Journal of Nepal Geological Society, 2009, Vol. 39, pp. 77—84

Tectonic setting of the Nepal Himalaya and its potential for hydrocarbon exploration

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ABSTRACT

Nepal lies at the collision zone between the Indian subcontinent and the Tibetan Plateau of the Eurasian continent. It is made up of enormous tectonic stacking of sedimentary and metamorphic rocks with granite intrusions that resulted from the collision and under-plating of the Indian Craton with the Lhasa block of Tibet. The five major tectonic zones separated from each other by thrust contacts from south to north are the Terai, Siwalik or Sub Himalaya, Lesser Himalaya, Higher Himalaya and Tibetan Tethys. On the northern margin of the Indian subcontinent, foreland sedimentary basins began to develop immediately after the terminal collision between the northward drifting Indian Plate and relatively passive Eurasian Plate in Late Eocene time. The southern part of Nepal known as the Terai and Siwalik foothill, lies in the northern margin of the Ganga Basin and Purnea Basin that extend from India. Such basins with thick accumulation of sediments are considered as the potential area for petroleum exploration.

Regional scale seismic reflection, gravity and magnetic data combined with surface mapping and basin analysis have established the subsurface framework of southern Nepal. Geological settings potential for hydrocarbon prospects recognized in Nepal include structural traps related to normal faulting involving pre-Siwalik formation and thrusting involving Siwaliks, structural traps associated with frontal blind thrusts, anticlines and thrust-faults, basement controlled structures and stratigraphic pinchouts.

Drilling data consists of only one well drilled in the eastern part of Nepal. Oil and gas seeps have been observed in Dailekh area emanating through deep faults. Geochemical analyses of these seep samples indicate that these oil and gas have geologic origin from mature source rocks. Various outcrop samples from different parts of the country have been found rich in organic carbon. Source-rock maturity basin modeling constructed for various sections indicates that the level of thermal maturity is within oil and gas generating window. The Potwar Basin to the west in Pakistan and Assam Basin to the east in India having similar geologic setting to that of Nepal are producing oil and gas for a long time. In the Indo-Gangetic Plain across the border on Indian side, many deep wells have recorded the presence of gas and high content of organic carbon. Assessment of the available data acquired so far indicate that there is a fairly good possibility of discovering petroleum resource in Nepal.

Keywords: Collision zone, foreland basins, structural trape, tectonic evolution, exploration blocks, basin analysis, thermal maturity, oil window

Recieved: 16 October 2008 **revision accepted:** 20 March 2009

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Nepal lies in the middle of the Himalayan collision zone. It is made up of a giant tectonic stacking of sedimentary and metamorphic rocks with granite intrusions that resulted from the dramatic collision and underplating of the Indian Craton with the Lhasa Block of Tibet. The country is naturally separated into five major morpho-tectonic zones (Figs.1 and 2) that are parallel to its long dimension (Slind 1993; Windley 1983; Stocklin 1980). In the south bordering India, the Terai is the Nepal portion of the Indo-Gangetic foreland basin which is underlain by over 1500 m thick unconsolidated Quaternary sediments overlying unconformably with Tertiary molasse deposits.

North of the Terai rising abruptly along the Main Frontal Thrust (MFT) lies the Siwalik Belt that constitutes thick beds of folded and faulted Neogene molasse sediments forming distinct foothills. The lithology of the Siwalik is shale, sandstone, mudstone and conglomerate. North of the Siwalik belt and sharply separated from it by the south-verging Main Boundary Thrust (MBT) is the broad and geologically complex Lesser Himalayan zone. The Lesser Himalaya consists of predominantly meta-sedimentary rocks of Kunchha group and Nawakot Group (Amatya and Jnawali 1994) of Proterozoic to Paleozoic age and in places fossiliferous sedimentary sequence of Mesozoic age (Tansen Group). Though various stratigraphic schemes with differing nomenclatures have been used to describe the Lesser Himalayan rocks, broadly they are correlated to each other. Geological maps produced during petroleum exploration in the southern part of the Lesser Himalaya have described these rock sequences under Lakharpata Group equivalent

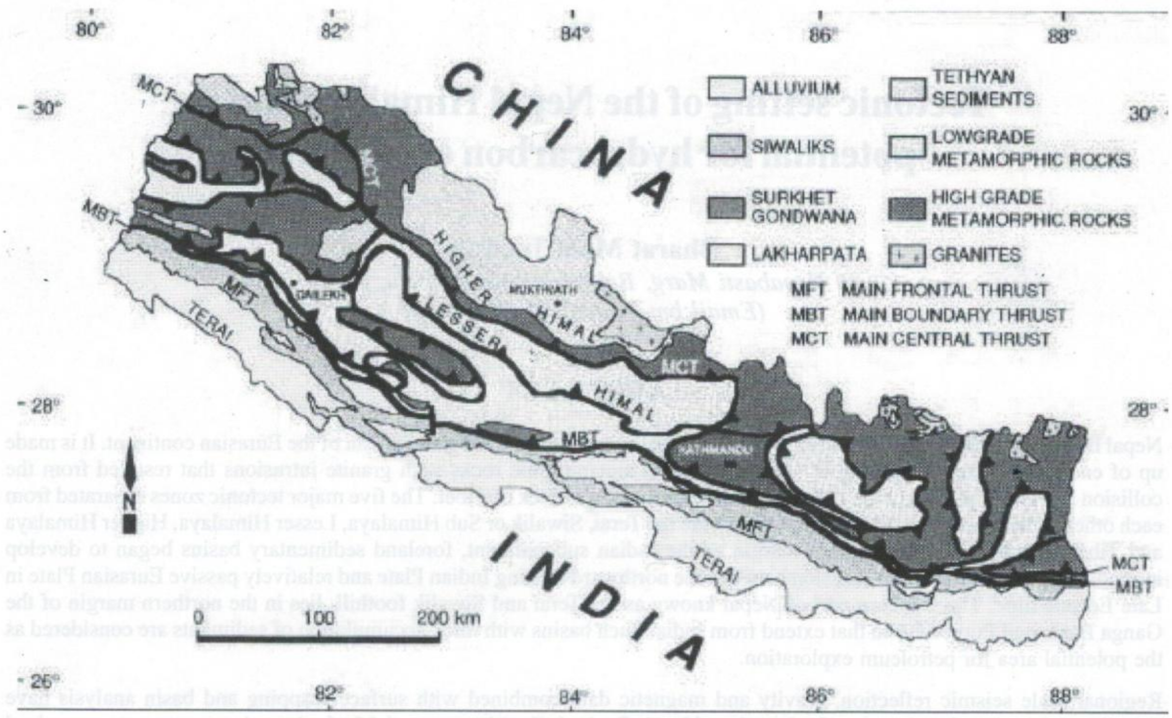

Fig. 1: Tectonic setting of Nepal (Slind 1993)

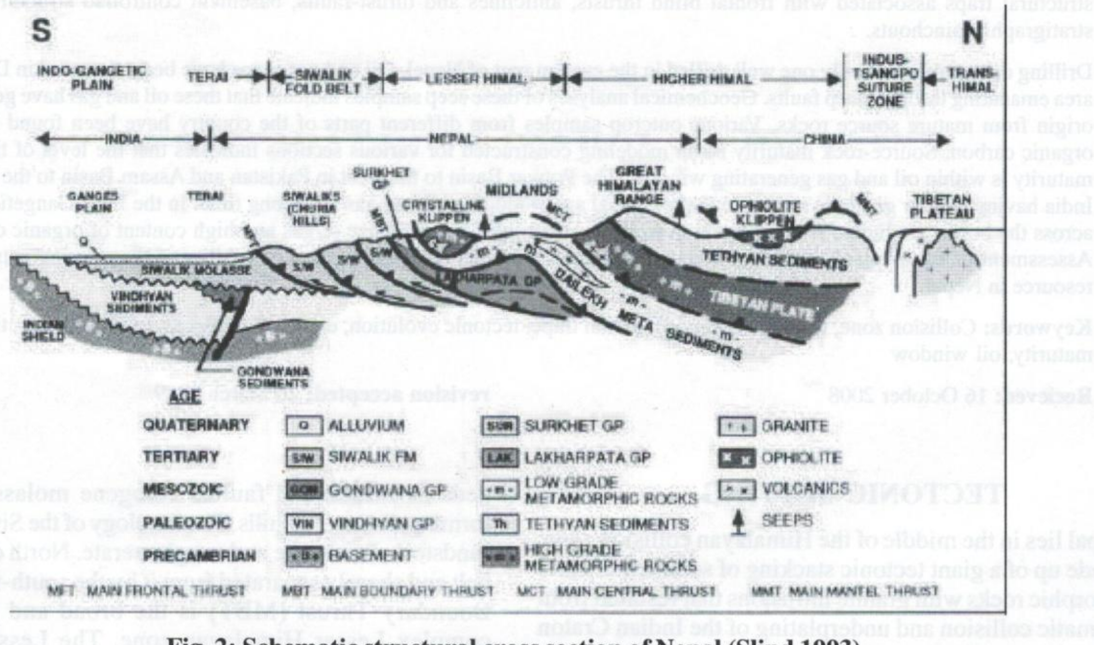

Fig. 2: Schematic structural cross section of Nepal (Slind 1993)

of Nawakot /Vindyan (Upper Paleozoic to Upper Proterozoic), Gondwana Group and Surkhet Group equivalent to Tansen Group of Upper Cretaceous to Lower Miocene age (PEPP Brochure 1996; Fig. 3).

The Lesser Himalayan zone is characterized by stacking of crystalline nappes that were transported from the north and now exist in the form large klippen masses represented by fossiliferous Phulchoki Group (Paleozoic) and unfossilliferous Bhimphendi Group (Pre-Cambrian). Massive to locally foliated lenticular bodies of two-mica granites of Ordovician age occur in the crystalline klippe of the Lesser Himalaya (Figs. 1 and 2).

North of the Lesser Himalayan zone along a distinct break in slope roughly coinciding with the Main Central Thrust (MCT) rises the towering walls of the High Himalaya. The Higher Himalayan rocks are over 5 -10 km thick metamorphic

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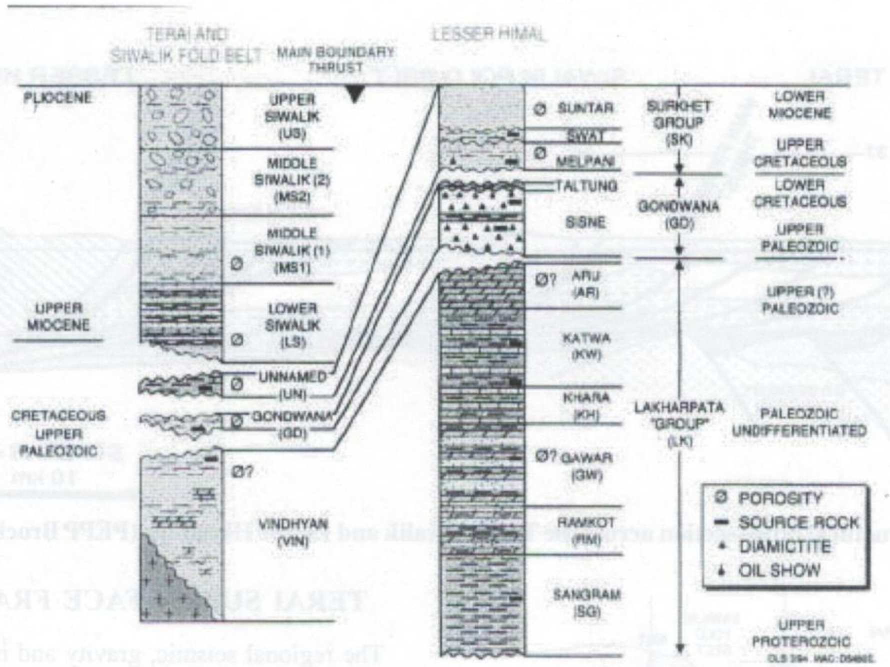

Fig. 3: Stratigraphic diagram of central southern Nepal (PEPP Brochure 1996)

Proterozoic basement supporting the Cambrian-Eocene Tethyan sedimentary sequence and represent a part of the upper crust that has been reactivated due to crustal shortening as a result of continent-continent collision during the Himalayan orogeny. Owing to intense deformation, migmatization and granitization, the lithology is altered and obliterated. A thick (over 10 km) fossiliferous Tethyan sequence lies in the Tibetan zone forming some of the highest peaks in the Himalaya. Several intrusions of Tertiary granites are associated with the Tehyan sediments. Gas seeps occur in the upper Tethyan of northern central Nepal at Muktinath.

TECTONIC EVOLUTION AND DEVELOPMENT OF FORELAND BASIN

The breakup of the Pangea into Eurasia and Gondwana in Early Cenozoic and northward drift of India from Gondwanaland eventually led to collision between India and Eurasia giving birth to the Himalaya. During this northward drift, north of India was subducted beneath Tibet and in the Eocene time, the collision of the Indian Plate with the Eurasian Plate led to the closure of the intervening Tethys Sea and the rise of the Himalayan range (Mitchell 1979). With continued post-collision northward movement of India, the Main Central Thrust (MCT) developed as an intra-crustal thrust that brought up the mid-crustal level rocks to thrust southward over the Lesser Himalayan rocks. This was the first thrust to break the Indian crust and carried southward on its back a pile of 25–30 km thick rocks for over 200 km. The continuing movement of the plates developed the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) progressively younger to the south and also some blind thrusts underneath the Terai. The MFT is the active leading edge of Himalayan deformation. All these thrusts join at depth in a flat-lying decollement called the Main Mantle Thrust (MMT). The decollement is a major crustal break separating the upper and lower continental crust of the Indian Plate. The relative motion of both plates is still continuing.

The compressive deformation in the Himalaya led to development of foreland sedimentary basins on the northern margin of the Indian Peninsula just after the terminal collision of northward drifting Indian Plate and relatively passive Eurasian Plate in Late Eocene time. As the southern Tibet began to rise in post-collision adjustment, the newly formed Nepal foreland basin was characterized by an unstable northern rim adjacent to the suture zone and a gentle southern rim bordering the Indian Craton. During the Paleogene period, differential movement along normal faults propagating southward from the collision zone utilizing lines of weakness created a normal-fault tectonic regime in which shoreland sands accumulated under local extensional control (Tater et al. 1989). The northern margin of the basin being unstable received both clastics and carbonates in a setting of strong depositional topography. During Early Miocene, thrusting along the MCT was accompanied by further uplift in the inner Himalayan core. The foreland basin was relatively passive with the initial faults dying out upward and being covered by shaly beds. By Middle Miocene time, thrusting at the MCT had emplaced giant crystalline klippen over the Lesser Himalayan low grade metamorphic rocks. That led to down-warping in front of the advancing thrust-sheets giving rise to the deposition of the Siwalik Group in the foreland basin in Neogene time. By the end of Pliocene, all the major structures of the Himalaya were already developed. The MBT juxtaposes pre-Siwalik rocks in the hanging wall with much

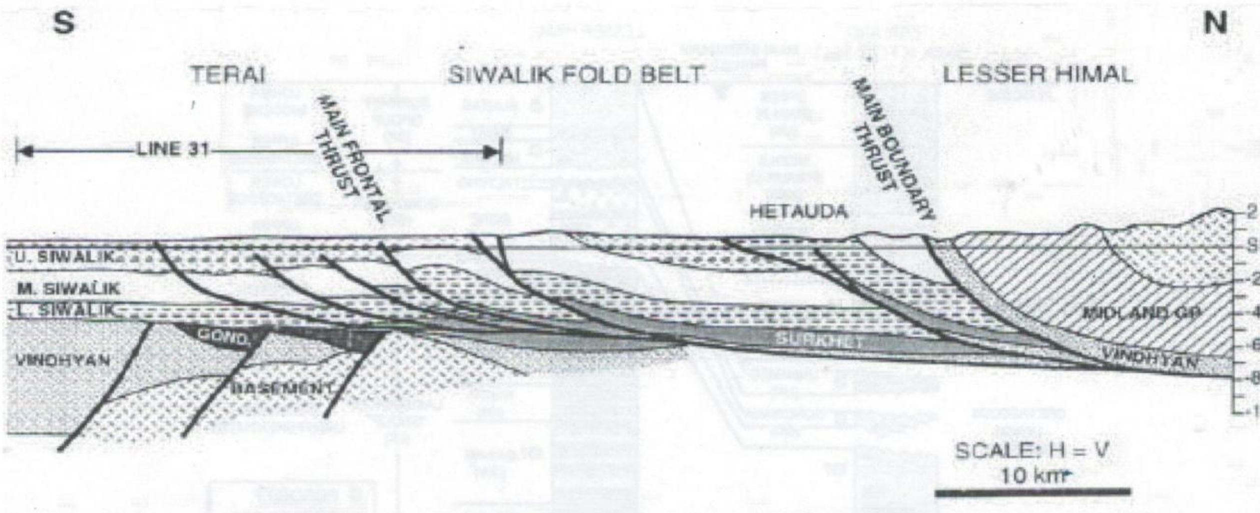

Fig. 4: Structural cross-section across the Terai, Siwalik and Lesser Himalaya (PEPP Brochure 1996)

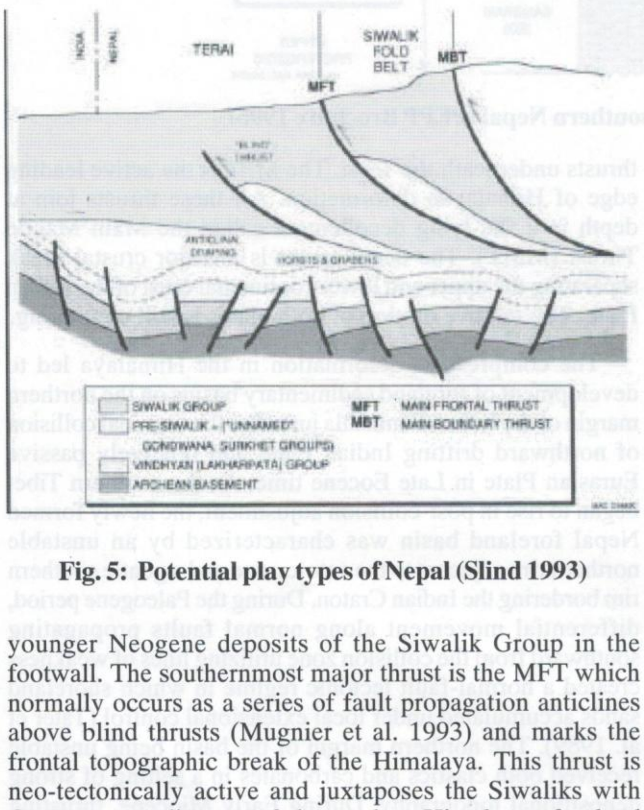

Fig. 5: Potential play types of Nepal (Slind 1993)

younger Neogene deposits of the Siwalik Group in the footwall. The southernmost major thrust is the MFT which normally occurs as a series of fault propagation anticlines above blind thrusts (Mugnier et al. 1993) and marks the frontal topographic break of the Himalaya. This thrust is neo-tectonically active and juxtaposes the Siwaliks with Quaternary sediments of the modern Himalayan foreland basin system.

The southern part of Nepal termed Terai lies in the northernmost edge of the Ganga Basin and Purnea Basin extending from India among several foreland basins developed on the northern margin of the Indian Peninsula. These basins are asymmetric with thickening Paleogene sediments towards Nepal. The Potwar Basin to the west in Pakistan and Assam basins to the east in India with analogous geologic history are producing oil and gas for a long time (PEPP Brochure 1996; Bashyal 1997).

TERAI SUBSURFACE FRAMEWORK

The regional seismic, gravity and magnetic surveys in conjunction with surface mapping and basin analysis have established the subsurface framework of the Terai and part of Siwalik foothills. The area is characterized by many basement-controlled structures offsetting sediment-filled basins and grabens beneath the Siwalik mollasse. The base of Siwalik is marked by an unconformity at depth between 3500 m and 4600 m below the Terai Plain. It is an important reflection horizon in seismic sounding data separating the relatively flat-lying Siwaliks (mid-Miocene and younger) from dipping older strata (Lower Miocene to Precambrian).

The seismic grid of 10 km by 15 km covering most of the Terai and Siwalik foothills led to identification of a number of structural leads. These include structural traps related to normal faulting involving the Siwaliks, subcrop traps involving pre-Siwalik sequences and structural traps associated with blind thrusts in front of the MFT (Fig. 4). In addition, under the Terai, we can expect structural closures associated with basement-controlled faults, graben edge folds, drapings over pre-existing highs and stratigraphic traps caused by reservoir pinchout, facies change, permeability barriers, etc (Fig. 5).

EXPLORATION POTENTIAL

Nepal occupies a portion of two major geologic provinces, the Indo-Gangetic Plain and the Himalayan chain. From petroleum exploration standpoint, the Indo- Gangetic Plain is of major concern. Lying between the Indian Shield to the south and the Siwalik fold belt to the north, the Indo-Gangatic Plain is the foreland of the Himalayan chain known as the Terai, which stretches some 20 to 40 km north of the Nepal/India border.

The Terai is underlain by the thick sequence of Quaternary sediments comprised of sands, silts and gravels

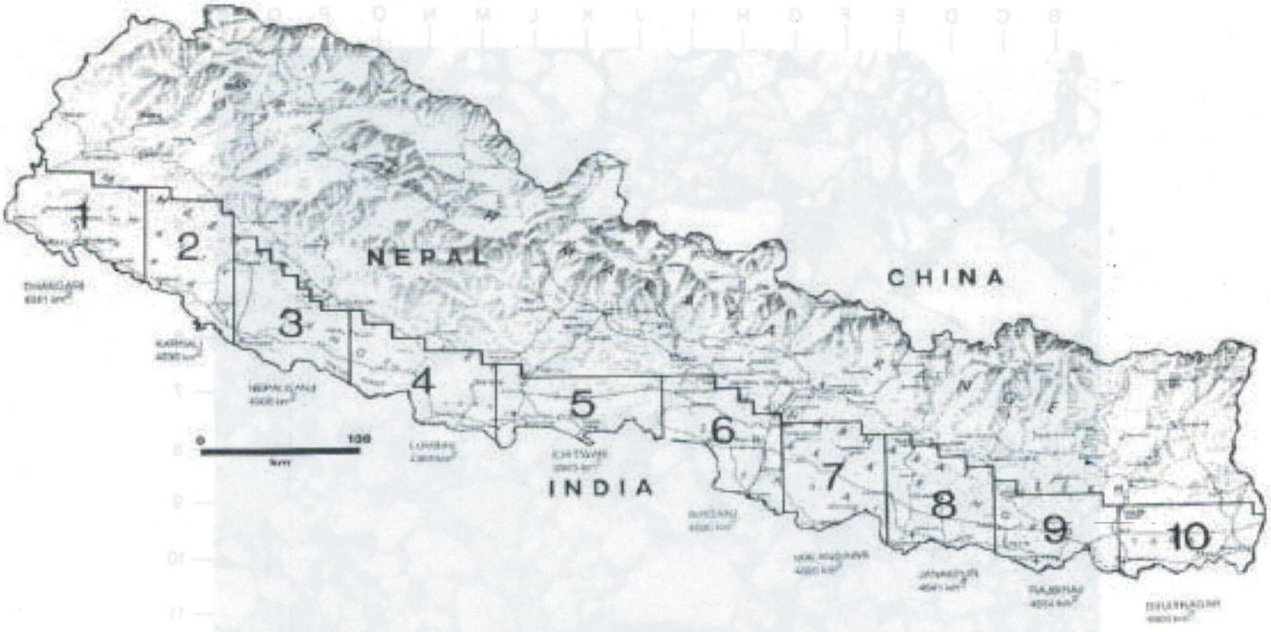

Fig. 6: Exploration blocks in Terai plain and Siwalik foldbelt (PEPP Brochure 1996)

and a thick accumulation of upper Tertiary molasses, the Siwalik Group. The molasses unconfomably overlie rocks of the Indian Shield including Archean crystalline/metamorphic basement, Precambrian to Lower Paleozoic sediments (Vindhyan/Nawakot/Lakharpata), continental and marine strata of the Gondwana succession and possibly marine sediments of late Cretaceous to mid Tertiary age (Surkhet/Tansen Group). The Terai Plain and Siwalik foldbelt area considered as the potential area for hydrocarbon exploration is divided into 10 exploration blocks (Fig. 6). These are from west to east: 1- Dhangadhi, 2-Karnali, 3-Nepalgunj, 4-Lumbini, 5-Chitwan, 6-Birgunj, 7-Malangawa, 8-Janakpur, 9-Rajbiraj and 10- Biratnagar. Each block has an area of approximately 5000 km^2.

HYDROCARBON SOURCE, SEAL AND RESERVOIR ROCKS

For formation of oil and gas resources, four natural conditions are required: presence of source rocks, reservoir rocks, seal or cap rocks and thermal maturation of sediments. For the sedimentary basins to host petroleum, it must contain an effective mature source rocks. The petroleum accumulates in other rock types of entirely different properties than the source rock. A reservoir rock is any rock that has porosities high enough to store large amount of petroleum and permeability sufficiently high for petroleum to be able to flow towards the production well. Seal rock made up of impermeable beds is required to trap or preserve the oil or gas within the reservoir. We have all these three conditions, but if there is no sufficient thermal maturity of the buried sediments, hydrocarbon contained in the source rock cannot be released. Therefore, the natural condition of thermal maturity under appropriate depth within oil generation window is also a prerequisite for formation of oil. These important parameters essential for determining the potential of hydrocarbon resource have been evaluated in Nepal based on the study of various rock formations in terms of stratigraphy, structure, geochemistry and maturation.

Potential seal rocks are expected in the Lower Siwalik and Suntar shales. Main trapping opportunities occur in the frontal blind thrust folds of the Siwalik, the outcropping Siwalik folds themselves and possible trapping structure over basement highs in the Terai. Integrated geological, geophysical and geochemical studies carried out so far have indicated a number of areas with definite exploration opportunities (PEPP Brochure 1996). In the Dhangarhi area of far western Nepal, Siwalik folds and thrusts appear to contain potentially prospective pre-Siwalik formation. Under the Terai, the base of Siwalik is quite deep (over 3000 m), but there is a good possibility that the Surkhet Group (Paleogene to Lower Miocene which are hydrocarbon bearing in Potwar Basin, Pakistan) is involved in truncational traps and basement controlled structures.

In the Nepalgunj area of western Nepal, outer Siwalik folds and thrusts provide the major structural leads. The presence of well defined wedge of possible Paleogene age in the Dhangargi-Nepalganj Basin and possible buried structures below the MFT create favourable conditions for further exploration.

The Lumbini area of central Nepal is attractive because of its relative proximity to known potential source beds in outcrop. It contains a very thick pre-Siwalik section that could contain reservoirs and source rocks which are within a favourable organic maturity window.

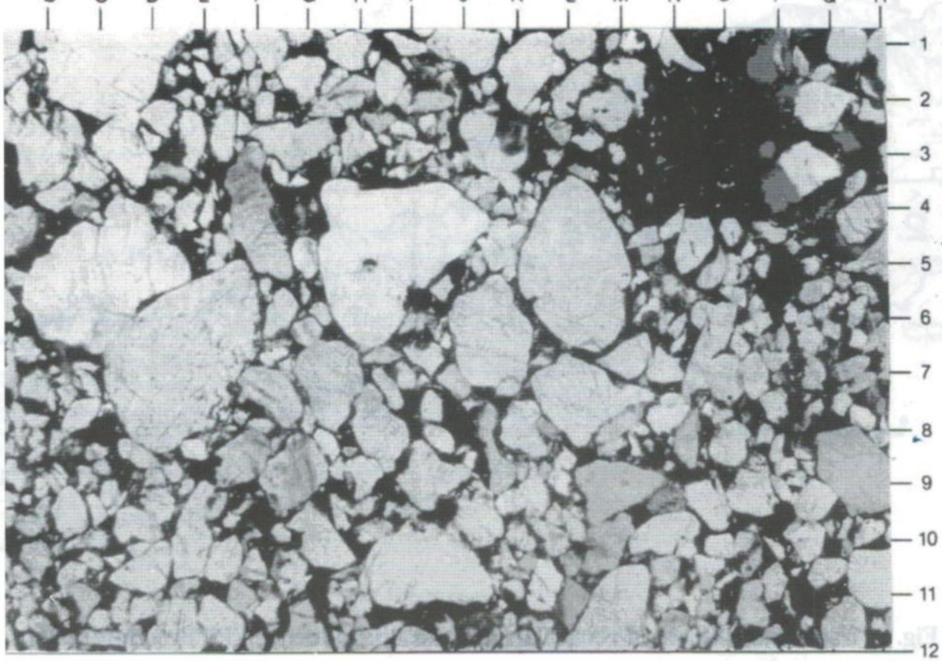

Fig. 7: Sandstone filled with solid Hydrocarbon

The western part of the Chitwan area (central Nepal) is attractive because of its proximity to the source rocks and because several major structures have been indicated by seismic data. The Hetauda-Birganj area (east central Nepal) contains pre-Siwalik cored thrust structures 'blind thrusts' and basement controlled structures. The Biratnagar area of far-eastern Nepal has numerous basement controlled structures and contains an untested pre-Siwalik section.

Nepal is unexplored by drilling except only one well was drilled on a seismically defined structure in Biratnagar block. The well abandoned at 3520 m after penetrating 3143 m of typical Siwalik molasse and 387 m of arkose and shale that was interpreted to be Eocene, but still doubted to be Siwalik. The well though dry provided valuable data concerning reservoirs, seal efficiency, source rock content and thermal maturity. Studies of outcrop samples and analyses of Biratnagar well drilled by Shell Petroleum indicate that effective reservoirs and seals are likely to be found in the Melpani sandstone of Surkhet Group belonging to the Paleogene wedge, in Lower Siwalik sandstone and shale, Surkhet and Gondawana sandstone and shales. Solid hydrocarbon filling the porosity of some Melpani sandstones (Fig. 7) alternating with bituminous shales has been found in Patu Khola, north of Tulsipur.

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SOURCE ROCK MATURITY AND BASIN MODELLING

A modeling study conducted for widely separated eastern (Biratnagar), central (Lumbini) and western (Dhangarhi) locations using a numerical technique suggested the level of thermal maturity to be somewhat higher in the west relative to the east for a given stratigraphic interval (Slind 1993; PEPP brochure 1996).The petroleum source rocks that have been identified below the Siwalik down to the upper part of the Vindhyan/Nawakot are expected to occur within the oil window at most locations in southern Nepal (Fig. 8). The timing of petroleum generation is probably within the last 5 to 10 million years. While the structural deformation which caused trap formation also resulted in the rapid burial of pre-Siwalik units, because of thermal time lag, oil generation, expulsion and migration are considered to have been contemporaneous with or to have post dated the formation of the traps.

VISIBLE OIL AND GAS SEEPS

In Nepal, oil and gas seeps occur in the western part of the country. The geochemical analysis of the oil seeps from Dailekh area indicates that these oil and gas have geological origin from a mature source rock and represent a severely biodegraded light oil. The proportion of higher homologs (C2 to C5) suggests that the gases were associated with oil. These seeps occur in a linear zone along Dailekh fault in the Lesser Himalayan meta-sediments indicating that source

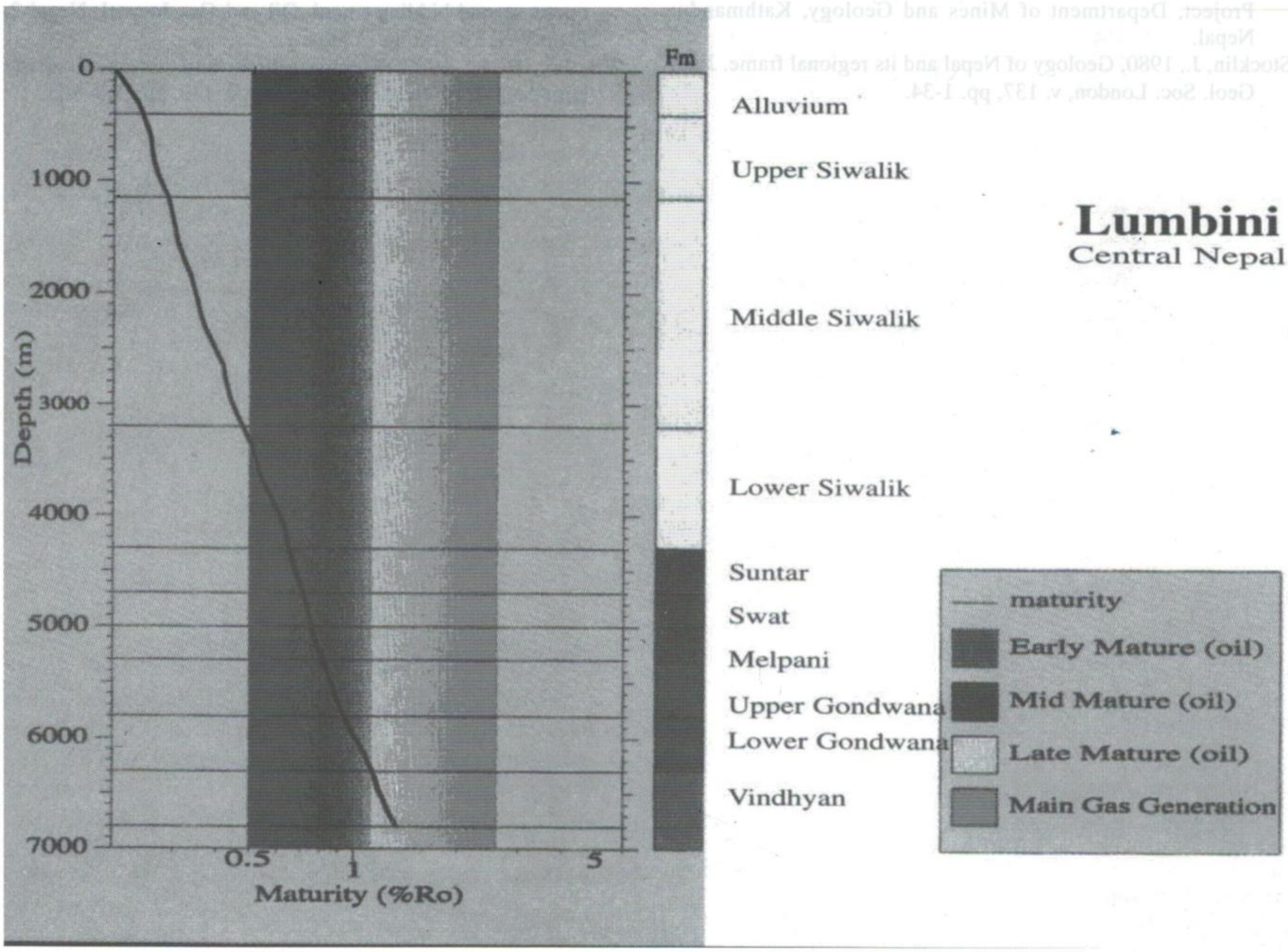

Fig. 8: Burial Depth vs. Maturity Plot, Lumbini, Central Nepal

rocks are buried below the thrusts and are expelling hydrocarbons.

CONCLUSIONS

Out of the five morpho-tectonic zones, only the Terai and Siwalik zones have potential for petroleum exploration. Exploration opportunities in the Terai include structures associated with blind thrusts, basement controlled structures, stratigraphic pinch-outs and subcrop traps. Major folds and thrusts in the Siwalik are likely to provide structural traps. Outcrop samples with significant source potential and thermal modeling suggests that these potential source rocks are in the oil and gas window. Effective reservoirs could be found in the Melpani Formation, Suntar Formation and Lower and Middle Siwalik. In view of the fact that similar geologic setting in Potwar Basin of Pakistan in the west and in Assam Basin of India to the east are producing oil and gas, the southern part of Nepal with known regional prospects and leads is attractive for hydrocarbon exploration.

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