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HYDROCARBON EXPLORATION IN ONLAND FRONTIER BASINS OF INDIA – PERSPECTIVES AND CHALLENGES*

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ABSTRACT

There are 26 sedimentary basins of India having an estimated resource of 29 MMMT, out of which only one-fourth has been converted to reserves. Most of the present production comes from the young passive margin and rift type of basins (mostly Tertiary), whereas the other basins - Compressional fold-thrust belt and foredeeps (Himalaya, Ganga/Punjab) and older rift basins (Proterozoic, Gondwana) are yet to be fully explored. There are seventeen basins considered as frontier basins, most of which are in the phase of knowledge building. Ideas and concepts play important role in their exploration. A few emerging concepts are discussed in this article, e.g. Vindhyan is an intra/pericratonic rift having well preserved sedimentary facies of different phases of rift development; Bundelkhand massif is a floating basement glided along south-vergent thrust sheets during Himalayan orogeny; possibility of existence of the Gondwana rocks below Vindhyans of Central India; coal has the potential to generate gaseous and even liquid hydrocarbons within the Gondwana basins of India; presence of Palaeozoic-Mesozoic sequence is envisaged below the Tertiaries of the Punjab plain in the Western Himalayan foredeep, etc. Hydrocarbon prospectivity of individual basins with the current state of knowledge has also been discussed. The basic constraints of exploration are identified, such as the identification of source pods through geochemical investigation and poor seismic images particularly in the complex orogenic belt, subtrap and subsalt conditions. It is felt that at the present stage of exploration of the Indian frontier basins, industry needs research support from the academia in a few key aspects such as geochemistry, geochronology and biostratigraphy. At the same time, sufficient thrust should be given to develop non-conventional petroleum system e.g. basin centered gas, biogenic gas and Coal-bed Methane.

Key words : Frontier basins, exploration, geodynamic evolution, Hydrocarbon prospectivity

INTRODUCTION

Although the global search for alternative energy sources has begun, the world's chief dependence for energy resources during the coming decades will be on oil and natural gas supplies. World's energy demand is projected to grow 60% till 2020. The growth of world economics will drive the increasing overall demand for oil where developing countries of Asia and South America are expected to double their consumption. The Third World as a whole will consume as much as 90% of oil as the dominant industrialized nation by that time. The use of natural gas is expected to be the fastest growing portion of the world's energy mix as demand for electricity surges in previously developing countries. It is predicted that the demand for gas will increase sharply from present 23% of the world's energy consumption. Keeping in view the growing demand of oil and gas, fluctuating market price and geopolitical uncertainties, a few measures have already been taken to improve our national hydrocarbon resource, and to add oil securities from foreign oil fields. In the national scenario, maximum thrust is placed on frontier basin exploration including the deep sea acreages. The recent advances in geoscientific understanding of these basins, role of non-conventional petroleum systems and development of frontier technologies are going to play critical role in identifying new petroleum provinces.

INDIAN ONLAND FRONTIER BASINS

India is bestowed with 26 sedimentary basins (fig.1) spread over 3.14 million square kilometer of both inland and offshore areas (up to 200m isobath) with a prognosticated

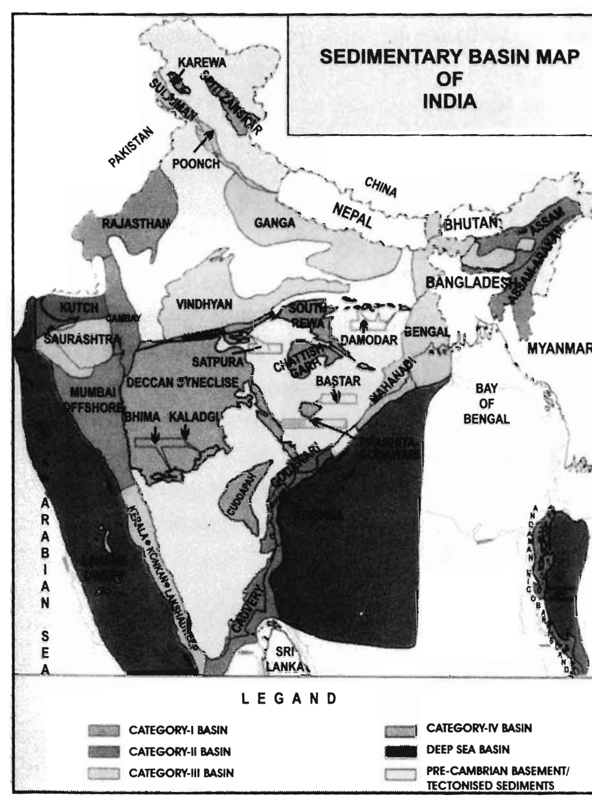

Fig. 1. Sedimentary basin map of India. Basins are categorized based on exploration status and prospectivity of the basins. Category I has basins with established commercial production. Category II has basins with known accumulation of hydrocarbons but no commercial production as yet. Category III has basins with indicated hydrocarbon shows that are considered geologically prospective and Category IV includes basins with uncertain potential which may be prospective by analogy with similar basins of the world. Offshore basins include both shallow water (up to 200m isobath) and deep water together.

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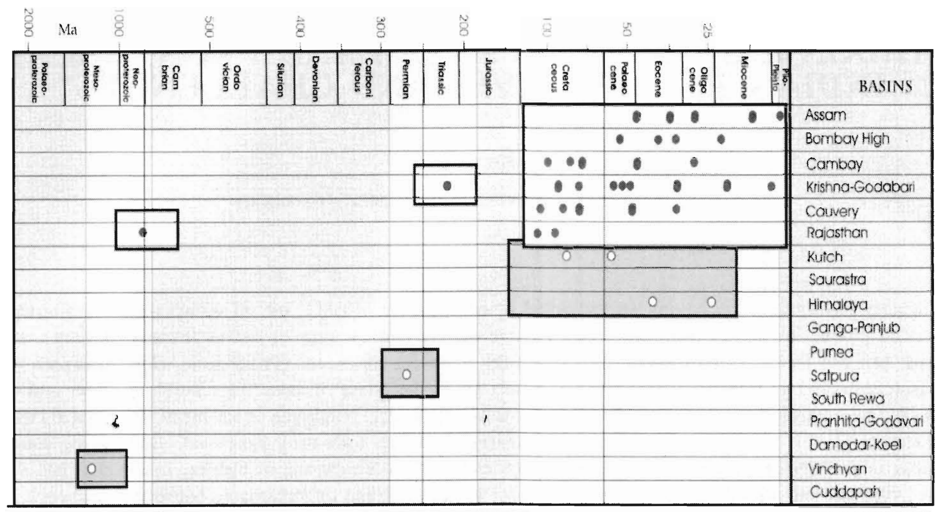

Fig. 2. Hydrocarbon occurrences in different Indian basins through time. The Assam shelf and the Assam-Arakan Basin are actually parts of the same Tertiary basin and are considered together under the heading of Assam basin. Except Bikaner-Nagaur, rest of the basins are mainly producing from the Tertiary sequence.

hydrocarbon resource base of 29 billion tons of oil and oil equivalent gases, of which only one-fourth has been established at proven reserves. Seven basins are presently producing, rest of the basins are at different stages of exploration, waiting to be listed on the hydrocarbon map of India (fig.2). Among the nineteen onland non-producing basins, seventeen are categorized under Frontier basins (prognosticated resource estimated at around 3.4 billion tons), which have either indication of non-commercial hydrocarbon shows or perceived prospectivity by analogy with other similar petroliferous basins of the world. Most of these basins are least explored and in the knowledge-building stage of exploration. These frontier areas hold the potential to contain vast hydrocarbon accumulations, the future oil and gas discoveries that could make the difference between self sufficiency in energy sector and economic bankruptcy. The frontier basins of yesteryears are the producing basins of today and the frontier basins of the present need to be converted as producing basins of the future.

GEODYNAMIC EVOLUTION OF INDIAN FRONTIER BASINS

Throughout the geological time crustal blocks have been evolving continuously through consumption and regeneration. Large continents were nonexistent during early Archean times and the small ones that had formed, were short-lived as they were mostly consumed into the mantle. Surviving detrital minerals (zircons), dated around 4.2 billion years in Australia are evidences of these early crusts that had existed (Maas *et al.*, 1992; Amelin *et al.*, 1999 and Sankaran, 1999). Relatively stable configuration of lands could materialize only during the long Proterozoic period (between 2800 and 570 m.y. ago) when several of the early blocks (cratons) came together at collision zones to form a giant supercontinent towards the close of this period (Sylvester *et al.*, 1997). Within the Indian subcontinent, Ravi Shankar *et al.*, 1999 have identified four Precambrian blocks which apparently represent a few of the several independent Archean fragments (cratons) that had fused to form the supercontinent of pre-Proterozoic period (>2400 m.y. period). The blocks are: (a) Bundelkhand block (BB), an early Proterozoic magmatic terrain of granitic and gnessic rocks enclosing remnants of 3.0–3.5 billion years old Archaean crusts and extending below the Himalaya northwards; (b) Dharwar block (DB), with Archean cratons –Karnataka, Bastar, and Singhbhum; (c) Trans-Aravalli Block (TAB), with remnants of Palaeoproterozoic granulitic and charnockitic rocks and younger granitic events; and (d) South Indian–Sri Lankan Granulite Block (SI–SLGB), showing >2.5 billion year old Archaean crusts (fig.3). The four blocks were welded together during two major tectonothermal events: i) around 1600 m.y. ago that welded BB, DB and TAB and sutured them to Western Australia and Antarctica to constitute east Gondwanaland; ii) around 500 m.y ago which sutured SI–SLGB with DB along the Palghat–Cauvery shear zone (PCSZ). With the closure of these two events, the making of the Gondwanaland was completed. Proterozoic basins of India range in age from Meso- to Neoproterozoic. They are generally placed along the fringes of those crustal blocks; Vindhyan, for example, is a rift related basin, whereas Cudappah shows the signatures of a thrust fold belt and associated foreland basin geometry. Thus, it can be presumed that the Wilson cycle responsible for the basin formation and destruction was also equally valid during the Precambrian time in the case of Indian subcontinent.

The correlation of Precambrian rocks of Peninsular and Extra-Peninsular India (Himalayan) is not very clear till date. Peninsular basins have mostly Mesoproterozoic fills. How-

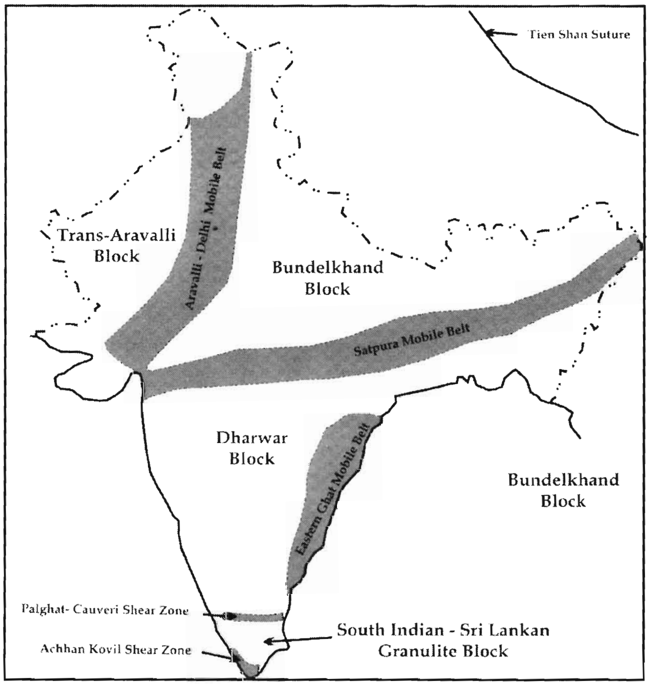

Fig.3. Precambrian cratonic blocks of Indian peninsula (after Radhakrishna, 1989). Three major mobile belts separate three major cratonic blocks. Most of the Precambrian frontier basins are located along the fringe of those mobile belts.

ever, the extensive passive margin sedimentation in the Himalayan region was more wide ranged. In the Lesser Himalaya, rocks of ~2500 Ma are reported from the volcano-siliciclastic association of Rampur window (Bhat and Le Fort, 1993). Most of the Shali and Simla groups of rocks range within the domain of Neoproterozoic. The Shali carbonate – siliciclastic sequence is of almost similar tectono-sedimentation milieu as that of Lower Vindhyan sediments. Lateral facies variation of isochronous sediments is also reported from the drilled wells of the Punjab basin. The carbonate sequence of Janauri changes to quartzite-shale in the Adampur well, which are corresponding to the exposed Delhi Group of sediments further south. In the Tethyan Himalaya, the Thango quartzite appears almost similar to the Rewa Quartzite of the Vindhyan system.

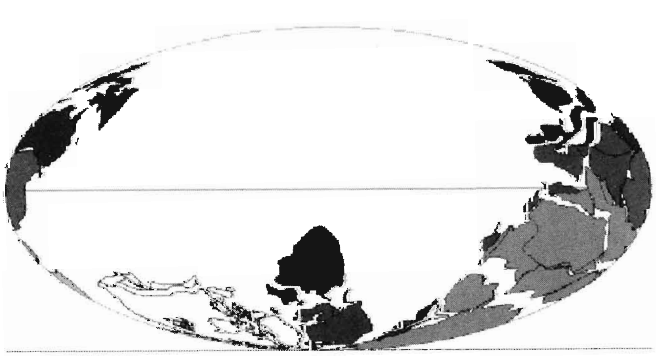

Fig.4. Late Neoproterozoic reconstruction of plates showing the equatorial position of India within northern hemisphere (Scotese, 1997).

There is a time gap of at least 200 million years between the rocks of the Pre-Cambrian and those of the Gondwana Supergroup. There is hardly any lithostratigraphic record representative of this period present in Central and South India. This could be either due to complete removal of rocks formed in this region or due to nondeposition during most of the Palaeozoic Eon. Continental to marginal marine sediments of this time containing '*Glossopteris*' flora and dinosaur fauna which is common with Africa, Antartica and Australia, indicate that Gondwana had not yet broken up. During the Late Carboniferous glaciation, India was an integral part of Gondwanaland, which in turn formed the southern part of Pangaea, with regional drainage from central Antarctica towards northwest across what later became the Indian peninsula (fig.5).

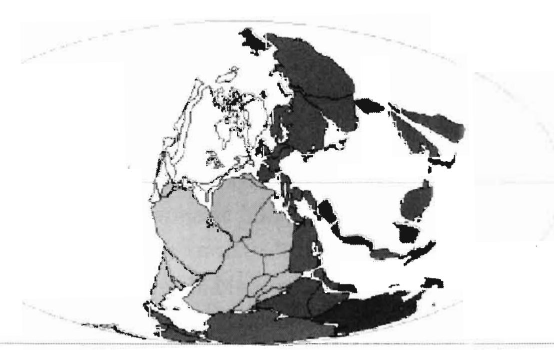

Fig.5. Permian Plate reconstruction shows the position of India (higher latitude within southern hemisphere) as a part of Gondowana Supercontinent (Scotese, 1997).

The next two hundred million years witnessed breaking of Gondwanaland, movement of Greater India towards equatorial latitudes and subsequent collision with Eurasian plate. Indian peninsula is presumed to have extended far towards north and its oceanic crust was consumed below Eurasian plate during the course of subduction. Thus, the basement of Himalayan foredeep is nothing but the extension of Peninsular India with sediment cover of Proterozoic and Gondwana affinity.

Post-Gondwana rocks of Late Cretaceous (Maastrichtian) age consist of fine lacustrine calcareous clays with evidence of root networks and calcrete, suggesting that these sediments occupied the lower parts of a low relief plain where groundwater levels were shallow but variable and evaporation rates were high.

The rifting and breakup of Pangea during Triassic–Jurassic periods was accompanied by massive volcanisms. Fragmentation within the Gondwanaland by development of rifts, isolated India from a composite Africa–South America and Antarctica–Australia combine on its either sides. The Indian plate became detached in the Mesozoic and moved northwards pushing thick Tethyan marine sediments towards the Asian plate, later to form the Himalayas (fig.6). However, con-

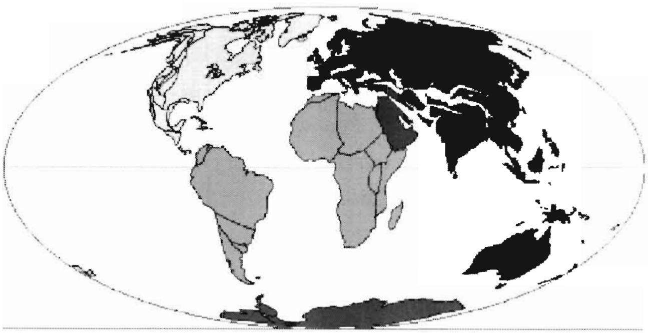

Fig.6. Miocene Plate reconstruction showing the progression of India nearer to Eurasian plate (Scotese, 1997).

ditions in the interior of the Indian plate remained stable during this period.

BASIN CHARACTERS

The onland frontier basins are in diverse tectonic set-up and can be grouped into a few broad categories as discussed below.

Compressional basins : The frontal thrust fold belt of the Himalaya (fig.7) has attracted attention for hydrocarbon exploration much early. Exploration in thrust-fold belt is most challenging throughout the world. Exploration in Outer Himalayan belt and frontal foredeep is being carried out for the last fifty years without any breakthrough. The subsurface imaging is a critical factor for exploratory success in these areas. Steep dips, complex trap geometry, burial and thermal history, besides, the inhospitable terrain pose great challenge. In addition to that, problem of modelling and locating areas of good source facies development (Subathu sequence) are equally challenging. In the foreland basin (Ganga and Punjab) seismics have provided good subsurface information. The Tertiary foredeep fill in this polycyclic basin is ubiquitous throughout, the Pre-Tertiary basin fill shows remarkable variability across different depressions ranging from Palaeo-Neoproterozoic–Early Palaeozoic to Gondwanic to Mesoproterozoic from west to east, suggesting a complex Pre-Tertiary evolutionary history of the basin. However, here the problem lies in the search of quality reservoir and adequately matured source facies.

Rift basins : In terms of frequency of hydrocarbon occurrence globally, rift basins are only next to the foredeeps. India is bestowed with a large number of rift basins of Gondwana age viz, Satpura-South Rewa-Damodar-Koel, Pranhita-Godawari and Hasdo-Mahanadi. Considerable exploratory inputs have been expended in Satpura and South-Rewa basins. Damodar sector is already in active exploration for Coal Bed Methane (CBM). Exploration problems in these basins are related to poor quality of reservoirs and absence of regional caps and criss-cross network of basic dykes. Intrusives often pose imaging problem on account of their high velocity that scatter seismic energy. Gravity data in the basin, nevertheless, provide very clear picture of the basin geometry, major depocentres and principal tectonic elements (fig.8). These basins hold largest repository of coal in India. The challenge is to establish coals and coaly shales as potential source rocks capable of generating and migrating hydrocarbons.

Concealed Rift Basins : A significant part of the west central India is covered by Deccan Basalt, which conceals the geology underneath. This province, referred to as Deccan Syneclise, also covers to varying degrees the Saurashtra, Vindhyan, Satpura, Saurastra-Kutch, Pranhita Godavari, Kaladgi and Bhima basins. Underneath Deccan Syneclise, a series of concealed grabens having a general NW-SE trend have been inferred from geophysical data. The nature of sedi-

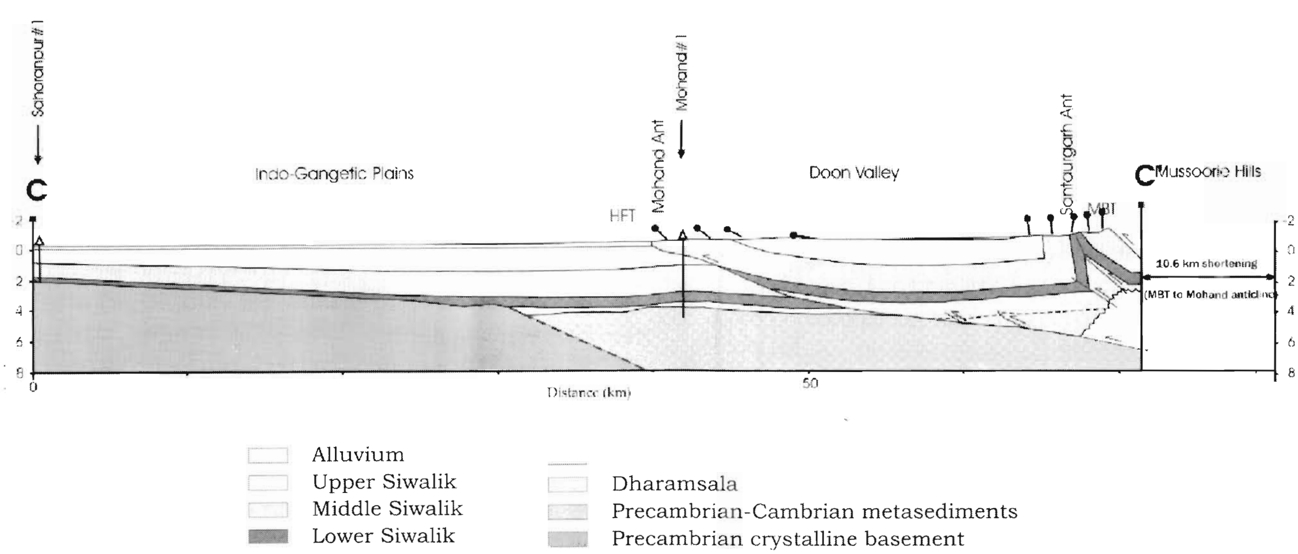

Fig.7. Balanced cross-section across the Himalayan foreland basin through Mohand (after Power, Lille and Yeats, 1998). The fault-propagated folds and low angle detachments are characteristic of the Outer Himalayan fold-thrust belt.

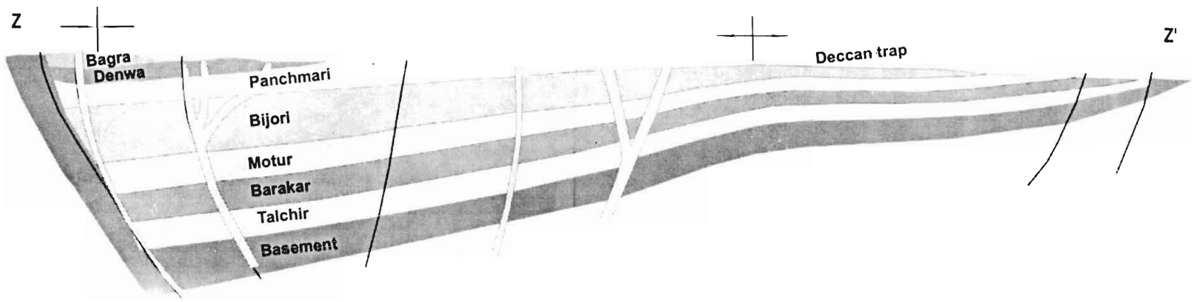

Fig.8. Schematic geological cross-section across the Satpura Basin. A typical half-graben structure of a rift basin cut across by a number of igneous intrusives.

mentary fill in these troughs is not confirmed as per available data or knowledge base, but at places, extension of these basins is seen around the periphery of the syneclise (fig.9). Commenting on the petroleum system of Deccan Syneclise is highly conjectural due to absence of ground data. The basin is at the stage of knowledge building and systematic geo-scientific inputs including parametric drilling are needed to decipher stratigraphy, regional configuration, lithofacies and structural style to comprehend its hydrocarbon potential. Gravity survey followed by modelling in conjunction with other non seismic inputs, viz. Magneto Telluric (MT), Transient Electro Magnetic (TEM), etc will surely come handy in unravelling the geology concealed beneath the basaltic trap.

Intracratonic basin : Most of the Proterozoic basins of Central and South India, viz. Cuddappah, Vindhyan, Chattisgarh, Bastar, Bhima, Kaladgi, etc have been considered in this category. Alternate carbonate and siliciclastic packages are the characteristic of most of these basins. Sediment thickness varies from basin to basin. G&G data quality is comparatively better than other contiguous frontier basins of India. Proterozoic source rocks, though present in other analogous basins of the world, are yet to be confirmed in these basins. Envisaged reservoirs are all tight and sometimes show density more than the Sialic basement rocks of surrounding areas. Hence, the challenge is to establish Proterozoic source and map sweet spot from where hydrocarbons can be produced.

Passive margin basin : Rajasthan shelf represents this type of basin and contains a thick Eocambrian package as passive margin sequence followed by Tertiary marginal marine sequences as the foreland sequence of Suleiman Range of Pakistan. Eocambrian is represented by mixed carbonate siliciclastic sediments with thick salt in Bikaner-Nagaur sector (fig.10). The basin is shallow and gradually sloping due west towards Suleiman Range of Pakistan. The basic problem encountered in this basin is that of imaging the sub-salt structures and identification of the basement. Sediment fills are lying mostly above the maturation window and interests lie in the identification of deeper pods (if any), present within this basin.

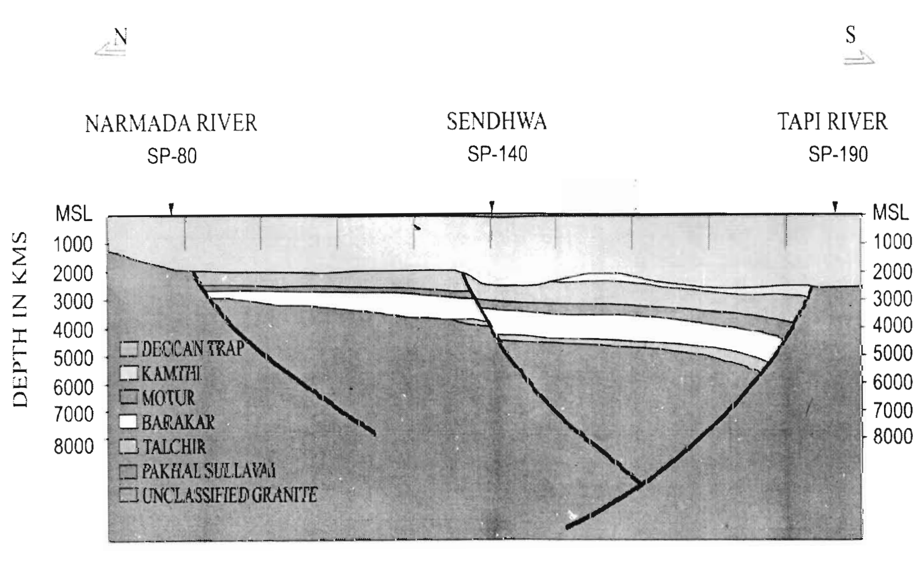

Fig.9. Schematic geological cross-section across the Narmada subtrap Basin. A half-graben is envisaged below trap filled by Gondwana sediments as modelled through DSS data. Trap thickness decreases northward.

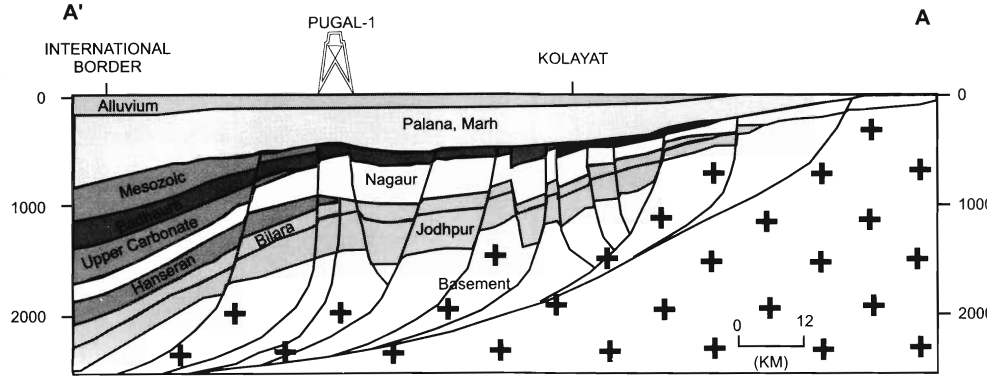

Fig.10. Schematic geological cross-section across the Bikaner-Nagaur Basin. An initial rift-related sediment fill followed by typical passive margin set up is the characteristic of the basin. Lateral facies change is common. The Hanseran Evaporite is a facies variant of the Bilara Limestone. The Upper Carbonate also changes laterally into the Nagaur Formation. Heavy oils are reported from the Jodhpur, Bilara and Upper Carbonate Formations respectively.

EMERGING CONCEPTS IN EXPLORATION OF INDIAN FRONTIER BASINS

A. Proterozoic Basins

Most of these Indian Proterozoic basins were earlier considered to have formed as interior sags where sedimentation occurred in epicontinental seas. However in recent years there have been significant change in the understanding of the structural differentiation at deeper levels in these basins and rift related origin of these basins are favoured.

It has now been understood that the Cuddapah Basin has a gently eastward dipping foreland/foredeep towards west and an intensely folded and thrusted eastern sector welded to the orogen's western limb. Closer scrutiny of the basin architecture (geometry, polarity, asymmetry in thickness, distribution, sedimentary history and structural style) suggests that this polycyclic basin initiated as a pericratonic rift and culminated as a foredeep with westward-directed orogenic front and domal structures (fig.11). Gravity, Magnetic surveys over the basin and two east-west oriented Deep Seismic Sounding (DSS) profiles were acquired by National Geophysical Research Institute (NGRI). These profiles reveal that the basin is fragmented into several blocks and separated by basement faults. the Cuddapah Basin presents a depositional environment of littoral, infra-neritic and beach with shifting depocenter, as is typical of foredeep basins.

Several models have been proposed on the evolution of the Vindhyan Basin. Contrary to the concepts of simple interior basin (Biswas *et al.*, 1993) and peripheral foreland basin (Chakraborty *et al.*, 1996), Jokhan Ram *et al.* (1996) based on geophysical data suggested that the Vindhyan Basin was initiated as an intra/pericratonic rift (half graben) with well defined Pre-, Syn-, Post-rift phases of development. They also pointed out that the horst and graben structural style of syn-rift phase was replaced by a carbonate-clastic ramp basin set up during the post–rift stage. Raza and Casshyap (1996), too, postulated that the U-shaped Vindhyan Basin developed as a post-orogenic Pericratonic Basin on the underlying Bundelkhand craton following the Middle Proterozoic collision with a southerly protocontinent and the Vindhyan Basin was formed largely through rift-controlled subsidence under extensional regime.

The Son valley-Vindhyan Basin is characterized by asymmetric geometry, gradually deepening due south and having the deepest part near southern margin along the Son-Narmada lineament (fig.12). A system of longitudinal, buried en-echelon ridges is present parallel to the basinal axis. The basin has

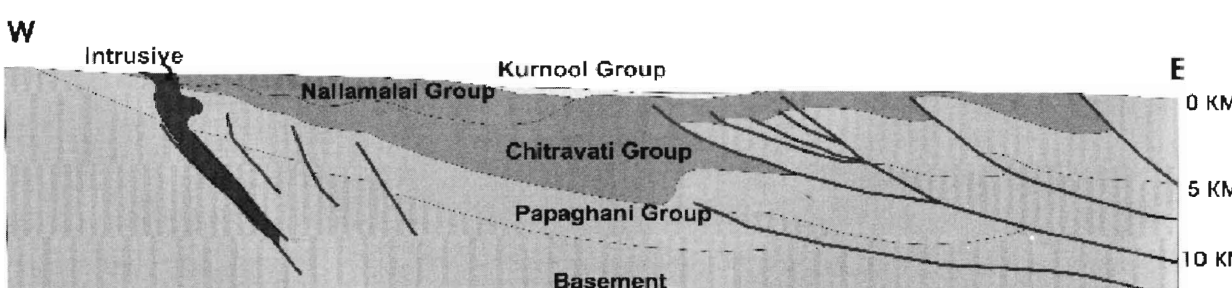

Fig.11. Schematic geological cross-section across the Cuddapah Basin. Except Kurnool, all other stratigraphic units are highly tectonised. The effect of thrust propagated compressional structures are dominant in the eastern margin adjacent to the Eastern Ghat mobile belt.

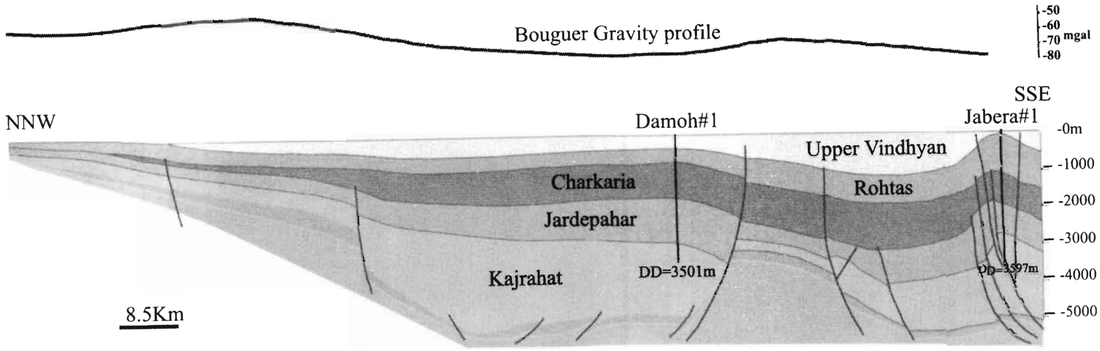

Fig.12. Geological cross-section across the Son valley of the Vindhyan Basin. Sedimentation of the Lower Vindhyan formations was controlled by growth faults. A major inversion structure developed in the southern margin (Jabera) adjacent to the Son-Narmada lineament.

witnessed post depositional compressive deformation leading to structural inversions. The basement ridge and its flanks are the possible locales of retention of primary porosity in potential reservoirs on account of less overburden. Away from the ridge the reliance has to be placed essentially on fracture porosity. The basin seems to have undergone several episodes of tectonic activity subsequent to cessation of Vindhyan deposition. Neotectonic reactivation is evidenced even in today's landscape. The last epeirogenic episode could be post Trap as Trap outliers are perched on Bhander sediments, south of Jabera, in a synclinal disposition. The first order folded structures along the northern edge of Son-Narmada Lineament like Jabera, Kharkhari, Aloni, Kudri and Sarsi anticlines and Murwara, Barhi synclines are in their late breaching stage and are not yet peneplained. This geomorphic attribute indicates that the last epeirogenic episode could well be as young as Miocene and even later. Negative excursions of Bouguer Gravity values are observed over the Bundelkhand massif which comprises granite-tonalite suite (fig.13). It is being opined that Bundelkhand is a floating basement disposed in its present position by virtue of a south vergent detachment relating to the Himalayas. Ravi Shankar (1993) has recorded unequivocal evidences and has suggested possibility of existence of marine and/or deltaic equivalents of exposed continental Gondwana rocks in Central India underneath the Vindhyan Plateau.

Acritarch and microfossil data suggests that sediments of the Vindhyan supergroup range in age from Upper Mesoproterozoic (Ectasian) to Neoproterozoic-III which approximately lies between 1300 Ma to 600 Ma on the

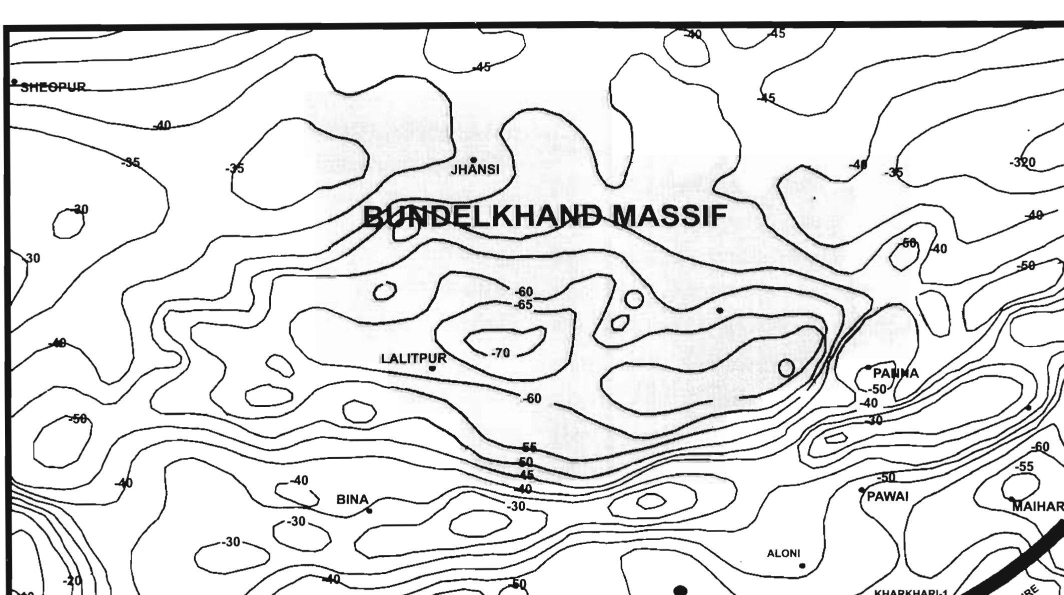

Fig.13. Bouguer gravity map of a part of Central India. A prominent gravity low is seen over the Bundelkhand massif which lead to consider a new concept of floating granitic basement over the Vindhyan sediments.

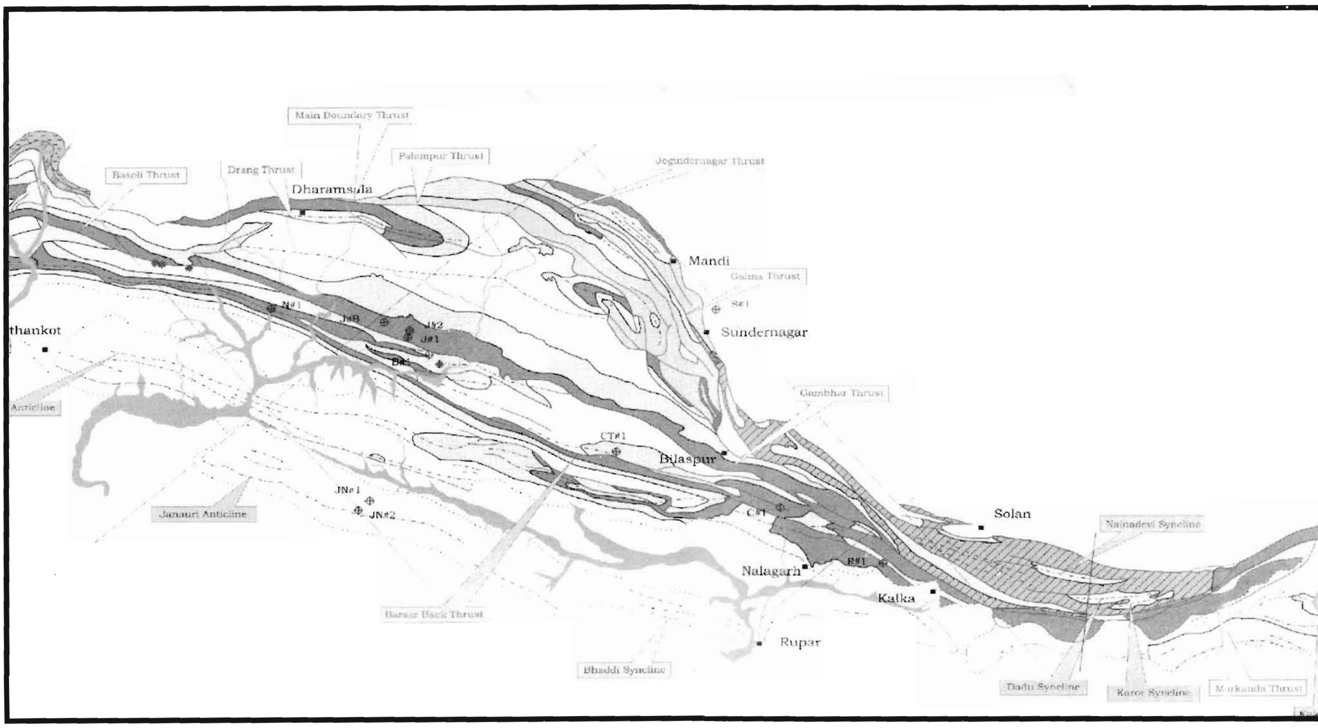

Fig.14. Geological map of the Outer Himalayan Belt between Ravi and Yamuna. A wide Siwalik belt is exposed within the re-entraint (Kangra), whereas the same is very narrow in front of the salient (Nahan). Duplexes are more common in the inner tectonic belt where Subathu and Dharamsala rocks are exposed. The Siwalik belt is characterized by fault propagated fold, fault bend fold and triangle zone.

biochronostratigraphic scale (Prasad *et al.*, 2003). Their study further reveals a shallow inner shelf depositional environment of Lower Vindhyan sediments (Semri Group); and littoral to marginal marine depositional environment of the Upper Vindhyan Sediments. Deposition of sediments within shallow marine environment sometimes interrupted by long hiatus has also been inferred by Akhtar (1996).

B. Gondwana Basins

There are many recently emerged perceptions in evaluation of hydrocarbon prospectivity of Gondwana sediments in India. Source potential of coal is by and large under-estimated but it is now established that coals can generate gaseous and even liquid hydrocarbons. Essential requirement to promote expulsion of hydrocarbons out of coal are bitumen yield over 30 kg/tonne and tectonic/hydraulic fracturing of coal and high sand-shale ratio for coal measures. Carbonaceous shales, particularly those within the Barakar Formation, are mostly gas prone with type III organic matter. But admixture of type II liptinitic material up to 40% can be a potential source for even limited amount of liquid hydrocarbons in the northern part of the Satpura and South Rewa Basins, northern sectors of the Pranhita-Godavari Basin and Damodar graben.

Effect of intrusive on sediments is found to be locally high due to contact metamorphism which in turn is responsible for higher vitrinite reflectance values in younger sediments (younger than Barakars). Development of comparatively low porosity and permeability in Gondwana reservoirs may be due to intense mechanical compaction and even formation of sericite due to low grade metamorphism as well as cementation with a mixture of quartz overgrowth, carbonate cements and mixed authigenic kaolinite and illite.

C. Himalayan Thrust Fold Belt and Foredeep

In the Himalaya, the inner belt of Kangra-Mandi needs additional attention (fig. 14). Widening of the belt in the form of re-entrant indicates presence of some additional structures in the subsurface. This along with the presence of Paror and Sarkaghat anticline make the area interesting for hydrocarbon exploration.

In J&K sector, seismic sections of the Kalakot-Naoshera-Punch area show presence of deeper sequences repeated by thrusts below the Tertiaries. Remarkable similarity in nature of seismic packages and structural styles, with those of the hydrocarbon-bearing Palaeozoic - Mesozoic - Palaeogene sequence of adjoining Salt Range - Potwar Basin makes the Pre-Tertiary sequence of this area interesting (Pennock *et al.*, 1989). It appears that the Naoshera - Rajouri- Punch sector of Jammu foot hills was in geological and depositional continuity with the Salt Range - Potwar depression during Paleozoic – Mesozoic (fig.15). A number of gas shows and few oil shows reported in this area, makes the area important for exploration.

The undisturbed foredeep plain of Jammu and Punjab do not have any geoscientific data except regional refraction lines and regional gravity-magnetic data. Magnetic maps show

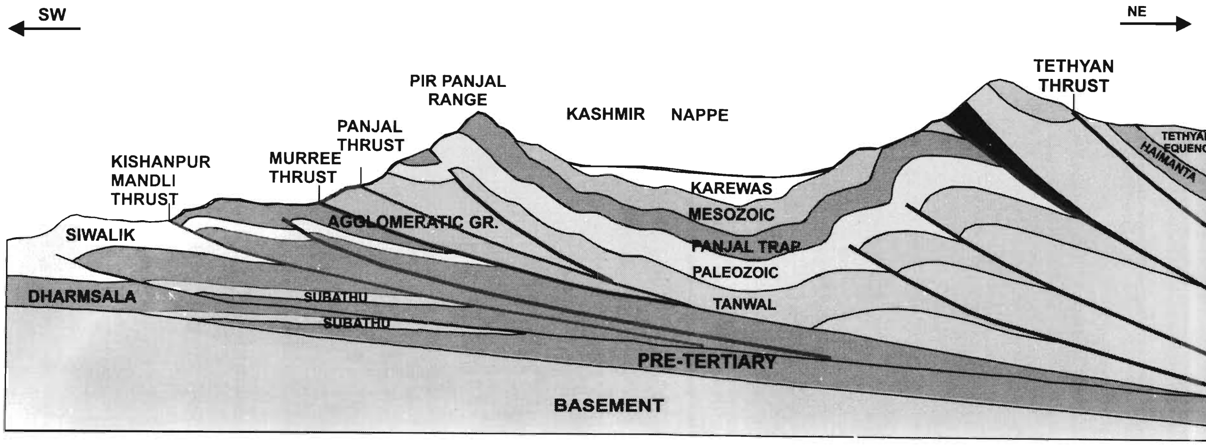

Fig.15. Schematic geological cross-section across the Kashmir Himalayas. Karewa is a piggy-back basin below which the Palaeozoic and Mesozoic sections of the Tethyan Himalaya are interesting targets for hydrocarbon exploration.

well developed linear depression in the Jammu–Pathankot-Hoshiarpur area trending NW-SE. A simple three tier stratigraphic framework is till date accepted for the Punjab foredeep (1) Basement Gneiss followed by (2) Proterozoic – Lower Palaeozoic platformal sequences and (3) Tertiary foredeep molasse. But a new thought has emerged recently related to the presence of Palaeozoic-Mesozoic sequences below Punjab alluvium (Samanta *et al.*, 2002). Late Palaeozoic rifting and the associated sedimentation and volcanism in the Himalayan Orogen is evidenced by the well-recorded Agglomeratic Group and Panjal Trap. Thrust-accreted Gondwana sediments are reported from the Nepal and Arunachal Himalaya. Within the foredeep set-up, the nature and extent of pre-foredeep sediment is a bit speculative due to lack of data. In Pakistan, west of Jhelum syntaxis, the Palaeozoic–Mesozoic sequences are extensively developed below the foredeep molasse. It is envisaged that in Punjab coeval sequence may have been preserved within fault bound basement lows, as identified from geophysical studies (fig.16). The exact nature and age of the sedimentary fill in Jammu - Pathankot - Hoshiarpur low is not known. It is expected that the low may contain Palaeozoic - Mesozoic sediments below Tertiaries and will definitely be interesting for hydrocarbon exploration. Paleozoic-Mesozoic petroleum system is expected to be present in the area.

Thick Palaeozoic-Mesozoic sequences are present below the Karewa sediments in Kashmir valley. No significant studies in Palaeozoic-Mesozoic sediments have been done till date. The Palaeozoic-Mesozoic Tethyan sequences are expected to have good source and reservoir facies. The Cambrian to Middle Carboniferous sequence below Panjal Trap may be expected to be over mature but the Permian to Jurassic sequences above the trap can very well be expected to be mature and likely to have generated hydrocarbons. Second order anticlines formed by the buried hinterland thrusts of Kashmir nappe are expected below the Karewas. These concealed structures, if identified, will be interesting for hydrocarbon exploration.

HYDROCARBON PROSPECTIVITY

In Proterozoic basins, hydrocarbon shows are recorded at four different levels of Cambrian – Infra-Cambrian sequences. The discovery of non-biodegraded, heavy oil in the Baghewala area has opened up a new exploration play in Bikaner-Nagaur sector for low-maturity oils generated from Infra-Cambrian source rock. The analogous sequences are producers in a number of petroliferous basins of the world.

The Lower Vindhyan sequence has well diversified sedimentary suite with adequate source development. Seals are

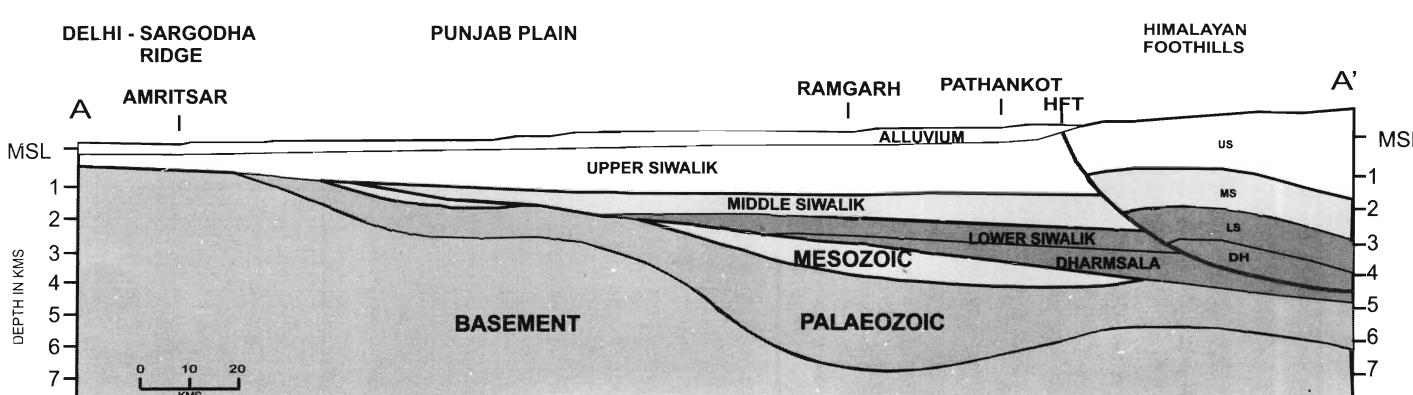

Fig.16. Schematic geological cross-section across the Punjab Plains. An additional package of Palaeozoic-Mesozoic rocks is envisaged below the Tertiary foredeep fill.

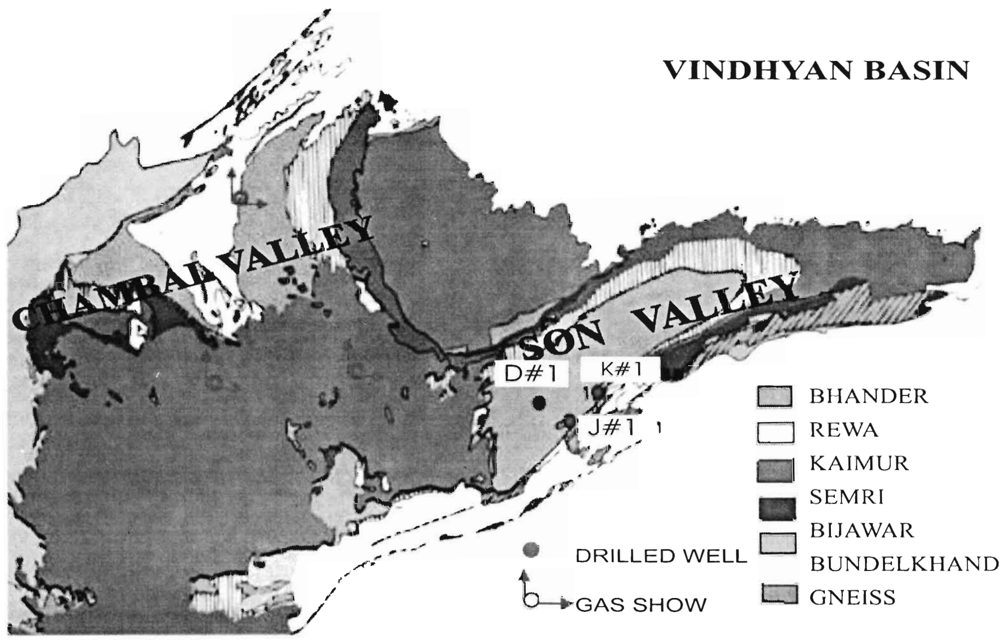

Fig.17. Geological map of the Vindhyan Basin showing two sub-basins (1) Son valley in the eastern part of Bundelkhand massif up to Son-Narmada lineament (at the southern margin) and (2) Chambal valley between the Aravalli fold belt and Bundelkhand massif respectively. The central part of the Vindhyan Basin is covered by extensive continental flood basalt (Deccan Trap).

also present; however, the reservoir remains an area of concern. The Upper Vindhyan has dominantly arenaceous sequence, therefore no petroleum system is visualized in it. Three possible play fairways recognized in the Son Valley Vindhyan Basin are (1) structural plays on the basement ridge, (2) wedge out on the southern flank of the ridge and (3) structural inversion in the southern depocenter. One well was drilled on one such structural inversion located in the southern part and it yielded 2000-3000 m^3 of gas per day (47-69% methane along with 6.5 to 8.6 % of higher hydrocarbon up to hexane). The main constraints observed in the basin are poor reservoir facies development. Identification and mapping of some sweet spots in otherwise non-porous siliciclastics and carbonates are the critical exploratory requirements for the basin/sector.

In the Chambal Valley Vindhyans, the regional gravity data show presence of several highs and lows within the basin. The detailed geological mapping carried out along the western margin indicates a restricred marginal marine depositional environment (back-barrier lagoonal to tidal flat) to the west and a deeper marine environment to the east. These may form good source-reservoir combination. Thermogenic gas shows reported in the Chambal Valley sector of the Vindhyan Basin (fig. 17) make it interesting from the perspective of hydrocarbon exploration. Inversion structures, hanging wall fault closures, roll-overs, wedge-outs against basement ridges, broad open folds and frontal folds of Great Boundary Fault (GBF) lineage are expected to form favourable entrapment (fig. 18).

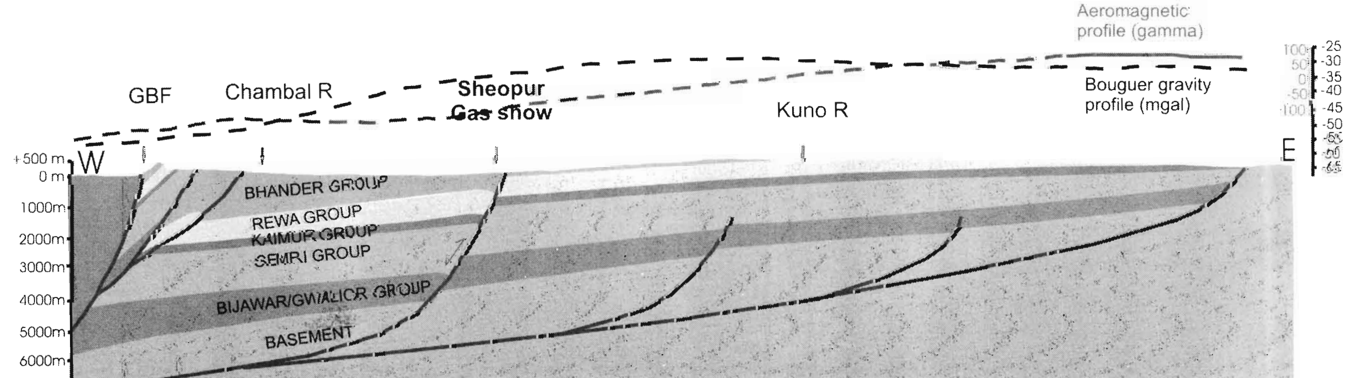

Fig.18. Schematic geological cross-section across the Chambal valley of the Vindhyan basin. The section shows normal growth faults for both Lower and Upper Vindhyan levels. The western margin of the basin is modified due to subsequent reactivation and compression related structures.

From hydrocarbon point of view, the Cuddapah Basin has so far been poorly studied and understood. ONGC has carried out spot sampling for determination of TOC. The carbonaceous shales of the Vempally Formation record a maximum TOC of 0.24%. The source rocks in the basin are in late catagenetic/ metagenetic stage and therefore generation of only methane gas is expected. The determination of fracture density in limestone-dolomite and fractured quartzite is important which are envisaged as suitable reservoir for methane gas from deeper sources. Numerous doubly plunging folds, domal structures and fault closures related to structural inversion frontal to Eastern Ghat orogenic belt are the likely structural plays for hydrocarbon entrapment.

The older stratigraphic unit of the Chattisgarh Basin, i.e. the Chandrapur Group is mostly arenaceous and does not have much source potential. However, the Raipur Group comprising the Charmuria, Gunderdehi and Chandi Formations and aggregating 1600 meters, possess intercalations of grey limestone and shale which can optimistically be regarded as source. Secondary porosity in the limestone of the Chandi Formation can serve as reservoir, while over 180 meter thick Teranga shale can form the seal. The spatial distribution of the optimally matured areas, reservoir and seals, together with proper linkages are still to be understood. The principal fairways envisaged in the basin are buried domes and inversion structures.

In the Kaladgi Basin, the petroleum system is only envisaged in the Bagalkot Group wherein stromatolites are reported to be in abundance. Argillite, dolomite and limestone units can be possible source rocks, though no geochemical data is available for the area. Secondary porosity is expected in the limestone and dolomite strata and the overlying shale can act as local / regional caps for accumulation of hydrocarbons.

Major constraint for hydrocarbon exploration in the Bhima and Bastar basins is low sedimentary thickness, although better thickness is expected in the northwestern part which is concealed under the trap.

The subsurface data of the Satpura Basin suggest presence of a thick sequence of sediments below Gondwana, which probably is Proterozoic (Vindhyan?) equivalent. These merit attention in view of the presence of hydrocarbon in a few known Proterozoic petroleum provinces of the world (Russia, Australia, Oman, etc).

Like other foreland basins of the world, the Punjab Basin is also envisaged to have a two-tier petroleum system. 1, Foredeep petroleum system and 2, pre-foredeep petroleum system. The principal geochemical attributes, i.e. total organic carbon, organic matter type, maturation and migration are still little known for the Tertiary foredeep system, whereas the pre-foredeep system is mostly speculative. Hence, a model-based approach is introduced to understand the possible petroleum system and related play fairways for initiating a systematic exploration in this part of the basin. In the Ganga Basin, the Lower Siwalik is found to contain moderately good TOC at few levels (range of TOC 0.04-7.68%). The Pre-Tertiary packages of Proterozoic as well as Palaeozoic domain are yet to be studied. But it is expected to have better quality organic matter within the carbonate-dominated Proterozoic (Vaishnodevi Limestone) and the carbonaceous shale rich Palaeozoic (Agglomeratic Group) sections. Present-day geothermal gradient of Punjab plain is $2^{0}C/100m$ similar to that of the Potwar region as well as the Ganga Basin. In Potwar, top of oil window occurs in the Miocene Murree Formation, whereas the rest of the Neogene package is undermature. Depth of burial for the Neogene is around 4000 m in Potwar. Similarly, in the Punjab plain, it is around 5000m and hence, it is possible that a part of the Neogene is placed within oil window at least in the deepest part of the basin. The formation water analysis shows the presence of Chloride calcium type of water, which is a direct hydrocarbon indicator (Collins, 1975). Na^{+}/Cl^{-} value (= 0.65) characterized a favourable condition for preservation of hydrocarbon. However, maturity modelling suggests that the optimum temperature of maturation in the Punjab foredeep was reached by the Subathu and the Lower Dharamsala sediments at around 10 Ma, whereas the critical time for the Lower Siwalik is dated as around 3 Ma.

Play fairway analysis shows a prominent trend (WNW-ESE) in the Himalayan foredeep. All major thrusts and their hanging wall structures within the Tertiary domain follow this trend. In Pre-Tertiary set-up, the possible rift orientations are also presumed to be of similar trend as reflected by the extensive exposures of Permo-Triassic volcano-sedimentary packages all along Panjal Thrust. The similar trend is also postulated for the Proterozoic basin margin where extensive carbonate platform sediments were deposited within northern part of Greater India. Probable Tertiary source pods with suitable maturation are expected, to the northern part, beyond the limit of the Punjab plain, hence the Tertiary structures within and surrounding the plain will be charged only through lateral migration within the range of 50 - 100km. The NW-SE trending highs like Soan, Bharwain and Janauri refer to the Tertiary fairways which are very young and formed after the migration of petroleum from the Tertiary source in this area. However, these can be very well prospective for the exploration of biogenic gas. Dinanagar seems to be a basement high and therefore this along with other such structures appears prospective.

For Pre-Tertiary play fairway, the best places to concentrate are the linear lows (Dasuya and others near Himalayan Frontal Thrust), which are supposed to be deep sedimentary enclaves having possible older petroleum system in it. If we presume regional source pod present within pre-Tertiary section, it must have been charged during early Tertiary and filled the suitable structures existing therein. The effect of post-charge structural modification is less in the Punjab plain, which adds further credit to this fairway. However in the adjacent Ganga basin, low amplitude folds and fault closures within Tertiary strata are visible and on this analogy, the Punjab Plain is also expected to have similar type of entrapment situations.

EXPLORATION CHALLENGES AND USE OF TECHNOLOGY

So far, we have discussed the geological problems of different types of basins. Exploration challenges are equally high for these basins. Problems are experienced in different stages of activity chain, i.e. during G & G data acquisition, processing and interpretation. Each basin has a unique geological history, with its inherent complexity and distinctive petroleum system which do not permit application of routine exploration methods. Besides the technical reasons, physiography, climate, logistics and sociopolitics also present major constraints in terms of time and cost escalation.

The challenges of hydrocarbon exploration can be grouped into two broad categories:

1. To ascertain the presence of significant pod of effective source rocks.
2. To image the subsurface and locate traps having reservoirs with adequate porosity.

Source rock : Geochemistry can take a leading role in generating confidence for taking up the basins for advanced exploration. At the outset, geochemical data allow explorationist to quickly and economically screen large target areas and prioritize prospective areas based on surface geochemical prospecting. Moreover, it can provide valuable input to exploration by identification of suitable source facies from surface and subsurface samples.

Seismic imaging : In general, a great challenge in almost all frontier basins is imaging the subsurface without which a successful exploration cannot be handled. Thick trap cover in parts of the Proterozoic (Vindhyan), Gondwana basins, presence of coal layers and the profusion of intricate network of high velocity sills and dykes result in transmission losses of seismic energy and generate short period multiples that interfere with primary reflections. Dykes and sills further act as scattering layers at depth which cause serious problem in imaging in the Gondwana basins. In complex geological set-up of thrust fold belt, repetitions of sequences due to overriding of older strata over younger strata cause velocity inversion. This, coupled with high dip and structural complexities, makes seismic imaging a major challenge (fig. 19).

The aforesaid problems can be tackled to some extent by increasing the source power, careful determinations of proper acquisition geometries and model-based approach through development of dedicated algorithms for improved processing. Pre-stack depth migration, velocity analysis and modelling have been successfully done for identification of volcanic intrusives in the Gondwana basins. Multi-Component surveys like 2D-3C seismic method in trap covered areas may be helpful in deciphering the type of lithology and fluids apart from solving the imaging problem beneath a high velocity layer. Wide angle seismic data have been acquired in Columbia Plateau to overcome the problems of normal incidence seismic imaging through basalt. Special recording spread and source-receiver pattern should be tried during seismic data acquisition to obtain improved signal-noise ratio, especially

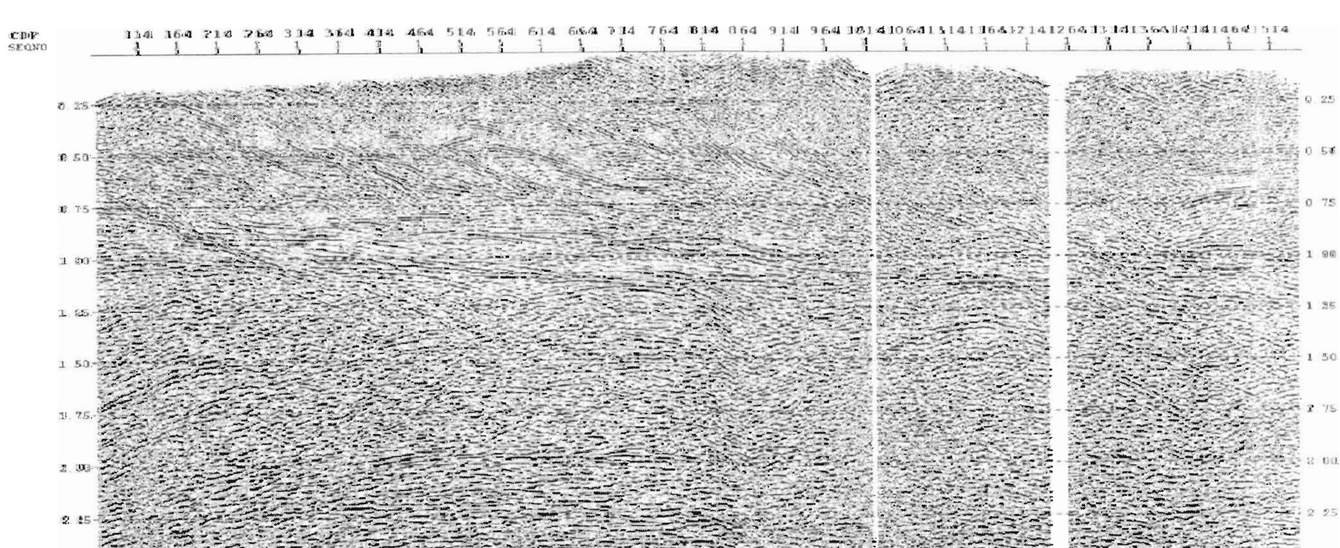

Fig.19. Seismic section across the Himachal foothills. A complex architecture of fold-thrust belt is a typical problem of seismic imaging in the Himalaya.

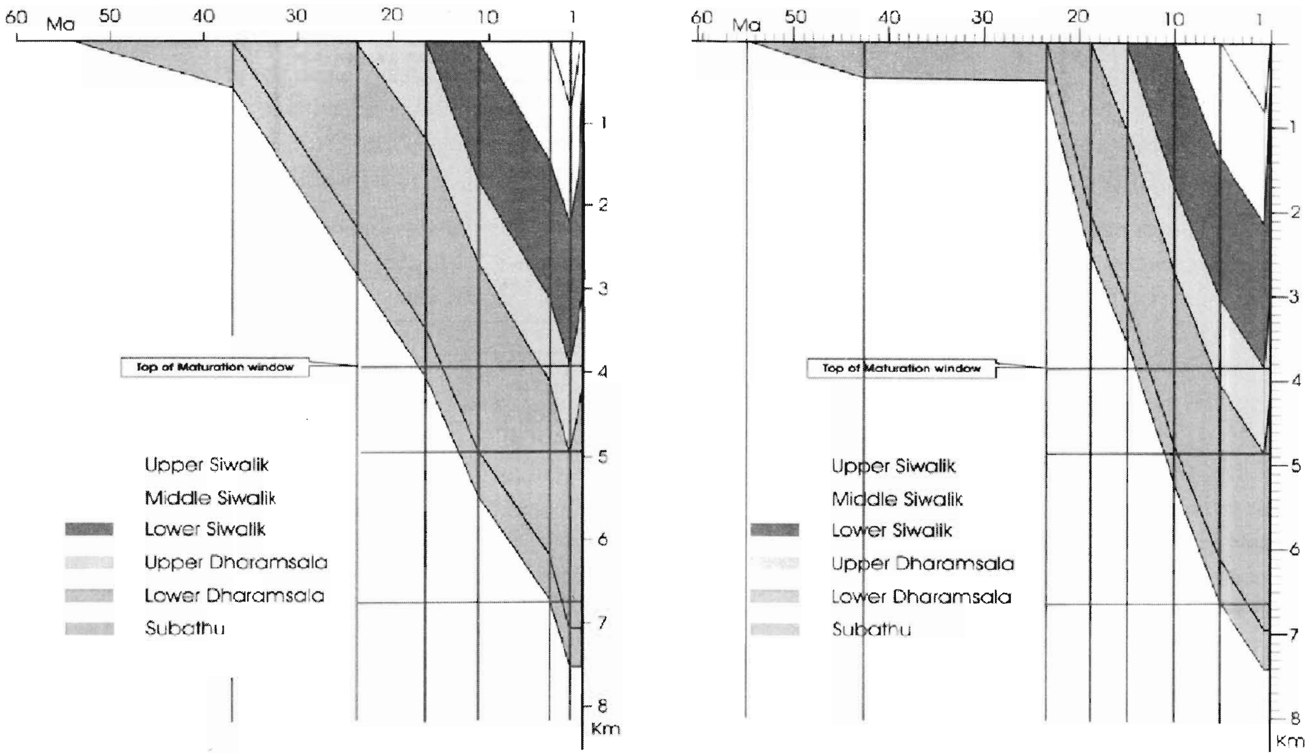

Fig.20. Variation of subsidence history with different sets of data at the same point of a basin. The left figure assumes continuous sedimentation, whereas the right one assumes an unconformity at the top of the Subathus. Rate of subsidence, sedimentation and critical timing for hydrocarbon generation vary significantly in these models.

in areas with inhomogeneities in basalt causing scattering of seismic energy.

Potential Field data : Most of the frontier basins are adequately covered by gravity and magnetic data with an average of 2-3 Km station spacing. The use of same Bouguer reduction density in whole of the basin complicates the quantitative analysis where the densities of the near surface rocks change laterally (particularly in sill/dykes, partially Deccan Trap covered areas and continuous change of surface lithology like in Himalayan foot Hills). The Bouguer density corrections are to be reviewed and require reprocessing of data in certain critical aspects. In highly undulatory terrains such as the Himalaya, a comprehensive terrain correction will lead to better residual gravity anomaly picture for proper interpretation. The other main problem of isostatic compensation in areas of high topography is also to be resolved.

Electrical methods: In the Gondwana basins, good electrical resistivity contrast exists between the Talchir and Barakar sediments. Deep electrical sounding method may effectively be applied for better subsurface imaging of trap-covered areas where subtrappean seismic images are generally of poor quality.

A combination of Controlled Source Audio Frequency Magneto telluric and natural Magneto Telluric methods have proved to be efficient in terrains like Eastern Hokkaido, Japan that are difficult for seismic imaging. Subthrust imaging in thrust fold belt can be another area of application of electrical methods.

The role of academia is of paramount importance in frontier basin exploration. *Geochronology is an essential tool for stratigraphic reconstruction of any basin. The entire concept of basin evolution and subsidence history is directly related to precise determination of ages of formations.* For example, there is a controversy in the presence of an unconformity around the Subathu-Dharasmsala boundary in the Himachal Himalayas. A 12-14 Ma unconformity is reported by various authors (Najman *et al.*, 2001), whereas others do not support the concept on the basis of ground evidences (Bhandari and Agarwal, 1965). Construction of subsidence curves leads to two different interpretations in the two cases. The rate of subsidence increases with younging of the basin if Subathu-Dharasmsala boundary is assumed to be conformable, whereas, if the boundary is assumed to be unconformable, the rate of subsidence of individual formations decreases with younging, though overall rate of subsidence is comparatively more (fig. 20).

Biostratigraphy is also an important tool. It helps to construct a meaningful subsidence history and maturation window of sediments and critical time for hydrocarbon generation in a basin. In India, good biostratigraphic control exists in the producing basins, whereas a lot of work has to be

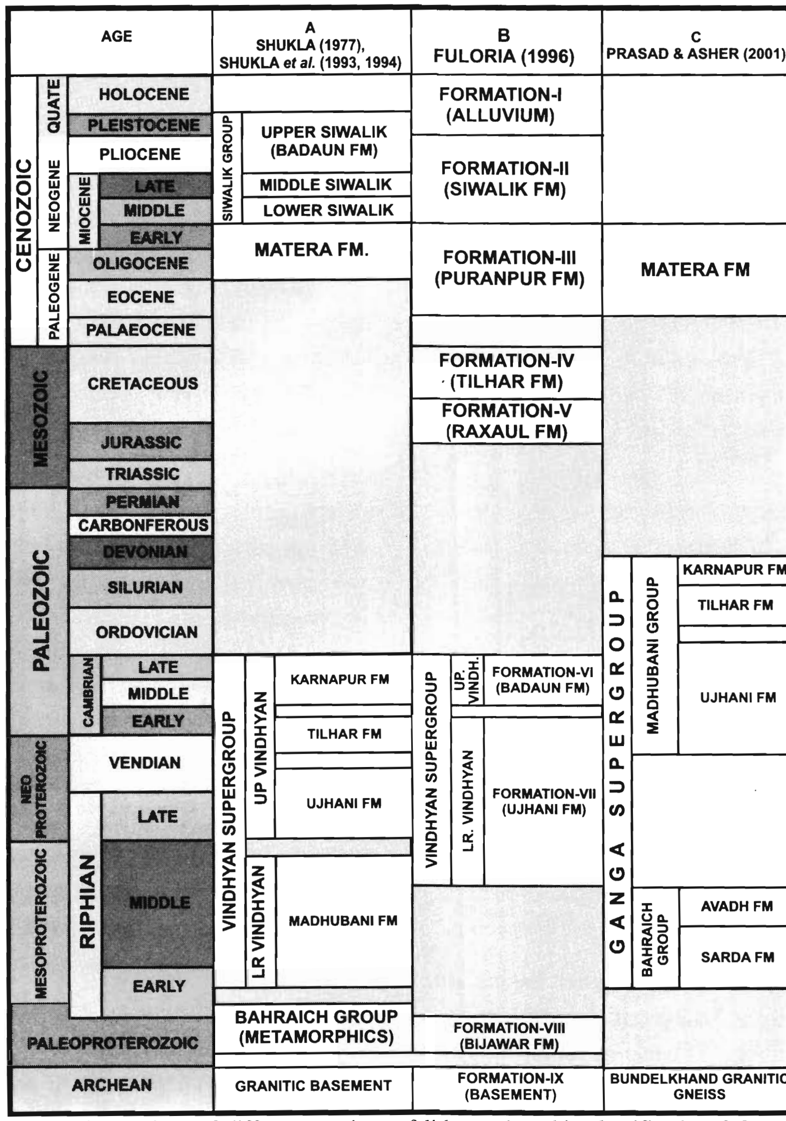

Fig.21. Comparison of different versions of lithostratigraphic classificationof Ganga Basin (after Prasad *et al.*,2002)

done for the frontier basins. A case is cited to understand its importance. The pre-Tertiary sequence of the Ganga basin has been considered to be Meso-Neoproterozoic in age, equivalent to the Vindhyans of Peninsular India. Prasad and Asher (2001) revised the lithobiostratigraphy based on acritarch studies (fig. 21). In their classification, the pre-unconformity sequence of the Ganga basin range in age right from Mesoproterozoic to Lower Palaeozoic. It comprises two groups. The older Baraich Group represents the Mesoproterozoic (Early-Middle Riphean) metasedimentary succession with the Sarda and Avadh Formations. The younger Madhubani Group represents the Lower Palaeozoic unmetamorphosed sedimentary succession comprising the Ujhani, Tilhar and Karanpur Formations. This age assignment increases the prospectivity perception of this Group as well as the Ganga Basin as a whole.

Geochemistry can be immensely useful in frontier basin exploration. In addition to identification of suitable source facies which is of paramount importance in hydrocarbon exploration in a basin, use of geochemistry can provide valuable input to exploration by solving stratrigraphic problems through isotope trend comparison, chemo-stratigraphic correlation and by establishing environment of deposition.

NEW THRUSTS: NON-CONVENTIONAL PETROLEUM SYSTEM

Exploration of non-conventional petroleum systems is getting momentum in recent years in different parts of the world. Basin centered gas, Biogenic gas and Coal Bed methane are a few important non-conventional gas systems presently under exploration worldwide.

Basin Centered Gas : They are regionally pervasive accumulations in low permeability reservoirs that are gas saturated, abnormally pressured and commonly lack down dip water contact. They may also contain oil if the system has an oil prone source rock in it. In the United States, about 15% of the total annual gas production comes from basin centered gas. This type of petroleum system is yet to be explored in India, but presence of good reserve of basin centered gas is envisaged in the Cambay Basin of Gujarat.

Biogenic Gas : It is a comparatively new play concept that is under active exploration worldwide. Gas generation begins through decomposition of organic matter by anaerobic bacteria at low temperature soon after deposition of sediments. Gases are compositionally methane and are not thermally mature. More than 20% of the world's discovered gas reserves are of biogenic origin. Mesozoic and Tertiary biogenic gas systems have been reported throughout the world; among them a few like Siberian gas fields are classified as giants. In India, the Himalayan foreland basin and the coastal basins have good prospects for biogenic gas.

Coal Bed Methane : Coal bed methane is under active exploration in different countries including India. Adsorbed gas in coal beds are produced from shallow depths. Development and production techniques in this case are different from that for conventional gas. Presently, ONGC is pursuing exploration of coal bed methane in Damodar valley coalfields and a few blocks in central India.

CONCLUDING REMARKS

In order to enhance the energy security of the country, seventeen onland frontier basins of India need reinvigorated exploratory effort with improved geoscientific understanding of the basins and advanced technologies. Geodynamic evolution of the Indian subcontinent as a whole played a major role in the development, architecture and evolution of the frontier basins. These basins are in diverse tectonic set-up, each having unique geological history with inherent complexities and distinctive petroleum system.

Various new ideas have emerged regarding the architecture, evolution and prospectivity of different basins. The Lower Vindhyans of Son Valley have adequate source development. Structural inversions on the basement ridge, wedge outs on ridgeflank and inversions in the southern part are the possible play fairways. The Chambal Valley Vindhyans present improved prospectivity perception. Possible Vindhyan equivalent sediments below the Gondwanas in the Satpura Basin merit attention. Paleozoic-Mesozoic pre-foredeep petroleum system is envisaged in addition to the Tertiary petroleum system in the Punjab plains and J & K Himalayas.

Subsurface imaging is a major challenge in the exploration of frontier basins. Difficult logistics, complex structural geometry and other problems arising thereof make seismic data acquisition in thrust fold belts a challenging task. Thick Deccan Trap basalts covering concealed basins within Deccan syneclise and parts of the Gondwana and Vindhyan basins poses the main hindrance in imaging the subsurface in these areas. Intricate network of high velocity sills and dykes as well as low velocity coal seams create imaging problems for the Gondwana basins.

The problems need to be tackled by using advanced technologies in seismic data acquisition as well as processing for thrust-fold belts. Improved methods of interpretation of potential field data should be used. Advanced technologies such as Deep Electrical Sounding, Controlled Source Audio Frequency Magneto Telluric, Natural Magneto Telluric, Wide Angle Seismic Profiling, etc. are expected to be beneficial for imaging the trap-covered areas. Geochemical methods should be widely used for identification of suitable source facies and areas with effective source rock development. The academia has an important role in the frontier basin exploration to solve problems of geochronology, litho/biostratigraphy, etc.

Focused attention should also be given to exploration of non-conventional petroleum systems, e.g. coal bed methane, basin centered gas and biogenic gas in different frontier basins.

It cannot be overemphasized that frontier basin exploration is a stupendous task on account of the vast expanse of the area as well as the challenges in terms of technology and logistics and thus has to be approached with a perspective of a national endeavour with synergy and total involvement of public/private sector oil companies, universities and national scientific institutions. This will certainly go a long way in fulfilling the increasing demand of energy in India.

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