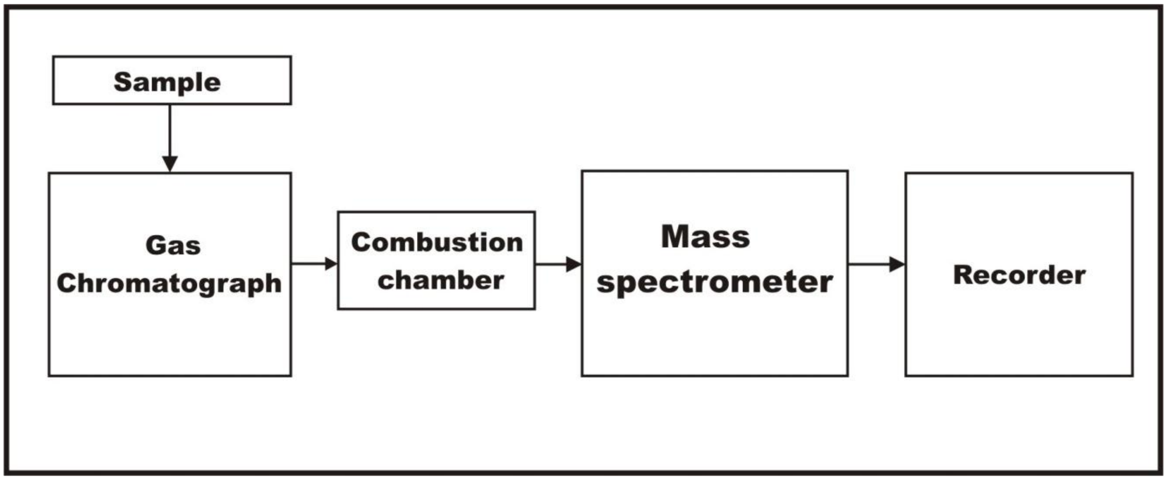


FIGURE 1.8: Schematic diagram of GC-C-IRMS

The Gas Chromatograph-Combustion (GC-C) device comprises of Agilent 6980 Gas Chromatograph fitted with Poraplot Q capillary column, oxidation and reduction reactor along with water separator. The oxidation reactor is a non-porous alumina tube in which three wires of copper, nickel and platinum of 240 mm identical length and 0.125 mm internal diameter are braided and centered end to end within the tube. The reactor is inserted into the Al_2O_3 furnace operated at 940°C. The reduction reactor is placed between the double T-piece and water separator and is identical with oxidation furnace except for the reactor filling which is pure copper with three copper wires of 240 mm identical length and 0.125 mm internal diameter. The reduction temperature is maintained at 640°C. The Delta plus XP CF-IRMS used in the isotope ratio determination comprises of i) electron impact ion source; ii) magnetic analyzer with effective magnetic deflection of radius of 180mm and iii) self-aligning Faraday collectors. The ISODAT software is used for the data acquisition (Thermo Finnigan Delta XP Manual).

The compound specific analysis of hydrocarbon mixture for $^{13}C/^{12}C$ ratio measurement has been carried out by injecting the sample mixture consisting of C1-C5 hydrocarbons into the gas chromatograph. The individual components after chromatographic separation are converted into CO_2 and H_2O in the combustion reactor. The CO_2 gas in the analytic stream is transported into the IRMS via an open split assembly. To minimize inaccuracies in measuring the absolute amounts of ^{12}C and ^{13}C, the ratio of the two in a sample is compared with that in a standard analyzed. By definition, the standard $\delta^{m}E$ value of a standard is $0^{0}/_{00}$, so negative values of a sample indicate depletion in the heavier isotope compared with the standard and the positive values indicate enrichment in the heavier isotope (for PDB $^{13}C/^{12}C = 0.011237$).

Absorbed Gas Analysis

One gram of 63 µm wet, sieved black shale sample was used to extract light gaseous hydrocarbons after acid treatment in glass degasification apparatus and was subsequently analyzed on Gas Chromatograph (GC) and Gas chromatograph–Combustion–Isotope Ratio Mass Spectrometer (GC–C–IRMS, Figure 1.9). During acid treatment, the dominant gas released was CO2, which was trapped in KOH solution. The rarer gaseous hydrocarbons were collected by water displacement in a graduated tube fitted with rubber septa. The volume of desorbed gas was recorded and 500 µl of desorbed gas sample was injected into Varian CP 3380 GC fitted with Porapak Q column, equipped with flame ionization detector. Using external standards methane, ethane, propane, *i*-butane and *n*-butane are used to calibrate GC. Quantitative estimation of light gaseous hydrocarbon constituents in each sample was made using peak area measurements and correction for moisture content on wet basis was also applied. The hydrocarbon concentration values of individual hydrocarbons from methane through pentane were expressed in parts per billion (ppb) on dry-weight basis. The accuracy13 of measurement of C1–C4 components was < 1 ng/g. Carbon isotopic composition of light hydrocarbons from soil samples was determined using GC–C–IRMS, which comprises of Agilent 6890 GC coupled to a Finnigan-Delta PlusXP IRMS via GC combustion III interface. Next, 1 ml of desorbed gas was injected to GC in split less mode with helium as the carrier gas at fixed oven temperature of 28°C. The light hydrocarbon gases eluting from the GC column entered the combustion reactor, Maintained at 960°C, where they were converted to CO_2 and water. Nafion membrane tube was used to remove water, prior to the entry of CO_2 into the mass spectrometer. The samples are mixed with known quantity of reference standards to monitor instrumental performance. The carbon isotope ratio in the sample was determined by comparing isotope ratios with those of standards, NIST RM 8560 (IAEA NGS2) using ISODAT software. The $\delta^{13}C$ was calculated using the following equation:

$\delta^{13}C = \{[(^{13}C/^{12}C)/\ (^{13}C/^{12}C)] - 1\} \times 1000$.

The carbon isotopic composition was reported in per mil (‰) relative to the PeeDee Belemnite (PDB).The precision of the isotopic analysis14 was ± 0.5‰.

In the present study, the magnitude of each of the five organic constituents (C1, C2, C3, *i*C4 and *n*C4) in soil samples was measured and expressed in ppb. The compositional characteristics of these hydrocarbon gases desorbed from black shale samples indicate the presence of methane (C_1), ethane (C_2), propane (C_3) *i*-butane (*i*C_4) and *n*-butane (*n*C_4).

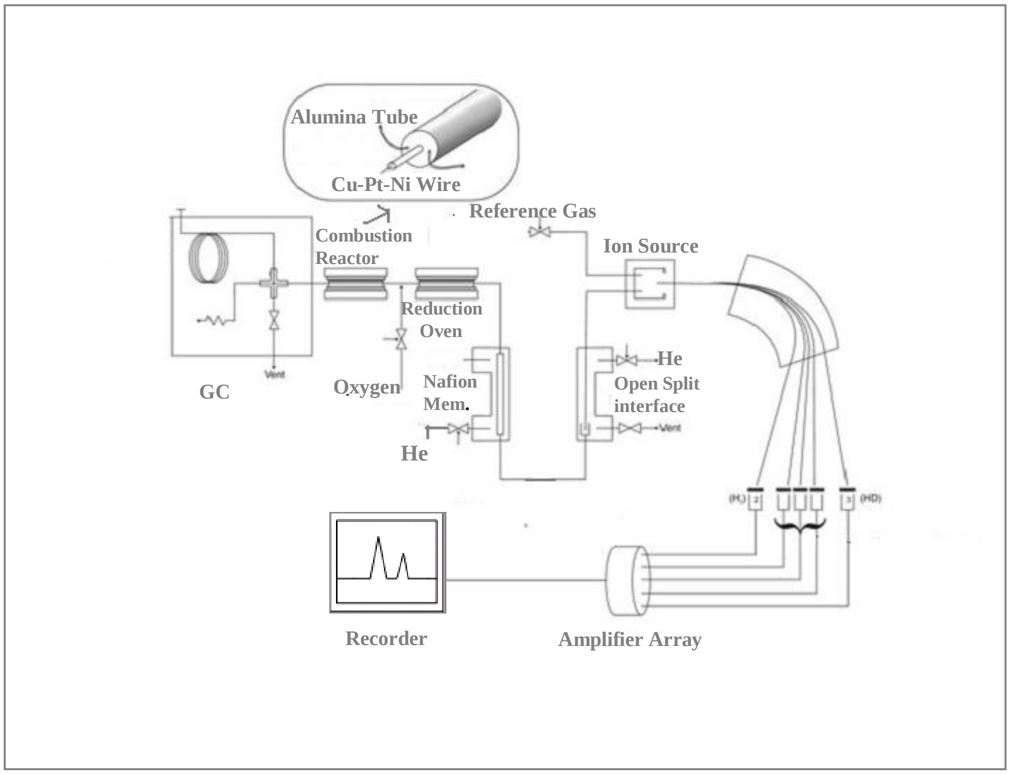


FIGURE 1.9: Schematic diagram of GC-C-IRMS system

CHAPTER 2 – LITERATURE REVIEW

2.1 LITERATURE REVIEW

The latest Paleocene–middle Eocene Subathu Formation and the Oligocene–Miocene Dagshai and Kasauli formations of the Himalayan foreland basin record the early evolution of the Himalayan fold-thrust belt. Sandstone petrography of the Subathu Formation shows a predominantly recycled sedimentary source, with a distinct ophiolitic and volcanic influence that was drastically reduced by the time of deposition of the Dagshai Formation. Sandstones in the Dagshai and Kasauli Formations consist predominantly of metapelitic detritus. The metamorphic grade of metapelitic lithic grains increases with time, from dominantly very low grade at the base of the Dagshai Formation to dominantly low grade in the Kasauli sandstones. Mudstone geochemistry documents the presence of a mafic-ultramafic source during the time of deposition of the Subathu Formation that becomes significantly less important by the time of deposition of the Dagshai Formation. Compositions of Subathu Formation detrital spinels show they were either derived from both mid-ocean ridges basalt–type and arc-type ophiolites or from an ophiolite of composite origin, and that southerly derivation from the Deccan Trap continental flood basalts is unlikely. Kasauli

Formation garnet compositions suggest derivation from medium-grade metamorphic rocks to amphibolite facies (Najman and Garzanti, 2000).

Subathu Formation composition reflects provenance influence from the Indus suture zone during latest Paleocene–middle Eocene time, indicating initiation of continent-continent collision and development of the foreland basin by this time. Suture-zone influence was drastically reduced by the time of deposition of the Dagshai Formation, when the embryonic thrust belt provided a barrier sufficient to partially separate the suture zone from the Himalayan foreland basin. The first appearance of Himalayan metamorphic detritus occurs in the Dagshai Formation at the close of Oligocene time, whereas the Kasauli Formation records erosion to deeper metamorphic levels during earliest Miocene time. The occurrence of garnet and higher grade metamorphic lithic grains during early Neogene time is coincident with the timing of displacement along the Main Central thrust and South Tibetan detachment zone.

Composition of early foreland basin sediments from Pakistan (Balakot, Murree and Kamlial Formations) to Nepal (Bhainskati and Dumri Formations) and Bangladesh (Kopili, Barail Formations; Surma Group) indicates diachronous arrival of ophiolitic to low-grade metamorphic detritus derived respectively from the Indus Suture and early Himalayan thrust sheets in the north. This is consistent with progressively later closure of Neotethys along the suture, from latest Paleocene time in the west to Eocene time or even later in the east.

Over the years, considerable work has been done on various aspects of the Sub-Himalayan Palaeogene, yet a comprehensive picture is lacking. The general understanding about the Hydro carbon potential of these interesting sequences in the context of India-Asia collision is poor primarily due to the lack of multidisciplinary and coordinated effort to their study. An integrative approach involving various disciplines including paleontology, sedimentology, Biostratigraphy, geochemistry, will be more useful for getting newer and better perspective.

Many workers have outlined the various aspect of the Himalayan region (Raiverman (1971, 1972, 1979, 2000), Mathur (1975, 1977, 1978, 1979, 1983,1997),Karunakaran and Rao (1976)Bhatia (1980, 1982), Rao (1963, 1980, 1986), Najman et al (1993, 1994 , 2000 , 2004), Valdiya (1980, 1998, 2002) , Yin (2005) etc. in their review papers have discussed about the formation of Himalayan foreland basin , Characteristics of Subathu basin, age and bio chronology of the Subathu formation and the stratigraphic sequence between the Subathu, Dagshai and the Kasauli formations including the status of hydrocarbon in the Himalaya region (Table 2.1).

TABLE 2.1: Variation in the stratigraphic classification used for the Subathu Formation

Author	Stratigraphic classification	Rank
Vicary (1853)	Informal	'Nummulitic Beds'
Medlicott (1864,1869)	Chronostratigraphic	Stage
Oldham (1893)	Lithostratigraphic	Group
Pascoe (1964)	Chronostratigraphic	Series
Datta *et al.* (1965)	Lithostratigraphic	Group/Subgroup
Raiverman & Sheshavataram (1965)	Lithostratigraphic	Group/Subgroup
Chaudhry (1966, 1968)	Chronostratigraphic	Series

Krishnan (1968)	Lithostratigraphic	Bed
Raiverman & Raman (1971)	Lithostratigraphic	Group
Raiverman (1972, 1979)	Lithostratigraphic	Group
Singh (1973)	Lithostratigraphic	Group
Wadia (1975)	Chronostratigraphic	Series
Chaudhri (1976)	Lithostratigraphic	Formation
Khanna (1978)	Lithostratigraphic	Formation
Mathur (1978)	Lithostratigraphic	Formation
Singh (1980)	Lithostratigraphic	Group
Bhatia (1982)	Lithostratigraphic	Formation
Loyal (1984, 1986a, 1986b)	Lithostratigraphic	Formation

TABLE 2.2 Suggested correlations of lower lithounits in the Lesser Himalayan Zanskar Tethyan and Indus Suture zone, after Mathur, 1997

RAD Age	**Age**				**Lesser Himalayan Zone**	**Zanskar Tethyan Zone**		**Indus Suture Zone**	
						South Zanskar Belt	**North Zanskar Belt**		
41.3 my	**EOCENE**	**MIDDLE**	**LUTENIAN**	**L**	**Dagshai Formation**	**Chulunga Formation**	**Unconformity**	**Hemis Conglomerate**	
				MID					
50.3 my		**EARLY**	**YPRESIAN**	**LATE**	**Subathu Formation**	**Kong Formation**	**Kong Formation**	**Indus formation**	**GongMarula Jurutze MB**
									Nummulitic MB
				EAR		**Dibling Formation**	**Lingshet Formation**		
54.9 my	**PALEOCENE**		**THANETIAN**		**Kakara Formation**				**Sumdha Gompa MB**
61.5 my			**DANIAN**			**Stumpata Formation**	**Goma Formation**		
66.7 my	**Lat. Cret**		**Maastrichtian**			**Marpo FM**		**Unconformity**	

Detailed geological work on the lower Tertiary sequences in the Lesser Himalayan, Zanskar Tethyan and Indus Suture zones by a number of geologists has led to correlate the various litho units in these zones in the Table 2.2

Ranga Rao (1963) based on the field study concludes occurrence of Subathu marine sediments unconformably above the strata of different ages in the Lesser Himalayas. The outcrops in the Solan and Bidhalna regions show Subathu formation resting on the ancient Simla slates and the Krol group rests on the Limestone. Mr Rao in one of the lectures reviews the existing data on the geology of North west Himalayan foothills. Based on the stratigraphic, chronologic and structural aspects the inferences concluded on various phases of the earth-movements affecting Jammu Himalayan region and the listed sequence in the order of recent to older formation are Upper Siwalik , Boulder conglomerate , Middle Siwalik , Lower Siwalik, Murree and Subathu.

Bhatia and Mathur (1965) were pioneers to identify presence of pulmonate gastropods in the Subathu Formation through their field work in the Dharampur region of Simla hills. They reviewed the contact between Subathu and Dagshai to ascertain conformable contact between Subathu and Dagshai formations. The controversy around conformable or unconformable contact existed as the Dagshais are devoid of any fossils whereas the Subathus have yielded rick microfauna. After detailed study they observed the passage between Subathu and Dagshai is always confirmable expect when they are separated by faults.

Raiverman and Raman (1971) present the facies relations in the sediments of Subathu Formation based on his analysis in the Simla Hills. The three distinct lithofacies depending on the dominant shale color namely green, red and grey facies are identified. The evidences of these facies on the basis of sedimentary structures are described in detail. The author also introduces the possibility of Subathu sediments deposited in an unstable basin corroborating the theory of unconformity in the stratigraphic sequence.

Khan (1975) analyzed the Subathu unconformity and age of Murree rocks in the Jammu Kashmir. He also analyzed the Stratigraphic position of Kalakot zone based on palaeontological evidence.

Chaudhari (1976) critically analysis the Stratigraphical aspects of Cenozoic sediments and proposes Sirmur group and Siwalik group as new classifications corresponding to close approximation of to Paleogene and Neogene periods. His analysis also reported the contact between the Lower Siwalik formation and the Lower Tertiary rocks are of tectonic nature.

Singh (1976-77) discusses the sedimentological and Palaeoecological aspects of Subathu – Dagshai – Kasauli succession of Simla hills. Based on the field reports the author concludes Subathu-Dagshai-Kasauli succession represents more or less continuous sedimentation without major unconformity in between. This analysis corroborates the findings of the thesis author during the field study as well. The abundant Thalassinoides, Chondrites and Tigillites fossils found in the Subathu formation represent deposits of an open tidal sea with varied sub-environments resulting into different facies. The Dagshai shows abundant burrows, biotrubated horizons and minute feeding burrows representing deposits of estuarine complex. The Kasauli sediments show horizontal surface burrows of various insects, e.g. cricket and beetle representing deposition in an alluvial plain with rapidly shifting shallow braided streams.

Mathur (1977) clarifies the age of Subathu and Tal formations based on palaeontological evidences to conclude the age of Tal formation between Cretaceous to Lower Eocene and the Subathus between the Upper Paleocene to Lower Eocene in the Garhwal region. The author worked out the stratigraphic sections at Singtali, Nilkanth, Dhamand, Bidasini and Dogadda regions and this stratigraphic analysis are very relevant to the thesis.

Khanna (1978) presents a critical appraisal of the Stratigraphic status of the elements in reference to code of Stratigraphic Nomenclature of India. He discusses the stratigraphic position of Subathu and the age of the formation based on unpublished flora and fauna evidences.

Gaur and Dave (1978) analyzed the geology and structures of Rishikesh Garhwal region. The paper discusses the stratigraphic sequence of Garhwal Syncline, lithology and the structural elements of the region in detail. They also discuss the depositional environments of Infra Krol, Krol and Tal group. The Subathu formation exposed in Rishikesh region is also discussed.

Singh et al. (1978) worked on the Palynological zonation of the Subathu Formation. On the basis of qualitative and quantitative distribution of the palynoflora they proposed to divide the Subathu Formation into 8 cenozones. The extension of these Palynozones has helped in stratigraphic study of the region.

They worked on Palynostratigraphic correlation of the Subathu Formation during 1979 correlating the eight measured sections representing Subathu Formation. Based on the absence of some common cenozones in the different sections were attributed to unfavorable environmental conditions for the organic matter preservation, presence of microenvironment in the depositional basin which modifies the composition of the sediments and the lithofacies laterally and all sections of the Subathu formation do not expose the entire thickness of the formation.

Mathur (1978) based on the elaborate study in the Subathu formation in the Kumaun Himalayas reports Subathu sediments were deposited from shallow – marine , brackish-water depicting fluctuating environment. During the biostratigraphic investigation rich assemblage of fauna was encountered and the author Mathur (1978) in another paper details nine biostratigraphy zones ranging from I – IX in ascending order with 3 sub-zones under zone III and 2 sub-zones under zone IV . The study area for this investigation primarily on the Subathu Formation comprises of 7 blocks, which are Morni, Garkhal, Subathu, Arki, Nilkanth and Dogadda. He also discusses different views on the Age of the Subathu formation ranging from Paleocene to Upper Eocene. Based on his findings and biostratigraphic studies Mathur assigns Upper Paleocene to Middle Eocene as the age of Subathu formation. He also reports definite relationship between the facies and fauna. His study also indicates sedimentation of Lower Tertiary sequence to be more or less continuous.

The note on geology of the Subathu succession of Nilkanth region by Singh (1980) depicts the geological succession of Subathu in the Nilkanth area. The author attempts to correlate Subathu successions at Nilkanth and Kalakot regions and ascertains the age of Subathu group in the Nilkanth region as Late Paleocene to early Middle Eocene.

Singh and Khanna (1980) worked on the Palynology of the Paleogene marginal sediments and concluded the presence of Palynomorph complexes in the Subathu formation. Based on the abundance two broad Palynozones the lower and upper parts of Subathu Formation were identified. Palynological succession between Jabli and Kumarhati indicates marginal environment of the basin. Subathu and Dharampur show Palynological differences of local importance. The Microplankton/Pollen ratio indicates major transgression followed by north-westward regression with in the Subathu basin. The Palynological changes across the Subathu – Dagshai boundary are related to changes from shallow marine to coastal-transitional deposition.

Ranga Rao (1980) tabulated the results of investigations on the Stratigraphy and depositional environment of the Subathu Formation. He concluded that Subathu Formation can be divided into two units “A” and “B”, based on lithology and the maximum thickness of the Subathu Formation does not exceed 2500 ft. The green shales of the formations are christened as “A” and multi-variate sequences of red, green are named as Unit “B”. The lithologies suggest the deposition was transgressive, still-stand and regressive in nature. The age of the Subathu Formation ranges from Lower Eocene to early Middle Eocene.

Raiverman et al. (1983) discusses various aspects of stratigraphic correlation between the surface and subsurface sections of the Cenozoic sediments using time related energy-sequence and heavy mineral stability order in the sediments. They reviewed the geological and geophysical data on the structural tectonics and proposed a new scheme of classification based on number of depressions or sub-basins. They also discussed in detail the hydro carbon prospects in the region.

Mathur (1983) when analyzing the stratigraphy of the Cretaceous – Eocene sequence in the five marine Cretaceous – Eocene belts namely Karakoram , Shyok , Indus (north Tethyan belt), Zanskar (south Tethyan belt) and Subathu (Lesser Himalayan belt) correlates the biostratigraphy of these belts and concludes that the Cretaceous – Eocene sequence of these marine belts belong to the same faunal province , This is a significant information which can be used to correlate the sediments and thereby the origin and the age of these regions.

Wells and Gingerich (1987) analyze and correlate the deposition of Subathu Formation at Kotli, Northeastern Pakistan with the Kalakot in Jammu Kashmir. The author established the single cycle of transgression and regression during the early Eocene. The Paleoenvironmental interpretation done by the author establishes the presence of innumerable fossils like Oysters, Nummulites. These analyses provide further evidence aiding the presence of Hydrocarbons in the Subathu Formation. The author also describes the lithofacies of the formations and attempts to correlate the same between the regions.

Jolly and Bajpai (1988) discuss the Paleobiogeographical significance of the Indian Osteoglossidae through the work done by them in the Kalakot (Middle Eocene) region. The fossils of fish and reptilian fauna found in the Kalakot region suggests Late –Cretaceous fish faunas persisted across the Cretaceous – tertiary transition into the Middle Eocene period of Lesser Himalayas. The halosteans and teleosteans found in the region strengthen the correlation of Middle Eocene Upper Subathus of India with Upper Kuldana Formation of Northwest Pakistan.

Sarkar (1989) established the age of Kakara series and the palynofossil assemblage recorded from the Kakara series of Simla hills the age of this series is Lower Eocene, differing from the earlier Paleocene dating based on foraminifer data.

Jafar and Kapoor, 1989 analyze the Late Maastrichtian – Danian Nannoplankton from the Subathu Formation. The discovery of Late Maastrichtian – Danian non floral elements suggest a Late Maastrichtian transgressive event along the Lesser Himalayan rift zone. The presence of plankton reinforces the Paleocene sediment present in the Subathu Formation. The marine invertebrates found in abundance in the region points to Cretaceous age.

Loyal (1990) details the lithostratigraphy of basal Subathu Formation exposed in the Kuthar river. Based on the analysis the author divides the basal sedimentary sequence into three synchronous Litho- Units comprising of Shale, Sandstone, Limestone and Conglomerates. The author also lists vertebrate fossils found in the

Kuthar river and establishes Subathu Formation as rich fossiliferous unit in the Lesser Himalayas.

Najman et al. (1994) studied the sedimentology and structure of the Late Cretaceous-Early Tertiary facies exposed in the Lesser Himalaya. They concluded, the Indian craton submerged and formed stable shallow marine conditions during Late Cretaceous-Paleocene times. The Subathu Formation was deposited during-the suturin of India and Eurasia and the Dagshai units were deposited due to crustal thickening.

Najman et al. (1997) discuss the results of Paleomagnetic dating of the Himalayan foreland basin. After elaborate analysis the Dagshai Formation dated around 35.5 Ma with a tolerance of 6.7 Ma.

Najman et al (1997), Calculated the oldest depositional ages of < 28 Ma for Dagshai Formation at one locality and < 25 Ma at a second locality, whereas the deposition of Kasauli Formation occurred after the range of 28 Ma - 22Ma on the bases of ^{40}Ar/^{39}Ar dating of single detrital muscovite grains.

Najman et al (2000) analyzed the Petrography of sandstone of Subathu Formation shows recycled sedimentary source, with distinct ophiolitic and volcanic influence, that was drastically reduced at the time of deposition of Dagshai Formation. The grade of metamorphism increase with time, Dagshai Formation show first appearance of metamorphism (very low grade) at the close of Oligocene time while Kasauli Formation shows low grade of metamorphism during the earliest Miocene time. According to Najman (2004), shallow marine sediments of the Paleocene-lower Lutetian Subathu Formation are unconformably overlain by continental alluvial Dagshai and Kasauli formations and Siwalik Group, in the Subathu sub-basin and continental deposition start dated at younger than 31Ma Himalayan Orogenesis.

Decelles et. al. (1998) interprets the Bainskati Formation as backbulge depozone deposits on the basis of their shallow facies and their Himalayan derived provenance, similar to Subathu Formation in India. DeCelles et.al. (1998) gave the information about Neogene foreland basin deposits of the Western Nepal Himalayan fold-thrust belt.

Powers et. al. (1998) found out that the Sub Himalaya, between the MBT and HFF, is the primary surface expression of shortening between the Himalaya and the Indian plate. He observed, the Kangra and Dehradun re-entrants display fault propagation folds having steep limbs in the north, and gently north dipping limbs in the south. Structural and shortening of the Western Sub-Himalaya. Raviverman (2000) have compiled huge information of Himalaya in the form of his book Foreland sedimentation in Himalaya Tectonic Regime.

Najman and Garzanti (2000) found that the sandstones from Subathu Formation were derived from a mixture of Sedimentary, Volcanic and Ophiolitic rocks. The terrigenous units of Subathu, Dagshai and Kasauli consist of recycled orogenic quatrzose-lithic sandstones.

Lakshmi and Kumar (2001) investigated the accumulation rates of Subathu basin at different times though magnetostratigraphy studies. They calculated the accumulation rates of Subathu, Dagshai and Kasauli formations helping correlation between initial collision and uplift during deposition. They found four episodes of deposition in the Subathu Formation and three episodes of deposition during the sedimentation of Dagshai-Kasauli formations.

Raiverman (2002) has detailed the orogenic process which was the source of sedimentation of Foreland basin. It details a comprehensive study of the Himalayan foreland basin, more focused on the Western Himalayas. He analyzes the structural tectonics, sedimentation material, uplifting of the region, mountain building process, in addition to origin of the Orogenic process in detail.

Kumar and Kad, 2002 have reported a fossil dental remains of a small primitive cricetid rodent *Primus microps* (Hystricomorpha, Muroidea), from the Murree group near Kalakot, Jammu & Kashmir The authors identify the age of the formation as Early Miocene age and these analysis support the theory of considerable difference between Subathu Formation of Himachal Pradesh and Murree formation of Jammu and Kashmir.

Najman et al. 2004 discusses evolution of the Himalayan foreland basin through elaborate studies done in the Kangra and Subathu sub-basins. The authors compare sediments of Nepal and Pakistan with the sub basins of Western India to establish the features of the broader Himalayan Foreland basin.

Yin (2005) systematically reviews the essential observations relevant to along-strike variation of the Himalayan geologic framework and its role in Cenozoic Himalayan metamorphism and sedimentation in the foreland basin. He elucidated the emplacement history of the high grade Greater Himalayan Crystalline Complex (GHC) that occupies the core of orogen. He observed that the Main central thrust (MCT) has flat-ramp geometry. The thrust flat in the south carries a

2-15 km thick slab of the GHC over the Lesser Himalayan Sequence (LHS), in western Himalayan orogen at the longitude ~ 77^0 E; the MCT exhibits a major lateral ramp known as Mandi ramp. On the west of the ramp the low-grade Tethyan Himalayan Sequence (THS) overlays the low grade LHS, whereas on the east the high grade GHC overlays low grade LHS. He found changes in Stratigraphic juxtaposition and metamorphism along the strike. He also found a westward decrease in its slip magnitude along the MCT, possibly a result of a westward decrease in total crustal shortening along the Himalayan orogen.

Bhatia and Bhargava 2006, presents paleontological and field evidences to show the Biochronological sequence of marine Subathu aged Late Thanetian to Middle Lutetian to Late Bartonian to Rupelian Dagshai Formation. The authors details the passage beds aged Late Lutetian to Middle Bartonian which connects Subathu and Dagshai formations of the Himalayan Foreland basin. The authors identifies similar sequence in the Sulaiman Range, of Oligocene age .The paper discusses the evidence of Nannoplankton in the Subathu Formation.

Siddaiahand Kumar in 2006 discovered a volcanic ash bed from the Subathu Formation. Their field studies along the Subathu Zones resulted in the discovery of 1.5 meter thick volcanic ash bed along the Koshaliya river, aged late Paleocene to middle Eocene. The lithology, mineral disposition and geochemistry identify the ash bed as volcanic origin and the stratigraphic position indicates occurrence of volcanic events during early Eocene.

Jafar and Kapoor, 1989 analyze the Late Maastrichtian – Danian Nannoplankton from the Subathu Formation. The discovery of Late Maastrichtian – Danian non floral elements suggest a Late Maastrichtian transgressive event along the Lesser Himalayan rift zone. The presence of plankton reinforces the Paleocene sediment present in the Subathu Formation. The marine invertebrates found in abundance in the region points to Cretaceous age.

CHAPTER 3 – GEOLOGY AND STRATIGRAPHY

3.1 HIMALAYAN GEOLOGY

3.1.1 INDIA-ASIA COLLISION

As Indian moved towards the Asian mainland and increasingly approached the active continental margin of Asia, the ground of the Neotethys Sea subsided. By Early Cretaceous, thick deposits of flysch accumulated along the continental margin of India. The steepening of the shelf-slope triggered submarine slides, rubble flows and murkiness currents. By the Late Cretaceous the two continents had moved closer to each other and the slippery sea floor beneath the Asian Plate resulted in the formation of deep oceanic trench. During this period materials resulted from the converging continents, preponderantly from the Indian Plate were deposited in the deep trench. The convergence of continents continued till India plate was resisted by Asian land mass. The north-western portion of the Indian plate docked with the Kohistan and became part of the Asian land mass. Due to immense pressure created between the contacting zones, the rocks of the Kohistan were pushed against the Indian continental margin. The fossils found in the sedimentary rock within the contact zone along the Indian continental margin

Indicate a timeline of sixty five Ma (Beck et al., 1995) for the collision to complete.

The collision activity was completed in three phases –

- Suturing between Kohistan arc and Karakoram micro plate of Asia margin in the Middle Cretaceous,
- Collision of north-western tip of the Indian Plate with the Kohistan-Karakoram in the Paleocene, and
- Oblique collision between the western margins of Indian Plate in the Late Eocene to Early Oligocene (Zaman et al., 1999).

The collision of Indian plate has interested lot of research and multiple collision theories are proposed by various Geoscientists. Interestingly, the speed of northward moving India at the rate 180-195 mm/ yr. suddenly slowed down to 45 mm/yr. at 55 Ma, implying the resistance that the fast-moving Indian Plate had encountered due to its collision with Asia (Klootwijk et al., 1992). Based on global Paleomagnetic data, it is inferred that the rate of northward moving India abruptly decreased at 57±3 Ma, corresponding to the time when India collided with Asia (Acton, 1999). The various researches conclude it took nearly 8 to 10 million years during the Mesozoic-Tertiary transition period for the complete amalgamation of India with Asia.

There was large-scale differential melting of the crustal rocks during collision, giving rise to an anatectic granitic magma. The granite granodiorite-tonalite plutons feature along collision zone south of Asian main land for about 2700 kms, as discordant bodies such as batholiths and stocks. It extends from Kohistan in the west, through Karakoram and Kailas, to Gangdese in Tibet and then to the eastern part of the Lohit district in Arunachal Pradesh. The granitic activity of the magmatic arc was spread over a long period of time between 110 Ma and 42 Ma, the peak being in the 60-45 Ma interval (Gansser, 1991; Debon, 1995; Copeland et al., 1995). While one pluton was dated 153±6 Ma, the other gave an age of 30.4±0.4 Ma (Murphy et al., 1997). In the Kohistan sector, basalt, andesite and pyroclastics of the Teru area were emplaced during the Late Cretaceous to Paleocene time (Danishwar et al., 2001). Some of the lavas belong to the early Eocene (45 Ma) (Petterson and Windley, 1985). The andesite, rhyolite and ignimbrite volcanics associated with the granites of the Gangdese mountain range in age from 119 Ma to 38 Ma.

The sedimentary accumulations in the oceanic trench, along the continental margin and the interior basins are severely compressed, tightly folded, and split by multiple thrusts, when the two continents collided. The deeper ultrabasic heavy rocks were pushed up and got impregnated within the sedimentary rocks, giving rise to the melanges of rocks in the zone of collision.

The melange-bearing tectonized zone was named the Indus-Tsangpo Suture (ITS) by Gansser (1966, 1977, 1981, and 1991). Rivers Sindhu (Indus) and Tsangpo (Yarlung-Zangbo) carved out their courses in this tectonized zone. The Nidar Ophiolite sequence, which includes oceanic plagiogranite, originated from sub alkaline tholeiitic magma by fractional crystallization aided by filter-pressing process. In Ladakh the melange associated with the ITS is known as the Nidar Ophiolite (Thakur and Bhat, 1983; Sachan, 2001).

In many sectors, the severe impact of collision of the continents resulted in squeezed, out-abducted ophiolites and ophiolitic melanges and these were thrusted southwards 30 to 80 km away from their roots.

3.1.2 EVOLUTION OF HIMALAYAN FORELAND BASIN

Along its southern margin of the Himalayan zone in the Lesser Himalayan sub-province, due to bending down of the crust and crustal thickening, a flexural depression developed immediately south of the emerging young mountain. This was a consequence of tectonic loading resulting into a basin that deepened away from the Indian Shield.

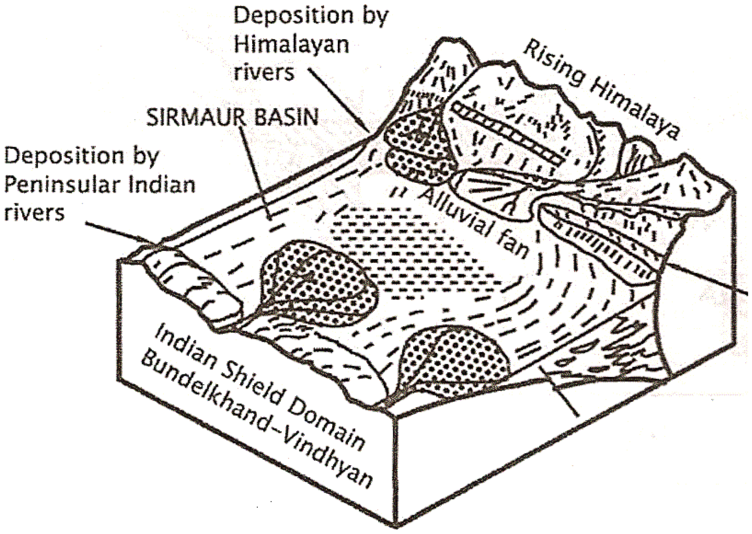


FIGURE 3.1: The block diagram showing rivers building fans of sediments (deltas) at their mouths (Valdiya, 1998).

The oceanic water invaded the depression zone and the basin formed was named as the Sirmaur Basin (Valdiya, 1998), named after the district in south-eastern Himachal Pradesh (Figure 3.1). Eroded material from the nascent, growing orogen filled the basin progressively even as its floor sank due to growing load of the accumulated detritus. The formation of Sirmaur basin dates back to Early Paleocene and during the same period, Ranikot (Pakistan), Tera (Himachal Pradesh) and Amile (Nepal) were formed. This the long shallow Sirmaur Basin extends from the Ranikot-Laki belt in Sindh in the west to Meghalaya and beyond.

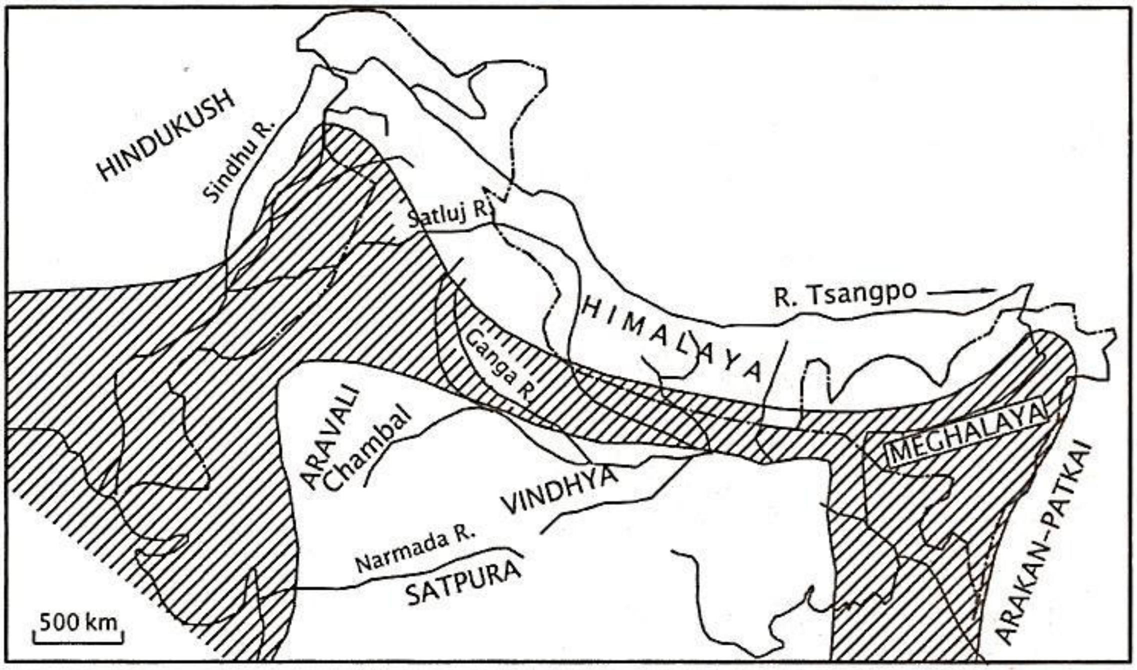


FIGURE 3.2 : Extent of the Himalayan Foreland Basin encompassing both Sirmaur and Stuiclik basins (After Valdiya, 2002)

It is linked with the Bay of Bengal in the east through the Bengal Basin and in the west, connected to Arabian Sea though western Rajasthan (Figure 3.2). The Himalayan foreland basin covered

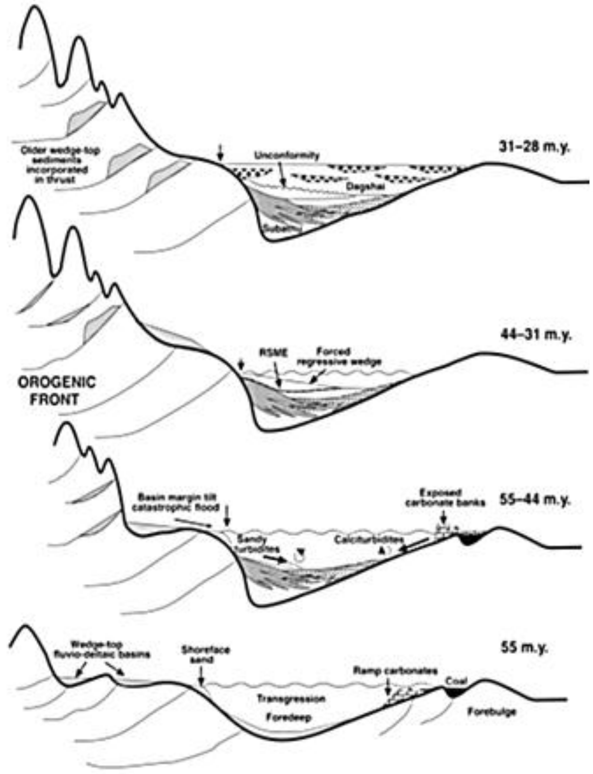
- Jaisalmer-Palana Barmer belt in western Rajasthan,
- Salt Range-Hazara region in central, western and northern Pakistan,
- Kakara-Subathu belt in Himachal Pradesh,
- Phart-Singtali-Satpuli area in Garhwal,

- Amile-Bhainskati-Dumri sector in Nepal,
- Yinkiong-Dalbuirig area in Arunachal Pradesh,
- Kopili area in Assam, the Jaintia Hills in Meghalaya and
- Indo-Myanmar ranges.

The foreland succession has a widespread distribution and its basal part is exposed in Ranikot and Rakhashani in Balochistan, Kalakot in Jammu, Kakara-Subathu in Himachal, and Therria in Meghalaya.

3.1.3 EVOLUTION OF SUBATHU BASIN

The early Himalayan foreland basin sediments in India are the Subathu, Dagshai and Kasauli Formations. The evidence of collisional processes between India and Eurasia are preserved in these formations. The marine, nonelastic Subathu Formation' (Paleocene -mid-Eocene), the oldest of the three formations was deposited on the open shelf during the early stages of collision.



Completion of Basin

Forced Regression

Sediments filling the Basin

Creation of Basin and Transgression

FIGURE 3.3: Formation of Subathu basin- Diagrammatic representation

It bears minimal evidence of terrigenous clastic influence indicating its formation before the Himalayan uplift and the beginning of erosion, exhumation and uplift, with deposition of the detritus in the basin to the south (Figure 3.3).

Subathu rocks were deposited during period of initial contact, collision and suturing. Being marine, are consistent with deposition during the initial down warping stage of the foreland basin. The marine Subathu Formation to continental Dagshai Formation transitional phase is M. Eocene. At Dogadda (Pauri Garhwal) reducing facies are present probably recording location of an over building delta.

3.2 STRUCTURAL AND TECTONIC FRAMEWORK OF THE STUDY AREA

The Himalayas represent one of the few places of the earth where continental crust attempting to under thrust continental crust. Indus-Tsangpo suture zone of Tibet and India mark the Paleogene collision of India with Eurasia. Farther to the south, Precambrian basement of High Himalaya and a relatively complete cover Phanerozoic rocks (Tethys Himalaya) were thrust southward over a discontinuous sediment sequence along the Main Central Thrust (MCT). The Precambrian and younger rocks of the Himalaya and Tethy Himalaya were originally part of India's north passive margin. Deformation of MCT began before 10 Ma and continues today. South of the Main Boundary Thrust (MBT), numerous faults displace Siwalik strata; the southernmost is termed the Himalayan Frontal fault.

The Himalayan tectonic system consists of features produced by the Cenozoic Indo-Asian collision, the Himalayan orogen, the active Himalayan foreland basin and the Indus and Bengal fans. The Himalayan Foreland basin is a broad, "up-side down U-shaped" basin in map view. Its basement dips at about 2–3 degrees towards the Himalayan orogen, with the thickness of basin fill increasing to about 4–5 km against the Himalayan front (Hayden, 1913; Rao, 1973; Lyon-Caen and Molnar, 1985; Raiverman, 2000). The northern boundary of the depression is sharply defined, whereas the southern boundary is diffuse and highly irregular.

TABLE 3.1: Consolidated Geographical, Stratigraphic and Structural division of Himalayas, after YIN, 2005

Geological / Topographical Division	Litho and chrono-stratigraphy	Structural Division
Tibetan Plateau	1. Siwalik Group : Neogene fine to coarse – grained continental strata (-20 -2 Ma) 2. Lesser Himalayan Sequence (LHS) : Metasedimentary and metavolcanic strata , augen gneiss (1870-1800 Ma) 3. Greater Himalayan Crystalline Complex (GHC): High Grade metamorphic rocks (800-400 Ma) 4. Tethyan Himalayan Sequence (THS): Late Precambrian to Eocene (~650 -40 Ma) Sedimentary sequence locally Interlayered with Volcanic flows. a. Late Prot ,-D: Pre-rift b C-J1 :syn rift c. J2-K : Passive Margin d. Paleocene – Eocene: Syn- collision. 5. North Indian Sequence (NIS); Phanerozoic cover sequence above LHS (520-20 Ma)	1. STD Hanging wall --------STD-------- 2. MCT Hanging wall --------MCT-------- 3. MBT Hanging wall --------MBT-------- 4. MFT Hanging wall --------MFT ------- 5. MFT Footwall
-----Indus River/ Yalu Tsangpo ---		
North Himalaya		
----------Himalayan Crest------------ Higher Himalayas Base of North most steep slope Lower Himalaya Lowest Intermontane valley Sub Himalaya		
--		
Upper Himalaya (>3500 M) Middle Himalaya (1500-3000m) Basal Himalaya (50-1500m)		

Western Himalayan Orogen (west of 81 E, including salt range , Kashmir , Zanskar , Spiti, Himachal Pradesh , Garhwal and Kumaun Central Himalayan Orogen (81 E to 89 E) including Nepal , Sikkim and south-central Tibet Eastern Himalayan Orogen (East of 89 E , including Bhutan , Arunachal Pradesh and southeast Tibet)		

Heim and Gansser (1939), based on their work done in the Kumaun region of NW India, divided the Himalaya region in to four geological domains corresponding to east-trending geographic belts. These geographic and geologic zones are assumed continuous along the entire Himalayan orogen (Gansser, 1964; LeFort, 1975) and

Include:

- Sub-Himalaya (Tertiary strata);
- Lower Himalaya (Also known as the Lesser Himalaya, consisting of non-fossiliferous low-grade metamorphic rocks (LeFort, 1975);
- Higher Himalaya (Also known as the Greater Himalaya, crystalline complex consisting of aplitic granites and gneisses (LeFort, 1975); and
- Tethyan Himalaya (consisting of fossiliferous marine strata).

The major lithological units in the Himalayan orogen consist of the Neogene Siwalik Group, the Proterozoic Lesser Himalayan Sequence (LHS), the Proterozoic–Ordovician Greater Himalayan Crystalline Complex (GHC), and the Proterozoic to Eocene Tethyan Himalayan Sequence (THS) (Table 3.1) (Le Fort, 1996).

The major tectonic elements in the Himalayan orogen from north to south include:

1. The south-dipping Great counter Thrust (GCT) immediately south of the Indus–Tsangpo suture zone (also known as Renbu–Zedong thrust or Himalayan Backthrust)
2. The North Himalayan Antiform (NHA) (Hauck et al., 1998), also known as the Tethyan or North/Tethyan Himalayan gneiss domes commonly associated with Miocene leucogranites
3. The Tethyan Himalayan fold and thrust belt (THFTB) in the North Himalaya
4. The South Tibet Detachment System (STDS), also known as the North Himalayan Normal Fault

5. South Tibet fault system (STFS)
6. The Main Central Thrust (MCT)
7. The Lesser Himalayan Thrust Zone (LHZ)
8. The Lesser Himalayan Crystalline Nappes (LHCN), which are either segments of the MCT hanging wall or thrust sheets carried by imbricates in the MCT footwall
9. The Main Boundary Thrust (MBT)
10. The Main Frontal Thrust (MFT)
11. North-trending Neogene rifts

Structures within the Sub-Himalaya are consistent with thin-skinned fold and thrust deformation above a gently dipping detachment. The detachment does not extend southward beneath the unreformed Indo-Gangetic plains.

The latest Paleocene–middle Eocene Subathu Formation and the Oligocene–Miocene Dagshai and Kasauli formations of the Indian foreland basin record the early evolution of the Himalayas. Petrography analysis of Sandstone of the Subathu Formation shows a predominantly recycled sedimentary source. The distinct ophiolitic and volcanic influence identifies with the reduced deposition time of the Dagshai Formation.

Dagshai and Kasauli formations sandstones primarily consists metapelitic detritus (Najman and Garzanti, 2000). The metapelitic lithic grains of metamorphic grade range between to dominantly low grade in the Kasauli sandstones to very low grade at the base of the Dagshai Formation. Mudstone geochemical analysis points to the presence of a mafic-ultramafic source during the time of deposition of the Subathu Formation that becomes significantly less important by the time of deposition of the Dagshai Formation.

Compositions of Subathu Formation detrital spinels show they were either derived from both mid-ocean ridges basalt–type and arc-type ophiolites or from a composite origin ophiolite. It's unlikely for the Subathu composition to have southerly derivation from the Deccan Trap continental flood basalts. Kasauli Formation garnet compositions suggest derivation from medium-grade metamorphic rocks to amphibolite facies.

The composition of the Subathu Formation dated during latest Paleocene–middle Eocene time reflects strong influence from the Indus suture zone. It indicates initiation of India – Asia collision and development of the foreland basin. By the time of Dagshai Formation deposition, the Suture-zone influence was drastically reduced, when the embryonic thrust belt acted as a barrier sufficient to partially separate the suture zone from the Himalayan Foreland basin. The Dagshai Formation shows appearance of Himalayan metamorphic detritus at the close of Oligocene time. The erosion to deeper metamorphic levels during earliest Miocene time happened during the Kasauli Formation. The occurrence of garnet and higher grade metamorphic lithic grains during early Neogene time is coincident with the timing of displacement along the Main Central thrust and South Tibetan detachment zone.

Composition of early foreland basin sediments from Pakistan (Balakot, Murree and Kamlial Formations) to Nepal (Bainskati and Dumri formations) and Bangladesh (Kopili, Barail formations; Surma Group) indicates diachronous arrival of ophiolitic to low-grade metamorphic detritus derived respectively from the Indus Suture and early Himalayan thrust sheets in the north. This is observation is consistent with the progressively later closure of Neotethys which happened along the suture, from latest Paleocene time in the west to Eocene time or even later in the east.

Significantly, while the Subathu is made up predominantly of recycled detritus derived from the ophiolites and basic volcanic rocks of the Indus-Tsangpo Suture Zone, the Dagshai-Kasauli sediments are characterized by clastics of metamorphic rocks of the Himalayan terrains (Najman et al., 2004). Mineral spinel is characteristic of the Subathu, and the clastic fragments of metamorphic rocks in the Dagshai-Kasauli sediments show progressive increase in the grade of metamorphism, implying exhumation or exposure to surface of progressively higher grade rocks through the time in the provenances.

As shown in the Table 3.2, In the Hazara region in northern Pakistan and adjoining Jammu sector, the 6,000 m thick succession of deltaic-alluvial sediments is known as the Murree Group. In the Balakot area, the Murree comprises multiple cycles of sediments, each cycle commencing with typical channel-fill sediments passing upwards into tidal flat deposits and ending up with red clayey siltstones with calcareous concretion or fossil caliche (Bossart and Ottiger, 1989).

TABLE 3.2 Correlation of the Palaeogene-Neogene formations of the Sirmaur Basin (After Valdiya, 1998a)

Sindh-Salt Range	Potwar-Jammu	Himachal – Kumaun	Nepal	Arunachal Pradesh	Assam	Indo- Myanmar Range
Gaj	Murree	Kasauli	Dumri		Surma	Bokabil
						Bhuban
Nari		Dagshai				Renji
-------------------------------------	-------------------------------------	-Unconformity-	-------------------------	-------------------------	Barail	Jenam
Kirthar	Chhharrat Ls	Subathu	Bhainskati	Yinkiong		Laisong
Laki Ghazij						Kopili
						Sylhet
	Hill Limestone	-------------------Unconformity	----------	----------	Jaintia / Disang	Langpar
						Therria
Ranikot		Kakara-Bansi	Amile		Lakadong	

In the southern Sulaiman region, the meandering rivers of the early Murree time were succeeded by the braided rivers of the later epoch. They flowed in the SSW direction (Waheed and Wills, 1990). Layers of conglomerate at the base of the Murree Group in the Potwar and Kohat plateaus indicate that the beginning of the fluvial sedimentation was marked by a hiatus. In the Poonch area in Jammu-Kashmir, the passage is transitional or slightly disconformable. The sediments were deposited by SSE to SSW-flowing rivers (Singh 2000).

3.3 REGIONAL GEOLOGY

The Sub-Himalayan Palaeogene succession comprises mainly of the Subathu and Dagshai and Kasauli formations and their equivalents. The collisional processes between India and Eurasia are recorded in these formations. The pre-Siwalik succession represented by the Subathu-Dagshai-Kasauli and coeval beds was deposited in several sub-basins separated by basement ridges and spurs (Raiverman et al., 1983). A major part of the overlying Kasauli Formation is considered to be of post-Palaeogene age.

3.3.1 SUBATHU FORMATION

The Subathu Formation is the oldest (Paleocene -mid-Eocene) and predominantly consists of fossiliferous marine limestones and shales. It is evidently formed before Himalayan upheaval as it bears minimal evidence of terrigenous clastic influence. The sequence then passes conformably into the Dagshai Formation. The Dagshais are characterized by clastic red beds consisting of continental alluvial deposition of sandstones, siltstones, mudstones and caliche. The sandstones of the Dagshai Formation contain significant proportions of clastic terrigenous material (e.g., lithic fragments and mica), indicating newly uplifted landmass to the north. The presence of Sandstone compared to Shale in the Dagshai Formation increases towards north uplifting landmass and by Kasauli Formation period the formation comprise of Sandstone.

Litholog of Subathu Formation (Shimla hills) depicted in the Figure 3.4

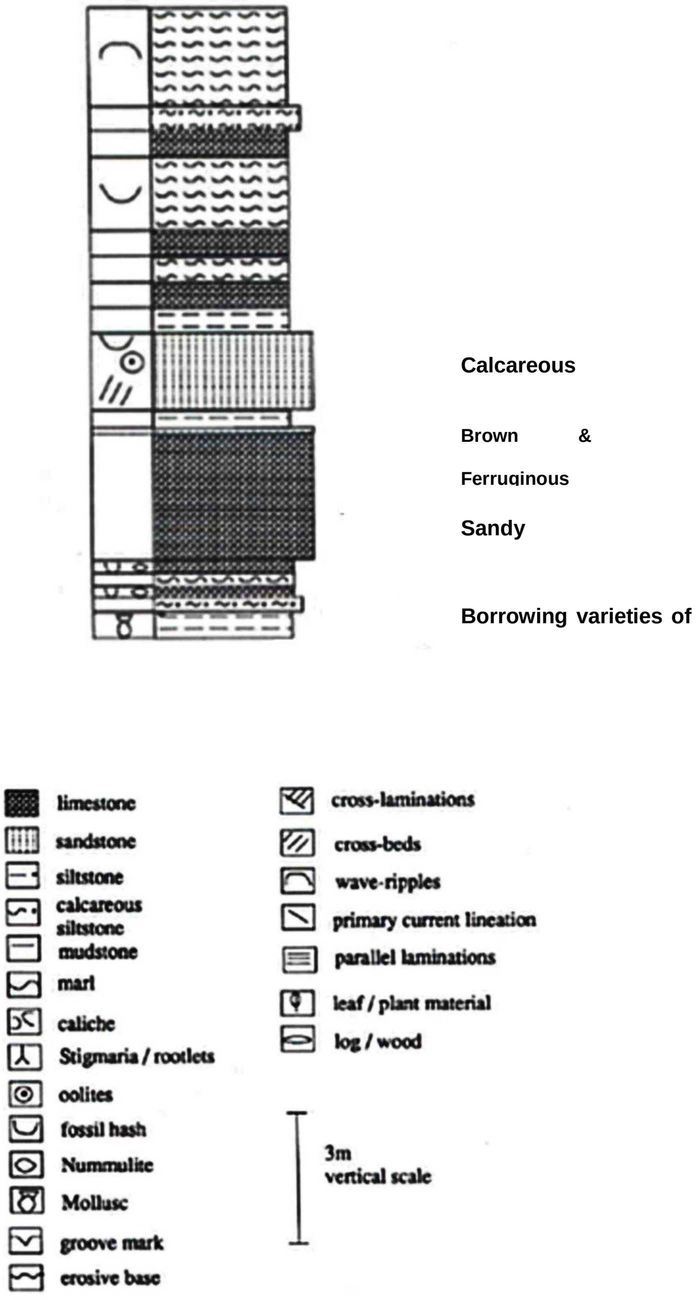


FIGURE 3.4 Litholog of Subathu Formation in the Shimla Hills ,(taken from Najman et al , 1994)

The marine, non-elastic Subathu Formation were deposited on the open shelf during the early stages of collision between India and Eurasia. The subsequent sedimentary transition to clastic sedimentation in a continental environment (the Dagshai Formation) indicates the beginning of erosion, exhumation and uplift, with deposition of the detritus in the basin to the south.

3.3.2 DAGSHAI FORMATION

The Dagshai Formation overlies the Subathu Formation conformably though earlier researches suggested a sedimentary break as long as Late Eocene-Oligocene (N.S Mathur 1978). The stratotype section indicating the Dagshai-Subathu contact is exposed near the Dagshai town.

FIGURE 3.5: Contact between the Dagshai and Subathu formations along the road section near the Koshaliya river bridge

The Dagshai Formation is a widespread succession of bright red and maroon shale, siltstone, sandstone and clay conglomerate and also grey and purplish grey sandstone. The red coloration of the Dagshai beds is due to the presence of ferric oxide, which suggests that they have been oxidized (Chaudhary 1972). The base of the Dagshai Formation is marked by the presence of 2 to 10 m thick white or greenish white quatrzose sandstone, which overlies the purple maroon fossiliferous shales of the Subathu Formation in Surajpur tectonic unit. It directly overlies the Nummulitic green shales of the Subathu Formation in Bilaspur unit. (Figure 3.5)

The white quatrzose sandstone is fairly persistent and serves as a marker bed. It looks quite different from the younger Dagshai sandstone beds in color, being better sorted, more winnowed, more quartz rich and having more rounded grains. It has been attributed to beach sand by Singh and Khanna (1980), Raiverman et al. (1983) and Srivastava and Casshyap (1983). However, according to Najman et al. (2004) the typical beach sedimentary structures are rare in this bed and it commonly has an erosive base. The under surface of this sandstone bed exposed near the Koshaliya River bridge shows load cast grooves. A major part of the Dagshai Formation is a cyclic sequence of sandstone and mudstone. Its lower part is dominated by shales in various shades of maroon and purple with mottling and calcrete features. In the upper part of the sequence the sandstone beds are thicker and more frequent while the shales are minor and more homogenous as opposed to nodular shales in the lower part.

The Dagshai sandstones are generally fine grained, massive and structure less with thickness of individual beds ranging between 1.5 and 7 meters. They are mainly lithicwackes with abundant unstable constituents and some rock fragments. Heavy minerals in Dagshai sandstones include tourmaline, garnet, plagioclase, kyanite, zircon and derived glauconite (Srikantia and Bhargava, 1998). Sedimentary structures like cross-bedding and ripple marks are fairly common in the Dagshai succession. The formation is poor in biotic remains and is devoid of animal fossils. So far only some plant remains consisting of imperfectly preserved stems, leaves and seeds, trace fossils of worm tracks and burrows found from several localities and stratigraphic levels.

The plant species reported from the Dagshai Formation include Poacites sp., Millettia asymmetrica, Bauhinia sp., Persea lakhanpalii, Mallotus sp., Ficus kumarhattiensis, Ficus spp., Carpolithus sp. (Mathur et al., 1996).

There are contrasting views regarding the depositional environment of the Dagshai Formation. Based on floral remains it is considered to have deposited in a terrestrial regime akin to present day Indus Ganga plane whereas Singh (1978) envisaged shallow marine deposition in an estuarine complex. According to Najman et al (1993), a high mudstone to sandstone ratio in Dagshai beds suggests channel meandering over a wide flood plain. Based on pedogenic features from the Dagshai and the Lower Murree sediments Mehta (1988) suggested that these are indicative of fluctuating climatic conditions. The combined floral and lithological/ sedimentological evidence (channelized and calcified red sediments) suggests a fluctuating fluvial environment with semi-arid setting.

Litholog of Dagshai Formation (Shimla hills) is depicted in the Figure 3.6

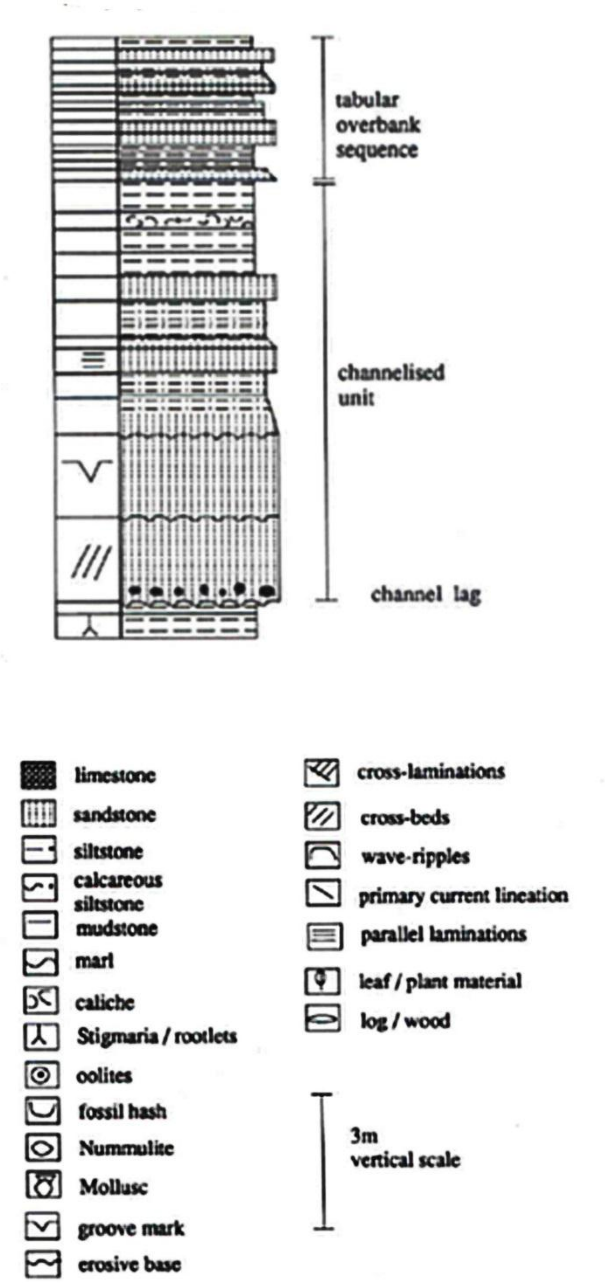


FIGURE 3.6 Litholog of Dagshai Formation in the Shimla Hills ,(taken from Najman et al , 1994)

Similar to the Subathu and Dagshai contact, the contact between the Subathu and Murree is also conformable. There are no definitive evidences regarding the lower and upper age limits of the Dagshai Formation. If it is assumed that both Subathu-Dagshai as well as Dagshai-Kasauli contacts is conformable the age of Dagshai Formation will range from Late Eocene to Oligocene (Sahni and Kad 1998). However, due to the marked paucity of quality palaeontological data from the Dagshai the arguments on this aspect have remained inconclusive.

At one point of time it was also suggested that the Subathu and Dagshai may represent a single lithounit showing intertonguing of red (=Dagshai beds) and green (=Subathu beds) facies (Raiverman and Raman 1971), but this view did not find support as geological mapping and stratigraphic evidence favor the discreet nature of these two lithounits. Pangtey (1999) based on magnetic polarity stratigraphy of Subathu-Dharamsala sequences concluded the existence of a major hiatus between the two formations. Similar studies by Lakshmi and Sudheer Kumar (2001) corroborate the same. Najman et al. 1997, based on 40Ar/39Ar dating of detrital muscovite grains concluded that most of the Dagshai Formation was younger than 28 Ma thus indicating a considerable gap between the Subathu and Dagshai formations. However, since the lower part of the Dagshai Formation is generally mica-free this conclusion may not be accurate.

Najman et al. (2004) used an alternative technique – dating of detrital zircons from the basal Dagshai sandstone and obtained an age younger than 31 Ma, which corroborated their earlier view of a pronounced unconformity between the two formations. Although the authors claim that their results suggesting an unconformity are conclusive, the fact that the disposition of Subathu-Dagshai exposures in the Shimla Hills area is so complicated because of tectonic disturbances, isoclinal folding and faulting. Therefore, reservations remain, also because the physical contact between Subathu-Dagshai is sharp and well defined without any observable angular unconformity anywhere in the basin. Bhatia and Bhargava (2006) have argued in favor of biochronologic continuity between the Dagshai and Subathu formations.

3.3.3 KASAULI FORMATION

The Kasauli Formation has a gradational contact with the overlying Dagshai Formation. It differs from the latter mainly in its higher sandstone to mudstone ratio, dominantly grey color, and richness in well preserved flora as against higher mudstone to sandstone ratio, dominantly red color and imperfectly preserved plant remains of the Dagshai Formation. Its stratotype section is exposed around the Kasauli town but there are several other good sections as well in the Solan District, e.g., Kalka-Jangeshu-Kasauli road, Garkhal-Kasauli road, Garkhal-Nambsari road, and Kheel Ka More-Subathu link road (Figure 3.7), Koshaliya River Section, Kalka-Shimla Highway between Datyar and Koti and near Barog. Its contact with the Dagshai Formation is marked with a thin tephra layer and is best exposed at Kheel Ka More near Kumarhatti on Kalka-Shimla Highway.

It consists essentially of brownish yellow and greyish green medium to coarse grained sandstone with subordinate yellowish green, greyish green and purple shales. Its basal part is dominated by flaggy sandstone (with false bedding due to two sets of joints) with abundant fossilized wood logs.

FIGURE 3.7: Field photograph showing normal contact between the Dagshai (older) and Kasauli (younger) formations, Kheel Ka More, Kalka-Shimla Highway

FIGURE 3.8: Fossilized tree trunk in the basal part of the Kasauli Formation exposed near Kheel Ka More, Kalka-Shimla Highway.

In the lower part of the formation the individual sandstone beds are one to two meter thick but in the upper part their thickness reaches up to 15 m. The sandstone shale ratio in the lower part of the sequence is 2:1 but in the upper part it is generally greater that 4:1. The Kasauli sandstones are generally coarser grained and more micaceous as compared to Dagshai though some Dagshai sandstone units (e.g. near Kumarhatti) are just about as coarse as Kasauli’s; these are at times felspathic with garnet as a common heavy mineral. The Kasauli shales are generally of yellowish green or greyish green color, but also purplish sometimes and often rich in fossil leaves while the sandstone beds particularly in the lower part of the sequence are characterized by large wood logs (Figure 3.8). The uppermost part of the Kasauli Formation is characterized by harder sandstones. The maximum measured thickness of the Kasauli beds is 1250 m (Srikantia and Bhargava 1998).Litholog of Kasauli Formation (Shimla hills) is depcted below in the Figure 3.9

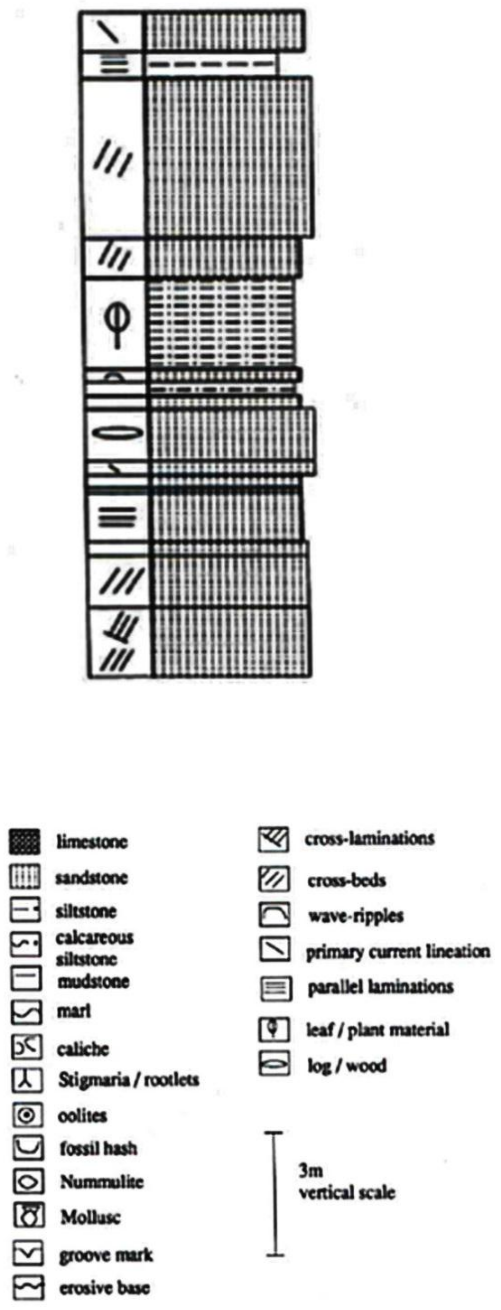


FIGURE 3.9 Litholog of Kasauli Formation in the Shimla Hills ,(taken from Najman et al , 1994)

3.3.4 SOURCE ROCK STUDY OF SUBATHU FORMATION

The attempt to find the Source rock for the Hydrocarbon occurrence in the Himalayan region narrowed down to Subathu Formation. Various literature reviews indicated encouraging Hydro carbon presence in Subathu (Yin, Najman Sand Mathur etc) compared to Krol & Infra Krol. Based on these inputs Subathu Formation was zeroed in for field study, sample collection and further analysis. In Sub-Himalayas, these Palaeogene Subathu outcrops occur around the Rajauri and Riasi districts of Jammu and Kashmir in northwest through Sundernagar, Kangra, Bilaspur, Solan and Sirmur in Himachal Pradesh, Lansdowne, Dogadda and Rishikesh in Uttarakhand to Nepal in southeast. The following regions were identified for further field study and analysis

- Nilkanth , Uttarakhand
- Dogadda, Uttarakhand
- Rishikesh, Uttarakhand
- Subathu Dharampur, Shimla hills, Himachal Pradesh

3.3.4.1 Nilkanth

The Subathu Group has decent exposure in Nilkanth (30°4' 47" N: 78° 20' 23' E) located at a distance of about II Km. SE of the holy town of Rishikesh. The outcrops of the Subathu Group are seen in the foot hills of the Himalaya from Poonch (Kashmir) to Dha ding (Nepal). Since the formation was formed by narrow deposition of Tethys Sea, the lithological characters of the different formations in different areas are more or less similar. The Tethys Sea transgressed the sub-Himalayan region from the west of Rawalpindi to the east of Nepal during the Late Paleocene and early Eocene The second arm transgressed the Zanskar region. The transgression in the Late Paleocene was mild. It is represented by carbonaceous shales and coal. Major transgression took place in Early Eocene and marine sedimentation was continued up to early Middle Eocene. The stratigraphy of the Tal valley is depicted in the Table 3.3

TABLE 3.3: The Stratigraphic set-up in Tal Valley, Garhwal Himalaya (modified after Mathur and Juyal, 2000).

Lithounits Characters	Age	Lithological
Garhwal Group	Precambrian	Phyllite
--- Thrust Contact ----------------------------		
Subathu Formation	Ypresian	Calcareous Shales , Nummulitic limestone, Grey-olive green , Siltstone, mudstone
Kakara Formation	Late Thanetian	Carbonaceous Shale , Siltstone, Mudstone
---Unconformity -------------------------		
Shell Limestone Formation (Nilkanth Formation)	Late Cretaceous	Oolitic , Shelly Limestone

The Subathu Formation is exposed in the region as thin beds of black shale quartz-wacke and Quartzarenite. In the Nilkanth area, it is exposed on a mule path between Pundras and Nilkanth. The contact between the Subathu Group and the Tal Limestone is exposed at the last turning of Bidasini nala on its North –West bank. The dark grey fossiliferous limestone of the Kalakot Formation is exposed in a nala flowing in the vicinity of Nilkanth temple and on a mule path between Nilkanth and Kothar village. It is also exposed around the Bhadsi, Maral and Khargosha villages and has yielded *Nummulites atacicus Leymerie N. subataciclls Douville, N. (Assilina) subspinos* a *Davies and Diclyoconoides uredenburgi Davies* which were earlier recorded by Tewari and Kumar (1967). Pant (1962) from the limestone bands of the Kalakot Formation of the present area and suggested that probably Ranikot horizon is present in the Nilkanth region. The Arnas Limestone is exposed near Maral and Bhadsi villages and contains broken shells of gastropods, larnellibranchs and for arniniferids- *Trilocuiina spp. and QuinqlleloClttina*. Tewari and Kumar (1967) suggested early Eocene age for the dark grey fossiliferous limes tone bands of the Kalakot Formation of this area.

On the basis of the above data, the Subathu Group of Nilkanth area ranges in age from the Late Paleocene to the early Middle Eocene. The Geological map of Garhwal syncline depicting Nilkanth, Bidasini and Dogadda is presented in Figure 3.10.

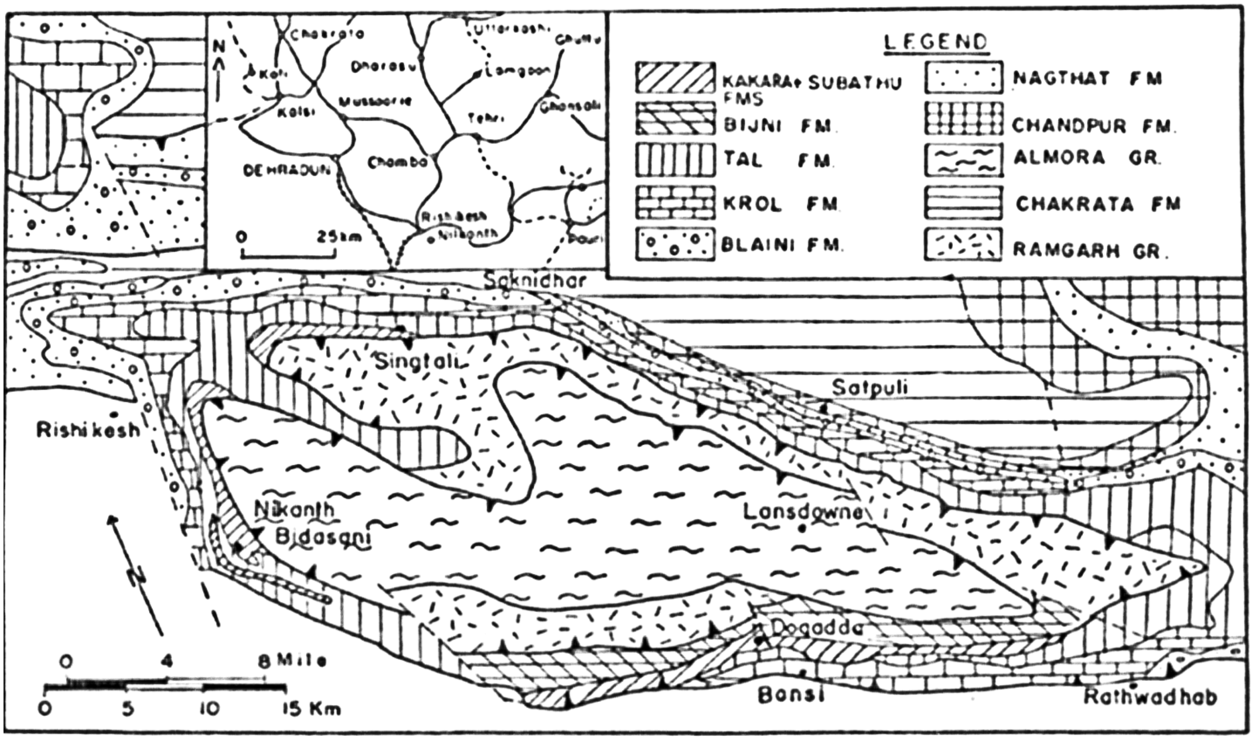


FIGURE 3.10 Geological map of Nilkanth, Bidasini and Dogadda regions based on Valdiya 1980.

3.3.4.2 Subathu – Dharampur, Shimla hills

The history of tectonic studies and evolution of the Lesser Himalaya goes back to 1928, when Pilgrim & West worked on the Late Precambrian- Eocene formations and presented detailed maps delineating the complex structure involving southwesterly verging thrusts, nappes, faults, klippen and windows.

TABLE 3.4: Lithostratigraphic units of lesser Himalaya After Loyal R.S, 1990

Siwalik Group	Tectonic Contact	Mid. Miocene – Pleistocene
Kasauli Formation	Gradational contact	Miocene
Dagshai Formation	Gradational contact	Upper Eocene – Oligocene
Subathu Formation	Gradational / unconformable contact	Up. Paleocene – Mid. Eocene
Tal Formation	Tectonic / unconformable contact	Cambrian/Jurassic/Cretaceous (?)
Krol Formation	Tectonic / unconformable contact	Precambrian/Permo-Triassic (?)
Infra-Krol Formation	Tectonic / unconformable contact	Precambrian/Permian (?)
Blaini Formation	Tectonic / unconformable contact	Up. Carboniferous
Jaunsar Formation	Tectonic / unconformable contact	Lr. Paleozoic - Devonian (?)
Simla Slate Formation	Tectonic / unconformable contact	Precambrian – Lr. Paleozoic (?)
Chail Formation	Tectonic / unconformable contact	Precambrian (?)
Jutogh formation	Tectonic / unconformable contact	Precambrian (?)

Subsequently, Auden (1934, 1937), Gansser (1964), Rupke (1974), Wadia (1975), Kumar (1977), Valdiya (1980), Valdiya & Bhatia (1980)) arid numerous others have made important contributions to the Lesser Himalayan region on a very regional scale.

The stratigraphy of the Lesser Himalayan formations is given in Table 3.4**.**

The strange mixture of different ages for a given unit has resulted from several factors, viz. extensive and complicated folding and thrusting, which has made the structure extremely complex and caused its misinterpretation; and recent discoveries and also from misidentification of extremely doubtful and reworked fossils in otherwise barren units.

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The sub-Himalayan pre-Siwalik succession represented by the Subathu-Dagshai-Kasauli and coeval beds was deposited in several sub-basins separated by basement ridges and spurs (Raiverman et al., 1983). Medlicott (1864) first used the term ‘Subathu’ for a thick succession of conformable strata comprising the ‘Nummulitics’ or Subathus, the Dagshais and the Kasaulis, exposed near the Subathu Cantonment in the Solan District of Himachal Pradesh. In the Lesser Himalayan region of India, the Subathu Formation is the only richly fossiliferous unit that holds the key to deciphering stratigraphic and age relationships, biostratigraphy, palaeoenvironments and paleobiogeography during Early Tertiary times.

The geological map of Subathu area, Himachal Pradesh is presented in the Figure 3.11.

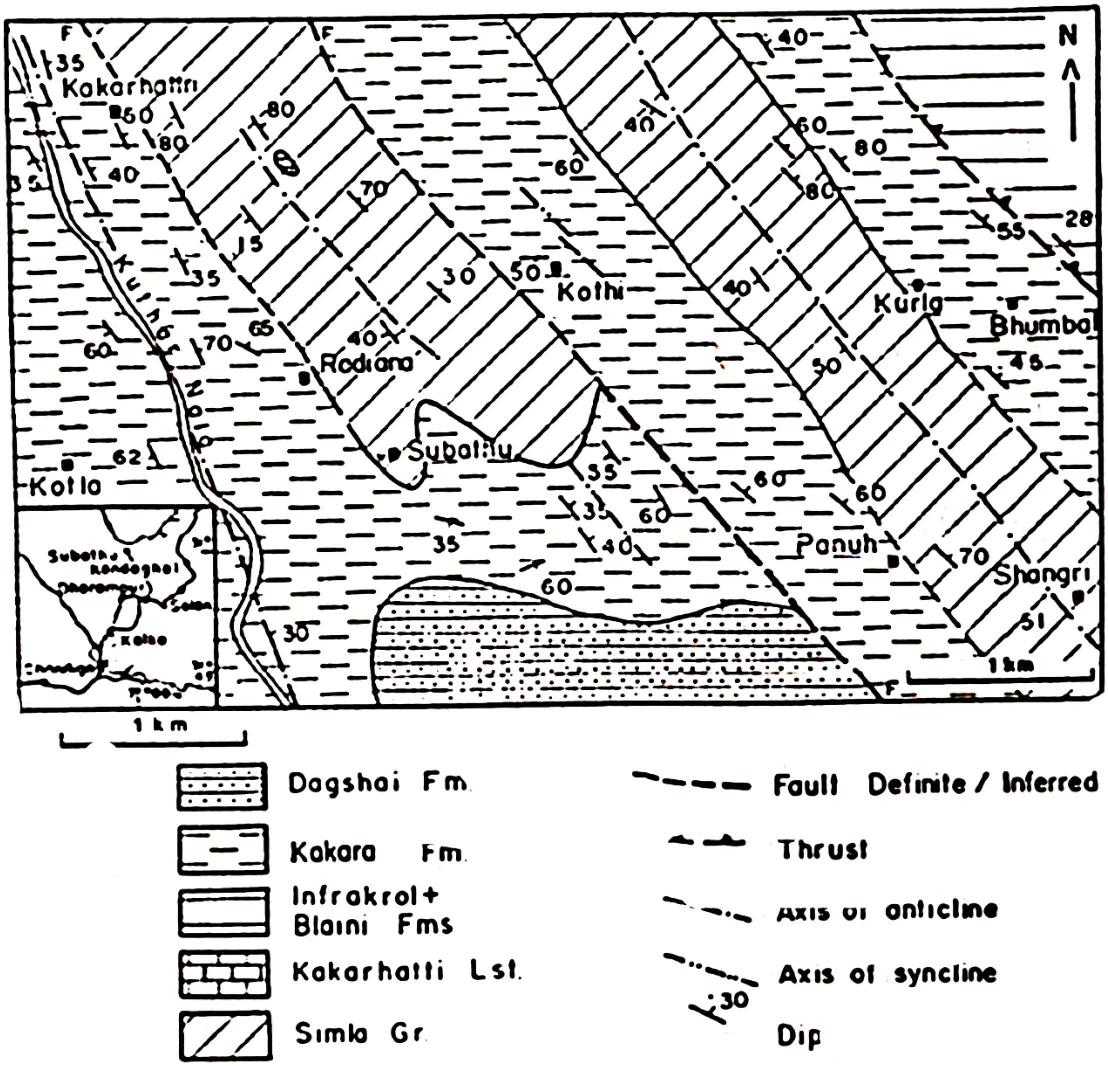

FIGURE 3.11: Geological map of Subathu area, Himachal Pradesh, Lesser Himalayas, After Mathur, 1997.

The Subathus along with the overlying Dagshai and Kasauli horizons form a Palaeogene para-autochthon south of the allochthonous crystallines (Kumar, 1977). This succession then formed the lower part of Medlicott's 'Sub-Himalayan Series' which also included the Nahan Formation ('Nahuns') and the Siwalik Group ('Sivaliks') as its middle and upper parts, respectively. Later, Medlicott renamed the Subathu-Dagshai-Kasauli succession as 'Sirmur Series' in

1876 and restricted the term ‘Subathu’ was for its lowermost marine part. Subsequently, the ‘Nummulitics’ of the Rajauri District of J. & K. were also included in the ‘Subathu’ by La Touche (1888). The evolution of Subathu lithography is presented in the Table 3.5.

TABLE 3.5: Evolution of Subathu lithostratigraphy (after Kumar & Loyal 2006)

<table>
<tr><th colspan="3">Medlicott 1864</th><th colspan="2">Medlicott 1876</th><th colspan="2">Present</th></tr>
<tr><td rowspan="6">Sub Himalayan Series</td><td colspan="2">Sivaliks</td><td colspan="2">Sivaliks</td><td colspan="2" rowspan="2">Siwalik Group</td></tr>
<tr><td colspan="2">Nahuns</td><td colspan="2">Nahuns</td></tr>
<tr><td rowspan="4">Subathus</td><td>Kasaolis</td><td rowspan="4">Sirmur Series</td><td>Kasaolis</td><td rowspan="2">Murree Group</td><td>Kasauli Fm.</td></tr>
<tr><td>Dugshais</td><td>Dugshais</td><td>Dagshai Fm.</td></tr>
<tr><td rowspan="2">Subathus</td><td rowspan="2">Subathus</td><td rowspan="2">Subathu Group</td><td>Subathu Fm.</td></tr>
<tr><td>Kakara Fm.</td></tr>
</table>

Following the Code of Stratigraphic Nomenclature of India (1971), a lithostratigraphic nomenclature has been followed for the constituent units of the Sirmur Series.

Singh (1980) assigned a ‘Group’ status to the Subathu succession of Jammu and Kashmir and recognized three formations within this group. In ascending order, these formations are Beragua, Kalakot and Arnas Limestone (the youngest formation with three members - Ans, Chinkah and Chenab). The lateral and lithological continuity of these ‘formations’ is yet to be established in the stratotype area. The Paleocene part (=basal part of the Subathu beds) of the Subathu succession is now equated with the ‘Kakara Series’ of Srikantia and

Bhargava (1967) and it has been formally named as the Kakara Formation; the name Subathu Formation has now been restricted for the parts of the succession, which do not include any Paleocene beds (Juyal and Mathur, 1990, 1992; Mathur, 1997; Juyal, 1997). In view of this, the Subathu succession is here referred as the Kakara-Subathu succession and the name 'Subathu Group' as designated by Singh (1980) is retained for this pending formalization of appropriate nomenclature.

The Kakara-Subathu succession or the Subathu Group occurs mostly in the cores of anticlines (e.g., in stratotype area, H.P.) or in the form of tectonic inliers (e.g., in Rajauri District). Its thickness varies from about 175 m in J. & K., 400 m in H.P. to about 170 m in Uttarakhand, and it rests on various rock types indicating a marine transgression over predominantly Precambrian basement except in the Dogadda (Uttarakhand) and Nilkanth, where it overlies the Tal Formation of Cambrian age (Valdiya, 1980). The Precambrian basement rocks for the Subathu Group include the Great Limestone/ Sirban Limestone/ Vaishnodevi Limestone in J. & K., the Bandla Limestone in the Bilaspur area, H.P., the Dharamkot Limestone in Dharamsala area (Himachal Pradesh.), the Tundapathar Limestone in the Morni area (Haryana), and the Simla Slates in the Subathu stratotype area, Himachal Pradesh.

In Shimla Hills region it was deposited in Subathu and Kangra sub basins. The Subathu sub-basin has exposed the complete sequence including the Subathu, Dagshai as well as Kasauli formations. However, in the Kangra sub-basin, only the middle and upper parts of the succession represented by the Lower

Dharamsala and Upper Dharamsala formations are exposed and the lower part, i.e., the Subathu Formation is very poorly represented. The geological map of Subathu and adjoining regions in Himachal Pradesh is presented in Figure 3.12.

In the Subathu sub-basin the whole of pre-Siwalik succession in general and its oldest unit i.e., the Subathu Formation, in particular are structurally as well as tectonically quite disturbed and therefore not very suitable for extensive sedimentary logging, and magneto stratigraphic, fission track and isotopic dating etc.

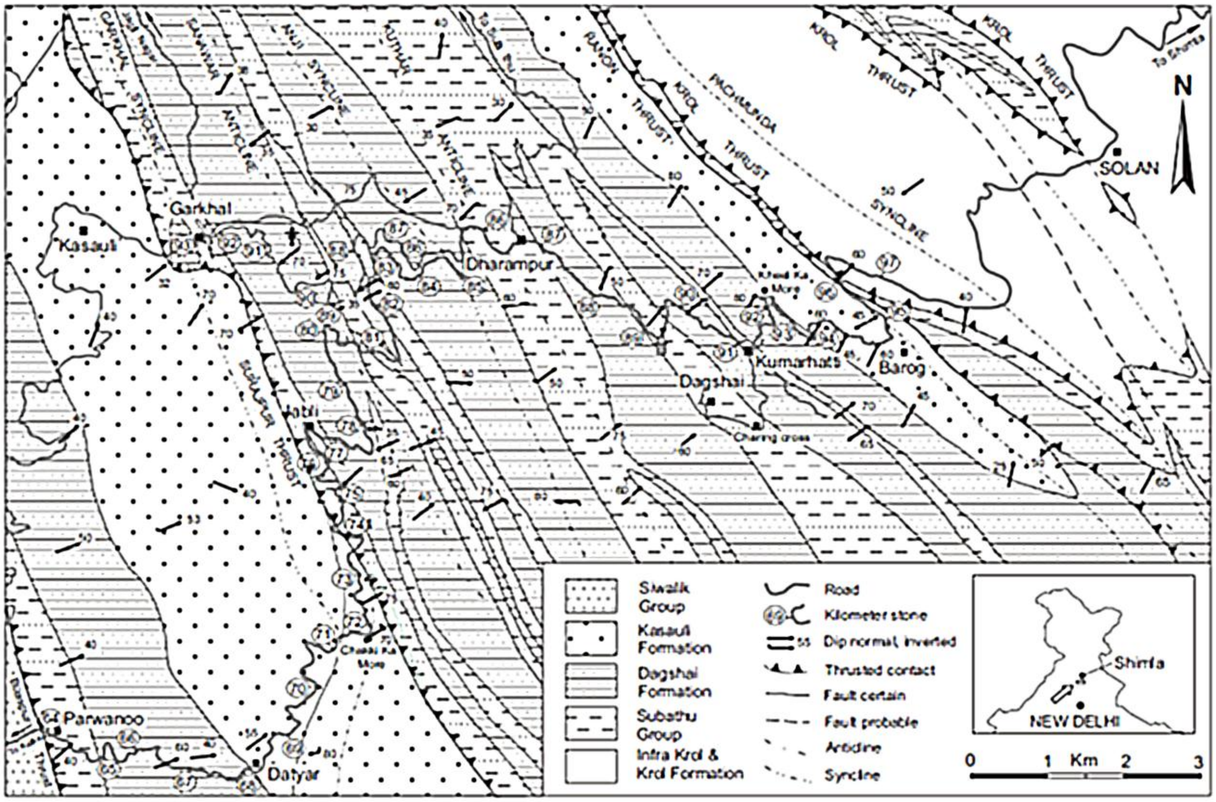

FIGURE 3.12: Geological map of Kalka, Kasauli, Dharampur, Kumarhatti, Barog and Solan areas of Himachal Pradesh (Modified by Kumar and Loyal 2006 after Raiverman 1979)

The same succession in the Kangra sub-basin is less disturbed but there it almost lacks its most crucial part, i.e., the Subathu Formation. In this respect, the Palaeogene succession of Jammu region exposed around Kalakot is the best particularly for any dating and magneto stratigraphy. Here the sequence is nearly undisturbed, has all the characteristic lithologies and is well constrained biostratigraphically. Moreover, the overlying Murree Group, an equivalent of the Dagshai-Kasauli succession has yielded some invertebrate as well as vertebrate fossils too and is thus better constrained Khan, 1973; Khan et al. 1974; Ranga Rao, 1986; Mal Barna, 1988; Mehta and Jolly, 1989; Kumar and Kad, 2002, 2003. The oldest unit of the sub-Himalayan Palaeogene succession, i.e., the Subathu Group was largely marine; the continental conditions developed only towards its terminal stage, whereas the Dagshai and Kasauli formations are continental deposits. The stratigraphic succession of Subathu Sub basin is presented in the Table 3.6

TABLE 3.6: Stratigraphic succession of Subathu Sub Basin

Subathu Sub – Basin
(Solan & Sirmur districts , Shimla Hills)
Siwalik Group
----------------------Thrust Fault -------------------------
Kasauli Formation
Dagshai Formation
-----------------------Unconformity / Passage beds ---------------------
Subathu Formation
----------------------Krol Thrust ------------------------
Krol Belt Succession / Simla Slates

This formation is well developed in the classic area of the Simla Hills of Himachal Pradesh and is separated from the pre-Tertiary Blaini-Krol sequence towards the northeast by the Krol Thrust sheet and from the Neogene-Quaternary Siwalik rocks by the Main Boundary Fault (M.B.F.) in the southwest. Between these two boundaries, the Subathu and the overlying rocks are repeated across the regional NW-SE strike trend with lateral persistence and uniformity. Of these two boundaries, the southern contact marked by the M.B.F. is thought to be of considerable geotectonic significance and shows a conspicuous NW-SE strike trend parallel to that of the country rocks.

Along the well-defined belt of the Lower Tertiary sequence (Loyal, 1986a); the Subathu outcrops are exposed in the cores of tight anticlines and as para-autochthonous tectonic outliers in the form of scales and wedges in the window zones. For instance, a complex tectonic feature is observed among the Subathus in the pre-Tertiary Shali window (31° 50' N: 78° 41' 21" E, 200km NW of Subathu), indicating enormous over thrusting along an almost horizontal plane.

The upper contact of the Subathu Formation is the overlying Dagshai unit in the Simla region (Murree Group in Jammu and Kashmir; Dharamsala Group in Dharamsala-Mandi Himalaya). The Himalayan correlation is provided in the Table 3.7.

The Subathu Formation is a fossiliferous sequence of olive green, khaki, variegated Shales, limestone bands, along with fine grained limestone and sandstone bands. In the basal part, gypseferous, pyritiferous, and carbonaceous shales with thin coal bands are commonly present.

TABLE 3.7: Himalayan Correlation, After Loyal (1990)

Shimla Himalaya	**Jammu & Kashmir Himalaya**	**Dharamsala – Mandi Himalaya**
Kasauli Formation	Murree Group	Dharamsala Group
Dagshai Formation		
Subathu Formation	Subathu Formation	Subathu Formation
Simla Slate	Great Limestone	Dharamkot / Shali Limestone

The Subathu Group consists of three main lithological units, as presented in the Table 3.8 –

- Lower black-grey unit, characterized by basal carbonaceous black shale and the vertebrates include large marine mammals representing Sirenia (Ishatherium subathuensis) and Cetacea (Himalayacetus subathuensis), and a variety of marine fish dominated by rays (Sahni and Kumar, 1980; Kumar and Loyal, 1987; Bajpai and Gingerich, 1998.)
- Middle green-grey unit, dominantly green shale-limestone unit constituting the middle part consists mainly of green (turn olive green/ khaki on weathering) and grey splintery and calcareous shales interbedded with thin dark grey-coloured limestone, siltstone and sandstone beds.
- Topmost red bed unit. Constituting the upper part consists of maroon to purple shale (with thin bands of granulestone) siltstone and mudstone with calcareous bands and marl. This unit is also referred as ‘passage beds’ or ‘transitional beds’ between the Subathu and Dagshai formations (Bhatia and Mathur, 1965; Kumar and Sahni, 1985)

TABLE 3.8: Subathu Succession, after Kumar & Loyal 2006

	Nanda & Kumar 1999	Mathur and Juyal 2000	Ranga Rao 1986	Singh 1980	Ranga Rao 1971
Kakara – Subathu Succession (Subathu Group)	Red bed Unit	Zone VIII (in part) (passage beds Bhatia & Mathur 1965)	Kalakot Formation (Subathu Group)	Basal Murree	Kalakot Zone (Lower Murree)
	Grey-Green Unit with older red beds	Zone VIII (in part) to Zone III (In part)	Subathu Formation	Arnas Limestone Formation, Kalakot Formation	Subathu Formation
	Black – Grey Unit	Zone III (In part) to Zone I		Beragua Formation	

The black-grey unit is characterized by basal carbonaceous black shale, which in the Rajauri District (J. & K.) contains commercially exploitable coal deposits (Beragoa, Metka and Mohgala mines). Coal seams are not so well developed in the stratotype area where the dark grey shales are intercalated with very fine-grained green sandstone. Associated with the green sandstone are also a few oyster-bearing limestone beds.

The grey-green unit constituting the middle part of the succession consists mainly of green (turn olive green/ khaki on weathering) and grey splintery and calcareous shales interbedded with thin dark grey-coloured limestone, siltstone and sandstone beds. In the lower-middle part of this unit a >30 m sequence of variegated (purple and sea green) but dominantly purple shales is also present but only in stratotype area. These shales are compact and have green patches and enclaves. Below these beds there are some oyster limestone bands. In the upper part of grey-green unit, thick limestone beds occur. Some of these beds are unfossiliferous while others are highly fossiliferous yielding oyster coquinites. Coquinites are definite indicators of brackish water conditions that progressively changed into fresh water conditions during the deposition of the upper Subathu sediments (red beds). The grey-green unit is richly fossiliferous.

The red bed unit constituting the upper part of the Kakara-Subathu succession consists of maroon to purple shale (with thin bands of granulestone) siltstone and mudstone with calcareous bands and marl. This unit is also referred as ‘passage beds’ or ‘transitional beds’ between the Subathu and Dagshai formations (Bhatia and Mathur, 1965; Kumar and Sahni, 1985). The red bed unit is overlain by white or greenish white orthoquartzitic sandstone, which is considered as a marker horizon between the Subathu and the overlying Dagshai Formation. The marker white sandstone is followed by sandstone, siltstone, and mudstone cycles of the typical Dagshai Formation. The red beds of the Dagshai Formation are distinct from those of the Subathu and comprise bright brown red sandstones, micaceous siltstones and nodular mudstones with burrow structures and calcrete layers. The red beds of the Subathu Formation clearly depict a faunal and sedimentary transition from a marine set up to brackish and fluvial conditions - extensive oyster-bearing beds overlie the nummulitic limestones and shales. The oyster beds are overlain by variegated shales, pisolitic granulestone, siltstone and claystone containing pulmonate gastropods and varied continental vertebrates concentrated in a bone bed which is traceable even in Pakistan.

3.3.5 GEOLOGICAL FIELD STUDY / TRAVERSE

3.3.5.1 Dogadda

In the Garhwal region, the Tal formations are succeeded upwards by the Subathu formation with a thin band of laterite (0.3 to 1.2 m thick) at the base which indicates a minor unconformity. At several places there is no true laterite but is represented by ferrugineous shale. The exact age of this formation in the Garhwal region has also been controversial since long. Pant S C assigned a probable Ranikot age to this formation on the basis of larger foraminifers during year 1961.

3.3.5.2 Nilkanth

Traverse details: Code NL - Nilkanth

Location: NL 01, N: 30^{o}07.347’, E 78^{o}21.650’

Remark: Uphill track on the Rishikesh Nilkanth road. Thick beds of Limestone interlaced with Quartz vein with Quartz crystal.

Location: NL 02, N: 30^{o}04.740’, E 78^{o}21.757’

Remark: Uphill track on the Rishikesh Nilkanth road. Crushed zone with presence of Pyrites.

Location: NL 03, N: 30^{o}04.576’, E 78^{o}20.907’

Remark: Uphill track on the Rishikesh Nilkanth road. Majority of the area is crushed with crumbled materials of Shale and Limestone. Presence of bands of Limestone interbedded with dark black shales.

Location: NL 04, N: 30^{o}04.813’, E 78^{o}20.662’

Remark: Near Nilkanth Mahadev temple, Upper part of Subathu exposed. Purple color Siltstones, fractured crumbled brown Shales (Figure 3.13), width 100-150 meters.

FIGURE 3.13: Fractured Brown shales found during in the Nilkanth traverse

Location: NL 05, N: 30^{o}04.813’, E 78^{o}20.662’

Remark: Near Nilkanth Mahadev temple, Upper part of Subathu Shales exposed (Figure 3.14).

FIGURE 3.14: Subathu Shales exposed near Nilkanth Mahadev temple.

In the Nilkanth section the Kakara Formation lies unconformably over the Tal Formation (Cambrian). The former unit comprises hard grey, 'massive, oolitic shelly limestone. The Kakara Formation is succeeded by the Subathu Formation which consists of grey, green to red shale with subordinate limestone.

In the Nilkanth section, the lithology and faunal content of the Subathu Formation are more or less similar to that of the Simla hills. However the faunal content in the former section is not so rich as compared to the latter one. In the Nilkanth section, the upper part of the Subathu Formation is missing, as it is in thrust contact with the rocks of the Garhwal Group (Precambrian)

3.3.5.3 Rishikesh / Bidasini

Traverse details: Code RB – Rishikesh/ Bidasini

Location: RB 01, N: 29^{o}59.856’, E 78^{o}79.342’

Remark: 300 meters from Bidasini Temple, upstream on the banks of the river channel flowing from Rishikesh. Subathu formation exposed, Purple shales, Silt limestones (Figure 3.15).

FIGURE 3.15: Subathu Limestone exposed on the banks of Canal in the Bidasini area.

Location: RB 02, N: 29^{o}59.856’, E 78^{o}19.372’

Remark: Upstream on the banks of the river channel flowing from Rishikesh. Subathu formation exposed, Characteristics of Subathu which is Purple shales exposed as crushed purple shales as presented in th Figure 3.16

FIGURE 3.16: Crushed Subathu purple Shales exposed on the banks of Canal in the Bidasini area.

Location: RB 03, N: 29^{o}59.861’, E 78^{o}19.411’

Remark: Upstream on the banks of the river channel flowing from Rishikesh, Subathu Formation is exposed as Bedded weathered Purple shales (Figure 3.17). The width of the Subathu formation here is about 400 meters (Figure 3.18)

FIGURE 3.17: Bedded weathered Purple shales exposed on the banks of Canal in the Bidasini area.

FIGURE 3.18: Depicting Width of the Subathu formation along the banks of Canal in the Bidasini area.

Location: RB 04, N: 29°59.853', E 78°19.417'

Remark: Upstream on the banks of the river channel flowing from Rishikesh. Gray Shales, Purple Shales, Quartz intrusion showing pinching and swelling (Figure 3.19).

FIGURE 3.19: Subathu purple Shales with Quartz intrusion along the banks of Canal in the Bidasini area.

The Subathu succession in this region rests unconformably over the Shell Limestone Formation (Nilkanth formation). The general stratigraphy of the Bidasini area in Tal Valley is given in Table 3.9. The Subathu Formation in this area consists of silty shales, oyster-bearing limestones, green and purple splintery shales which were deposited during the transgressive phase of the Subathu Epicontinental Sea. The Subathu formation is visible in and the thickness 10 m thick silty shale horizon of a 30 m thick stratigraphic section of the Subathu Formation (late Thanetianlate Ypresian). The section is well exposed near the village Bidasini in Tal Valley, Garhwal Himalaya, and Uttarakhand. The silty shale consists of centimeter scale alternation of dark grey and brown coloured horizons in which the dark grey horizon shows millimeter scale light and dark laminae.

TABLE 3.9: Stratigraphic set-up in Tal valley, Garhwal Himalaya (modified after Mathur and Juyal, 2000).

Lithounits Characters	Age	Lithological
Garhwal Group	Precambrian	Phyllite
-- Thrust Contact ---		
Subathu Formation	Ypresian	Calcareous Shales , Nummulitic limestone, Grey-olive green , Siltstone, mudstone
Kakara Formation	Late Thanetian	Carbonaceous Shale , Siltstone, Mudstone
---Unconformity ---		
Shell Limestone Formation (Nilkanth Formation)	Late Cretaceous	Oolitic , Shelly Limestone

3.3.5.4 Shimla Hills

In the Simla Hills region good sections of the Kakara, Subathu, Dagshai and Kasauli formations are exposed in the Dharampur, Subathu, Garkhal, Dagshai and Kasauli areas. In the Kuthar Nala section, the Kakara Formation rests unconformably over the rocks of the Simla Group (Precambrian), the unconformity being marked by a bed of pisolitic laterite. The Kakara Formation comprises carbonaceous shale in the lower part and hard massive limestone with intercalated shale in the upper one. The Subathu Formation passes upwards conformably into the overlying argillaceous-arenaceous Dagshai Formation. The latter unit has so far not yielded any age diagnostic fossil. Therefore this unit has tentatively been assigned middle -late Lutetian age. The contact of the Subathu Group with the underlying basement rocks (=Simla Slates) is exposed only around Subathu town and in Arki area. Although good sections of Subathu sequence are exposed around Subathu town and along the Kuthar River, they are often quite disturbed with faulting and isoclinal folding. The best section of its basal and lower parts is exposed along the Lower Koshaliya River near Kalka whereas the best exposures of the middle and upper parts are present along the Upper Koshaliya River near Koti. Nearly complete section of Dagshai Formation is exposed along the Kalka-Shimla Highway between Dharampur and Kheel-Ka-More. Very good exposures of Dagshai Formation are also present in the Lower Koshaliya River Section. Along the Upper Koshaliya River only the lower part of the Dagshai Formation is exposed. Excellent exposures of the Kasauli Formation can be found on Kalka-Shimla Highway between Kumarhatti and Barog, on Kheel-Ka-More-Subathu road, on Garkhal-Dochi-Nambsari road, and on Kalka-Jangeshu-Kasauli road etc.

Traverse details: Code SH – Shimla Hills

Location: SH 01, N: 30^{o}63.398’, E 77^{o}03.319’, Elevation 1681 meters. Kheel Ka More near Kumarhatti

Remarks: The gradational contact between the Dagshai and the Kasauli formations, notable presence of volcanic ash layer and wood logs in the Kasauli sandstones. The basal Kasauli beds comprise brownish yellow sandstone whereas the topmost Dagshai beds consist of purple shales. At this spot a very clear gradational contact between the Dagshai and Kasauli formations is exposed. The topmost beds of the Dagshai Formation comprise purple shales whereas the basal part of the Kasauli Formation consists of brownish yellow medium grained sandstone at the base of which there is a 30 cm layer of yellowish green shale. Between the two formations lies a 5-10 cm thick in-cohesive layer of dirty white clay which has been identified as a tephra (volcanic ash) layer by Mathur et al. (1996) and Arya (1997) based on petrographic and geochemical analysis.

The Kasauli sandstone is hard and compact with at least two sets of joints giving an impression of false bedding. Small and large logs of trees (dark brown color on surface) can be seen just 4-5 meters above the base of the sandstone. The basal sandstone unit is about 50 m thick and it is overlain by a 2 m bed of purple nodular shale (see lithological section in (Figure 3.). The same section continues along the highway as well as on link road that goes towards Subathu and joins the highway at the hairpin bend. On the highway the section continues with progressively younger beds (sandstone-shale cycles) generally well exposed right up to Barog Bus Stand.

Location: SH 02, N: 30^{o}63.662’, E 77^{o}01.433’, Elevation 1493 meters. Dharampur entry near CRPF camp

Remarks: Contact between the Subathu and Dagshai formations. Green and red (transitional) facies of the Subathu Formation is exposed.

Location: SH 03, N: $30^{o}51.339'$, E $77^{o}00.408'$, Elevation 897 meters. Parwanoo - Khaddin - Bhojnagar link road, near the bridge over Koshaliya River.

Remarks: Contact between Subathu and Dagshai formations; green Nummulitic shales of the Subathu Formation; palaeosol zones in the lower part of the Dagshai Formation. Just before the bridge over the Koshaliya River, a bridal path goes upstream (left side of Road, right bank of river). A few meters ahead on the path the contact between the Subathu and Dagshai formations is clearly seen (Figure 3.20). An unusual thing about the contact here is that the topmost red beds (=passage/transitional beds) of the Subathu Formation are missing. The quartzose sandstone marking the base of the Dagshai Formation lies directly above the green Nummulitic shales of the Subathu formation

FIGURE 3.20: Gradational contact between Subathu and Dagshai.

Location: SH 04 N: 30°51.356’, E 77°00.379’, Elevation 889 meters. Lower Koshaliya river bank, about 50 mts from the bridge.

Remarks: Contact between older and younger Subathu formations, Nummulitic limestone of the Subathu (Eocene) Formation. A kutcha track that descends into the river bed about 50 m ahead of the bridge and moving downstream in the Koshaliya River, good exposures of the Subathu Formation are visible.

Location: SH 05 N: 30°51.357’, E 77°00.405’, Elevation 904 meters. Lower Koshaliya river bank, below the bridge

Remarks: Contact between the Subathu and Dagshai formations; passage beds. This spot lies just after the bridge over the Koshaliya River. Here a normal and visibly conformable contact between the Subathu and Dagshai formations is very clearly exposed. White Quartzose sandstone marks the contact (Figure 3.21)

FIGURE 3.21: Sandstone between Dagshai and Subathu Contact

Location: SH 06 N: 30°51.150’, E 77°00.428’, Elevation 894 meters. Lower Koshaliya river bank.

Remarks: Subathu formations black shales (Figure 3.22). Crushed black shale splinters, with thin limestone blocks in between. Samples were taken for source rock analysis from this location.

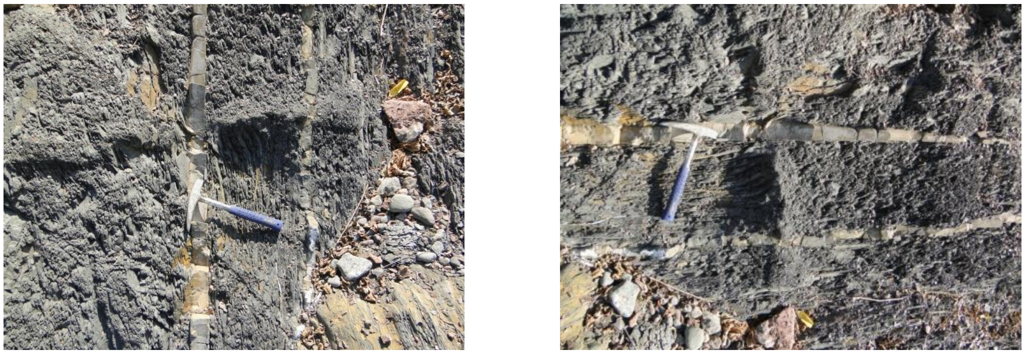

FIGURE 3.22: Crushed Black Shales

Location: SH 07 N: 30^{o}51.128’, E 77^{o}00.385’, Elevation 881 meters. Koshaliya river bank near the pillar of old broken bridge

Remarks: Thrusted contact (Surajpur Thrust/ Koti fault) between the Subathu and Kasauli formations; fossiliferous green (marine) shales of the Subathu formation. Along the thrust there is 10 m thick crushed zone consisting probably of grey shales of the Subathu Formation coming in direct contact of the Kasauli Formation (Figure 3.23). Above the thrust the oldest good exposures of the Subathu Formation comprise grey crumpled/ phyllitic shales with frequent calcareous and siliceous veins.

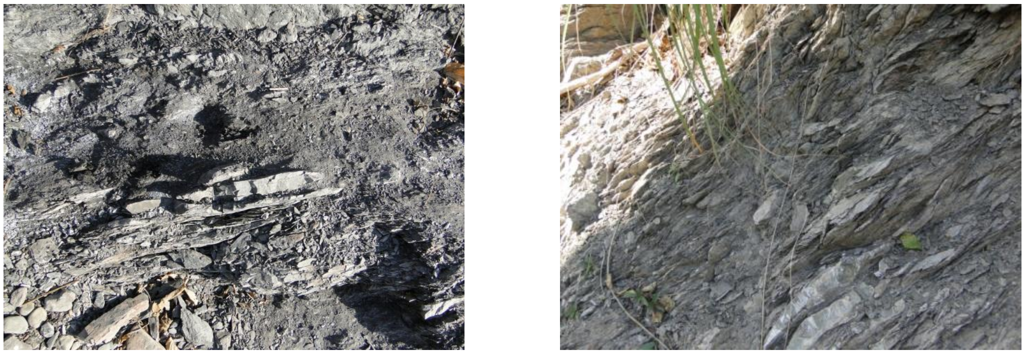

FIGURE 3.23: Crushed Grey Shales at the Surajpur Thrust/ Koti fault

Location: SH 08 N: 30°49.858', E 76°58.059' near the bridge over Koshaliya river the Parwanoo – Khaddin - Bojpur road.

Remarks: Subathu – Dagshai Contact with red facies and greenish grey shales in contact with Quartzose Sandstone of Dagshai. Here a normal and seemingly conformable contact between the Subathu and Dagshai formations is very clearly exposed along the road (Figure 3.24). At the contact we see a 4.5 m thick unit of reddish maroon & Greenish grey shales constituting the top of the Subathu formation and underlying a prominent band of white to greenish white Quartzose Sandstone which marks the base of the Dagshai Formation. Subathu shales samples were taken for source rock evaluation.

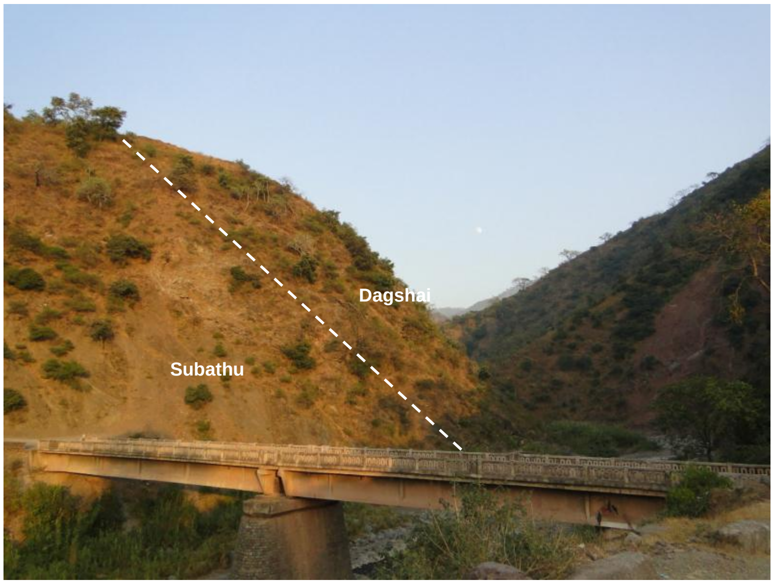

FIGURE 3.24: Dagshai Subathu contact exposed along the road leading to bridge over Koshaliya river.

Location: SH 09 N: 30^{o}49.761’, E 76^{o}57.750’ Elevation 617 meters, located around 200 meters from Kasauli Bridge.

Remarks: Subathu – Siwalik contact (Figure 3.25). At this stop a very clearly exposed thrusted contact between the Subathu (older Tertiary) and Siwalik (younger Tertiary) beds can be seen. This tectonic plane is referred to as Bilaspur Thrust/ Nahan Thrust / Main Boundary Fault. The Siwalik beds at the contact comprise green sandstone with purple shale bands and are generally considered as belonging to the Lower Siwalik Subgroup.

FIGURE 3.25: Subathu – Siwalik contact exposed near the Koshaliya bridge.

Location: SH 10 N: 30^{o}49.909’, E 76^{o}57.891’ Elevation 623 meters, located around 125 meters from the Kasauli Bridge, upper Koshaliya river bank

Remarks: Presence of Subathu greenish Gray blackish shale along with white grey is limestone bands along the river bed (Figure 3.26), samples taken for analysis. The Location and Geological map of Upper Koshaliya River is presented in (Figure 3.27)

(A)

(B)

FIGURE 3.26 (A&B): Subathu greenish Gray blackish shale along with white grey along Koshaliya river.

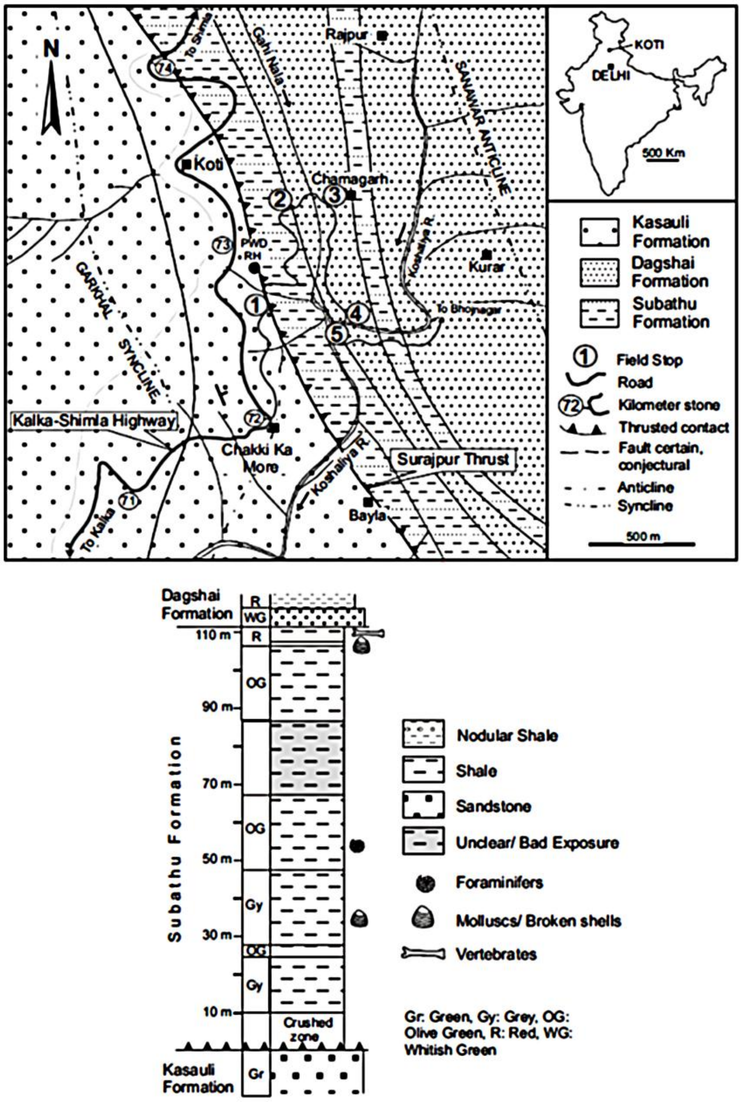

FIGURE 3.27 Location and Geological map of Upper Koshaliya River (Modified after Bhatia and Bagi 1991) and lithological log of Chakki-Ka-More- Gahi Nala bridge road section (after Kumar and Loyal 2006)

Location: SH 11 N: 30^{o} 57.765’, E 76^{o}59.516’ Elevation 1290 meters, Subathu forest guest house.

Remarks: Reference location

Subathu town is situated on top of a synclinal ridge, which has a general strike trending NNW-SSE. The Subathu ridge is flanked by the Kuthar River on its western side and Dabar River on the eastern side (Figure 3.28). The Kuthar starts from near Dharampur, flows along the general strike of the Subathu ridge and joins the Gambhar River (the main river) near Haripur village whereas Dabar follows a zig-zag course approximately in NNW direction and joins Gambhar 0.5 km before Kuthar. Both Dabar as well as Kuthar rivers have exposures of the Subathu Formation but in Kuthar they are more widespread. The Litholog presented in the Figure 3.29 shows the Kuthar river section near the Kanda bridge.

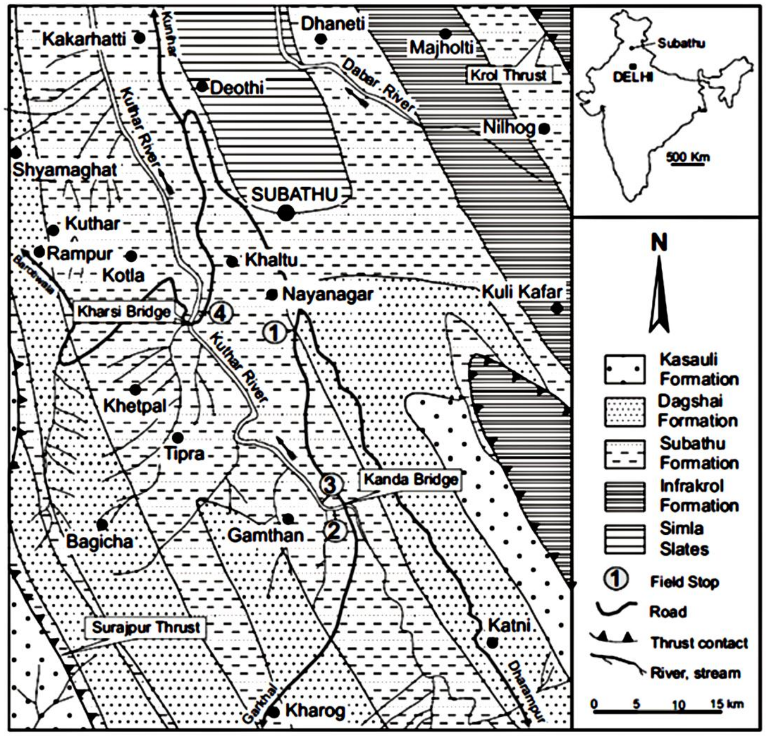

FIGURE 3.28: Location and Geological map of area around Subathu and Kuthar river (After Kumar and Loyal, 2006)

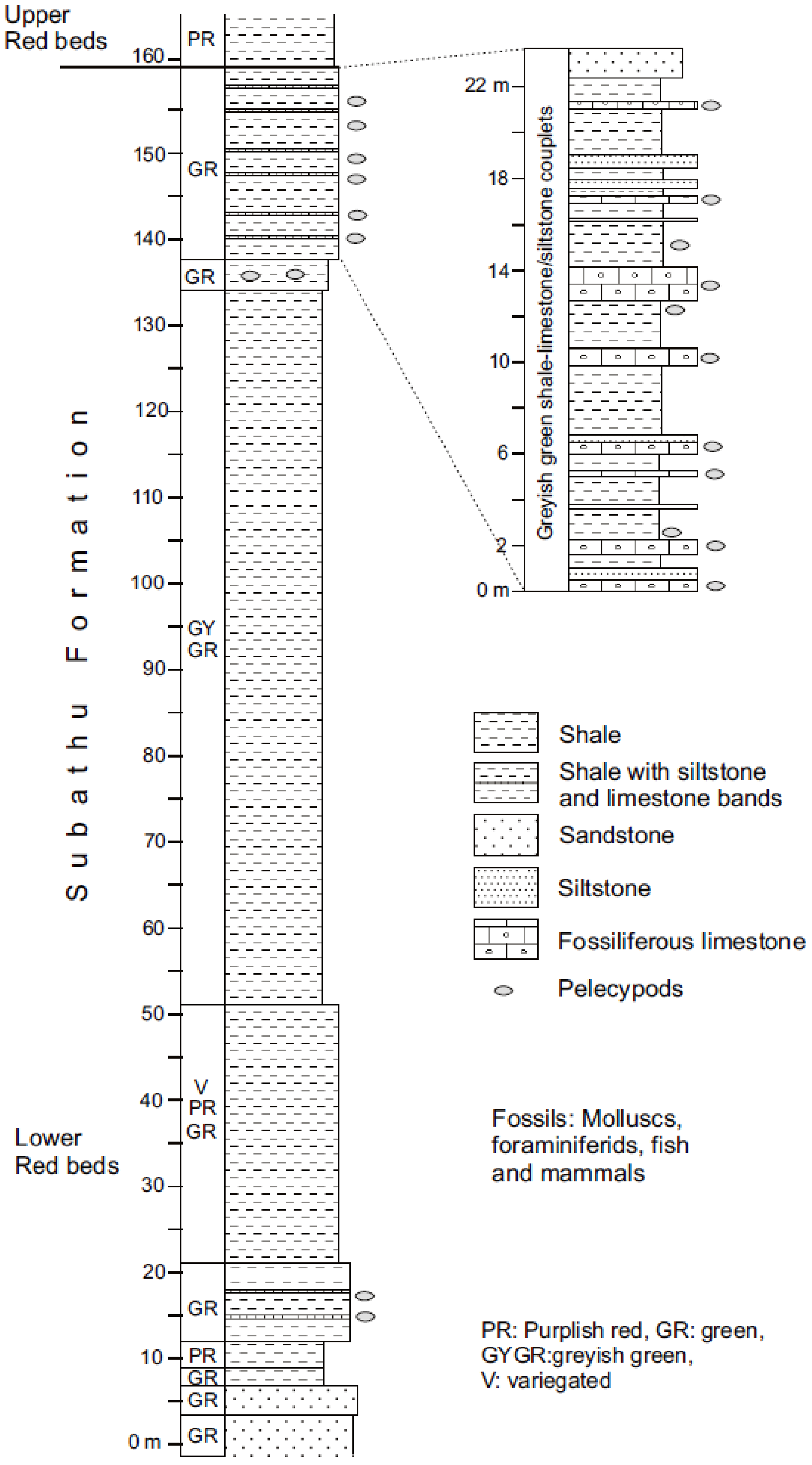

FIGURE 3.29 Litholog of Kuthar River section exposed downstream from Kanda Bridge (After Kumar and Loyal, 2006)

Location: SH 12 N: 30^{o} 56.745’, E 76^{o}59.854’ Elevation 1050 meters, Kuthar River downstream at 100 meters from the Kanda bridge.

Remarks: The location shows red facies (Figure 3.30) of Subathus along with sandstone conglomerate, middle part of Subathu formation.

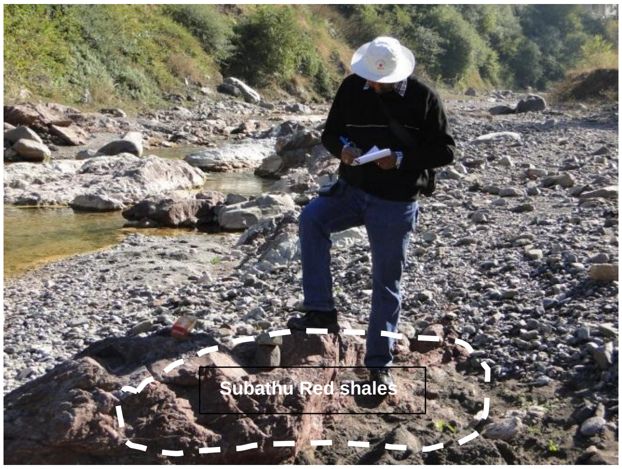

FIGURE 3.30: Red facies of Subathu shale

Location: SH 13 N: 30^{o} 56.749’, E 76^{o}59.805’ Elevation 1043 meters, Kuthar River downstream, left bank.

Remarks: Presence of Greenish grey Subathu shales (Figure 3.31), middle part of Subathu formation, samples collected for maceration

FIGURE 3.31: Greenish grey facies of Subathu shale

Location: SH 14 N: 30^{o} 56.692’, E 76^{o}59.707’ Elevation 1024 meters, Kuthar River downstream.

Remarks: Sandstone blocks, middle part of Subathu formation.

Location: SH 15 N: 30^{o} 56.693’, E 76^{o}59.726’ Elevation 1022 meters, Kuthar River downstream, opposite to water mill.

Remarks: Black Subathu shales, samples taken for source rock analysis

Location: SH 16 N: 30^{o} 56.793’, E 76^{o}59.642’ Elevation 1023 meters, Kuthar River downstream.

Remarks: The location shows the feature of overturning of beds due to folds, depicting heavy tectonic activity in this basin We could see near vertical beds of Subathu shales (Figure 3.32) in the region. Samples were collected for Source rock analysis. The area is heavily disturbed and can find folded rocks namely Shales, Sandstones and pyrites (Figure 3.33) and (Figure 3.34).

FIGURE 3.32: Vertical Subathu shale bed due to overturning of beds along the Kuthar river section.

FIGURE 3.33: Folded rock structure along the Kuthar River due to Tectonic activities.

FIGURE 3.34: Sandstone and Pyrites

Location: SH 17 N: 30° 56.642’, E 76°59.963’ Elevation 1032 meters, Kuthar River upstream, 50 meters from Kanda bridge

Remarks: Green Subathu facies are exposed well in this belt, thick rhythmic sequence of siltstone and calcareous shale/ limestone couplets.

Location: SH 18 N: 30° 56.658’, E 76°59.943’ Elevation 1032 meters, Kuthar River upstream, near Kanda bridge

Remarks: Red Subathu facies are exposed well, samples taken for maceration.

Location: SH 19 N: 30° 58.595’, E 76°59.844’ Elevation 1158 meters, near Subathu Cantonment

Remarks: Subathu beds that can be seen in contact with the Simla Slates that form the basement for the Subathu Formation in the stratotype area. The slates are overlaid by Subathu black shales (Figure 3.35). Contact between older Subathu formation & newer Subathu black shales along with volcanic ash.

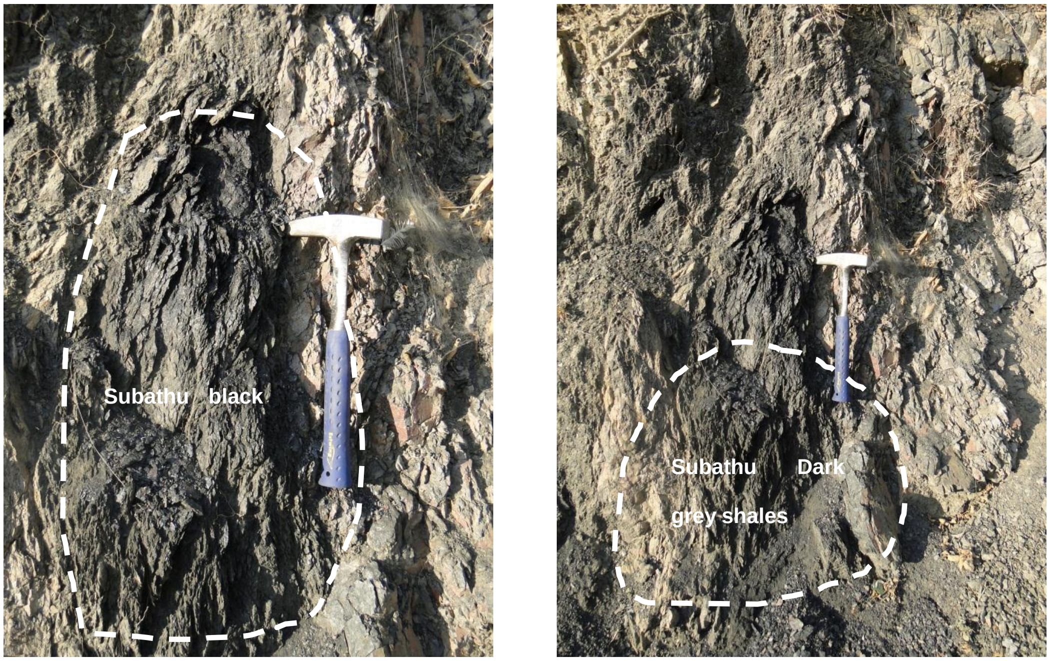

FIGURE 3.35: Subathu Black Shales found along the road section at outskirts of Subathu town.

Location: SH 20 N: 30° 58.595’, E 76°59.844’ Elevation 1165 meters, outskirts of Subathu Cantonment.

Remarks: Think band of Subathu Khakhi shales (Figure 3.36) along with shell limestone is visible in this region, collected Khaki shale samples for source rock evaluation.

FIGURE 3.36: Subathu Khaki Shales found along the road section at outskirts of Subathu town.

CHAPTER 4- BIOSTRATIGRAPHY

4.1 BIOSTRATIGRAHY AND ITS RELEVENCE IN THIS RESEARCH

Biostratigraphy is a significant concept of sedimentary geology created based on the physical zonation bio-elements to establish the relative stratigraphic position (i.e. older, younger, same age) of sedimentary rocks between different geographic localities. The biostratigraphic studies are carried out to identify fossil occurrences and correlate time-equivalent rock strata by the presence of a particular fossil species. The biostratigraphic zonation rules were established in the late 18th to early 19th centuries in Europe resulting in the development of the Relative Geologic Time Scale. The concept is a straightforward study primarily relying on the presence of a specific fossil species in the rock of sedimentary origin. The geographic localities indicate the rocks containing the fossil specimens were deposited at about the same time, thereby establishing rules for correlation. The complexities of biostratigraphy study are due to the complexities of biology of the organisms, preservation, their environmental range and evolutionary rates.

The sedimentary environment presents various fossil groups in land (terrestrial) and sea (marine) environments which are the basis of the biostratigraphic studies.

Land or Terrestrial sediments: The spores and pollen are the primary fossils groups. In case of large sediment samples other fossil groups such as vertebrates or other larger fossils are used and their use is limited to outcrop samples. The amount of oxidation experienced by the sediments after deposition limit the use of spore/pollen fossil group as the Oxygen removes organic material (spores/pollen) from the sediments. The geological time scales ranges for using Spores and Pollen vary from Devonian (approx. 400 million years) to recent sediments for spores and Upper Cretaceous (approx. 80 million years) to recent sediments for Pollens. The incidents of these in marine environment are attributed to transportation though wind (blown into marine environments) in considerable amounts.

Marine sediments: The primary useful groups are the calcareous nannofossils and can indicate time zones between Jurassic (approx. 210 million years) to recent sediments. The stratigraphic resolution resulting out of the calcareous nannofossils are high though the cost of preparation is cheap. These sediments are sometimes leached of calcareous particles, thereby removing calcareous nannofossils along like in deep sea sediments). Some species are associated with warm or cold water masses and can be used as limited environmental indicators.

Palynomorph: Acritarchs, Dinoflagellates, and Tasmanites are identified in most of sediment types with the exception of chalky limestone in Permian (approx. 260 million years) to recent sediments. Though the Stratigraphic resolution is high, the preparation is complex and involves dissolution of the surrounding sediments and is more expensive than nannofossils. The use of organic grain size and shape as environmental indicators are developed recently enabling it to be more useful in sub-recent sediments.

Foraminifera: Used in Shallow marine to middle bathyal, typically in the marine sediments and has unleached calcareous material present. They are good water depth environment indicators and the stratigraphic resolution can be high. They are found in sediments of Cambria to recent age. Unless thin-sections have to be used, their preparation cost is lower than that of Palynomorphs.

Silica enriched sediments: Siliceous microfossils such as diatoms and radiolarians can be of use. Preparation cost is high, Stratigraphic resolution can be high; it's under development for the other timeframes except Tertiary (approx. 65 million years).

The Biostratigraphic study is a critical component of this research aimed to identify the source rock of the Himalayan Hydrocarbon. It helps to study the fossils to identify the stratigraphic sequence in the highly tectonized Lesser Himalayan zone. The age, Palinspastic reconstructions, rock structure and its possible chemical compositions and structural complexities are studied leveraging the biostratigraphic information. The bio zones identified and documented by various researchers are used to correlate the findings with the biostratigraphic studies done in the Himalayan region.

In the Lesser Himalayan region, the Maastrichtian-early Lutetian sequence is represented by the Kakara-Subathu sequence in the Himachal Pradesh and Garhwal regions. The Kakara Formation has previously been named as the 'Kakara Series' in the Himachal Pradesh region and as the Bansi Formation/Singtali Limestone/Shankerpur Formation/Nilkanth Formation in the Garhwal region (Juyal and Mathur 1990, Mathur and Juyal 2000 and references therein). Some of the biostratigraphic aspects of the Kakara-Subathu sequence have been tackled by Datta et al. (1965), Bhandari and Agarwal (1967), Mathur (1977c. 1978), Bhatia (1982), Juyal (1988), Batra (1989) and Juyal and Mathur (1990, 1994), among others.

The three main formations which were studied elaborately as part of the search for identifying the source rock are Dagshai, Kasauli & Subathu formations.

In recent years, abundant, well preserved and varied plant fossils including monocot and dicot leaves, charophytes, flowers, buds, inflorescences, seeds, tree trunks and roots) have been reported from the Kasauli Formation though initial occurrences were recorded as far back as 1882 (Fiestmantel 1882, Arya and Awasthi, 1994, 1996, Mathur et al. 1996, Arya et al. 2001). Animal fossils recorded from the Kasauli include gastropods, pelecypods and a lone rhinocerotid (Mammalia) tooth fragment (Arya et al. 2004, 2005). The plant fossils include *Poacites* sp., *Sabalites* sp., *S. microphylla, Fissistigma shankerii, Mesua tertiara, Kayea, Murraya khariensis, Schleichera* sp., *Milletia singhii, Milletia* sp., *Dalbergia daghotaensis, D. umeshii, Cassia dayalii,C. satsangii, Bauhinia krishnanunii, Diospyros barogensis, Tabernaemontana misraii, T. sahnii, Persea sibdasii, Litsea sastryi, Ficus kasaulica, F. barogensis, Dicotylophyllum* sp., *Carpolithus* spp. (Mathur et al., 1996). Charophytes are represented by *Lychnothamnus kasauliensis* (Arya, 1998) and Characeae gen. et sp. indet. (Mathur et al., 1996).

Based on occurrence of the pelecypod Unio and the palm Sabalites, the Kasauli Formation is considered to be of a Lower Miocene age. The high sandstone to shale ratio in Kasauli Formation is suggestive of a more braided fluvial regime while the presence of more lithic fragments indicates greater sediment supply (Najman et al. 1994). The Kasauli flora including the large wood logs indicate humid, subtropical to tropical conditions under non-arid setting. Flora with rich foliage is suggestive of a moist tropical forest environment with increased precipitation (Mathur et al. 1996). The energy conditions apparently fluctuated almost throughout the Kasauli deposition from high (indicated by medium coarse grained sandstone with large wood logs) to very low (indicated by very fine siltstone and shale with the most delicate organic matter – the flowers, buds and inflorescences). Whereas the occurrence of mostly unbranched and unrooted large wood logs in the sandstone is indicative of considerable transportation requiring lot of energy, the preservation of flowers demonstrate zero transportation and on the spot burial quick enough to escape decomposition. The preservation of flowers is suggestive of deposition in a pond, lake or abandoned channel, which had a steady and ample sediment influx. (Arya 1997).

4.2 SUBATHU FORMATION

The Subathu formation was deposited between the initial and terminal phases of India-Asia collision, and this unit and the overlying succession represent southward pro-grading foreland basin successions related to progressive stages of the continental collision (Najman et al 1994).

The biozones classification of Subathu formation by N.S Mathur (1978) on the basis of fauna and lithology of the seven identified blocks, namely (1) Morni block, (2) Garkhal block, (3) Subathu block, (4) Kurla block, (5) Arki block, (6) Nilkanth block, and (7) Dogadda block divides the formation into nine zones, viz. zones I-IX (in ascending order). The age of these zones are classified as Zone I - Upper Paleocene (Montian-Thanetian), zones II to V -Lower Eocene (Ypresian) , and zones VI to IX - Middle Eocene (Lutetian) age .Zone III has been subdivided into three subzones, viz. IIIa , IIIb , IIIc (in ascending order) while zone V has been subdivided into two subzones, viz. Va and Vb (in ascending order).

ZONE I: Age Upper Paleocene.

The lowermost zone, viz. zone I, represents Upper Paleocene beds Montian and Thanetian. The zone is exposed in Morni, Subathu, Kurla, Arki, Nilkanth and Dogadda blocks. Kurla shows the thickest (16m) formation. The Subathu and Kurla shows this zone overlying Simla Slates with unconformity with junction marked by thin bed of pisolitic laterite of inconstant occurrence. In Nilkanth and Dogadda blocks they over lie on Cretaceous lower Paleocene Tal-formation with unconformity marked by bed of laterite/ferrugineous shale of impersistent occurrence. The zone is divisible into two parts. The lower part, carbonaceous shales occur in the Morni, Subathu, Kurla, Nilkanth, and Dogadda blocks. The upper part is fossiliferous and developed evidently in Kurla and Dogadda.

Zone II: Lower Eocene

This is the lowermost zone of Lower Eocene age and is exposed in the Morni, Subathu, Kurla, Arki, Nilkanth, and Dogadda blocks, it transitionally succeeds zone I of Upper Paleocene .In the Subathu and Arki blocks, and it is composed of fossiliferous glauconitic grey shaly limestone and in Dogadda block Shales and Sandstones. Unfossiliferous green to grey shales in the Morni and Nilkanth blocks and sandstones in the Kurla block probably correspond to fossiliferous equivalents of this zone in other blocks.

Zone III: Lower Eocene

This is zone of Lower Eocene age and is exposed in the Morni, Subathu, Kurla, Arki, Nilkanth, and Dogadda blocks. This zone is further divided in to 3 sub-zones, IIIa, IIIb, and IIIc (in ascending order). Sub zones IIIa and IIIb are composed of shales and shelly limestones with subordinate Sandstones. The fossil content of both the subzones is more or less similar but in sub-zone IIIc, it shows a marked decrease in the comparison to subzone IIIa. The middle sub-zone IIIb is characterized by unfossiliferous red and green shales. In the Subathu and Morni blocks, carbonaceous and pyritic shales occur. Arenaceous facies is also prevalent in the Kurla, Nilkanth, and Dogadda blocks.

Zone IV (Lower Eocene).

This zone is exposed in all the blocks. In the Garkhal, Subathu, Kurla, Nilkanth, and Dogadda blocks, the zone is composed of green to grey shales

Zone V (Lower Eocene).

This is a richly fossiliferous zone in the Subathus of the Kumaun Himalaya and is exposed in all the blocks. The zone is further divided into two subzones, Va and Vb (in ascending order). Subzone Va is composed of shales which are carbonaceous in the Morni block. Arenaceous facies in the Subathu and Arki blocks, Calcareous facies in the Subathu, Garkhal, and Arki blocks. Subzone Vb generally comprises of green to grey shales arenaceous facies in the Morni, Subathu, and Kurla and Arki blocks. Calcareous facies in the Morni, Subathu, Garkhal, Nilkanth and Arki blocks

Zone VI (Middle Eocene).

The Zone VI succeeds underlying Zone V which is fossiliferous in the Morni and Garkhal blocks. The unfossiliferous beds are found in Subathu, Kurla, Arki and Dogadda blocks. It also has of a thin band of hard fossiliferous limestone in the Morni and Garkhal blocks. This band is followed upwards by fossiliferous siltstone and shales in the Garkhal block

Zone VII (Middle Eocene).

It is composed predominantly of shales with thin bands of limestones in the Morni and Garkhal blocks.

Zone VIII (Middle Eocene).

It is well developed in Subathu, Garkhal, Arki and Kurla blocks. It predominantly has red to green shales and green to grey limestone. Shelly limestone occurs in the Subathu, Kurla, and Arki. Arenaceous facies is prevalent in the Subathu and Kurla blocks

Zone IX (Middle Eocene)

This zone represents the passage beds which are intermediate between true Subathus and true Dagshais. This zone is well developed in the Subathu, Kurla, and Arki blocks and has red and green shales which are Arenaceous in the Subathu block. Red and green sandstones are intercalated with the shales in the

Subathu block. The top of the Subathu formation is composed of grey to white quartzitic sandstone and is seen in Morni and Garkhal blocks. In the Garkhal block, the Subathu has a bed of intra formational conglomerate at the top. In the Subathu block, these beds are missing and the passage beds of zone IX pass into the Dagshais through alternations of sandstones, siltstones, and red nodular shales.

The further study of biostratigraphic successions in the Himalayan foothills belt suggests that marine conditions commenced in Maastrichitian and continued till early Leutian during which the Kakara-Subathu succession was deposited. During deposition of the Subathu sediments, there was a minor regression of the Tethys in the early late Ypresian times. The second and final regression took place in the early Lutetian times. These two regressive phases are evidenced by bio zones containing fresh to brackish water taxa namely Seila, Physa, Aplexa and thin shelled oyster (molluscs); Neocyprides and Iiyocypris (Ostracades); and Chara fruits. The first regression is related to collision between the two plates which resulted in uplift of the region in the early Late Ypresian times during which the beds of Cordiopsis subathooensis-turritella subathooensis Zone (Zone IV) were deposited.

The second regression which took place in early Lutetian times (-47 Ma) is also attributed to the uplift of the region due to continued collision between the two plates during which the beds of *Musculus nuttalli-Parinomya blandfordiana* Zone (Zone VIII) were deposited The beds of upper part of this zone have been named as the Subathu –Dagshai passage beds by Bhatia and Mathur (1965) These beds comprise mainly of purple siltstone / shale with calcareous nodules and at the places with Oyster bands and/or bone beds lie between the youngest Chalmys, *Bicorbula* and *Venericardia* – bearing Olive green shale and the overlying distinct quartzitic sandstone (Quartzarenite) forming base of Dagshai / Murree succession. It's therefore obvious that the Subathu Sediments were laid down during the last phase of Tethys in the Himalayan foot hills belt. The regressive phase is reflected by the lithological and facies variations as well as faunal assemblages (both vertebrates and invertebrates) (Mathur 1978 ,1997 ;Sahini et al 1983; Juyal 1997) However in certain sections (eg Garkhal section) during deposition of beds of this zone marine conditions continued as indicated by the occurrence of *Nautilus, Cordiopsis, Venericardia, Hermanates, Alocopocythere* and miliolids among invertebrates (Mathur 1969 ,1979 , Juyal and Mathur 1994) and of Sharks and rays among verbrates.

Based on invertebrate fauna, Mathur (1978) correlated the Subathu sediments of the Simla Hills region with those of the Laki Type Section (Ypresian) of Sind and Baluchistan with some forms similar to Kirthar (Lutetian) assemblage. In a comprehensive biostratigraphic work, Mathur and Juyal (2000) have delineated eight faunal assemblage zones (Zones I to VIII in ascending order) in the Kakara-Subathu succession. The faunal assemblage zones and their ranges as given by Mathur and Juyal (2000) are tabulated below

TABLE 4.1: Faunal Assemble zones, after Mathur and Juyal 2000.

Litho Unit	Zone #	Zone Name	Age
Subathu Formation	VIII	*Musculus muttalli-Parinomya Blanfordia*	Early Lutetian
	VII	*Assilina spira abrardi*	Early Lutetian
	VI	*Assilina laxispira-A. placentula grande*	Late Ypresian
	V	*Nummulites rotularius –Steginoporella*	Late Ypresian
	IV	*Cordiopsis subathooenisis-Turritella subathooenisis*	Late Ypresian
	III	*Nummulites burd.burdigalensis.-N.subramondi*	Late Ypresian
Kakara Formation	II	*Daviesina tenuis –Lockhartia conditi*	Thanetian-E Ypresian
	I	*Diplocava nilkanthi*	Maastrichtian-Danian

The lithological characteristics and significant fossils of different faunal zones of the Kakara-Subathu succession of the Subathu (Himachal Pradesh) are given in Table 4.1 (Mathur and Juyal 2000). The Subathu beds are profusely rich in fossils of diverse fauna and flora including pelecypods, gastropods, ostracodes, foraminiferids, scaphopods, anthozoans, bryozoans, nannofossils, fishes, reptiles and mammals. The plant fossils are represented mainly by charophytes and palynofossils.

The Subathu Group’s deposition of basal black-grey unit was probably initiated under coastal marshy conditions in a reducing environment, indicated by the formation of coal seams (N. Siva Siddaiah and Kumar, 2007), Figures 4.1 and 4.1 and presence of foraminifers.

FIGURE 4.1: Panoramic view of basal part of Subathu Formation showing BST and bounding coal seams, after N. Siva Siddaiah and Kumar, 2007

FIGURE 4.2: Enlarged view of basal part of Subathu Formation showing sharp contact of BST with the lower coal seam, after N. Siva Siddaiah and Kumar, 2007

The dominance of foraminiferids, ostracodes, echninoids and marine vertebrates including sharks, rays, tetraodonts, pycnodonts, etc in the green shale-limestone unit or the middle part of the Subathu Group indicates the formation to be predominantly marine. The oyster-bearing coquinites at the top indicates brackish water conditions gradually changing into fresh water environment during the deposition of upper Subathu red beds. The bone bed at the top of green shale-limestone unit also shows a mixing of typical marine and continental vertebrates. Some land dwelling vertebrate elements have also been found in the red beds occurring in the middle of this unit (e.g. in Kuthar section). These red beds just like the upper red beds are also preceded by some oyster limestone bands. The presence of red beds (older red beds occurring within green unit) with terrestrial vertebrates in the middle of green shale-limestone unit suggests a regressive phase of considerable duration. These red beds represent the oldest continental beds of the Palaeogene basin and show evidence of bioturbation. Although the green shale-limestone unit was a dominantly marine facies, near shore and tidal flat conditions with proximity of terrestrial habitats did prevail at times and particularly during the accumulation of older red beds. The red bed unit in the upper part of the Subathu Group (younger red beds) marks the onset of continental conditions in the Palaeogene basin, which was gradually transgressing the Tethyan shoreline following the withdrawal of this sea. This is suggested by the complete dominance of land dwelling and fresh water vertebrates in well-marked bone beds, which are traceable in several localities of Himachal Pradesh, Jammu and Kashmir as well as across the border in Pakistan.

Based on extensive palaeontological studies the Subathu Formation is generally considered to be ranging in age from Late Paleocene (Thanetian) to lower part of Middle Eocene or Lutetian (e.g. Mathur, 1978, Bhatia 1982, Kumar and Sahni

1985, Batra 1989, Jafar and Singh 1992, Kumar et al. 1997, Kumar 2000, Mathur and Juyal 2000, Bhatia and Bhargava, 2005). The basal fossiliferous shales of the succession, in most sections, yield characteristic index fossils of the *Daviesina tenuis-Lockhartia conditi* assemblage zone (Mathur and Juyal, 2000) indicating a Thanetian age. However, some sections also extend into the Early Paleocene (Danian) and Late Cretaceous (Maastrichtian). For example in the Nilkanth section of Uttaranchal, the oldest fossiliferous beds of the succession have yielded a typical Late Cretaceous bryozoan, *Diplocava nilkanthi* suggesting a Maastrichtian age. In Shimla Hills the oldest datable horizon of the Subathu succession is characterized by the presence of *Daviesina garumnensis* (SBZ 4); it is exposed around Kurla and Halog areas near Subathu (Mathur 1997, Bhatia and Bhargava, 2005). In other sections the basal Subathu beds are younger indicating a diachronous nature of Paleocene-Eocene transgression and or uneven basin configuration. A major part of the Subathu Formation represented by the grey green Nummulitic shales and seen in most of the sections (including upper Koshaliya and Kuthar) is of early Cuisian (SBZ 10, characterized by the occurrence of *Nummulites burdigalensis*) to middle Lutetian age (Bhatia and Bhargava 2005). The early Lutetian (SBZ 13) is marked by the presence of *Assilina spira abrardi* in beds about 20 to 50 meters below the top of the formation. The upper age limit of the Subathu Group is considered as Lutetian based on invertebrate fossils of faunal Zone VIII of Mathur and Juyal (2000), charophytes (Bhatia and Bagi 1991) and the mammalian fauna, including rodents (Kumar and Sahni, 1985; Kumar et al., 1997). However, according to Blondeau et al. (1986) the upper age limit for the Subathu Formation is Early Eocene or Ypresian, which he recorded from Jammu area.

Lakshmi and Sudheer Kumar (2001) based on magneto stratigraphic study of a 528 m thick section of Subathu Formation near Kalka in Himachal Pradesh estimated the age to be ranging from 61.50 to 43.70 Ma. Similar study by Pangtey (1999) also support the biostratigraphic ages.

The present study of the biostratigraphic sequences suggests that faunal similarity in these zones became apparent from Thanetian onwards. In this period, the Tethys separating the Indian and Eurasian plates became narrow enough for free migration of the benthic fauna. Shallow marine conditions, in general, existed up to the lower part of late Ypresian, upper part of late Ypresian and early Lutetian in the Indus Suture, Zanskar Tethyan and Lesser Himalayan zones respectively. This was followed by regression of the sea from these zones.

In the Himachal Pradesh and Garhwal regions of the Lesser Himalaya, the Kakara--Subathu sequence was deposited by a transgressive sea during the latest Maastrichtian to early Lutetian times. However the middle and top parts of the Subathu Formation contain several brackish to fresh-water fossils, namely *Seila, Physa, Bullinus,* and oysters (molluscs); *Neocyprideis and lIyocypris* (ostracodes); and chara fruits. This indicates that the middle and top parts of this unit were deposited in brackish water conditions during the regressive phases. The first regression may be related to collision between the two plates along the Indus Suture zone which led to uplift of the region in the beginning of late Ypresian. This regressive phase was short lived as the transgressive phase continued till the basal Lutetian times. The final regression of the sea from this zone took place in the early Lutetian times during which the top part of the Subathu Formation was deposited. This regression from the Lesser Himalayan zone has also been attributed to uplift of the region as a result of collision between the two plates as interpreted by Sahni et al, (1983). However Mathur (1977b, 1979) and Juyal and Mathur (1994) have reported the occurrence of shallow marine fauna from the top part of the Subathu Formation in a few areas. It is, therefore, interpreted that in the Lesser Himalaya remnants of the Tethys were left even after the final regression of the sea during early Lutetian times.

Geological and Palynological information shows Subathu Formation was deposited under shallow marine conditions and lies unconformably over the pre-Tertiary rocks. The sediments of Dagshai and Kasauli formations were deposited under coastal-transitional and fluviodeltaic conditions. The Palynological study of this area identifies the lower part of the Subathu Formation, by the presence and abundance of *Hystrichosphaeridium* and *Cleistosphaeridium*-complexes. This part denotes the transgressive phase of the Eocene sea. The upper part of the Subathu sediments is characterized by the presence and abundance of Thalassiphora-complex or trilete spore complex, marking the regressive phase of the arm of the epicontinental sea. The Subathu sediments contain poor to well-preserved Palynomorph assemblages (Table 4.2). The assemblages, though not much diversified in variety, consist of ystrichosphaerids, pteridophytic spores, gymnospermous and angiospermous pollen grains together with algal remains. (Singh and Khanna, 1977)

TABLE 4.2: Distribution of Palynomorph complexes in the Palaeogene Sediments of Subathu Formation modified after Singh and Khanna 1977.

1	*Hystrichospharidium Complex*	40%
2	*Cleistoophaeridium Complex*	37%
3	*Thalassiphora Complex*	30%
4	*Cyclonephelium*	27%
5	Trilite Complex	82%
6	*Inaperturopollenites Complex*	15%
7	*Podocarpdites Complex*	10%
8	*Palmaepollenites Complex*	10%
9	*Pediastrum*	20%
10	Colporate pollen complex	10%

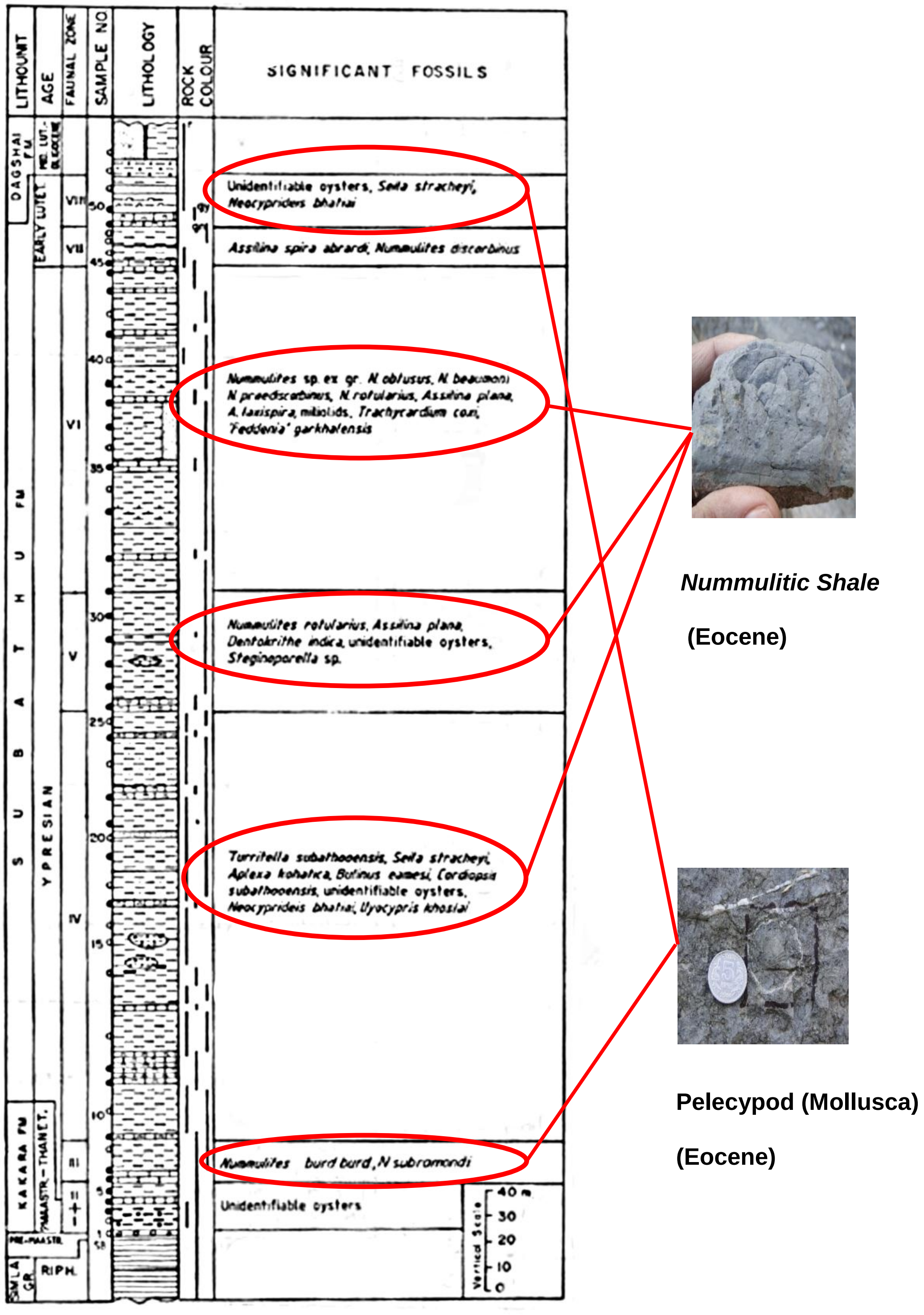

FIGURE 4.3 Biostratigraphy successions at Subathu Modified after Mathur, 1969, 1978, 1977, July 1998, based on the fossils found in the field.

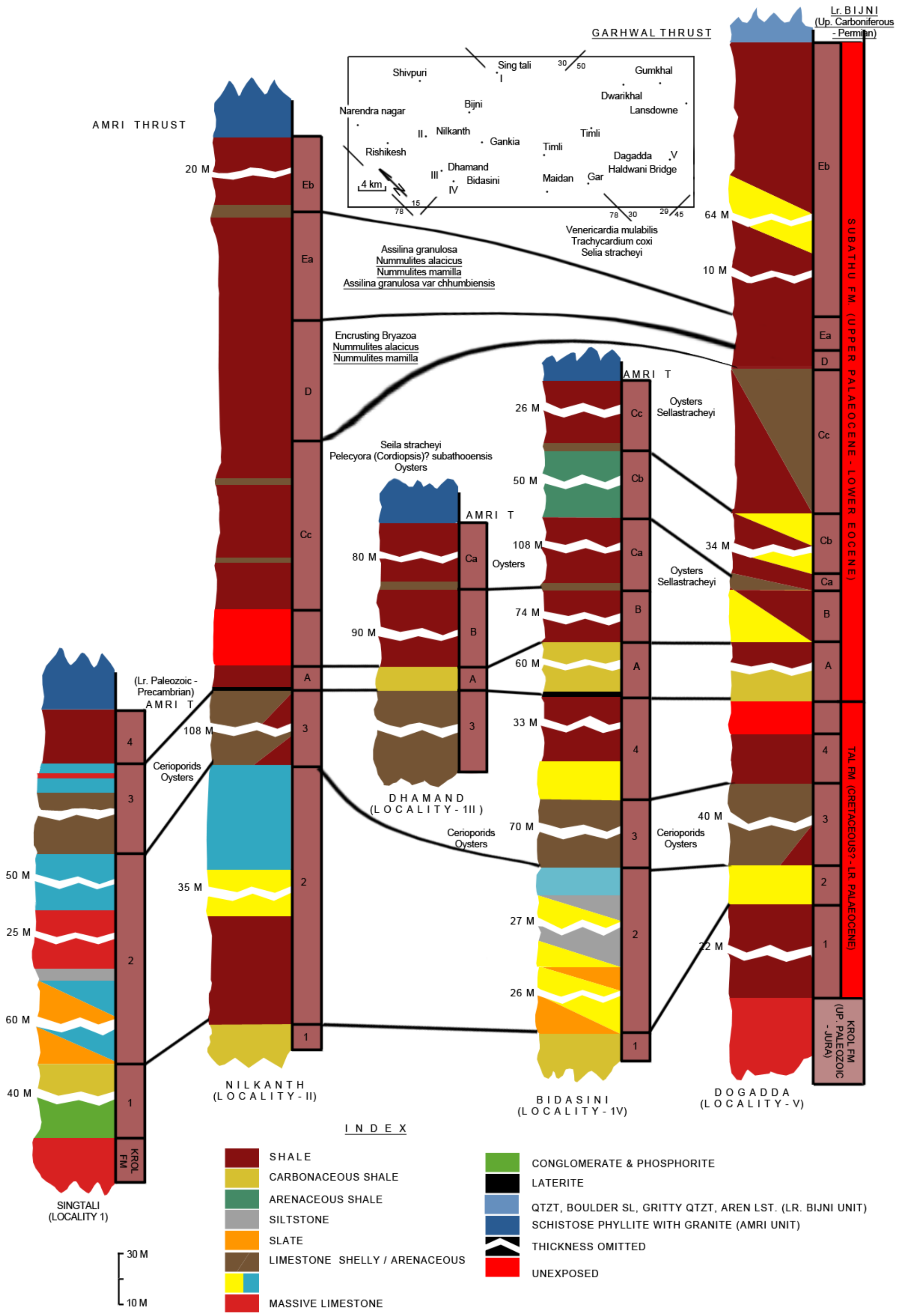

FIGURE 4.4 Biostratigraphy & Lithological Correlation between Subathu formations at Nilkanth, Bidasini & Dogadda

4.2.1 BIOSTRATIGRAPHY FIELD STUDY / TRAVERSE

The biostratigraphy study was carried out in the Nilkanth, Bidasini Dogadda and Shimla hills and the combined Biostratigraphy & Lithological Correlation of Subathu formation is depicted in the Figure 4.4

4.2.1.1 Dogadda

In the Garhwal region, the Tal Formation is succeeded upwards by the Subathu formation. The region has few interesting fossils, Pant and Iqbaluddin (1962) suggested the occurrence of Ranikot, Laki, and Kirtar stages in Simla-Garhwal region on the basis of larger foraminifers. Tewari and Kumar (1967) recorded *Dictyoconoides vredenburgi* (Davies), *Nummulites atacicus Leyrnerie, N. subatacicus* Douville, and *Assilina subspinosa* Davies. Tewari and Singh (1976) have assigned an Upper Paleocene to a Lower Eocene age to the Subathus of the Dogadda area on the basis of *Operculina patalaensis* Davies, *Nummulites c f. mamilla* (Fichte l and Moll), *N.atacicus* Laymerie, and *Assilina granulosa*. The Generalized biostratigraphic Section of Nilkanth Dogadda region is given below in the Table 4.3

In the Subathus of the region, the association of *Operculina patalaensis* Davies and *Nummulites mamilla* (Fichte l and Moll) in the lowermost zone, viz. Zone A, suggests an Upper Paleocene age. This association has been recorded from the Upper Paleocene beds of Pakistan by Davies and Pinfold (1937) and from the Subathus of the Dogadda area -by Tewari and Singh (1976). The first appearance of *Nummulites atacicus* Leymerie in Zone B indicates the beginning of Lower

Eocene. The occurrence of *Assilina granulosa* 'd' Archiac), *A. granulosa* var. *chhumbiensis* Gill, and *Dictyoconoides vredenburgi* (Davies) in the uppermost zone, viz. Zone E, suggests a Lower Eocene age. Thus the overall evidence indicates the age of Subathu Formation in the Garhwal region to be between Upper Paleocene to Lower Eocene.

TABLE 4.3 : Generalized bio Stratigraphic Section of Nilkanth Dogadda ,After Singh 1980

FM.	Age	Characteristics
Subathu Formation	**Lower Eocene**	**Zone E:** Grey to green shale and siltstone with *Assilina granulose* (d' Archiac), *A.granulosa* var. *chhumbiensis* Gill, *Nummulites atacicus* Leymerie, *N. mamilla,* (Fichtel and Moll), and *Dictyoconoides vredenburgi* (Davies) in the lower part (Subzone E a); red to green shale, sandstone, and shelly limestone with *Pelecyora (Cordiopsis)? subathooensis* (d' Archaic and Haime), *Venericardia (Glyptoactis*) *mutabilis* (d' Archiac and Haime), *Trachycardium coxi* Mathur, *Seila stracheyi* (d' Archiac Haime), and 'Turritellids?' in the upper (subzone Eb). **Zone D:** Green shale with *Nummulites mamilla* (Fichtel and Moll), *N. atacius* Leymerie, and unidentifiable Bryozoa. **Zone C:** Green to grey shale and shelly limestone with *Seila stracheyi* (d' Archiac *and* Haime), 'Turritellids ?', oysters, and *Venericardia* (*Glyptoactis*) *mutabilis* (d' Archiac *and* Haime) in the lower part (Subzone Ca); red to green unfossiliferous shale in the middle (subzone Cb);and grey shale and shelly limestone with oysters, *Pelecyora (cordiopsis) ? subathooensis* (d' Archaic and Haime), *Venericardia* (*Glyptoactis*) *mutabilis* (d' Archiac and Haime), and *Seila stracheyi* (d' Archiac Haime) in the upper (subzone Cc). **Zone B:** Green to grey shale and limestone with *Nummulites mamilla* (Fichtel and Moll), *N. atacius* Leymerie, and shell fragments

	Upper Paleocene	**Zone A:** Laterite and grey carbonaceous shale in the lower part and green to grey shale with *Operculina patalaensis* Davies, *Nummulites mamilla* (Fichtel and Moll), and *Seila stracheyi* (d’ Archiac Haime) in the upper.
		UNCONFORMITY
Tal Formation	(Cretaceous?-Lower Paleocene)	***Member 4 :*** Greenish grey shale with lenses of fossiliferous limestone (“Pundrasu shale” of Dhaundiyal and Kumar, 1976) ***Member 3:*** Compact shelly and frequently oolitic and arenaceous limestone with broken shell fragments, oysters, Cerioporids, Echinoid spines, and algae. ***Member 2:*** Grey sandstone often quartzitic with interbedded grey slate and greywacke, and purplish micaceous siltstone. ***Member 1:*** Grey carbonaceous shale often phosphatic and intraformational conglomerates.

4.2.1.2 Nilkanth

Traverse Details: Code NL – Nilkanth

Location: NL 01, N: 30^{o}07.347’, E 78^{o}21.650’

Remark: Uphill track on the Rishikesh Nilkanth road. The limestone does not show presence of fossils, presumably indicating Tal formation.

Location: NL 05, N: 30^{o}04.813’, E 78^{o}20.662’

Remark: Near Nilkanth Mahadev temple. The lower part of the Subathu Formation has yielded *Diplocava nitkanthi* (Singh)-a cyclostomatus bryozoan-and a number of other fossils of Maastrichtian age (Mathur 1977c; Bhatia 1980; Singh 1980). This unit has yielded a rich assemblage of larger benthic foraminifera and molluscs (Bhatia and Mathur 1965; Mathur 1975, 1977a) indicative of Ypresian-Lutetian age. The larger foraminifera are of great chronostratigraphic value.

In this section only three zones, namely *Nummulites burd. burd.-N. subramondi, Cordiopsis subathooenis- Turritella subathooensis and N. rotularius- 'Membranipora',* have been encountered

Traverse Details :Code RB – Rishikesh/ Bidasini

Location: RB 04, N: 29^{o}59.853', E 78^{o}19.417'

Remark: Upstream on the banks of the river channel flowing from Rishikesh.

The Subathu Formation in this area consists of silty shales, oyster-bearing limestones, green and purple splintery shales which were deposited during the transgressive phase of the Subathu epicontinental sea. Fossil cyanobacteria were recovered in these sections from the dark laminae of the grey-coloured horizon. It consists of dense fibriller network of filaments of Palaeoscytonema and nodular colonies of Gloeocapsomorpha prisca; the light-coloured laminae are rich in silt-sized clastic substances. The dark brown laminae of the laminated shales showed presence of fossils. The sediments which yielded Palaeoscytonema are dated as the early Ypresian on the basis of foraminifera (Mathur, 1977c).

The occurrence of *Palaeoscytonema* in association with colonies of *Gloeocapsomorpha prisca* (Zalessky, 1917) showing affinity to *Entophysalis* in the lower horizon of the Subathu succession clearly indicates that these sediments were probably laid down in a tropical, intertidalsupratidal zone during the initial phase of transgression of the Subathu epicontinental sea in this area. Well-preserved trichome, parallel laminations in the sheath as well as hormogones of Palaeoscytonema clearly indicate a favorable environment of fossilization during the deposition of these rocks. We are of the opinion that warm and humid climate and reducing environment are the two major factors that provided ideal conditions for the growth and preservation of this cyanobacterium in the Subathu sediments.

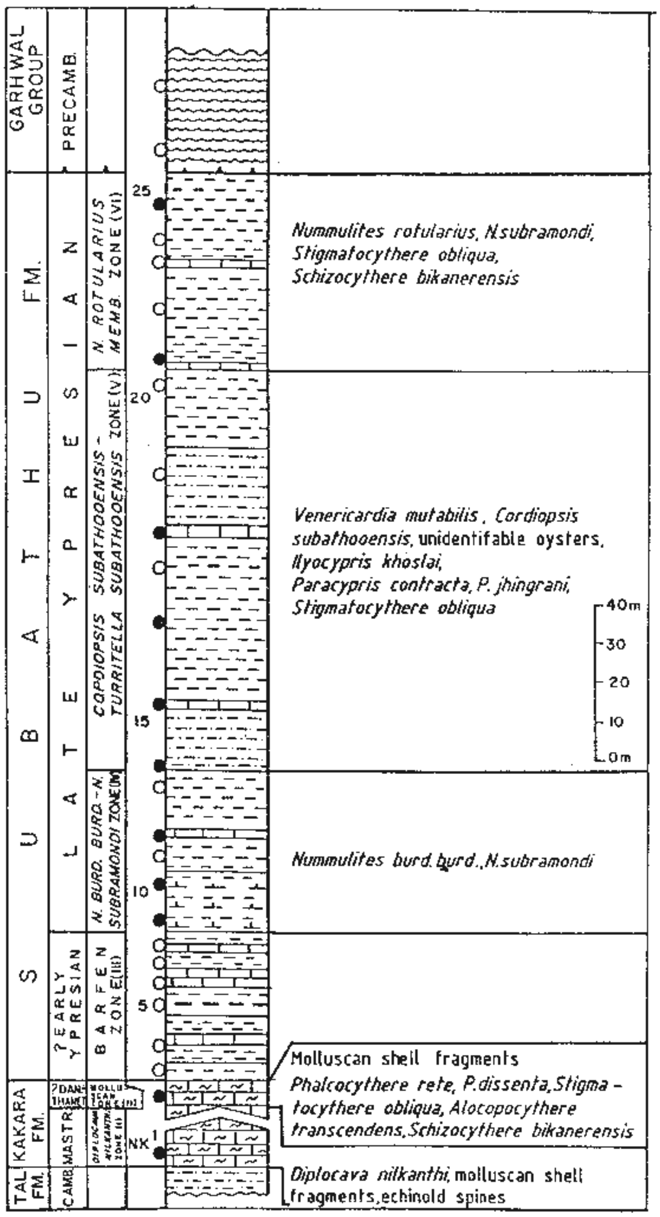

FIGURE 4.5 Biostratigraphic succession of the Nilkanth Section (after Mathur, 1997)

4.2.1.3 Shimla Hills

In the Simla Hills region good sections of the Kakara, Subathu, Dagshai and Kasauli formations are exposed in the Dharampur, Subathu, Garkhal, Dagshai and Kasauli areas The Kakara Formation comprises carbonaceous shale in the lower part and hard massive limestone with intercalated shale in the upper one. The limestone of the upper part contains a number of foraminiferal species of Oaviesina, Lockhartia and Rotalia indicative of Thanetian age.Though the lower part of this unit has so far not yielded any fauna, it may tentatively be assigned a Maastrichtian age on stratigraphic grounds. This part may correspond to *Abathomphalus mayaroensis* Zone.

Traverse details: Code SH – Shimla Hills

Location: SH 01, N: 30^{o}63.398’, E 77^{o}03.319’, Elevation 1681 meters. Kheel Ka More near Kumarhatti

Remarks: Dagshai Kasauli contact seen at the location along the road, A good wooden log fossil was found next to the contact (Figures 4.6 and 4.7)

Location: SH 02, N: 30^{o}63.662’, E 77^{o}01.433’, Elevation 1493 meters. Dharampur entry near CRPF camp

Remarks: Green and red (transitional) facies of the Subathu Formation is exposed. The upper part of the green facies around here has >1 m thick oyster limestone bands; both splintery shales and limestone yield vertebrate remains.

FIGURE 4.6 Field photograph showing normal contact between the Dagshai (older) and Kasauli (younger) formations, Kheel Ka More, Kalka-Shimla Highway

FIGURE 4.7 Fossilized tree trunk in the basal part of the Kasauli Formation exposed near Kheel Ka More, Kalka-Shimla Highway.

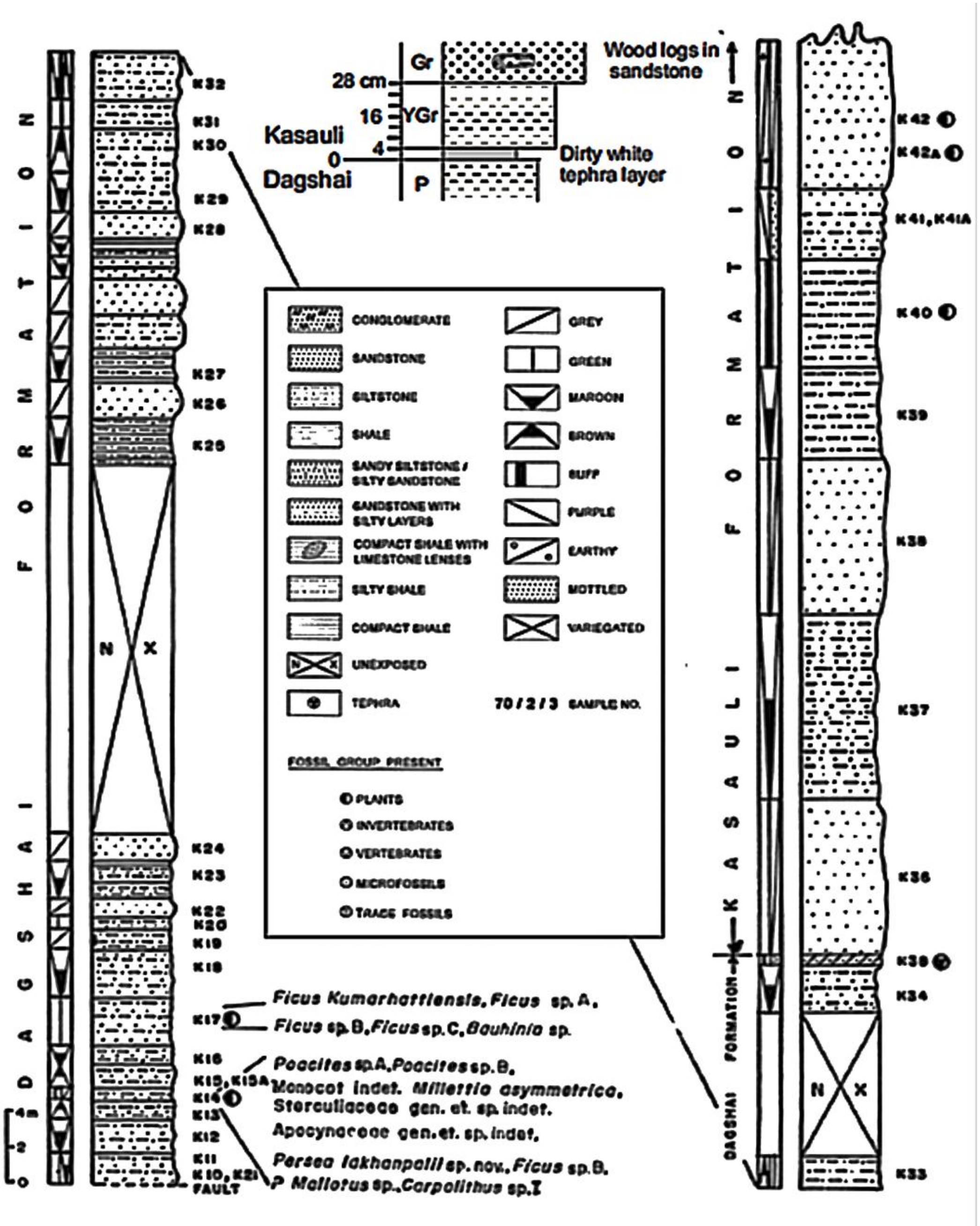

FIGURE 4.8 Lithological log of Dagshai and Kasauli formations exposed on Kalka – Shimla highway near Kheel Ka more (from Mathur et al 1996)

Location: SH 03, N: 30^{o}51.339’, E 77^{o}00.408’, Elevation 897 meters. Parwanoo - Khaddin - Bhojnagar link road, near the bridge over Koshaliya River.

Remarks: The youngest Subathu beds of this section (marine) contain abundant larger forams probably representing *Assilina spira abrardi*.

Location: SH 04 N: 30^{o}51.356’, E 77^{o}00.379’, Elevation 889 meters. Lower Koshaliya river bank, about 50 mts from the bridge.

Remarks: Good exposures of the Subathu formation are visible. They comprise grey Nummulitic limestone and limestone with molluscan shells. We get older Subathu beds downstream from here and younger beds upstream. The fossiliferous limestone bands are underlain by thick dark grey shales with extensive siliceous and occasional calcite veins.

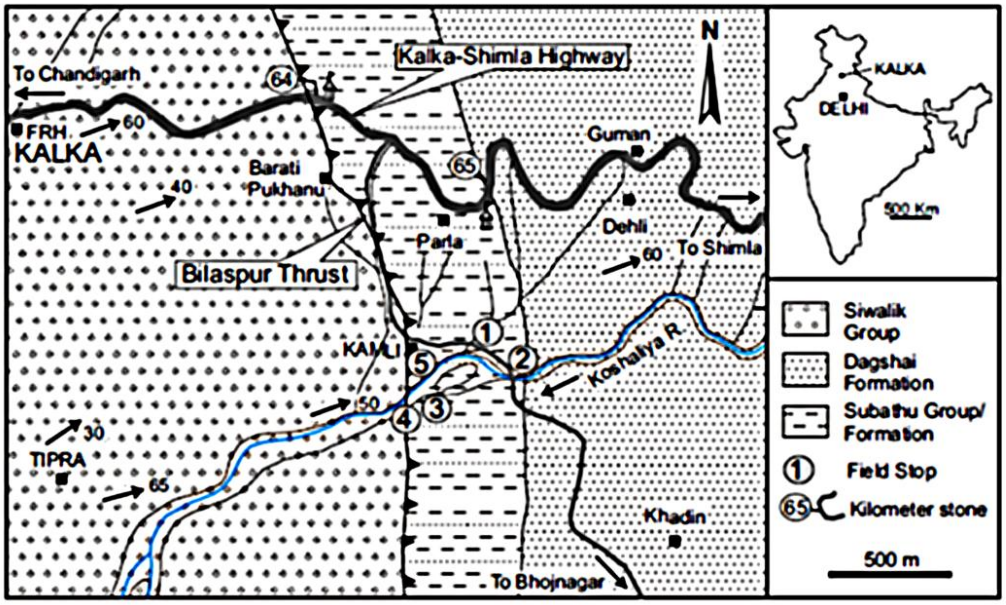

FIGURE 4.9 Geological map of Subathu formation exposed along Lower Koshaliya river (Kumar and Loyal 2006)

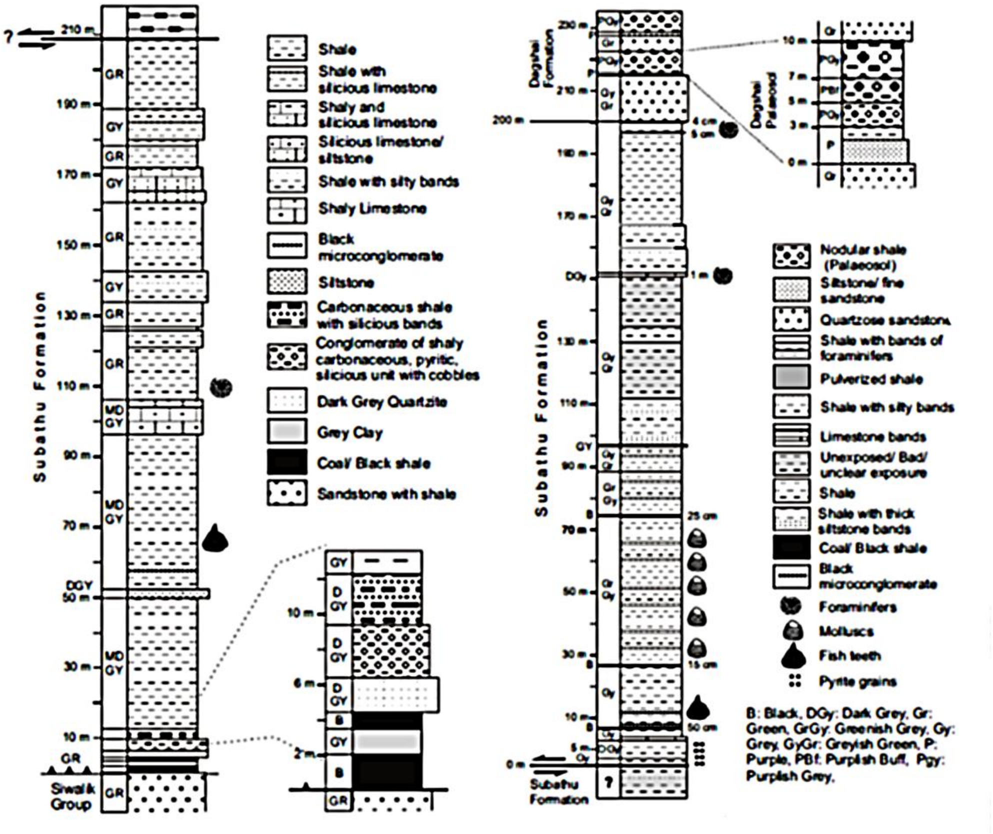

FIGURE 4.10: Lithologs of Subathu formation exposed along Lower Koshaliya river (Kumar and Loyal 2006)

FIGURE 4.11: Fossiliferous green shales from the middle part of the Subathu Formation, Upper Koshaliya River Section, Himachal Pradesh. Thin calcareous bands (encircled) are particularly rich in foraminifers

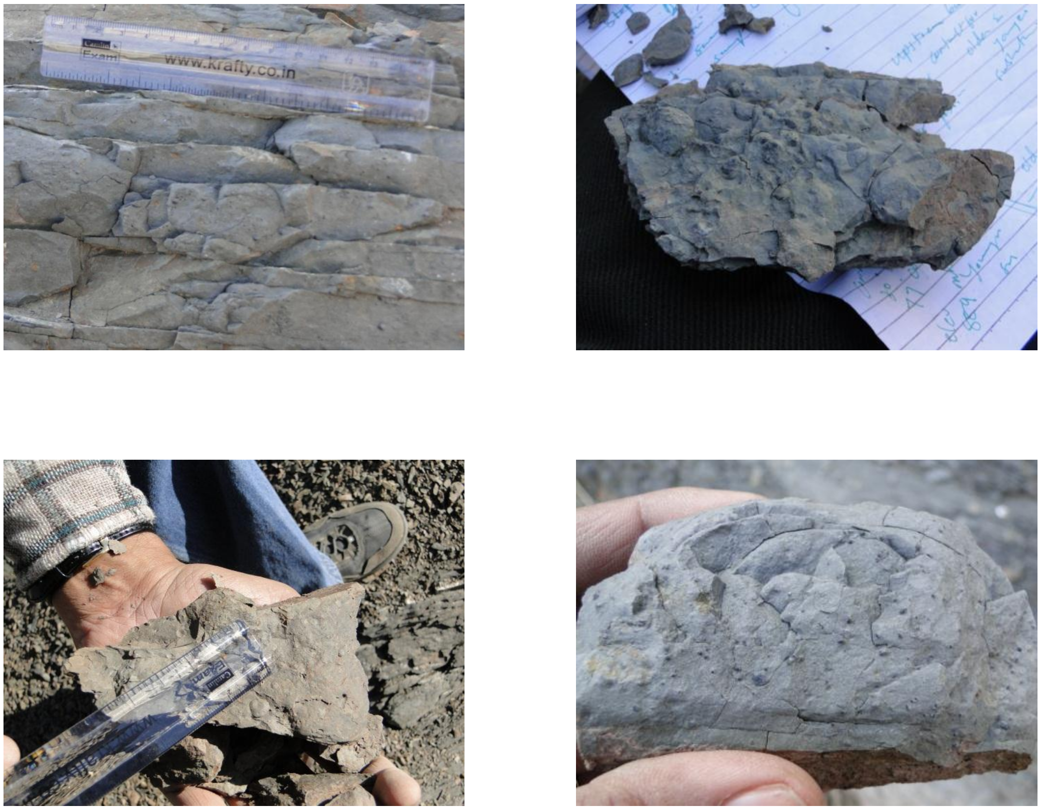

FIGURE 4.12: Hand specimens of shale rich in foraminifers (black specks).

Location: SH 16 N: 30° 56.793’, E 76°59.642’ Elevation 1023 meters, Kuthar River downstream.

Remarks: Interesting fossils of Sea Cow (Sirenia, Mammalian), Molluscs, and Shells were found in this region where the width of the river bed increases dramatically to almost twice the width in the previous locations.

FIGURE 4.13 :Top left: small scale folds in calcitic veins; Top right: Unidentified bone fragment in grey limestone (Lower Subathu, Eocene, Kuthar River); Second middle and bottom right: pelecypods (Mollusca) in the greenish grey limestone (Middle Subathu, Kuthar River); Bottom left: gastropod (Mollusca) in the greenish grey limestone (Middle Subathu, Kuthar River).

Location: SH 17 N: 30° 56.642’, E 76°59.963’ Elevation 1032 meters, Kuthar River upstream, 50 meters from Kanda bridge

Remarks: Many of the shale limestone bands are calcareous and rich in molluscan shells and other fossils. It also has certain thin lensoidal silty bands that contain fragmentary bones and teeth of terrestrial mammals. It forms the middle part of the Subathu Formation and indicates a regressive phase during the Ypresian time. Collected samples and fossils Molluscs, Shells Nummulites, fish etc are abundant in this location.

FIGURE 4.14 Marine fish remains (vertebrate fossils) occurring in the grayish black pebbly limestone, Lower Subathu, Eocene Kuthar River; top left: Fish spine; bottom: broken fish vertebra; Top right: unidentified fish bone;

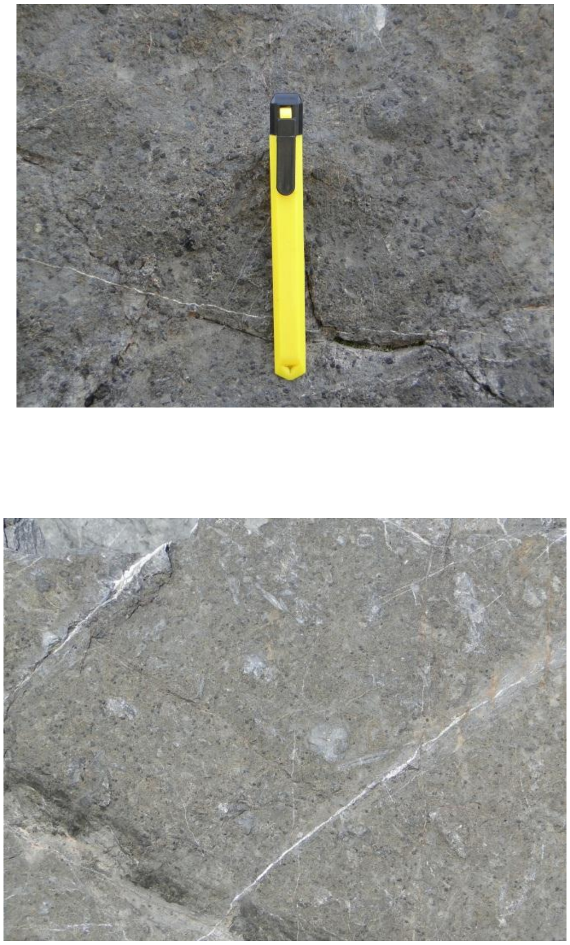

FIGURE 4.15: Close up of grayish black pebbly limestone showing black phosphatic pebbles, Lower Subathu, Eocene Kuthar River.

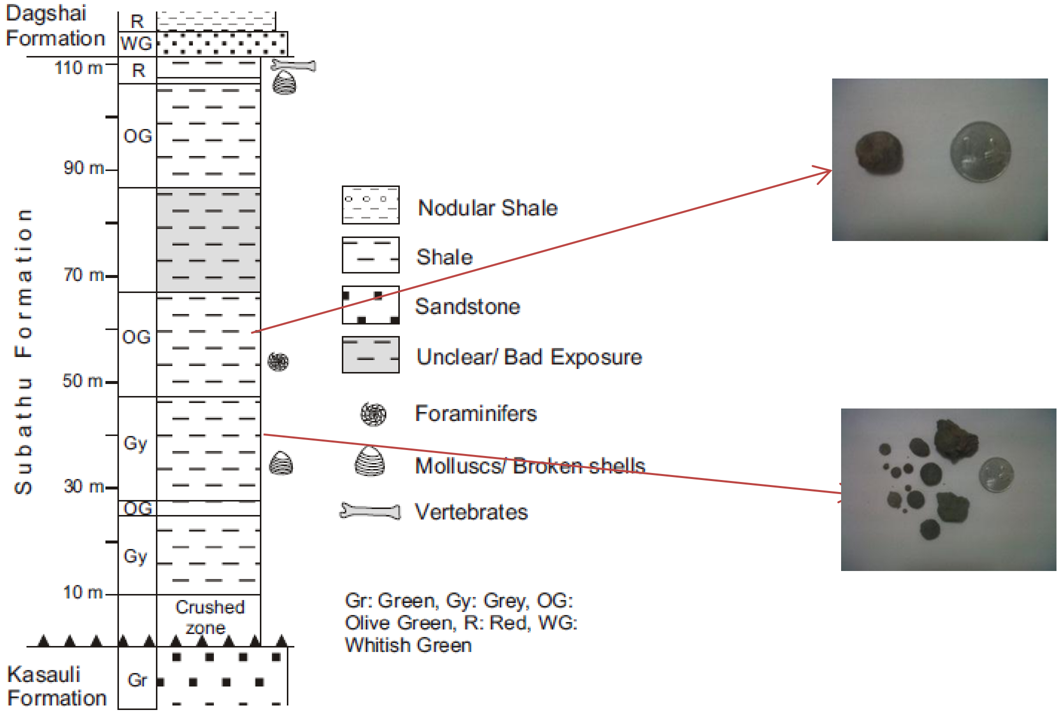

FIGURE 4.16 Lithological logs of Subathu formation along Traverse Chakki-ka-More modified after kumar and Loyal, 2006.

Location: SH 20 N: 30^{o} 58.595', E 76^{o}59.844' Elevation 1165 meters, outskirts of Subathu Cantonment.

Remarks: Think band of Subathu Khakhi shales along with shell limestone is visible in this region, collected fossil shells from the limestone band.

FIGURE 4.17: Khaki shales with molluscan shells (white) on surface, lower-middle Subathu, Eocene Exposed near the village Shadiyana near Subathu town.

CHAPTER 5 – ORGANIC MATTER MERCERATION, THERMAL ALTERATION INDEX AND SOURCE ROCK EVALUATION

Source Rock, the back bone of the petroleum system, refers to the rocks which generates hydrocarbon or has the potential to generate hydrocarbons. It’s an amalgamation of Organic matter and fine grained, impermeable rock. The Organic matter deposited in large basins along with sediments are preserved, cooked and transported to form a complete petroleum system. The generation of the crude oil/gas depends upon the formation of the Kerogen in the source rock, and has a direct relationship with the ratio of organic matter preservation and sediments deposition. If sedimentation rate > organic matter deposition leads to dilution and organic matter > sedimentation rate will not be conducive to preservation of organic matter, due to oxidation. The studies from different horizons of the Subathu Formation indicate good preservation of the organic matter supporting the formation of Kerogen.

This chapter discusses the evaluation of organic matter concentration in the Subathu Formation by total organic carbon (TOC) analysis, organic matter maturation by Thermal Alteration Index (TAI) and zone of hydrocarbon formation. It also presents the results and a brief discussion on the Organic Matter

(O.M.) of the Subathu Formation in the Lesser Himalayan region, and provides bulk characteristics of their organic matter content. Quantity, quality and maturation of organic matter of samples collected from Subathu Formation are estimated and assessed separately. This study also reviews the basics of accumulation and preservation of organic matter, the generation of hydrocarbons, and the application of the Rock-Eval/TOC pyrolysis technique to the characterization of sedimentary organic matter.

All these studies lead to the fact that Subathu Formation has good source rock potential and they could be the source rock for the Hydrocarbons presence in the Himalayan region. The information obtained from these analyses reinforces previous Paleobiological studies based on micro and macro fossils remains of the Subathu basin. The samples were taken for geochemical studies from different sections of the Subathu Formation, exposed in the Nilkanth, Bidasini and Shimla hills to evaluate the maturity and source rocks potential. Total Organic Carbon and Rock-Eval pyrolysis were carried out on 19, shales and carbonates samples, collected from the study area. The geochemical parameters discussed here are based on analysis done on the samples, at the Petroleum Geochemistry Laboratory of NGRI, Hyderabad. Details about materials and methods adopted are described in Chapter 1. The following studies, results, their significance and discussion about hydrocarbon prospects of the area are summarized in this chapter.

- Total Organic Carbon (TOC), in carbonates and shales of the Subathu Formation.

- Rock-Eval Pyrolysis of carbonates and black shales which have ≥0.5 % TOC.
- Palynofacies Analysis and Thermal Alteration Index (TAI)

5.1 TOTAL ORGANIC CARBON (TOC)

Total organic carbon (TOC) analysis was done using Elementar Liqui TOC Analyzer with the solid sample module. Selected Black shale, Khakhi shales, reddish maroon shales and silty unit samples collected from different locations in Uttarakhand and Himachal Pradesh states were chosen for TOC analysis. The black and khaki shales were collected from Nilkanth, Koshaliya River, Kuthar River and adjacent areas of the Subathu Cantonment. The carbonate samples were taken from Bidasini, Kheel ka more, Kalka – Shimla highway, Koshaliya and Kuthar river banks. The Total Organic Carbon values for the samples are provided in the Table 5.1

TABLE 5.1- Total Organic Carbon (TOC) distribution

S No	Sample	Litho Identification	Location	TOC %
1	KKM 1	Dagshai / Kasauli contact	Kheel Ka more	**0**
2	SH 30	Subathu Khaki shales	Out skirts of Subathu cantonment	**0.14**
3	SH 30B	Subathu Khaki shales	Out skirts of Subathu cantonment	**0**
4	KSH IND D	Fossil sample Koshaliya river bank	Koshaliya River	**0.2**
5	NKTH 1	Splinter shales	Nilkanth	**0.04**
6	KSH IND C	Contact between Subathu Dagshai near Kamli bridge	Koshaliya River	**0.1**
7	CKM IND E	Water mill	Chakki Ka more	**0.18**
8	SH 28A1	Black shale	Subathu road section	**15.04**

9	SH 28A	Lower black shale	Subathu road section	**6.71**
10	SH 2	contact Subathu black shale	Subathu road section	**15.1**
11	KTR 3	Limestone from Subathu/Dagshai	Kuthar river	**0.05**
12	KTR 3A	Subathu limestone	Kuthar river	**0.28**
13	KTR 3B	Subathu Black shale	Kuthar river	**15.04**
14	SH 4	Subathu Shale	Subathu road section	**0.33**
15	SH 24	Subathu limestone	Subathu road section	**0.18**
16	SH 27	Shale	Subathu road section	**0**
17	KSH 29	bridge at Koshaliya river downstream shale	Koshaliya river	**2.58**
18	SH 28B	Upper black shale	Subathu road section	**6.78**
19	KSH IND B	Koshaliya river downstream Subathu black shale	Koshaliya River	**11.6**

Total organic carbon contents vary with stratigraphic units in the Subathu Formation. The TOC values of the shale units of Subathu Formation range from 0% to 15.1%. (Table 5.1) These results indicate yields of extractable TOC are low in carbonates and average to moderately high in black shales. The results help in reinforcing Subathu Shales as the source rock for the Himalayan Hydrocarbons.

5.2 ROCK-EVAL PYROLYSIS AND KEROGEN TYPE

Petroleum generation results from the transformation of organic matter in the subsurface under the influence of both temperature and geological time. This transformation is attributed to the thermal cracking of the Kerogen which releases micro petroleum into the pore system of the source rock (Tissot and Welte, 1984;

Huc, 1990). Rock-Eval Pyrolysis permits rapid evaluation of the organic matter type, quantity, assesses maturity to provide information on the petroleum-generative potential. This technique is based on the production of hydrocarbons from a rock sample by steadily heating the sample. The rock samples showing high TOC (>0.5%) were selected for the rock-eval pyrolysis study, to assess the Hydrocarbon maturation level. Through rock eval pyrolysis, the hydrocarbon generative potential of the organic matter, S1, S2, S3, Tmax, derivatives hydrogen index (HI), oxygen index (OI) and total organic carbon (TOC) are known. The parameters obtained by the Rock-Eval pyrolysis are

- S1- represents the measure of hydrocarbons formed in the subsurface and already present in the rock, The S1 peak is measured during the first stage of pyrolysis at the fixed temperature of 300º C.
- S2- represents hydrocarbons generated during the pyrolysis process from the cracking of Kerogen.
- Tmax represents the temperature at which the largest amount of hydrocarbons produced in the laboratory when a whole rock sample under goes pyrolysis treatment.
- TOC values are a measure of total amount of organic carbon present in the rock.
- S3 expresses the milligrams of carbon dioxide generated from a gram of rock during temperature programming up to 390º C.
- Production index (PI) which is defined as the ratio S1/ (S1 +S2).

Total 6 samples are selected for the Rock Eval Pyrolysis, based on organic matter more than 0.5% TOC of samples weight. The results are summarized in given Table 5.2.

TABLE 5.2 : Rock-Eval Pyrolysis

S No	Sample	Litho Identification	Location	TOC %	T max	S1	S2	S3
1	28A1	Black shale	Subathu	**15.04**	**604**	**0.02**	**0.76**	**2.89**
2	28A	Lower black shale	Subathu	**6.71**	**599**	**0.04**	**0.4**	**2.79**
3	2	contact Subathu black shale	Subathu	**15.1**	**606**	**0.02**	**0.78**	**2.89**
4	3B	Subathu Black shale	Kuthar river	**15.04**	**599**	**0.02**	**0.79**	**2.89**
5	28B	Upper black shale	Subathu	**6.78**	**539**	**0.04**	**0.46**	**2.79**
6	IND B	Koshaliya river downstream Subathu black shale	Koshaliya River	**11.6**	**539**	**0.04**	**0.63**	**2.79**

Two types of plots are used to interpret the maturation level, type of organic matter and hydrocarbon generation potential are the Hydrogen Index (HI) versus Total Organic Carbon (TOC) plot (Figure 5.1) and Hydrogen Index (HI) versus Tmax plot (Figure 5.4) and. The Hydrogen Index (HI) versus Tmax plot (Gorin and Feist-Bukhardt, 1990) is based on the amount of hydrogen that the Kerogen contains and the amount of energy necessary to produce hydrocarbons from that type of Kerogen in the laboratory over a short period of time. Espitalié et al. (1977) defined the Hydrogen Index (HI) versus Oxygen Index (OI) plot where HI and OI are (S2/TOC) x 100 and (S3/TOC) x 100 respectively.

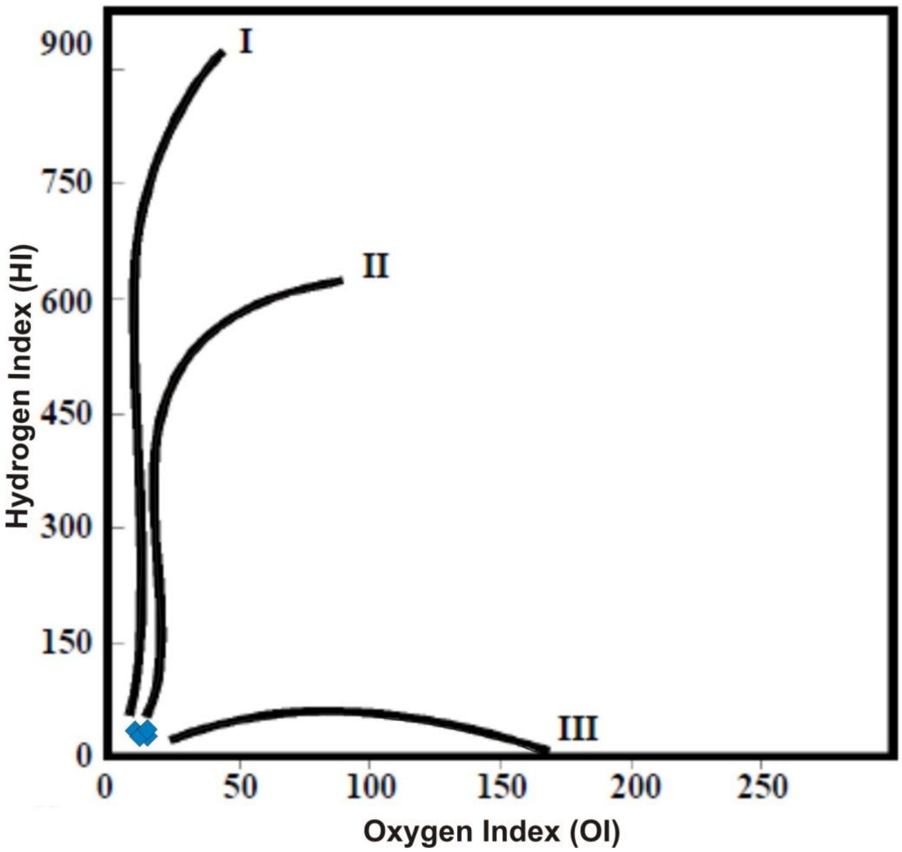

FIGURE 5.1- A plot of HI vs. OI from Rock–Eval pyrolysis of Subathu shales.

This plot provides rough information on the type of organic matter which represents the proportion of hydrogen bound in the organic structure. The HI represents the hydrogen richness and the OI depicts the organic oxygen content of the sample, both relative to the total organic carbon content (Snowdon, 1989). The type of organic hydrogen is controlled by the nature of the organic matter. Aquatic organic matter has high hydrogen content whereas terrestrially derived organic matter has low hydrogen content and variable high oxygen content. The HI vs. OI plot in the Figure 5.1 shows the organic matter of Subathu shales lies within the Kerogen Type I and Type II.

All samples of this study are very similar in organic matter content and type. These samples show very erratic Tmax and Production Index (PI) values, and low pyrolysis values varies such as S1 (0.0 to 0.04, average 0.026 mg HC/g rock), S2 (0-0.79 mg HC/g rock), S3 (0.02-2.89 mg HC/g rock), TOC (0.-15.1 wt. %), HI (0-12 mg HC/g rock, and highly variable OI.

The Production Index (PI) and Tmax are indicators of the degree of thermal maturity (Peters, 1986). It is also an indication of the amount of hydrocarbon which has been produced geologically relative to the total amount of hydrocarbon which the sample can produce.

PI values below 0.4 indicate immature organic matter; PI values between 0.4 and 1.0 indicate mature organic matter; and PI values above 1.0 are indicative of over mature organic matter.

The Tmax values lower than 435º C indicate immature organic matter (organic matter). Tmax values between 435º C and 455º C indicate "oil window” conditions (mature organic matter), between 455 and 470º are considered transitional. A Tmax higher than 470º C represents the wet-gas zone and over mature organic matter (Peters, 1986). The sample analysis shows a PI values are very close 1, (70% of the sample leaning towards 1). Tmax is between 539 and 606 º C. The lower S2 values at a higher TOC in the study samples imply the presence of hydrogen index in low concentration and over-mature organic matter (Sikander et al. 2000).

The samples showing depletion in S1 and S2 and high S3 values can be attributed to weathering. PI is defined as the ratio S1/ (S1+S2), and, hence, depletion of S1 and S2 may induce changes on actual PI values. Immature sediments commonly yield poorly separated S1 and S2 values leading to anomalous results.

Oxidation is the most common form of degradation of organic matter. Oxidation removes hydrogen and adds oxygen to the Kerogen, and, therefore, HI values are usually lower and OI values higher for outcrop samples than for fresh-core samples and this is true for the samples analyzed (Table 5.3).

TABLE 5.3 Hydrogen Index, Oxygen Index analysis values

S No	Sample	Litho Identification	Location	HI	OI
1	1	Dagshai / Kasauli contact	Kheel Ka more	**0**	**0**
2	30	Subathu Khaki shales	Subathu	**0**	**186**
3	30B	Subathu Khaki shales	Subathu	**0**	**357**
4	IND D	Fossil sample Koshaliya river bank	Subathu	**0**	**300**
5	NKTH 1	Splinter shales	Nilkanth	**8**	**175**
6	IND C	Contact between Subathu Dagshai near Kamli bridge	Subathu	**0**	**70**
7	IND E	Water mill	Chakki Ka more	**0**	**67**
8	28A1	Black shale	Subathu	**5**	**19**
9	28A	Lower black shale	Subathu	**7**	**42**
10	2	contact Subathu black shale	Subathu	**6**	**19**
11	3	Limestone from Subathu/Dagshai	Kuthar river	**9**	**60**
12	3A	Subathu limestone	Kuthar river	**0**	**14**
13	3B	Subathu Black shale	Kuthar river	**7**	**26**
14	4	Subathu Shale	Subathu	**0**	**6**
15	24	Subathu limestone	Subathu	**0**	**22**
16	27	Shale	Subathu	**0**	**0**
17	29	bridge at Koshaliya river downstream shale	Koshaliya River	**12**	**6**
18	28B	Upper black shale	Subathu	**6**	**42**
19	IND B	Koshaliya river downstream Subathu black shale	Koshaliya River	**9**	**42**

The S1 vs. S2 plot (Figure 5.2) shows a weak positive correlation, between S1 & S2 implies that the organic matter is more in the black shales

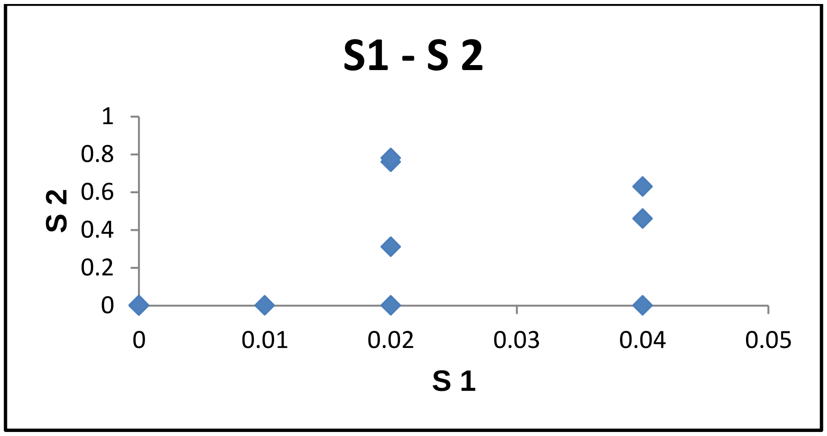

FIGURE 5.2: S1 Vs. S2 plot

The hydrogen index values are generally low ranging from 0 to 12 mg HC/g TOC (Tables XXXX). The plots of HI vs. TOC (Jackson et al., 1985) indicate a gas-prone source rock for the Subathu shales, indicating deposition of source beds in oxic conditions (Demaison and Moore, 1980; Olugbemiro et al., 1997).

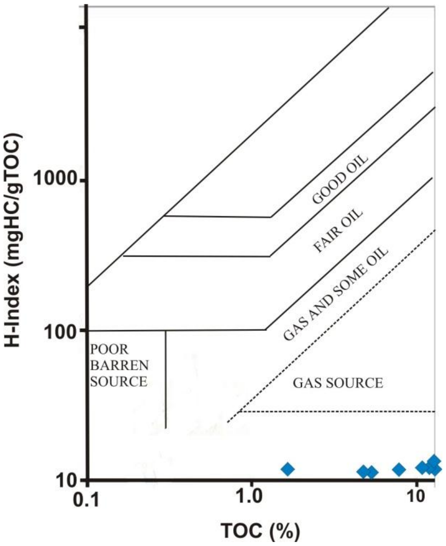

FIGURE 5.3- HI vs. TOC% Plot indicating gas prone Subathu shales

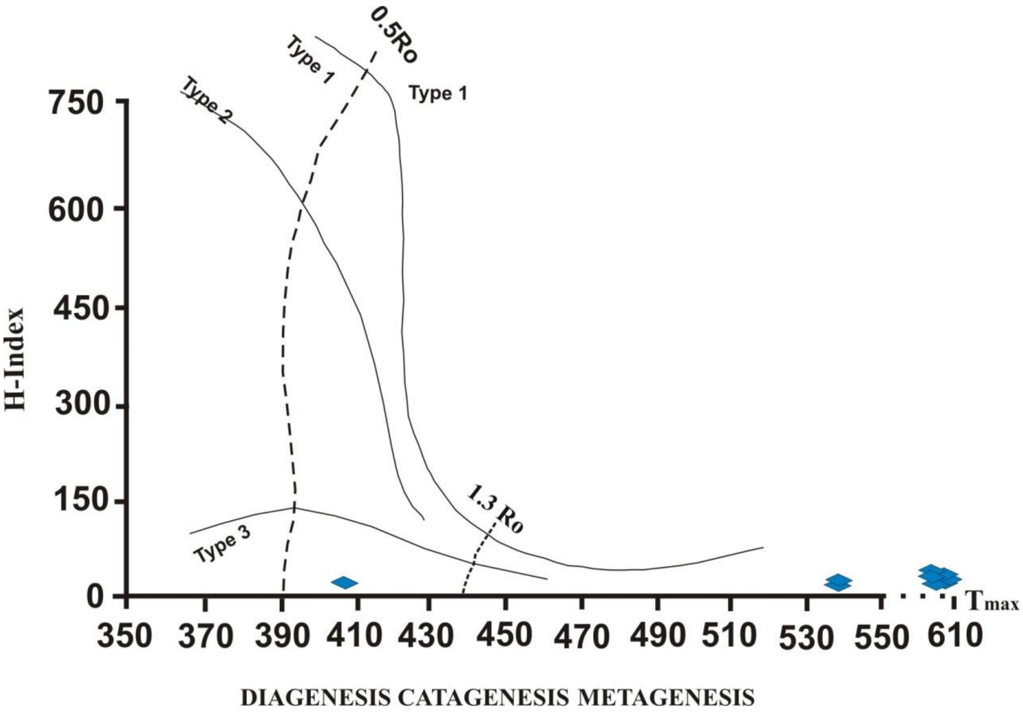

FIGURE 5.4- HI-Tmax plot for the interpretation of Kerogen type and maturity of organic carbon content of Subathu shales.

The HI vs. Tmax plot (Espitalié et al., 1984) of the Subathu samples show samples plot on the Type I and type II (gas prone) Kerogen field in Figure 5.4. In this diagram maximum samples lie in Tmax ranges, between 530 and 610, which indicate over maturation of organic matter.

Ramanampisoa and Radke, (1992) suggested, the values of S1+S2 is lower than 1mg HC/g rock and S1 of less than 0.4 mg HC/g rock indicates barely free hydrocarbons in the potential source rocks. In this study this type of indication shows, with the values of S1+S2 < 1 and also the values of S1 < 0.4. (Table 5.2)

Burgan and Ali (2009), plotted a diagram, S2 vs. TOC in order to know the characterization of the Black Shales of the Temburong Formation in West Sabah, East Malaysia, and suggested the types of organic matter content in it. On the basis of this, in present study most of the samples lie in Type II organic matter. This is also supported to the results obtained by Figure 5.5

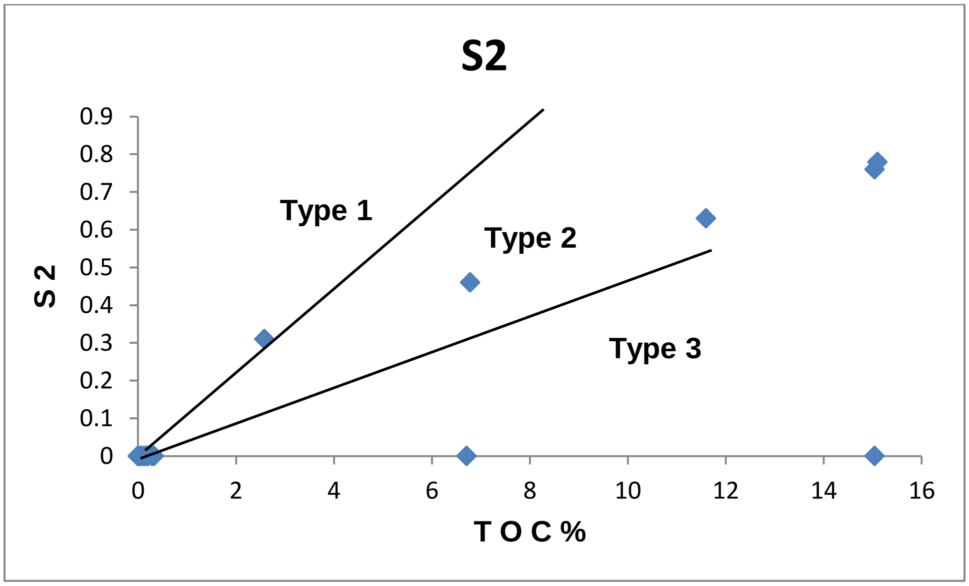

FIGURE 5.5- A plot of S2 vs. TOC defines a predominance of Type II organic matter in the Subathu shales

5.3 PALYNOFACIES ANALYSIS

For the Palynofacies analysis rock samples were collected from the different lithounits of the Subathu Formation exposed near Nilkanth , Bidasini, Kheel Ka more, Kalka – Simla Highway , Koshaliya river, Kuthar river , Subathu cantonment.

The organic matter dispersed and derived either from marine or non-marine sediments on reaching its maturation level over extended period of time contributes as source material for the production of hydrocarbons. Different classifications are proposed by researchers to study and categorize dispersed organic matter. Burgess (1974); Tissot et al (1974); Bujak et al (1977); Masron and Pocock (1981); Venkatachala (1981, 1984); Batten (1983,1996); Hart (1986); Pocock et al (1987); Tyson (1994) and Boussafir et al (1995) have contributed in proposing these classifications. Laboratories around the globe engaged in the task of petroleum exploration have developed classification of organic matter and they use these classifications for the study of organic matter. We have modified the classification of dispersed organic matter proposed by Venkatachala (1988) to a small extent for performing the study of the Subathu Formation. Many approaches involving advanced equipment and complex analytical techniques are proposed for determining thermal alteration of sediments, for this research we have used the globally accepted approach of visually assessing palynomorphs color to determine TAI (1 – 5 scale as proposed by Staplin 1969, 1977).

The hydrocarbon source rock potential of the Subathu shale exposed in the Nilkanth, Bidasini, Koshaliya River, Kuthar River, outskirts of Subathu cantonments in the Simla Hills are evaluated on the basis of dispersed organic matter and TAI. The standard maceration technique (Grey, K. 1999) (Figure XXX), which involves digestion with hydrochloric acid and hydrofluoric acid, is used for isolating the organic matter in the rock samples. The macerate is mounted on the zero cover glass slides using polyvinyl alcohol and Canada-balsam after washing thoroughly. The visual estimation and the classification described by Venkatachala (1981, 1984, and 1988) are adopted for quantitative estimation of the organic matter. Thermal Alteration Index values are identified on the 1–5 scale of Staplin (1969, 1977).

5.4 HYDROCARBON SOURCE ROCK EVALUATION

Source rocks are the sediments which would generate or have potential to generate petroleum. Some of the excellent source rock sediments are certain very fine-grained carbonates deposited under suitable conditions, Organic Shales, Silty mudstone and oxygen deficient waters. The autochthonous and allochthonous organic debris also contribute to the total organic matter (TOM) of a litho-unit. Organic matter types and its facies are very important parameters for evaluating source rock potential and must be identified and distinguished. Different types of organic matter have different hydrocarbon potentials and products. The organic matter that occurs in sediments is from terrestrial and marine sources (Table 5.4).

TABLE 5.4 : Different source of organic matters occur in sediments after Venkatachala, 1988

- Primary Material

    - Terrestrial Source
        - Plant leaf and stem
        - Plant spores and pollen
        - Lignified wood fragments – partially fusinised
        - Mineral charcoal – fusain, micrinite
        - Resin
        - Planktonic fresh water algae

    - Marine Source
        - Phytoplankton
        - Benthos – Bacteria, Algae and Fungi

- Modified Products

    - Sapropel
        - Fluffy to semi coherent masses
        - Finely dispersed organic matter

- Platy, translucent, brittle, amber material
- Resistant, inert, platy modified cuticular remains

The term Kerogen was defined by Crum Brown (1912) as solid bituminous, mineraloid substances in oil shales. Kerogen is the end product of mechanical, chemical and biological alteration of accumulated plant material. The formation of Kerogen depends upon the density of organic matter preserved in the sediments. Organic matter, in some cases occurs faster than the rate of breakdown and it is preserved and incorporated in the sediments. Terrestrially sourced material is also deposited in a marine environment, and gets mixed up with marine plant products resulting into a potential source rock.

The following type of organic matter can be recognized in sediments;

Structured terrestrial material (wood / cuticle): This organic matter comprises unaltered cellular remains of leaf, root and stem tissues. Terrestrial plants were absent in the Ediacaran time, hence present location represent absence of structural terrestrial material. This type is easily recognizable when fresh and has no significant hydrocarbon potential, but contributes for gaseous hydrocarbons.

Spores and pollen: These are resistive material and commonly preserved in sediments. Their content in sediments adds to the liquid hydrocarbon potential. The spore and pollen are present in the Subathu sediments.

Charcoal (fusinite): This is formed due to oxidation of structured terrestrial woody organic matter, which is extremely resistant to decay. It has no/negligible hydrocarbon source rock potential except for dry gas. Black color suggest oxidation environment during deposition. Absent in the studied formations.

Biodegraded terrestrial organic matter: This is terrestrial organic matter. In the first stage it is made up from hard and soft parts of plants (gymnosperms, angiosperms, bryophytes and pteridophytes). This type of material which is partly or completely biodegraded is subject to easy convention or thermal alteration to produce hydrocarbons. Biodegraded terrestrial organic matter is present in the Subathu Formation.

Biodegraded aqueous organic matter: Mostly algal remains formed this organic matter. The frequency of biodegraded aqueous organic matter in the investigated area is quite high 75%. This organic matter is considered to possess enhanced hydrocarbon source potential than structured terrestrial organic matter. The remains in this group are-

(i) *Phytoplankton:* This is indicative of marine environment. Grey amorphous organic matter or greenish yellow amorphous granular organic matter are indicative of marine origin source and generally associate with phytoplankton. Grey amorphous matter is formed in sealed basins and reducing environments while the greenish yellow amorphous matter indicates oxidizing environments.

(ii) *Thalloid algal matter:* It is preserved as dark brown and mostly structure less pieces under the light microscope; however they appear spongy under SEM. This is easily converted into amorphous organic matter and is sourced by mostly red and brown algae. Greenish yellow amorphous granular organic matter is also result of biodegradation of algal matter,

possibly large sea weeds. Marine grasses also possibly give rise to this type of organic matter.

(iii) *Filamentous algae:* These are remains of blue green algae and mostly associated with reducing environments. They formed algal mats which entrap sediments. Biodegradation of filamentous algae forms amorphous flanky or granular organic matter.

Amorphous organic matter: Amorphous organic matter is completely transformed material into structure less matter where all recognizable cellular structure has been lost. It is very hard to distinguish the source of this matter as terrestrial or aquatic. This organic matter is present in Subathu sediments. Such matter is spongy and appears porous and is generally yellowish – brown or orange in color. During thermal alteration process this type is converted from yellowish brown to dark brown in color. Amorphous organic matter formed by digenesis of organic matter at aerobic environments with limited supply of oxygen.

Organic matter of Bacterial Origin: This type of organic matter forms from the conversion of both terrestrial and algal organic matter by fungal and bacterial attack. Sometime whole organic matter is destroyed by the activity of fungus and bacteria, and the resultant product is called bacterial mush. The color of this organic material is yellowish green – brown and an excellent hydrocarbon source.

Grey amorphous organic matter: This matter is granular and flaky and commonly associated with phytoplankton remains which are indicative of marine source. Pyrite associated with it commonly, that’s indicating reducing environment of deposition. This represents very low frequency (0-1%). It converts into greyish – black or black matter after thermal alteration of organic matter.

Structured marine organic matter: Algae such as Dinoflagellates, acritarchs, diatoms, radiolarian, as well as remains of larger brown and red algae constitute this type. These are particulate and good source of hydrocarbons. Amorphous and semi-amorphous matter forms by the biodegradation and alteration of this matter.

5.5 THERMAL ALTERATION INDEX

For evaluating organic maturation level of the sediments vis-a-vis hydrocarbon potential, 1–5 scale representing TAI proposed by Staplin (1969, 1977) is used for the present study. The maturation color of organic matter indicates the associated TAI. The TAI values worked out for the sediments of the Subathu Formation are in Figure 5.6

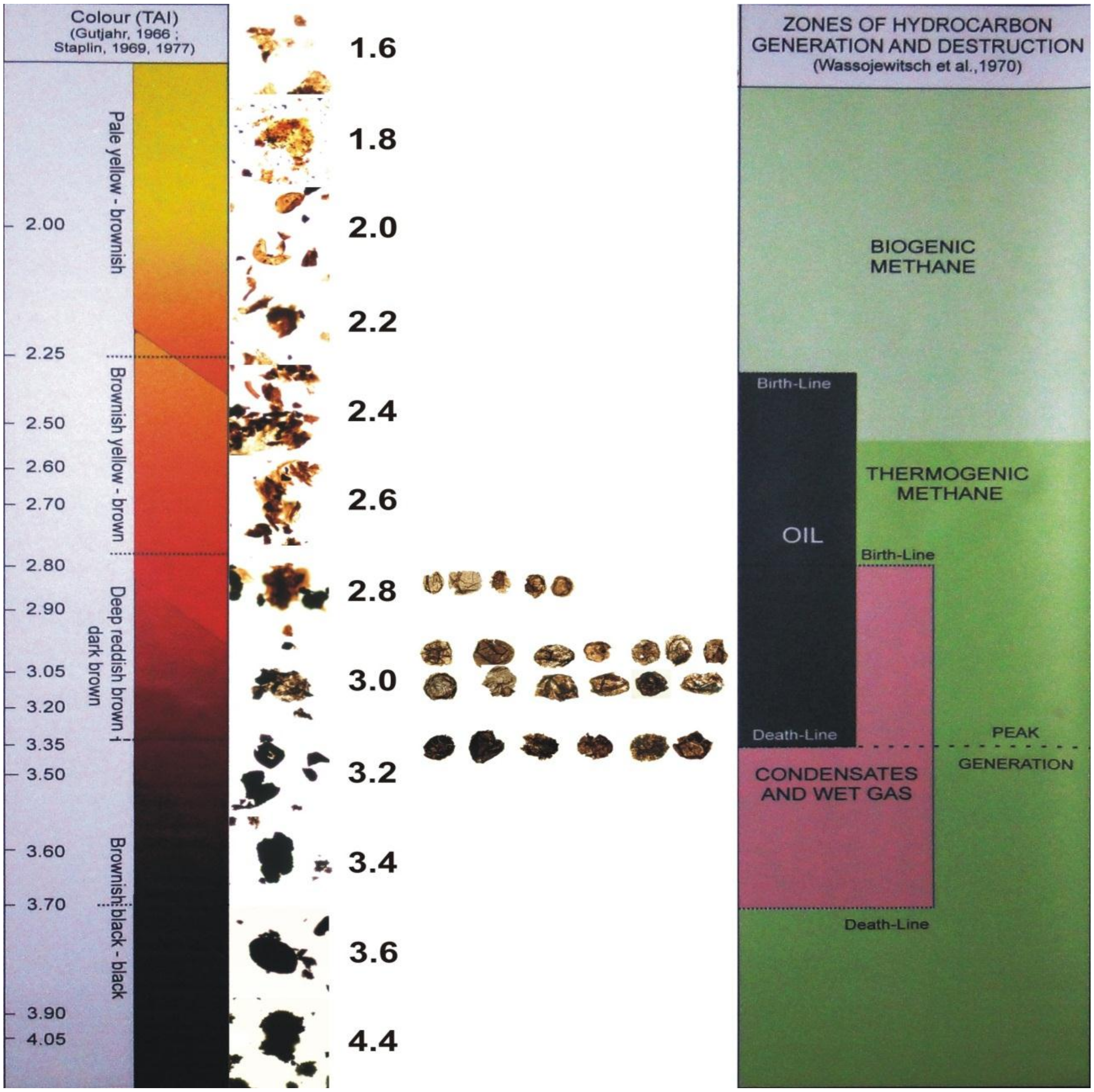

FIGURE 5.6 : Thermal Alteration Index Values against standard scale

The TAI analysis value is close to 3 and this indicates Gas condensate as per the Zones of Hydrocarbon Generation & destruction, this range represents an optimum maturation level of a good hydrocarbon source rock potential.

CHAPTER 6 – SUMMARY AND CONCLUSIONS

The present research thesis is an attempt to find the source rock for the Hydrocarbon ‘shows’ known from the Himalayan foreland basin (Lesser or Sub-Himalaya). The lesser Himalayan region comprises of Subathu, Dagshai and Kasauli formations and based on the literature analysis and discussions with experts, Subathu Formation was identified for the study .The main objectives of the study were:

- To understand the Biostratigraphy of the Subathu Formation
- Organic matter Maturation and TAI (Thermal Alteration Index)
- Organic Geochemistry for source rock evaluation

The areas which are part of the Subathu sub-basin in the Lesser Himalayas identified for this research were Nilkanth, Bidasini (Uttarakhand), Dogadda (Uttarakhand), Subathu, Dharampur (Himachal Pradesh).

These following methodology was adopted to achieve the objectives:

- Traverse Mapping (South to North), analyzing major Fold, Fault and depositional Structure, and collection of Surface Samples of Subathu Formation
- Paleontological studies
- Maceration & Thermal alteration Index study
- Geological setting and Biostratigraphy of Subathu

- Geochemical study for organic maturation done at NGRI, Hyderabad.

The Subathu succession is largely marine and the continental condition developed only towards its terminal stage. It is richly fossiliferous and has yielded assemblages comprising vertebrates, invertebrates as well as plants. The Subathu exposures occur mostly in the cores of anticlines (e.g. in its stratotype area in Himachal Pradesh) or in the form of tectonic inliers (e.g. in Kalakot, Jammu and Kashmir). The thickness varies from about 175 meters in J& K., 400 meters in H.P to about 170 meters in Uttarakhand. It rests on various rock types indicating marine transgression over predominantly Precambrian basement except in Dogadda and Nilkanth areas of Uttarakhand where it overlies the Tal Formation of Cambrian age. The Subathu succession consists of three main lithological units – a lower black grey unit, a middle dominantly green shale limestone unit and a topmost red bed unit.

The red beds in the upper part of the Subathu Formation clearly depict a faunal and sedimentary transition from a marine set up to brackish and fluvial condition – extensive oyster bearing beds overlie the nummulitic limestone and shales. The oyster beds are overlain by variegated shales, pisolitic granularstone, siltstone and claystone which contain pulmonate gastropods and varied continental vertebrates (such as rodents, artiodactyls and perissodactyls) concentrated in a bone bed. In the Kuthar river section some land dwelling vertebrate elements have also been reported in the red beds.

The green shales – limestone units of the middle Subathu is predominantly marine as indicated and evidenced by the dominance of Foraminiferids, Ostracods, Echninoids and marine vertebrates including sharks, rays, tetraodonts, pycnodonts etc. The top part of this unit includes oyster bearing coquinites, which are e suggestive of brackish water condition gradually changing into fresh water environment during the deposition of red beds of the upper Subathu.

Limestone bands exposed in the lower Koshaliya river bed (near Kamli village) are fossiliferous and are underlain by thick dark grey shales with extensive siliceous and occasional calcite veins. The basal beds of the Subathu Formation are marked by two conspicuous coal seams. Above the upper seam there is a 2 meter thick bed of dark grey quartzite followed by dark grey conglomeratic unit comprising carbonaceous shaly matter with pyrite, siliceous lenses and cobbles. Above this there is a 3 meter unit of thinly bedded carbonaceous shales alternating with siliceous bands.

In the Upper Koshaliya river section (near Chakki Ka More) the major thickness of the Subathu Formation comprises grey-green foraminiferal shales in marine and of an early Lutetian age. The maroon and purple red shales in the upper part of the formation have not yielded any foraminifers which suggest cessation of marine condition and onset of continental condition as also supported by the occurrence of terrestrial vertebrates and charophytes remains from this section. The contact between the Subathu and Dagshai formations is very clearly exposed in this section close to the bridge.

A good exposure of purple shales and thick sandstone constituting the lower-middle part of the Subathu Formation are evident in the Kuthar river section. Purple shales have some thin bands that contain bone pieces. Gypseous shales are also exposed upstream in a branch stream of Kuthar River that comes from Chanole side.

Despite the fragmentary nature of the mammalian remains which have been collected from the Subathu Formation they show considerably Paleobiogeographical and Phylogenetical interest because they document an early phase of mammalian evolution on the Indian Plate for which until recently no record was available.

In Nilkanth section the unit comprises hard grey, massive, oolitic shelly limestone. The lower part of this unit has yielded *Diplocava nilkanthi* a cyclostomatus bryozoan and a number of other fossils of Maastrichtian age. In the Kuthar and Kurla sections the limestone of the lower part of the formation contains a number of foraminiferal species of *Daviesina, Lockhartia and Rotalia* indicative of Thanetian age.

The study area shows the Kakara- Subathu sequence was deposited by a transgressive sea during the latest Maastrichitian to early Lutetian times. However the middle and top parts of the Subathu Formation contains several brackish to fresh water fossils, namely *Seila* , *Physa*, *Bulinus*, and Oyster (molluscs);*Neocyprideis* and *IIyocypris* (ostracodes); and chara fruits. This indicates that the middle and top part of this unit were deposited in brackish water condition during the regressive phases. The first regression may be related to collision between the two plates along the Indus Suture Zone which led to uplift of the region in the beginning of Late Ypresian. This regressive phase was short lived as the transgressive phase continued till the basal Lutetian times. The final regression of the sea from this zone took place in the early Lutetian times during which the top part of the Subathu Formation was deposited.

The following are salient points and the conclusions identified/arrived at and reinforced by this research:

- The Subathu Formation largely contains invertebrate's fossils represented by the Foraminifers, Ostracods and Molluscs. Besides a few vertebrates fossils have also been reported from the Subathu formation.
- Subathu rocks contain well developed macro and microfauna and are assigned Late Paleocene–middle Eocene Age. Dagshai sediments have failed to yield any definite flora and fauna.
- The surface samples show good Total organic carbon values ranging from 0.18 to 0.2 (Limestones), 0 to 0.14 (Khaki Shales) 0.04 to 2.58% (Grey Shales) and between 6.78 to 15.1 (Black shales) .
- The Tmax values for the Subathu Shales samples range between 539 and 604, this indicates Gas condensate.
- S1 & S2 plot implies that the organic matter is more evident in the Black Shales
- HI vs. TOC plot of Subathu Shales indicates a gas-prone source rock.
- HI vs. Tmax plot of the Subathu Shales indicates over maturity of organic matter, this may be due to weathered and oxidized surfaces samples.
- S2 vs. TOC plot indicate Type II organic matter classification for Subathu Black Shales.

- The TAI analysis value is close to 3 and this indicates Gas condensate as per the Zones of Hydrocarbon Generation & destruction, this range represents an optimum maturation level of a good hydrocarbon source rock potential
- We have tried to establish the correlation between Biostratigraphy (Paleontological & Palynological studies) and geochemical analysis and found that Subathu Shales show good Source rock potential for Gaseous Hydrocarbon.

Lead values, this opens a new chapter for the following:

- Further sub-surface studies for source rock evaluation analysis and Paleobiological studies of the fossils can be carried out for ascertaining the Hydrocarbon potential of Subathu Shales.
- Temperature and Pressure gradient analysis can be conducted to evaluate the Subathu succession.

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