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A review on shale gas prospect in Indian sedimentary basins

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ABSTRACT
Shale gas is a natural gas trapped within shales, which are fine-grained sedimentary rocks. Hydrocarbons are generated from organic-rich shale under an optimal temperature-pressure condition due to basin subsidence. A part of the generated hydrocarbons migrates and gets trapped in conventional reservoirs that can be produced commercially by standard techniques. Shale can act as both source and reservoir rocks. Depending on the type of organic matter and maturation level, unconventional hydrocarbons could be shale oil or shale gas or a combination of both. There is a sizeable deposit of shale formations in several sedimentary basins of India with different total organic (TOC) content and maturity history. The Cambay, Krishna-Godavari, Cauvery and Damodar valley are the four major basins of shale gas reservoirs as indicated by considerable thickness of shales; sufficient TOC (2 to 6 wt%) content; and good thermal maturity with vitrinite reflectance of more than 1.0. The Vindhyan, Upper Assam, Pranhita-Godavari and Rajasthan basins are other prospective basins that need to be probed by geo-scientific methods. The gas in these shale reservoirs can occur within the natural fractures or pore spaces or as adsorbed gas on the organic matter. This is considered as the next generation major energy resource after gas hydrates and coal bed methane.

INTRODUCTION

The shale gas is defined as the gas present as adsorbed form on the organic matters (the kerogene) or free gas contained within natural fractures or pore spaces of shales, which are fine-grained sedimentary rocks that can be rich sources of petroleum and natural gas. The gas is mostly thermogenic in origin but biogenic nature cannot be ruled out either. Shale can store a large amount of organic materials compared to other rocks, and are deposited under fluvial, marine and lacustrine environments. During burial, the organic components (algae-plants and marine organisms) are cracked to form hydrocarbons. A part of the hydrocarbons thus generated migrates and forms conventional reservoirs below the structural and stratigraphic traps. The level of maturity of the organic matters caused by thermal process decides whether the shale contains unconventional oil, or gas or both. The complex matrices of shale serve as the seal, reservoir and source for the gas. The geological parameters for shale gas evaluation are thickness and areal extent, type of organic matter and its richness, thermal maturity, mineralogy, faults and fractures, gas content /gas storage, adjacent water bearing formations etc. Shale occurs over a broad geological age from Proterozoic to Cenozoic across all the continents such as the North America (USA and Canada), South America (Argentina and Brazil), Africa (South Africa), Europe (Poland, Romania, Hungary, Germany), and Asia-pacific (Saudi Arabia, China, Mongolia, Australia) etc.

India is the fourth largest energy consumer in the world after USA, China and Japan. About 52% of her energy requirement is met by coal, 32% by oil and 6% by natural gas (Sen, 2013). Depletion of fossil fuels (coal, oil and natural gas) and non-discovery of major conventional hydrocarbon resources during the last few decades have prompted us to look for alternate sources of energy for development and sustainable growth of India. The Gas-hydrates, Shale gas and Coal bed methane are considered to be major potential resources of energy for India. The shale gas has stolen the spotlight in recent times after its successful production in USA using the hydraulic fracturing and horizontal drilling (King, 2010). The shale gas business is now well developed in USA followed by China and Poland. Recent status of shale gas exploration and development is available in many reports (Arthur et al., 2009; Boyer et al., 2006; Halliburton, 2008; Martinez and Horsfield, 2010). Interest has spread to tap this potential natural gas in Canada, Australia, and many other countries in Europe, Africa and Asia-Pacific because of its considerable reserve and less emission of greenhouse gas compared to other fossil fuels. The shale formations are abundant worldwide. According to the US Energy Information Administration (EIA) (2011), the economic extraction potential of shale gas is more than two times the projected production potential of natural gas, and can meet from 125 years to over 250 years of global energy requirement at the current rate of consumption. Over 40,000 wells have been drilled for shale gas production, and today more than 20% of domestic requirement of natural gas is met by shale gas in USA (US EIA, 2011). Indian industries have taken positive strides towards the exploration and exploitation of shale gas as one of the feasible and economic unconventional energy resources that could contribute to the energy security of India. Prospective blocks are being identified for detailed exploration and development by Oil & Gas industries and research Institutes such as the ONGC Limited, Reliance Petroleum, Directorate General Hydrocarbons, National Geophysical Research Institute etc (Mishra, 2009; Rao, 2010; Petrotech, 2012; Dayal et al., 2013; Kumar, 2013; Padhy and Das, 2013).

India has a number of sedimentary basins from Proterozoic to Cenozoic, which contain organic rich shales. By extracting relevant information mostly from a report of the US EIA, World Shale Gas Resources with Advanced Resources International (ARI), we see that some of the Indian basins especially the Cambay, Krishna-Godavari, Cauvery and Damodar Valley have good prospects of shale gas (Fig.1). Several other basins such as the Vindhyan, Upper Assam, Pranhita-Godavari and Rajasthan, though show thermal immaturity, contain measurable thickness of shale with good TOC content.

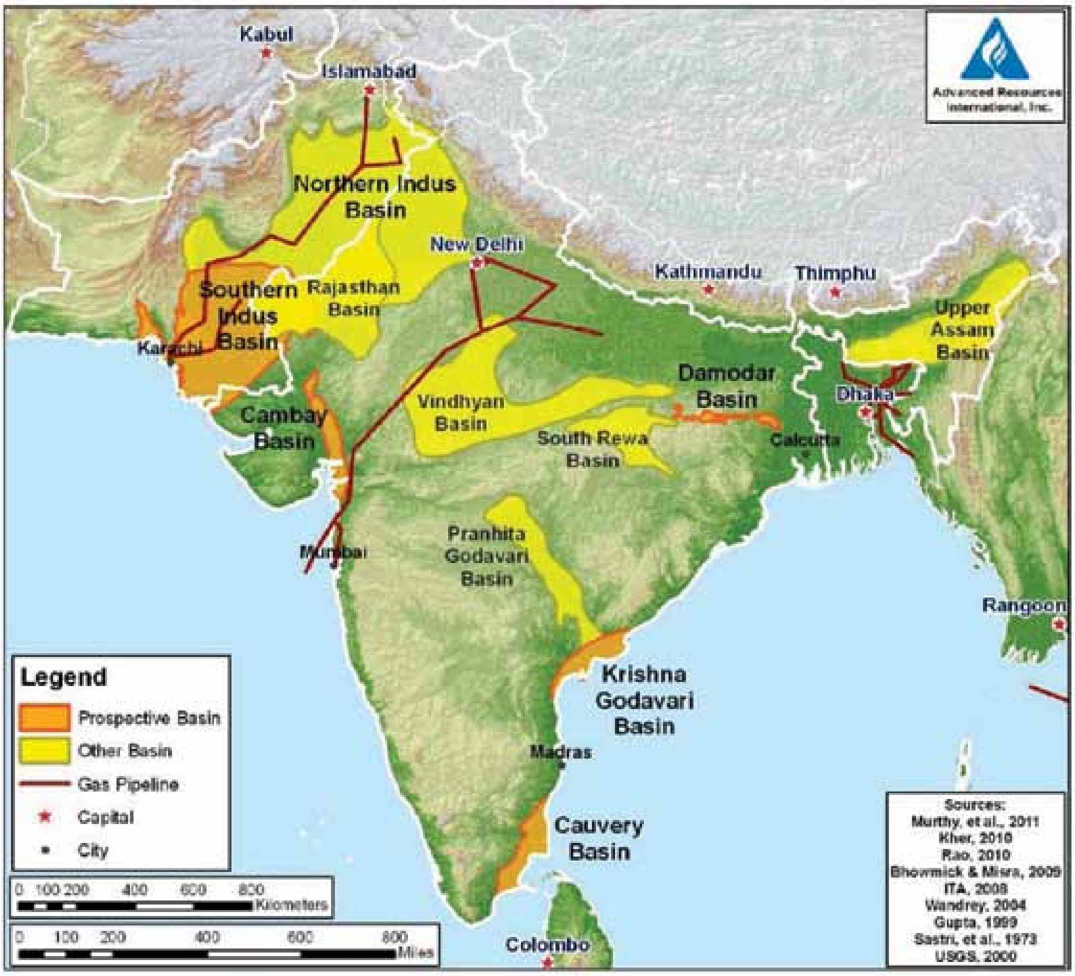

Figure 1. Shale gas basins of India (Source: US EIA 2011 and references therein, few are indicated at the bottom-right corner).

The cumulative thickness of shale formations within Indian sedimentary basins is comparable to or more than the global best shale plays. The reservoir properties and resource potential (290 TCF) of shale gas, estimated by ARI, are shown in Table-1. It is estimated that shale gas resources in India are more than 500 trillion cubic feet (TCF), and spread over many sedimentary basins. However, the technically recoverable shale gas is estimated at 63 TCF, which could be increased with the collection of additional reservoir information. Although the shales in the Cambay basin have been identified as a priority area by ONGC Limited, no plans for exploring these shales have yet been publically announced (Misra, 2009; Jaiswal and Pandey, 2012). This shale is the source rock for the conventional oil production in the Cambay basin but there significant thickness and thermal maturity indicate good prospect for shale gas. ONGC in collaboration with Schlumberger has drilled first R&D well (RNSG-1) near Durgapur in West Bengal in the beginning of 2011. This produced shale gas from the Barren Measure formation (985 to 1843 m) of Permian age. Out of 26 sedimentary basins in India, which are considered prospective for oil and gas exploration, almost all onland basins have considerable thickness of shale sequences that need to be looked into for shale gas. The Category-I and Category-II basins are very important for shale gas exploration point of view. The prosperous basins are described briefly.

CAMBAY BASIN

Thick Cambay Shale has been the main hydrocarbon source rock in the Cambay basin (Fig.2). The TOC content and thermal maturation suggest good prospects of shale gas in this basin (Fig.3). The shales of the Ankleshwar/Kalol formations are rich in organic matter, thermally mature and have generated oil and gas in commercial quantities. The same is true for the Tarapur Shale. The Shales within

Table-1: Shale gas reservoir properties and resource potential of India. (Source: ARI and US EIA 2011)

	Basin/Gross Area		Cambay basin ($20,000\ mi^2$)	Damodar Valley basin ($1,410\ mi^2$)	Krishna-Godavari basin ($7,800 mi^2$)	Cauvery basin ($9,100\ mi^2$)
Basic data	Shale Formation		Cambay Shale	Barren Measure	Kommugudem Shale	Andimadam Formation
	Geological Age		Upper Cretaceous/ Tertiary	Permian-Triassic	Permian	Cretaceous
Physical Extent	Prospective Area(mi^2)		940	1,080	4,340	1,005
	Thickness (ft)	Interval	1,600-4,900	0-2,100	3,100-3,500	600-1,200
		Organic Rich	1,500	1,050	1,000	800
		Net	500	368	300	400
	Depth (ft)	Interval	11,500-16,400	3,280-6,560	6,200-13,900	7,000-13,000
		Average	13,000	4,920	11,500	10,000
Reservoir properties	Reservoir Pressure		Moderately Overpressured	Moderately Overpressured	Normal	Normal
	Average TOC (wt. %)		3.0%	4.5%	6.0%	2.0%
	Clay Content		Medium	High	High	High
Resource	GIP Concentration(BCF/mi^2)		231	123	156	143
	Risked GIP (TCF)		78	33	136	43
	Risked recoverable(TCF)		20	7	27	9

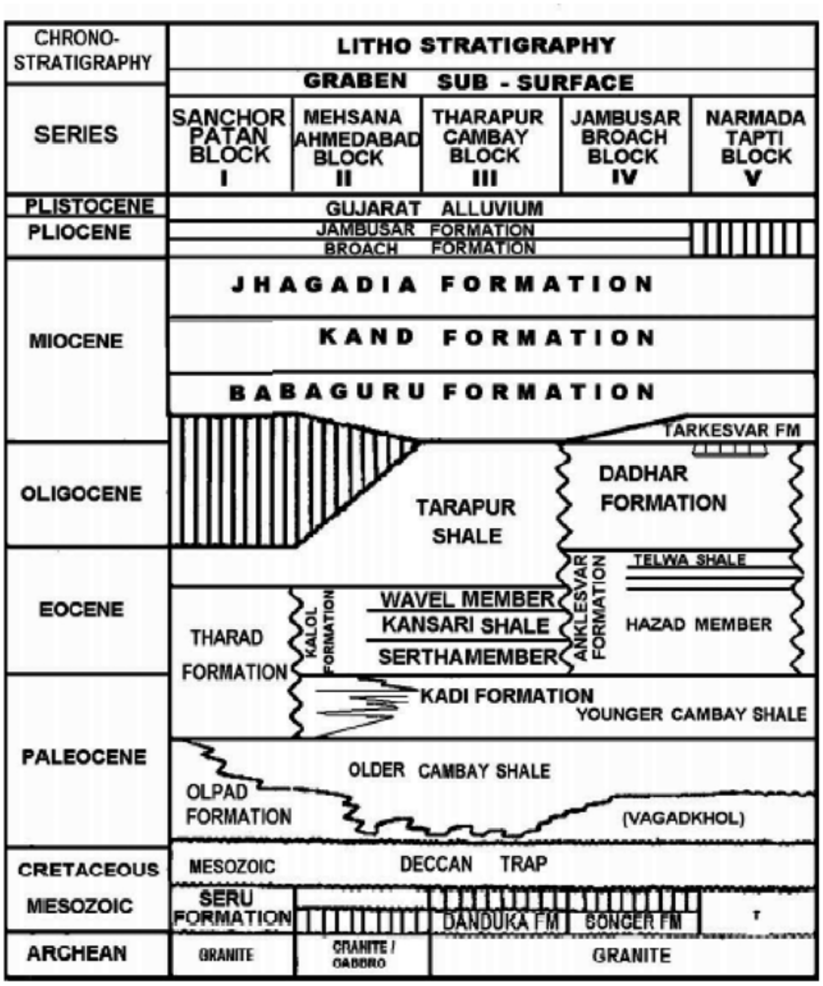

Figure 2. General stratigraphic column of the Cambay Basin (after Sivan et al., 2008).

the Miocene section in the Broach depression might have acted as source rocks. The northern part of the Mehsana-Ahmedabad Block, which is well developed within the deltaic sequence in Kalol, Sobhasan and Mehsana fields, is inferred to be an important hydrocarbon source rock.

Based on the criteria of vitrinite reflectance of more than 1.0%, an area of 1,940 mi^2 has been calculated as prospective for the "Black Shale" (source for gas) in the Cambay basin between 10,000 and 16,500 feet formation depth. The Cambay Shale is dark grey to black marine shale with pyrite and siderites at places. The structural inversion has brought the shale sequences at shallower depths at some places, which may provide good locales subject to other favorable conditions.

The Cambay basin contains five distinct fault blocks (Fig.2) from north to south: (1) Sanchor Patan; (2) Mehsana-Ahmedabad; (3) Tarapur; (4) Broach; and (5) Narmada. These blocks are characterized by local lows, some of which appear to have sufficient thermal maturity for shale gas.

MEHSANA-AHMEDABAD BLOCK

Three major depressions exist in the Mehsana-Ahmedabad Block - the Patan, Worosan and Wamji. A deep well (Well-A), drilled in the eastern flank of the Wamji Low to a depth of nearly 15,000 feet, was terminated below the "Black Shale". Additionally, few more wells were drilled in the Cambay Shale in axial part of the graben low. A high pressure gas zone was encountered in the Upper Olpad section next to the Cambay Shale, showing methane increasing with depth. The geochemical modeling indicates an oil window at 6,600 feet, a wet gas window at 11,400 feet and a dry gas window at 13,400 feet respectively.

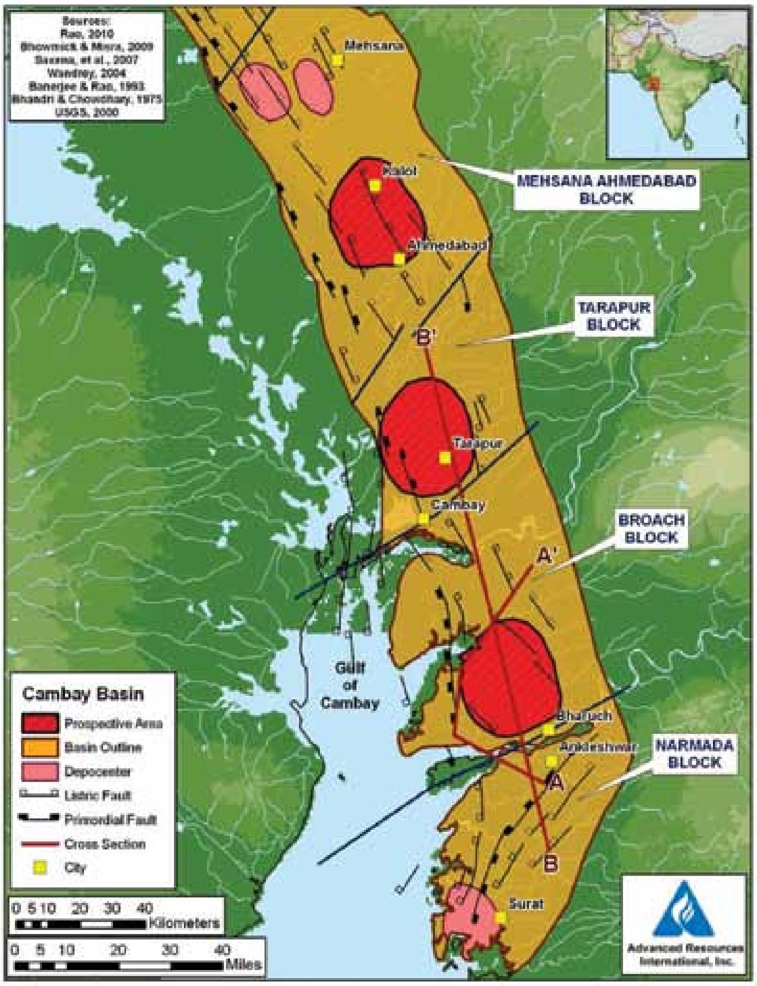

Figure 3. Prospective area for the Cambay "Black Shale" (Source: US EIA 2011 and references therein; few are indicated at the top-left corner). Inset shows the location of basin over Indian map.

TARAPUR AND BROACH BLOCKS

The deeper Tankari low in the Broach Block and the low in the Tarapur Block appear to have a similar thermal history as that of the Mehsana-Ahmedabad Block depression and thus may have shale gas potential, particularly in the lower interval of the Cambay "Black Shale".

KRISHNA-GODAVARI BASIN

The Krishna-Godavari Basin extends over a 7,800 mi^2 area on land (Fig.4) plus the offshore area. The 4,340 mi^2 prospective area of the Kommugudem Shale is limited to four grabens (sub-basins) where the thermal maturity is sufficiently high for wet to dry gas generation. Based on an average resource concentration of 156 BCF/mi^2, total shale gas was estimated at 136 TCF with technically recoverable amount of 27 TCF.

The basin contains a series of shales, rich in organic matter, including the deeper Permian-age Kommugudem Shale, which is gas prone (Type III kerogene) and appears to be in the gas window. The Upper Cretaceous Raghavapuram Shale and the shallower Paleocene- and Eocene-age shales are in the oil window. The Kommugudem Shale is a thick Permian-age rock containing alternate sequences of carbonaceous shale, claystone, sand and coal. The Mandapeta graben, the most extensively explored area, provides geological characterization of this basin. The interval thickness of shale ranges from 945 to 1,065 m in thickness. The TOC content of the Kommugudem Shale varies from 3% to 9%.

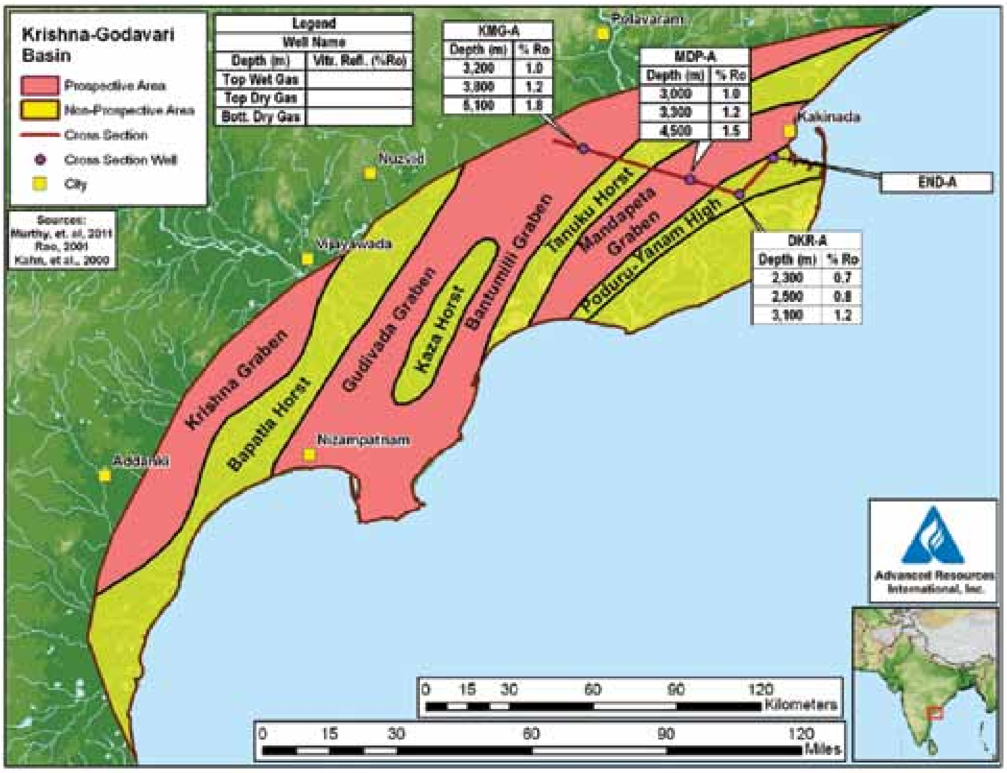

Figure 4. Prospective area for shale gas in Krishna-Godavari Basin (Source: US EIA 2011 and the references therein; few are indicated in the left). Inset shows the location of basin over Indian map.

Age		Formation	Cap/Play/Source	Thickness (m)
Recent to Mid. Miocene		Tittacheri Sandstone		300-500
Lower Miocene		Madanam Limestone Vanjiyur Sandstone Shiyali Claystone	 Cap	600-1200
Oligocene		Kovikalappal Fm. Niravi sandstone	 Play	500-800
Eocene		Pandanallur Fm. Karaikal Shale Up. Kamalapuram Fm.	 Cap Play	200-400
Paleocene		Lr. Kamalapuram Fm.	Play	200-800
Cretaceous	Upper	Porto-Novo Shale Nannilam Fm. Kudavasal Shale	Cap Play Cap	600-1500
	Lower	Bhuvangiri Fm. Sattapadi Shale Andimadam Fm.	Play Source + Cap Source + Play	1000-1500
Archaean		Basement	Play	

Figure 5. General stratigraphy of the Cauvery Basin

CAUVERY BASIN

The Cauvery Basin (Fig.5) covers an onshore area of about 9,100 mi^2 on the east coast of India plus an additional area of about 9,000 mi^2 in the offshore (Fig.6). The basin comprises numerous horsts and rifted grabens containing a thick interval of organic rich source rocks in Lower Cretaceous Andimadam and Sattapadi shale formations (which contain thermogenic natural gas) over the Archaean basement. The source rock is generally Type III along with a mix of Type II. The oldest rocks are the shallow marine, Late Jurassic sediments and Early Cretaceous deposits. The thickness of the Lower Cretaceous interval is 3,000 to 5,000 feet, with the Andimadam/Sattapadi Shale accounting for the bulk of the gross interval. The TOC content of the Andimadam/Sattapadi Shale is estimated at 2% to 2.5%. The basin contains a series of depressions (sub-basins) that hold promise for shale gas. Two of these sub-basins are Ariyalur-Pondicherry and Thanjavur containing thick thermally mature shales. The in-place shale gas is calculated as 43 TCF, of which 9 TCF is considered as technically recoverable.

ARIYALUR-PONDICHERRY SUB-BASIN

The Ariyalur-Pondicherry depression is in the northern portion of the Cauvery Basin. The Lower Cretaceous Andimadam/ Sattapadi Shale encompasses a 5,000 feet thick interval at a depth of 6,600 to 11,600 feet. The TOC content ranging from 0.3 to 2.8% with an average vitrinite reflectance of 1.15% place the shale in the wet gas window at 10,000 feet deep. The onshore prospective area with thick organic-rich shale is rather small, estimated as 620 mi^2.

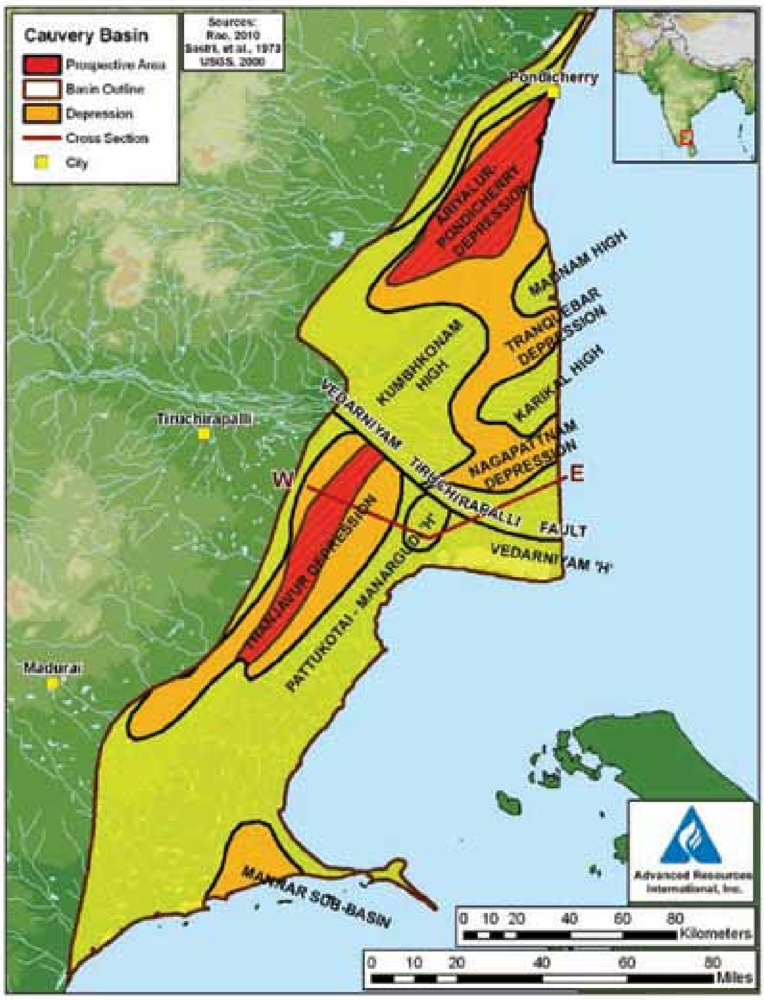

Figure 6. Prospective areas for shale gas in Cauvery Basin (Source: US EIA 2011 and references therein; few are indicated at the top). Inset shows the location of basin over Indian map.

THANJAVUR SUB-BASIN

The Thanjavur depression in center of the Cauvery basin has a thick section of Andimadam and Sattapadi Shale encompassing 8,000 foot thick interval at a depth of 5,000 feet (top of Sattapadi Shale) to 13,000 feet (base of Andimadam formation). The onshore prospective area with thick organic-rich shale is small, estimated at 385 m^2.

DAMODAR VALLEY BASIN

After the Cambay basin, the Damodar Valley basin (Fig.7) is the next priority basin for the exploration and production of shale gas. The Damodar Basin is a Permian basin that has huge thickness of organic rich shales in the Barakar and Barren Measure formations. The Barren Measure formations have fair hydrocarbon potential with low hydrogen index and gas-prone type-III organic matter. The formation thickness varies up to 1200 m in the deepest part with average TOC content varying from 4.2 to 6.6 %. The shale in Barakar formation has higher TOC values ranging from 4.40 - 8.29 %, which makes the formation targetable for shale gas exploration. The basin contains a favorable resource concentration of 123 BCF/m^2 with approximately 7 TCF of technically recoverable shale gas from the Barren Measure shale. The Damodar Valley basin comprises a series of sub-basins from west to east - the Hutar, Daltonganj, Auranga, Karanpura, Ramgarh, Bokaro, Jharia and Raniganj. Though these sub-basins have similar geological history, tectonic events and erosion since the Early Triassic have made extensive variability in the depth and thickness of Barren Measure Shale formation.

VINDHYAN BASIN

The Vindhyan basin in the north of central India contains a series of Proterozoic-age shales. The Hinota and Pulkovar shales appear to have some organic richness with probable TOC values of 0.5 to 3.8%. The basin contains shallow marine deposits as thick as 6000 m. Sandstone, shale and limestone are deposited in marine environment. Presence of algal origin fungi, acritarch remains and stromatolites in this basin suggests the organic matter as Type-I and Type-II.

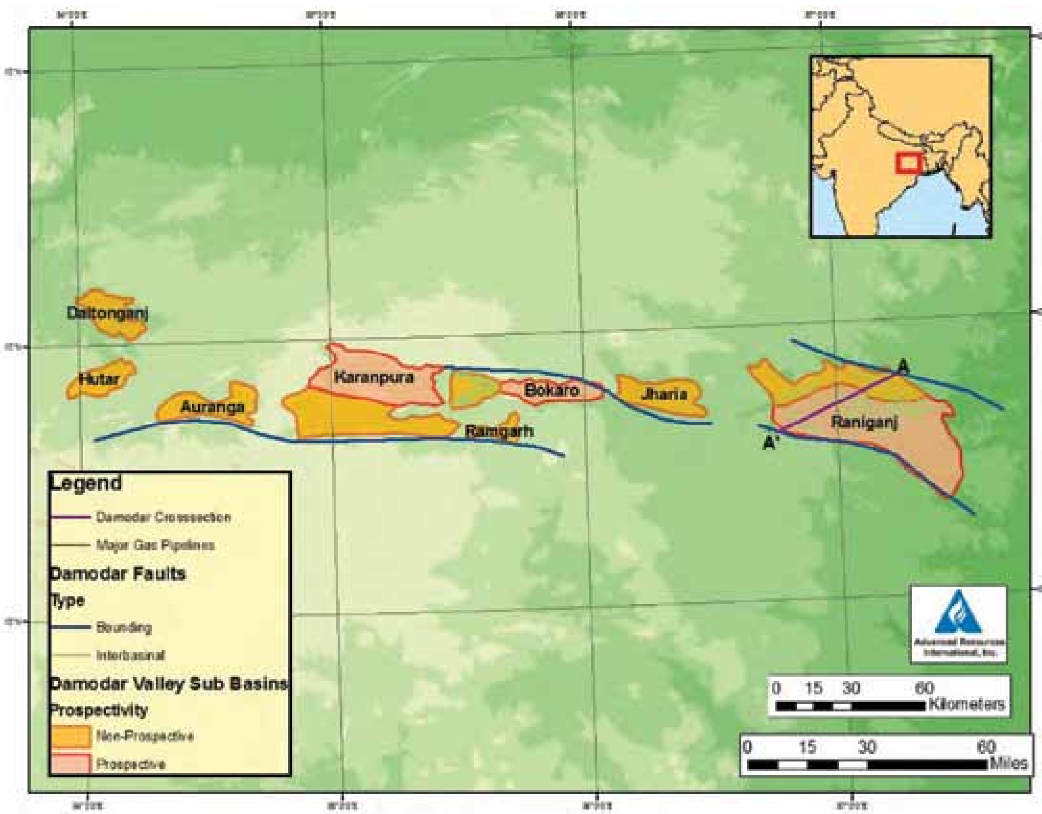

Figure 7. Damodar Valley basin and shale gas prospects (Source: ARI and US EIA 2011). Inset shows the location on Indian map.

UPPER ASSAM BASIN

The Upper Assam basin is a very important petroleum province in the northeast India, which has produced oil and associated gas mainly from the Upper Eocene-Oligocene Barail Group of coals and shales. The TOC content in the lower source rocks varies from 1 to 2%, and reaches up to 10% in the Barail Group. These source rocks are in the early thermal maturity stage (beginning of the oil window) in the shallower parts of the Upper Assam Basin and may have sufficient thermal maturity for peak oil and onset of gas generation in the deeper parts of the basin toward the south and southwest. With regard to thermal maturity, the vitrinite reflectance range from 0.5 to 0.7% for the Sylhet and Kopili formations and from 0.45% to 0.7% for the Barail Group, placing these shales in the early oil window. While the shales may reach the wet gas window in the deepest portion of the basin, the measured vitrinite reflectance is still at 0.7% (oil window) down to a depth of 14,800 feet.

PRANHITA-GODAVARI BASIN

The Pranhita-Godavari Basin in the eastern India contains thick and organic rich shales in Permian-age (Lower Gondwana) Jai Puram and Khanapur formations with Type III (humic) kerogen favorable for gas generation. The vitrinite reflectance of 0.67% indicates that the shales are thermally immature for shale gas production.

RAJASTHAN BASIN

The Rajasthan basin covers a large part of the northwest India. The basin is structurally complex and characterized by numerous small fault blocks. The Permian-age Karampur Formation is the primary source rock, which is a Type III and classified as mature.

GEOPHYSICAL RESPONSES OF SHALE-GAS PLAYS

To understand the geophysical properties of shale-gas reservoir rocks, it is important to know the factors controlling the rocks physical properties (Passey et al., 2010; Zhu et al., 2011). Rock physics along with seismic modeling provides crucial links between microscopic rock properties and macroscopic physical characteristics such as the seismic velocity and resistivity. This is the basis for predicting in-situ rock parameters such as the TOC, porosity, and mineral composition from geophysical data (Fig. 8). Since organic matter influences the sonic properties, there is a necessity to appropriately handle the TOC effects while analyzing the geophysical data (e.g., log and seismic). The change in effective velocities due to TOC and mineralogy also influences the AVO behavior of a shale-gas formation. The change in Vp/Vs in silica-rich formations may be a useful attribute for seismic characterization of shale-gas rocks. While in clay-rich mudrocks, the P-wave impedance may be a useful attribute. Like many other disciplines, it is expected that geophysics will play an important role in shale-gas exploration and development. Generally, shale gas is characterized by high gamma value, high resistivity, low density etc.

There lies a challenge in terms of characterizing shale reservoirs, estimating resource potential and recoverable amount, and optimizing the fracture stimulation techniques. We do not have or have limited rock property data, which are crucial to understand the reservoirs. Hence, we need to acquire all types of rock property data for integration with log data, stimulation techniques, and production test, which, in turn, will provide the critical parameters to optimize the production costs of shale gas.

SHALE GAS PROSPECT

The basic criteria for evaluating shale gas prospects depends on organic richness or TOC, thickness of kerogene rich interval, non-clay fraction, likelihood of natural and induced fracturing, maturation, thermal history, hydrocarbon saturation, porosity, permeability, gas generation, brittleness, mineralogy, pore structure etc, which includes geosciences, geochemistry, reservoir engineering and economics. These are often unknown in a virgin area. Organically rich shale reservoir contains TOC up to 20-25 wt%, whereas organically lean shales contain TOC of 0.8 wt%. When exposed to heat, the organic materials undergo cracking and conversion into oil. If exposed to higher and higher temperatures, they would undergo further cracking with production of condensate or dry gas. Porosity in the shale reservoirs varies between 2 to 8% with seldom exceeding up to 12-14%. The permeability lies in the nano-darcy

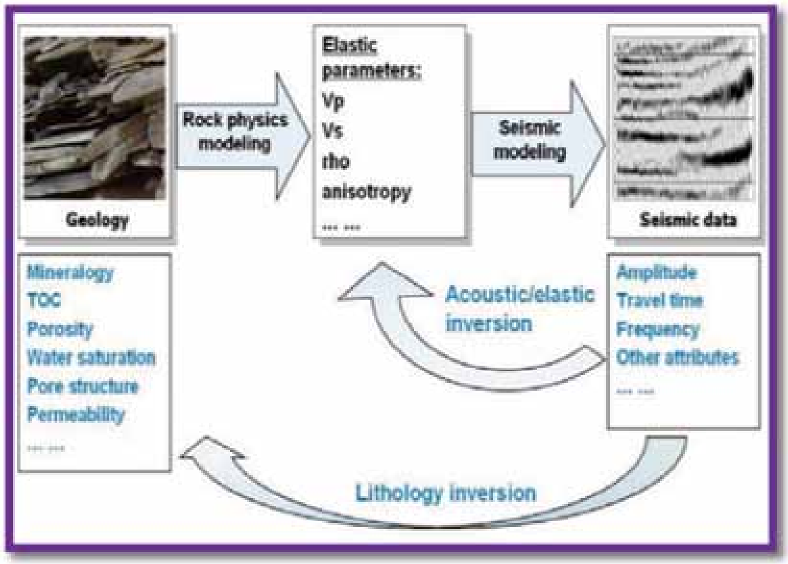

Figure 8. A general rock physics and seismic modeling/inversion workflow (after Zhu et al., 2011)

range. Due to low porosity and very low permeability, commercial production of hydrocarbons from shale reservoirs is possible by extensive stimulation or hydraulic fracturing.

CONCLUSIONS

India has a fairly large number of sedimentary basins with proven 'shale gas reservoirs' in Permian and Cretaceous sequences in the Cambay, Krishna-Godavari, Cauvery and Damodar basins along with the Proterozoic basin like the Vindhyan and Ganga basins. The Upper Assam, Pranhita-Godavari and Rajasthan basins could also be potential targets. Shale gas is envisaged as one of the most feasible and economic unconventional energy resources of India. Initial results are encouraging. However, a concerted geo-scientific study is required for delineating and assessing the resource potential of shale gas to boost the exploitation program. Drilling of hundreds of well, defining the trajectories for horizontal drilling, understanding the geo-mechanical processes, and massive hydrofracturing are some of the factors that need to be addressed. Availability of huge quantity of water for hydrofracturing, disposal of flow back water, water treatment are some of the key challenges. The high clay content in the shale reservoir posing threat to effect hydrofracturing and reservoir monitoring at nannoscale are to be taken care for viable production of shale gas. So the Oil & Gas industries have to come forward to develop a systematic approach for the production of shale gas in an environment-safe manner coupled with monitoring the impact of production on environment.

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