Unconventional Petroleum Systems Analysis for Evaluation and Resource Estimation of Potential Shale Plays of Indian Basins: Present Status and Path Forward

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Unconventional, Petroleum Systems, Shale Plays, Resource, Sweet Spots

Abstract

The economic development of Shale gas and Shale oil depends to a large degree on the ability to find "Sweet Spots" in a resource base. Identification of such sweet spots requires a much more detailed understanding of reservoir and fluid properties. To address different aspects of these Shale Plays, Unconventional Petroleum Systems Analysis plays an important role.

In India, there are several Potential Shale Plays in different Basins. In this paper, a comprehensive attempt was made on how Unconventional Petroleum systems Analysis plays an effective role in evaluating, defining Risk associated with Shale Plays of Indian basins and in delineating the assessment Units for the Resource estimation of Shale Plays. This paper also reviewed the latest workflows pertaining to the Evaluations, Risk assessment and challenging issues already encountered during the ongoing Exploration campaign and give insights to the critical geoscientific issues and difficulties need to be addressed.

1.0 Introduction to Unconventional Petroleum Systems

Advances in fundamental geological theory and analytical technology for oil and gas enable the implementation of quantitative research on the process of the hydrocarbon generation, expulsion, migration and accumulation. Let me define the major characteristics of Unconventional Petroleum Systems.

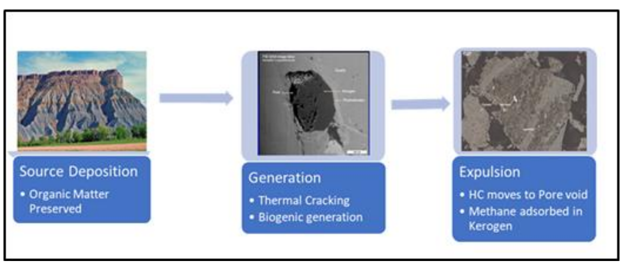

Figure-1: Generalities of Unconventional Petroleum Systems

The first most important is the generation mechanism of hydrocarbon and how best you can able to evaluate hydrocarbon generation process, oil and gas generating potential evaluation from scattered organic matter from source rocks. Then after expulsion from the Source, how best we can able to evaluate the retained hydrocarbons in the source rocks.

For better understanding of all these processes, we need to first synthesize the different attributes of Reservoirs and types of accumulations and state of hydrocarbons in those reservoirs. Normally the reservoirs are tight-very tight (in micro to nano darcies range). However, there are also reservoirs of higher permeabilities.

The characteristics of the Unconventional hydrocarbon resources are as follows: the source and the reservoir coexist; the porosity and the permeability are ultra-low; nano-scale pore throats are widely distributed; there is no obvious trap boundary; buoyancy and hydrodynamics have only a minor effect. Unconventional gas resources are generally non-buoyancy driven accumulations. Non-buoyancy-driven accumulation means that buoyancy has a weak effect on hydrocarbon migration and cannot overcome resistance. The average pore-throat diameter of the shale gas reservoirs is 5–200 nm and that of the shale oil reservoirs is 30–400 nm.

Three models of unconventional hydrocarbon distribution can be determined in petroliferous basins, namely the intra-source rock model, the basin-centered gas model, and the source rock interlayer model

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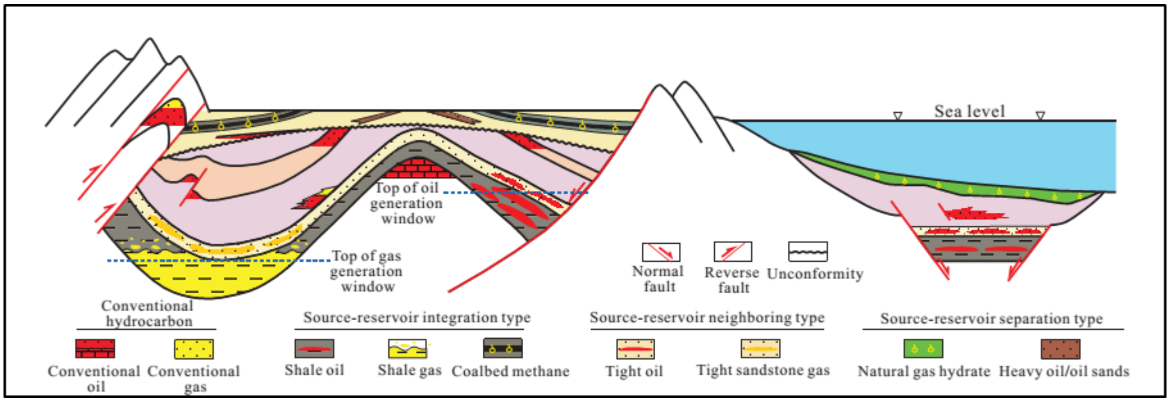

Figure-2: Spatial Assemblage of Source and Reservoirs (Li et al., 2016)

Spatial assemblage of source rocks and reservoirs plays a critical controlling role in the formation of Unconventional oil and gas. Unconventional hydrocarbons primarily characterized by retention or short-distance migration are less demanding for trapping and capping conditions. Thus, the assemblage of source rock and reservoir becomes a decisive factor for unconventional hydrocarbon accumulations.

Hydrocarbon retained in the mudstone-shale is the major type of Source-Reservoir integration resources, mainly distributed in various sedimentary basins. Mudstone-shale belongs to fine grained sediments with grain sizes smaller than 0.0039 mm which mainly formed in the sedimentary environment with weak to quiet hydrodynamic conditions. The organic rich mudstone-shale is primarily deposited under anaerobic and reducing environment.

2.0 Generalized Workflow on Data Integration:

Before discussing the data integration, we need to investigate the Play identification in a Basin. Exploration decision points often are specific to an area of investigation and tied to the level of understanding of a Play. These areas can be associated with key play characteristics that help to define and assess the area.

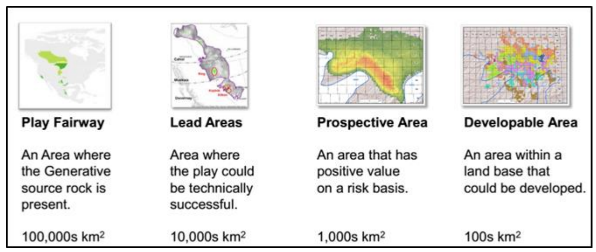

Figure-3: Generic workflow on Play Fairway Mapping for Unconventional Petroleum Systems Analysis

Play Fairway Mapping is the most adaptable methodology to define the assessment units. Geoscientists need to identify and rank Lead areas within a play fairway that have potential to deliver a technically successful Unconventional resource. Regional Mapping is the first level of delineation of Shale Plays, then we need to narrow down to Lead Areas identification. It is the identification of prospective area where the play can deliver value and describe a likely economic and productive scenario. The main components are to calculate Probabilistic Resource-in-place, Well/Pad Design and Cost Scenarios, Unit Area Type Curves, Relative Resource Value by Unit Area. In this step, Selected Play Leads for continued analysis for finalization of Prospective areas are delineated.

The final step is the Developable area evaluation to determine investment. The main goal is to assess full cycle, risked economics for developable units.

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Unconventional Systems are extremely complex and heterogeneous at all scales. To have an effective Petroleum System Analysis for Unconventional, a robust data Integration is required. Here I have emphasized on the best approach to demarcate the Assessment units for Lead areas.

3.0 Workflow for Evaluation & Assessment

To start with, Evaluations often have to be made in areas with sparse or even no data, and a typical question is what data is required to start. It is seen that a full 3D geological model is the best starting point as the goal is always to create maps, so it is important to show how meaningful 3D geological models can be constructed and modeling can be performed in these areas. For early-stage exploration for Unconventional resources, Petroleum Systems modeling delivers essential initial information. As petroleum systems models are dynamic models which evolve through geologic time, they enable properties to be determined that are a function of processes and these can then be related to the structural evolution.

Maturation distributions for organic material, Play and product type prediction can be assessed effectively through petroleum systems modeling. Even Product volumetrics can be determined more accurately than with any other method as they are contained in and directly controlled by the 3D geological framework (range from basin scale resource assessments to play to prospect scale).

Unconventional Petroleum Systems workflow has the following main steps:

(a) G&G Data Handling: Management of all G&G data including Quality checking, compilation and interpretation tasks for an assessment of a basin / sub-basinal scale area of interest.

(b) Basin-to-Prospect-scale process modeling with advanced technology which is directly linked to the G&G platform. In this case, this enables the areas to be clearly defined in which the source rocks contain Oil or Gas so that Assessment Units for Oil and for Gas can be accurately differentiated.

(c) Play Chance Mapping within the work environment to map areas with favorable combinations of properties. For resource assessments, this is the step where Assessment Units and Sweet spots can be mapped.

(d) Statistical Assessment of Resources: The final step of the Resource Assessment is the statistical analysis of the potential resources which can be provided as recoverable resources using appropriate analogs.

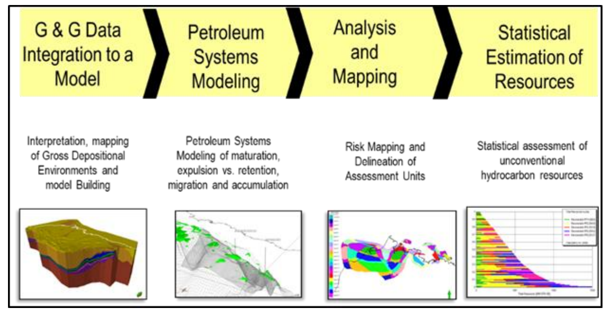

Figure-4: Modern Unconventional Petroleum Systems Analysis Workflow (Mishra et al., 2014; Bryant et al., 2013)

4.0 Shale Plays in Indian Basin

Before starting a comprehensive look on Shale Plays of Indian basins, we need to have an idea about the different attributes figured out till date of Indian Shales.

The first one is the in terms of Age. The Indian Shale Plays varies from Meso-Proterozoic-Oligocene in age (Figure 5) in comparison to major North American Shale of Paleozoic-Mesozoic age range. The Shale Plays are younger in age. Let us discuss about the Character of major Shale Plays in terms of attributes like Source and Reservoir (Table-1), and Producibility (Table-2). In the Table-1, 2; different attributes related to 9 major Shale Plays of 6 basins of India are listed. In addition to that other potential Shale Plays exist e.g. Early Permian Barakar Shale of Satpura Basin, Lower Ordovician Shale of Ujahani Formation of Ganga Basin, Neo-Meso Proterozoic Shales of Vindhyan Basin.

4.1 Source Attribute:

Identification of Source rocks: Source rocks occurrence, extension and quality in the subsurface are usually characterized directly from well data. Seismic characterization (pre-stack gathers extracted 3D survey and wells with a complete set of wirelines and petrophysical logs, Impedance inversion, AVO and seismic attributes (Monte et al., 2018) is however becoming an emerging technique for extending source rock properties beyond well locations and an effective tool for mapping their lateral and vertical heterogeneities. In Indian basin such attempts of effective integration of geophysical techniques need to be carried out as feasible methods for the investigation of source rock attributes.

Thickness of Source: The thickness ranges of different Shale Plays vary in between 600-2600 meter (Table-1). It helps us to have an idea about target zones for better production optimization.

Richness of Source: The average Total Organic Carbon (TOC) of Shale Plays varies between 1 and 3.5% (average 2-2.5%) with few exceptions like Plays of Rajasthan. In majority of Plays, there are multiple units showing different average TOC content ranges. For Example, in Cambay Shale Plays, 4 units of distinct Organic rich zones are identified in T-R sequence of 3rd order. Though it is a detailed study in Cambay Shale, we need to have such understanding of Organic matter richness in different Shale units of different Shale Plays of other Potential basins.

Kerogen Type: Organic facies are dominantly Type III with minor contribution of Type II with an exception of Rajasthan Shale Play. Average HI ranges from 150-350.

Average depth ranges of Indian Shale Plays vary from 2000-5000 mts. In comparison to Global datasets of Shale Plays, Indian Plays have greater depth of occurrence and large thicknesses.

Present day Maturity status: Shale Plays like Cambay Shale, Raghavpuram Shales gone through early Oil generation to late Oil window (VR_0 0.6-1.2), thus proving Shale-Oil system in place. Other Shale plays lie in Gas window (VR_0 1.2-2.0 range) thus defining potential gas Shale plays. In the last decade, an overall general understanding has been made on the maturity status of different Shale Plays based on general Petroleum Systems Analysis. Now we need to further scale down our maturity observations in different Sub-units of Indian Shale Plays (though we have few studies on sub-units)

4.2 Reservoir Attribute:

Effective Source Pods demarcation: Present Day Maturity Estimation helps us to define Potential Hydrocarbon Type Zone like Oil zones and Gas zones. But we need to focus ourselves on Total Organic Carbon Content (TOC) % of different Units of Shale Plays. Quantitative prediction of TOC in shale-gas reservoirs using seismic data and rock physics workflow is achievable. 3D seismic data can be combined for prestack simultaneous inversion to obtain the most sensitive elastic parameter data volume and then transformed the sensitive elastic parameter data volume to the TOC content volume (Chen et al., 2018). Also, empirical equation for predicting TOC is developed, tested in different environments based on artificial neural network (Mahmoud et al., 2017) in well explored area. In Indian Shale Plays, such attempts need to be undertaken in different depositional environment settings to assess Organic richness of multiple Shale Units.

Porosity Evaluations: The nanometer pores in shale are mostly organo pores (pores within organic matters in shale) created from hydrocarbon generation during formation subsidence and thermal evolution. Presently in general we believe that the organo pores in organic matters generated during hydrocarbon generation make a significant contribution to gas reservoir space. Using the material balance principle and chemical kinetics, an organo-porosity evaluation modelling method for shale rocks can be developed. This organic porosity prediction is an important aspect of Unconventional Petroleum Systems analysis. We have a few case studies of organic porosity prediction like in Cambay Shale of Broach depression (Das et al., 2015).

Porosity and Pore size distribution: Pore Size Distributions (PSD) are essential petrophysical parameters controlling permeability and storage capacity in shale gas reservoirs. The shales of studied Indian basins are chiefly bimodal (Tripathy et al., 2018) consisting of mesopores (2–50 nm) and micropores (<2 nm). The micropores were efficiently accessed using CO_2, while N_2 was effective on characterizing the mesopore region. MIP analysis was used to infer the pore throat area. The average pore diameter of samples ranged from 3.38 nm in Damodar valley to 3.94 nm in the K-G basin, while

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SHALE PLAYS	BASIN	AGE	Source Attributes				Reservoir Attributes			
			THICKNESS MTS	TOC RANGE%	KEROGEN TYPE	MATURITY VR0	SHAPE/SIZE OF PORES	POROSITY %	PERMEABILITY	GAS CONTENT cc/gm
Barail Shale	Assam Arakan	Oligocene	50-500	5	III	0.5-0.7	NA	NA	NA	NA
Lower Barmar Hill	Rajasthan	Eocene	100-400	4-12	I and II+ III	0.6-1.2	NA	3-18	1-30 mD	6-13mmstb/km2 Oil
Cambay Shale	Cambay	Eocene	600-1600	2-4	III	0.6-1.2	Interparticle type	11-14	3.7-20 nD	0.74-2.41
Kopili Shale	Assam Arakan	Upper Eocene	500	1-6.2	II-III	Moderate	NA	NA	NA	NA
Raghavpuram Shale	Krishna-Godavari	Early Cretaceous	>1000	2-6	II-III	0.5-1	3.94 nm	8	NA	0.69-2.53
Sattapadi Shale	Cauvery	Cretaceous	>1000	2-2.5	II-III	1-1.2	3.88 nm	NA	NA	NA
Kummugudem Shale	Krishna-Godavari	Permian	900-1100	8	II-III	>1.2	NA	NA	NA	NA
Barren Measures	Damodar	Late Permian	>600	3-20	III / IV	0.6-1.0	Ink bottle,slit shape	0.89-2.28	0.41-0.75mD	0.5-1.1
Barakar Shale	Damodar	Early Permian	1200-1500		III	1.2-1.4	Ink bottle shape			

Table-1: A Synoptic View of Source and Reservoir Attributes of major Indian Shale Plays

	Producibility Attributes				
SHALE PLAYS	Depth Range in mts	QUARTZ%	CLAY VOLUME%	Youngs Modulus Gpa	Reservoir Pressure
Barail Shale	>2000	NA	NA	NA	Normal
Lower Barmar Hill	2500-5000	NA	NA	NA	NA
Cambay Shale	2000-4000	29-47	Low-Med	6133-6694 MPa	Moderate Overpressure
Kopili Shale		NA	NA	NA	Normal
Raghavpuram Shale	1200-4500	16-30	High	NA	11.85-13 Mpa
Sattapadi Shale	2000-4000	NA	High	NA	Normal
Kummugudem Shale	1700-4200	NA	HIgh	NA	Slight Overpressure
Barren Measures	1500	34.2-40.2	21.3-53.7	3.3-7.89	Slight Overpressure
Barakar Shale	2800-6000	22.4-40.8	38.3-58.7	7.12-26	Slight Overpressure

Table-2: A Synoptic View of Producibility Attributes of major Indian Shale Plays

Cauvery and Cambay basin samples possessed 3.88 and 3.86 nm, respectively. Both N_2 and CO_2 adsorption (type II and type I, respectively) suggested the presence of micropore infilling in all of the basin samples.

Permeability Estimation: Very few data on Permeability are available on different Shale Plays of India (Table-1). Recently, Zhao et al. (2018) devised a methodology for predicting the permeability of shale-gas reservoirs from porosity and rock compositions including mineralogy and organic matter content, which is applicable to laboratory data and downhole measurements.

Studies on gas-in-place, sorption parameters of Indian Shale Plays have been undertaken to understand the fundamentals of shale gas reservoir in virgin blocks of South Karanpura, Barmer-Sanchor basin, Raniganj, Neyveli, West Godavari and Narmada Broach and for Shale Oil parameters in Barmer Basin (Table-1).

Beside evaluations of all these Source and Reservoir attributes, we need to focus on Source-Reservoir characteristics (Spatial Assemblages). In its simplest construction, there are three possible pairings: Source – Reservoir are equivalent, Source – Reservoir are different and Source – Reservoir Hybrid. There should be systematic study to delineate the different types of Shale Plays in each basin focusing the Spatial assemblages.

4.3 Producibility Attribute:

Clay Mineralogy: Clay minerals have huge surface areas due to prevailing laminated structures, and the deficiency in positive charges in the combination of tetrahedral and octahedral sheets in clay minerals produces strong cation exchange capacities (CECs), all of which factors create huge gas storage capacity in clay-abundant shale formations. However, the existence of large amounts of tiny clay particles separates the contacts between quartz particles, weakening the shale formation and enhancing its ductile properties.

Furthermore, clay minerals' strong affinity for water causes clay-abundant shale formations to have large water contents and therefore reduced gas storage capacities. Clay-water interactions also create significant swelling in shale formations. All these facts reduce the productivity of these formations. In Table-2, a synoptic view of Clay and Silica content of major Shale plays is listed. Generally Indian Shales have high clay contents. Along with the richness of Silica, it plays a role on how effective we can address the producibility of hydrocarbons.

Geomechanical attributes: Geomechanical qualities of the reservoir (Table-2) and surrounding beds directly influence our ability to access the resource beyond borehole.

• Rock properties such as elastic moduli that influence fracture initiation, propagation and closure

• Structural fabric such as Faults, Bedding and Natural Fractures

• In-Situ Stress state and its local variations

The results of the numerical simulations show that for a wide range of stress-dependent fracture permeabilities, stress-dependent matrix permeabilities, and fracture spacings, the productivity of a gas shale reservoir is limited by inefficient gas transport through the matrix. The matrix permeability below which gas production is sub economic is not a specific value but varies with the effective fracture spacing and with fracture permeability. The matrix permeability and effective fracture spacing have a greater impact on the producibility of strata with larger fracture permeabilities. The influence of the effective fracture spacing on production is greater than the influence of the matrix permeability.

The production simulations (Bustin and Bustin, 2012) also show the strong dependence on the geomechanical properties of the rock, which affect how the gas transport through the matrix and fractures changes with stress. The influence of the geomechanical properties on the producibility depends on whether the production is limited by the gas transport through the matrix. Also different stress regime in the Shale Plays like Normal Stress (Low fracture Intensity, Tectonic fractures, open Regional fractures, Non-fractured), Strike-slip stress (moderate regional fracture intensity), Normal to Strike Slip Stress (high regional fracture intensity) need to be worked out to address the producibility issue effectively.

Based on Source, Reservoir and Producibility attributes, we need to effectively characterize all the Potential Shale Plays.

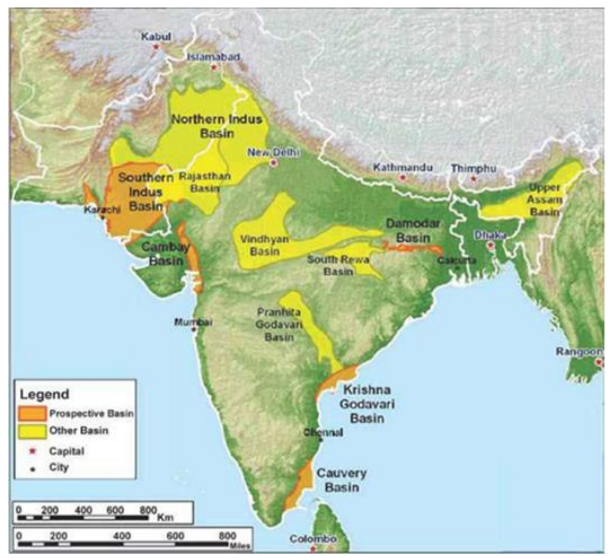

Figure-5: A synoptic View of Indian Shale Plays in Indian Subcontinent

5.0 Evaluation of Indian Shale Plays

Though much of the Indian Shale Plays were studied in terms of maturity, Organic carbon content, probable depth range occurrences, data on important parameter estimations which are the key inputs of evaluations are meagre. A systematic attempt is needed to fill up these gaps to effectively address the main characteristics and effective Unconventional Petroleum systems Analysis.

"**Sweet spots**" are defined as the most prospective volumes of the Shale Play. They are primarily targeted to achieve early economic production. They are characterized by higher resource concentrations with potential for economically viable development. The identification of Sweet Spots is primarily based on zones of good formation volume which has low water saturation with high TOC content and high kerogen content; low clay content and high brittleness index for fracturability; higher porosity; higher (effective interparticle) permeability; and low fracture initiation pressure preferably evidenced by natural fractures.

Let us look at Cambay Shale play, one of the most studies Shale Plays of India. A pilot Shale (Padhy et al., 2016) well was drilled in Broach-Jambusar block of Cenozoic Cambay basin and extensive core has been collected in the Cambay Shale section. Detailed shale specific geological, minerological, geochemical, petrophysical, geomechanical, desorption and adsorption isotherm studies were conducted and 60 mts of Shale Play was hydro fractured and it yielded light 40 API oil. The hydrocarbon bearing zone within the well and its fair degree of spatial extension, based on T-R cycle analysis, have been envisaged on the preliminary study of a couple of wells drilled for shale oil exploration in Broach-Jambusar block.

Limited show of minor oil after hydrofracturing in Basal Transgressive Unit (BTU) of KG Basin in an assessment well suggest possible shale oil resource concentration and needs further investigations. Recently, an Integrated approach was undertaken to assess storage and productivity potential of a frontier Unconventional Shale oil play in Lower Barmer hill formation of Barmer Basin, Rajasthan (Dutta et al., 2019). The modelled oil storage capacity varies from 6 to 13 MMBOE/km^2. In Damodar Basin, Barren Measure Shale was tested by 3 phase hydrofracturing and Gas-in-place volumes are established.

For effective delineation of Sweet Spots, we need to follow the Paly Evaluation methodology (Figure-3) and Unconventional Petroleum Systems Assessment workflow (Figure-4) up to Play Chance Mapping to find the best areas. As already described, we need to have more focus on the different Sub-units of Shale Plays and on performing Organic Porosity modeling, Adsorption modeling and Geomechanical modeling (Mishra et al., 2014; Das et al., 2015).

6.0 Resource Assessment of Indian Shale Plays

Evaluating the shale gas and oil resources of India posed a series of challenges. Only limited publicly available data exist on the geologic setting and reservoir properties of the numerous shale formations in India. In addition, few Shale Plays in basins in the country are geologically highly complex. Many of the basins in India, such as the Cambay and the Cauvery, comprised a series of extensively faulted horst and graben structures. As such, the prospective areas for shale gas and oil in these basins are often restricted to a series of isolated basin depressions (sub basins). While the shales in these basins are thick, considerable uncertainty exists on the areal extents of the prospective areas in these basins.

Based on the geo-scientific data collected during the exploration of Conventional oil and gas, assessments have been made regarding the possible potential of shale gas/oil resources in the Indian sedimentary basins as estimated by various agencies from time to time. In 2011, Schlumberger made an initial gas-in-place estimate of 300-2,100 trillion cubic feet (TCF), In the same year, a study conducted by the Energy Information Administration (EIA), the US assessed risked gas-in-place of 290 TCF with technically recoverable resource of 63 TCF for 4 (Cambay Onland, Damodar, Krishna Godavari Onland & Cauvery Onland) This was upgraded to 584 TCF in 2013 by the EIA, in addition to putting shale oil estimates at 87 billion barrels.

In 2013, both ONGC and Central Mine Planning and Design Institute (CMPDI) came up with their shale estimates. While ONGC put the shale gas estimates to 187.5 TCF of shale gas in 5 basins namely, Cambay, KG, Cauvery, Ganga & Assam and Assam – Arakan, CMPDI had estimated 45 TCF of shale gas in six sub basins (Jharia¸ Bokaro, North Karanpura, South Karanpura, Raniganj & Sohagpur).

Now the time is ripe to have a proper Resource Assessment of Indian Shale Plays of Indian basins. Though we came across a couple of Reports on

Resource estimation of Cambay Shale in Broach depression (Das et al., 2015) and in Ankaleswar (Ariketi, 2017), we need to have a systematic study to estimate the Shale Hydrocarbon resource of India (refer Figure-4). The only viable option is to have a proper Unconventional Petroleum Systems Modeling done in Individual Potential basin to demarcate multiple assessment Units for further resource Estimation.

7.0 Critical Geoscientific studies

The following key geoscientific studies need to be undertaken in our exploration campaign for effective Evaluation and Assessments.

• Stratigraphic architecture basin characterization to establish the framework which includes rock types
• Stratigraphic modeling to insure a most likely 3D distribution of the main facies and their associated reservoir properties and reservoir quality and parameters
• Organic matter and heterogeneities distribution in terms of fracture, mineralogy and diagenesis characterization
• Sampling strategy and Laboratory characterization for specific parameter which has direct impact on effective Petroleum systems Analysis like kinetic determinations, maturity trend determinations with organic porosity and brittleness estimation etc.
• Geomechanical properties evaluation (Discrete Fracture Network Numerical Simulation and Connected cluster DFN simulation used to model multiple, complex and discrete fractures in shale formations. Stresses, fracture width, height and length can be estimated by the simulation by running numerical simulators) of Shale plays using latest technology
• Migration Modeling Technology Implementation: Any evaluation of petroleum saturations in low permeable lithologies requires careful treatment of capillary entry pressure curves and their saturation dependency. This can only be done using the "refined" Darcy flow method.

8. Conclusions and Path Forward

In essence, the following THREE things are key to Success for Shale Plays:

• Understand the Geology, Focus on Unconventional Petroleum Systems Analysis
• Understand the available Technology
• Use Models to leverage the appropriate Technology and create value for successful exploration

So by considering the Critical issues/studies and by adopting the latest described workflow implementation, step by step evaluation approach, Indian Shale Plays can be assessed in each Potential basin effectively. Though sporadic work is going on in different basins by PSUs, a rigorous workflow and Three-Dimensional evaluation in PAN Indian scale will enable the demarcation of best Assessment units to get hold of Sweet spots within Each Shale Play. This will again create avenues for Resource Estimations of multiple Unconventional Shale Play units.

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