Customized interpretation workflow for simultaneous assessment of unconventional shale-gas reservoirs and conventional reservoirs using seismic and log data

Harilal
GEOPIC, ONGC, Dehradun, India
lal_hari@ongc.co.n

Abstract

The same geophysical and geologic data has been interpreted for both unconventional shale-gas and conventional sandstone reservoirs, simultaneously, by using a customized workflow. The customization was needed because of differences in properties of two types of resources.
Unconventional shale-reservoirs differ significantly from conventional reservoirs in depositional environment, digenesis, physical properties and production techniques. Magnitudes and patterns of reservoir properties (e.g., velocity, resistivity, radioactivity, porosity, permeability etc.) of shales differ significantly from sandstone/carbonate reservoirs. In conventional-play, we generally search for intervals with relatively low gamma, high resistivity, and low neutron porosity where as in shale-gas we search for intervals with very high gamma, relatively higher resistivity than lean shales, low velocity and very high neutron porosity. Production from shales is largely due to horizontal drilling, hydro-fracturing and stimulations. The shale-gas reservoir properties are mainly governed by organic-richness and its thermal maturation. Organic material has significant impact on the elastic/petrophysical properties which are manifested in log and seismic responses. Thus, identification and mapping of shale-gas reservoirs is mainly based on mapping of TOC (total organic carbon) rich zones.

The customized workflow was developed for identification of shale-dominant intervals and organic-rich-zones within it by integrating log and seismic data. Shales generally show low amplitude signals and internal reflection configurations are not easily identified. Seismic data conditioning and seismic attributes, e.g., phase and perigram were applied for internal geometry mapping. Once shale-gas markers were identified, mapping of shale boundary, depth, thickness, areal extent was done in similar ways like conventional plays. Sweet spots were identified by generating and analysing log property volumes like impedance, sonic, resistivity and neutron porosity. Natural fracture which are helpful in designing well trajectory were mapped through geometrical seismic attributes like curvature and dip-azimuth.

This study has enhanced geologic understanding and hence mapability of shale-gas plays along with conventional plays. The customised workflow is applicable in a particular or all stages of shale-gas play exploration and development.

Introduction

Unconventional shale-gas systems are formed by fine-grained organic-rich low-porosity and ultralow-permeability shales which act as source, seal, and the reservoir rock. Recently, shales have been developed as important source of hydrocarbon in United States of America, and are being considered future energy source in other parts of the world also. In US, commercial shale-gas wells were drilled in 1990s in Mississippian Barnett Shale by Mitchell Energy after prolonged (about 17 years) experimentations and advancements in drilling and stimulation techniques (**Bruce Hart et al., 2011**). In India, gas from Barren Measure Shale of Damodar Basin has been struck in January 2011 (**Press Trust of India, 27th January 2011**). According to an estimate shale gas resources in India are high as 527 TCF (http://www.dnaindia.com/money/report_india-holds-527-tcf-of-shale-gas-reserves_1685334) and spread over many sedimentary basins of the country.

Production from shale-gas reservoirs is technology intensive and it is dependent mainly on advancement in horizontal drilling and stimulations by hydraulic fracturing. All shales are not shale-gas resource and, hence, these have to be identified by estimating traditional reservoir parameters like depth, thickness, area, porosity, permeability, saturation and geo-mechanical properties like rock strength, stresses, fractures, brittleness, and geochemical properties like total organic carbon (TOC) and thermal maturity. Shale-gas reservoirs differ significantly from non-shale reservoirs in elastic (velocity, density) and petrophysical properties (lithology, porosity). Log properties of reservoir/source shale and non-reservoir shales estimated from a well of Mumbai Offshore Basin, India, are compared in **Table 1** (**Harilal, 2012**).

Table 1. Log properties of reservoir and non-reservoir shales and coals (Computed from log data)

Interval (m)	Rock type	Sonic (µs/m)	Velocity (m/s)	Resistivity (ohm-m)	Density (g/cm^3)	Neutron-porosity (%)	Gamma-ray (API)	Impedance (m/s*g/cm^3)
2243-46	Reservoir shale	430	2325	207	1.95	52	51	4520
2235-42	Non-reservoir	290	3450	15	2.6	43	50	8980
2273-78	coal	460	2150	610	1.8	56	13	3850

Why simultaneous Interpretation?

A review of shale-gas reservoirs in the USA shows that often these reservoirs occur within the depth range of conventional reservoirs (sandstone, limestone etc.). The Mississippian Barnett Shale-gas reservoir of USA occurs within depth range of 2000 to 2800 m (**Table 2)** where overlying and underlying zones (**Fig.** 1) are oil and gas bearing from conventional reservoirs. This shows that conventional and unconventional reservoirs may be vertically stacked. When we interpret data of such a field, we may get anomalies that are not explained with knowledge and experience of conventional reservoirs. But if we have knowledge of geophysical and petrophysical responses of unconventional reservoirs, the unexplained anomalies may be used for identification of, new, shale reservoir. Since properties of shale-gas reservoirs differ significantly from the properties of conventional reservoirs, customized interpretation workflow is required for interpreting both the plays simultaneously.

Source rock properties

Assessment of source potential is predominantly through geochemical methods applied over rock samples in laboratory. The Total Organic carbon (TOC) is an indicator of the organic richness and generative potential of source rock. Based on TOC content (wt% of rock) shales are grouped as non-source (<0.5), fare (0.5-1.0), good (1.0-2.0) and excellent (>2.0). Depending upon type of organic matter (kerogen type) and thermal maturity, oil and gas or both can be generated during maturation. The thermal maturity of the organic material is typically determined from vitrinite reflectance (Ro). An Ro of ~0.6% corresponds to the onset of oil generation an Ro greater than 1.2% is primarily associated with gas generation. Characteristics of major source/reservoir shales of USA and prominent shales of Indian basins are given in **Table-2** and **Table 3**, respectively.

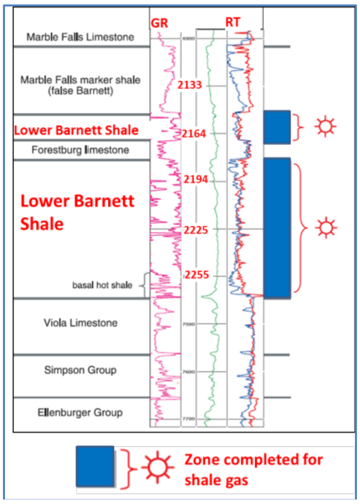
The Interpretation Workflow

During evaluation of G&G data for exploration or development for conventional reservoirs mainly two major task are performed; first, development of geologic framework, and second, find the possibility of getting hydrocarbon by examining all the element of petroleum system. We identify potential reservoirs, traps, seals, mature source rocks and HC migration pathways etc. and identify the drillable exploratory location. For development and production, mapping of spatial distribution of fluids and reservoir rock properties are additionally required. In unconventional reservoirs, mainly, TOC, maturity, natural fractures and brittleness are focused along with depth, thickness and area etc.

The use of seismic method for shale-gas is based on two fundamental concepts: i. shales which are good source are also good reservoir rocks, ii. the elastic, petrophysical and geomechanical properties of shales are manifested in seismic response and by inverting seismic; those properties can be estimated back. The specific properties in shales come from organic richness (TOC) and its maturation which make the shale into effective source and reservoir. Thus, by characterizing the TOC rich formations we can characterise shale-gas reservoirs. The major steps of interpretation workflow for conventional vis-a-vis their customization for unconventional are described below:

A. Data conditioning/enhancements and calibration

Shaly sequences generally have weak reflections. Prior to starting actual interpretation often random noise attenuation and image enhancement processes may be applied which improve continuity and correlatability and attribute analysis. In **Fig. 2**, an image enhanced PSTM sections shows weak amplitude reflection below the Older Cambay Shale (OCS) top reflector. Seismic attribute volumes such as Phase and COSIGN of phase further improve the continuity. Shale sequences are often deposited during transgression, top of which is represented by maximum flooding surfaces (condensed sections). Prior to seismic to well tie (if wells are available), the logs may be interpreted for identification of TOC rich zones. Seismic and log signatures of TOC rich zones may be matched through synthetic seismogram generation **(Fig. 3**). Additionally, maximum flooding surfaces may be focused instead of tops of conventional pays.



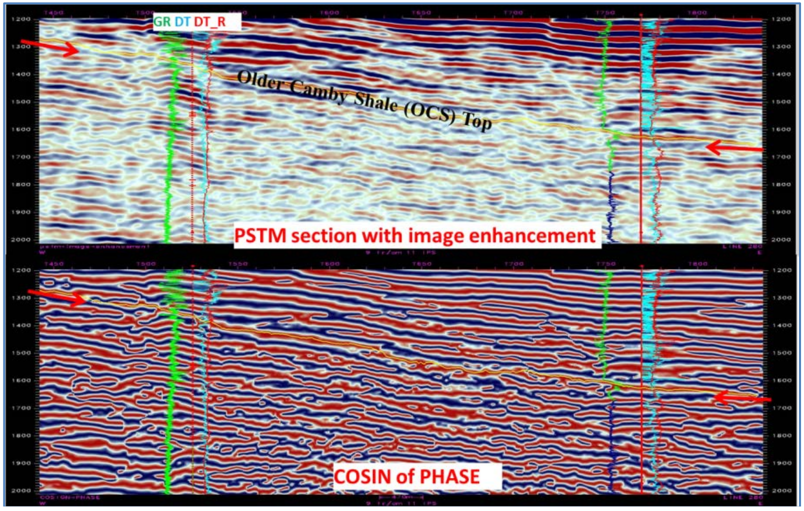


Fig. 1Barnett Shale Play (USA). Fig. 2 Normal seismic (upper) and COSIN of Phase (lower) sections.

Table. 2. Reservoir characteristics of major shale gas plays of North America

Name of Play **Net thick (m)**	**Basin**	**Age**	**Depth (m)**	**Source Parameter**		**Reservoir Parameter**		
				TOC (wt%)	RO	Porosity (%)	Permeability (milidarcy)	**Sw (%)**
Barnett Shale 15-30	Fort Worth, Texas, USA	Mississippian	2000-2800	4.5	0.6 -1.6	3-6	.02-0.1	25-40
Haynesville Shale	Northwestern Louisiana	Late Jurassic	3200-4100	2.8	2-0-2.8	9	n/a	10-20
Marcellus Shale	Appalachian	Devonian	1500-2500	2-12	1.6	6	.13-.77	20-45
Lewis shale	San Juan	Late Cretaceous	900-1800	.5 – 2.5	1.6-1.88	5	n/a	10-80
Eagleford 10-90	East Texas	Up. Cretaceous	1200-4500	2.45	n/a	7	n/a	n/a

Compiled from: Kathy R. Bruner and Richard Smosna, A Comparative Study of the Mississippian Barnett Shale, Fort Worth Basin, and Devonian Marcellus Shale, Appalachian Basin, US Department of Energy, April 2011, ***DOE/NETL-2011/1478****,* ***The Energy Lab****, and other documents freely available on internet*

Table 3 Source rock characteristic of shales of different Indian Basins

Basin	**Formation/Age**	**Thickness (m)**	**TOC (%)**	**VRo**	**Kerogene Type**
Cambay	Cambay shale/ Lower Eocene	520-1500	1.00-4.0	0.75-0.85	II&III
Assam Arakan	Bhuban/ Miocene	800-1000	0.31-1.36	0.90-1.00	II&III
Damodar (Gondwana)	Barren Measure*/ Late Permian	900	4.0-10	1.0-1.2	III
KG Basin	Raghavapuram Up. Cretaceous	1800	1.0-4.0	0.9-1.30	II&III
Mumbai Offshore	Panna Shale/ Lower Eocene	500-3000	1.5-15.0	0.2-1.4	I, II, III

*Compiled from different unpublished/published reports/papers of ONGC, * well drilled for shale gas*

B. Geologic Framework building

Geologic framework may be built by correlating seismic horizons and faults using phase and COSIN of phase sections (**Fig. 2**). Spectral inversion may also be generated before correlation and acoustic inversion. Thick shale intervals appear as weak reflection zones on the seismic section (**Fig**. **2**). Perigram attribute may locate isolated high amplitudes. Thin shales are often found to be intercalated with coals, sands and/or carbonates. In coal-shale-sand intercalation, carbonaceous shales may appear similar to sandstones in some log (e.g., gamma ray, resistivity, etc.) and interface properties. In such cases, reflectivity is generally high and horizon correlation is rather easy but lithologic interpretation, based on seismic alone, may be ambiguous. Integration of impedance/velocity may reduce the lithologic ambiguity. Shales are found to be anisotropic and depending upon composition, shales may show great variability in elastic properties.

C. Seismic attributes, Post-Stack Inversion, AVO and Pre-Stack Inversion

Before attempting to attribute and inversion it is important to know the properties of shale-gas reservoirs which directly affect the seismic and log response. The shale-gas reservoir properties are mainly governed by organic-richness and its thermal maturation (**Vernic and Milovac, 2011**). Organic material has significant impact on the elastic/petrophysical properties which are manifested in log and seismic responses. Thus, identification and mapping of shale-gas reservoirs is mainly based on mapping of TOC (total organic carbon) rich zones. The TOC causes increase in gamma ray, neutron porosity and decrease in seismic velocity and bulk density as compared to lean shales. If TOC is matured (has produced gas) it will show relatively higher resistivity. The TOC can be directly estimated from the logs (**Fig. 4**) by sonic-resistivity overlay method (**Passey et al, 1990**) modified by **Thamas Bowman, 2010**.

- Calculate LogR of Resistivity log
- Cross-Plot LogR vs Sonic (DT), Porosity log may be used in place of DT. DT log on y-axis and LogR on x-axis. The crossplot may be colour coded with gamma ray (GR) log
- Determine low Resistivity Shale line from cross-plot
- Calculate new Sonic (pseudo-sonic DT_R) from Shale line [DT_R=c-m*LogR], where c is intercept and m is slope.
- Overlay pseudo-sonic (DT_R) over sonic
- Highlight crossover of pseudo-sonic with DT
- Interpret Organic shale section

Figure 4 shows application of the above method in a well of Cambay Basin. Using this method TOC log may be prepared. The interpreted organic richness and its maturation in another well (**Fig 5)**, are matching with geochemical study of the section which has shown good organic richness (TOC 6 to 12.7%) and sufficient maturity (T_{max} ranges from 437 0 C to 441) C). Many sections have attained adequate thermal maturity and generated oil and gas (**Rajeev Sharma et al. 2003**).

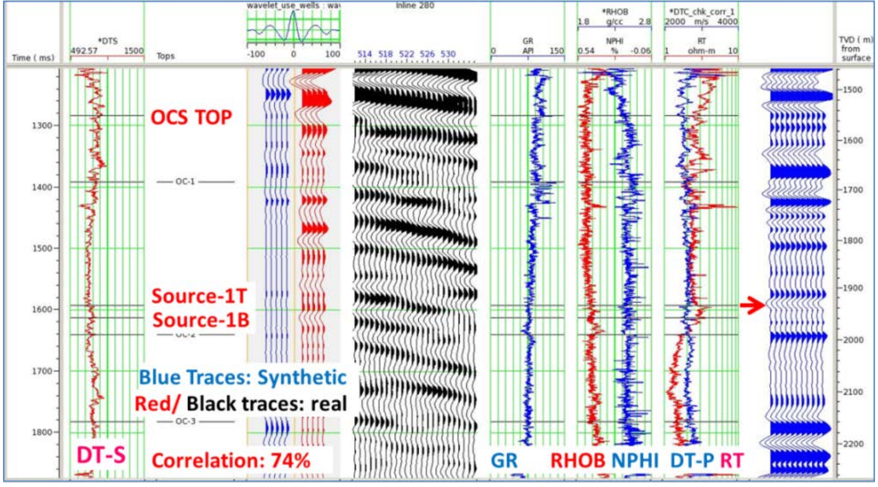
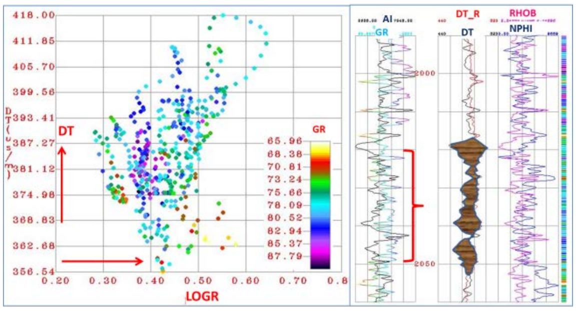


Fig. 3 Seismic to well tie. Synthetic signature of one TOC zone is marked by arrow.



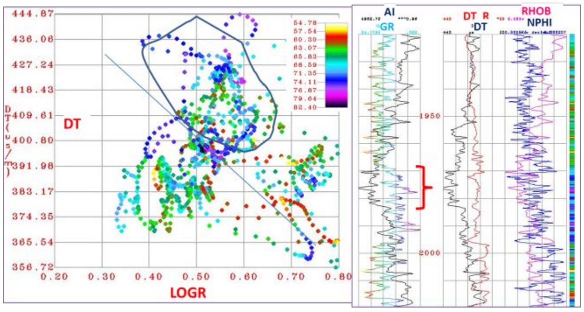


Fig. 4 TOC zone identification with overlay method. Fig. 5 TOC Zone interpretation

Post Stack Inversion: The matured TOC has low impedance than lean-shale and other conventional reservoirs. Model based post-stack acoustic impedance inversion can provide potential TOC rich zones. In case shales are associated with coals, the lowest impedance may indicate coal rich zones **(Table 1)**. To differentiate between coal-rich and TOC-rich shale, resistivity log may be used.

Seismic guided log property mapping: The seismic attributes alone may give ambiguous results for mapping of targeted geology and property. Seismic guided log property mapping methods (**Hampson, et al., 2001**) directly estimate the targeted property, e.g., DT and RT, and hence more reliable maps of desired geologic objects. For success of this method adequate number of wells with good logs, and good seismic data are required. Impedance volumes may also be used as external attribute input. Application of this method for identification shale-gas sweet spot has been demonstrated by the author in another area of Mumbai Offshore Basin (**Harilal, 2012**).

AVO analysis: Advances in AVO and pre-stack inversion initially developed for conventional reservoirs are well-adapted for shale-gas reservoir. AVO modelling from logs of a well of Camby Basin has shown Class-IV type anomaly from the top of a TOC rich zone in Older Cambay Shale (**Fig. 5**). The Class-IV anomaly associates with the reflection coefficient which becoming more positive as the offset increases, but the magnitude decreased as the offset increases. It is generated for a very large value of intercept, and a small change in *Poisson's ratio*. It is seen that shale-gas reservoirs are often bounded by lithology which has high seismic wave velocity, such as lean-shale, siltstone, tightly cemented sand, or carbonate.

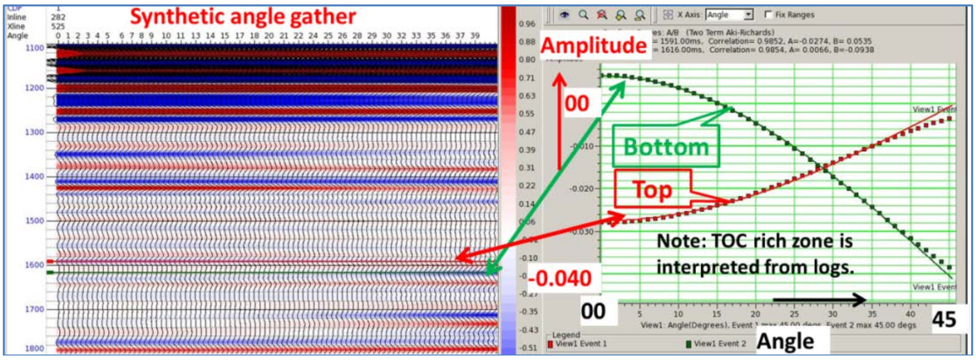


Fig. 5 Synthetic angle gather and AVO curve showing Class-IV AVO anomaly from top of zone

Pre-stack inversion: Through simultaneous pre-stack inversion acoustic impedance (Zp), shear impedance (Zs), Vp/Vs and density can be estimated and from them lambda-mu-rho (λ μ ρ) and other elastic constants can be estimated. In shale-gas reservoir these parameters can be used for identifying brittle porous zones. Zones with high Young's modulus and low Poisson's ratio are expected to have brittle rock with better reservoir quality.

D. Direct Hydrocarbon Indicator (DHI) Analysis

The DHI, particularly "flat-spot", are not applicable for unconventional shale-gas reservoirs because of lack of gravity driven stratification of fluids in the reservoir. Mostly gas occurs in adsorbed form. Due to significant lowering of impedance in gas saturated zones, the top and bottom interfaces of a shale-gas reservoir may generate respective high amplitude events with opposite sign (**Fig. 6**). Other indicators, e.g., absorption and lowering in frequency may also be observed.

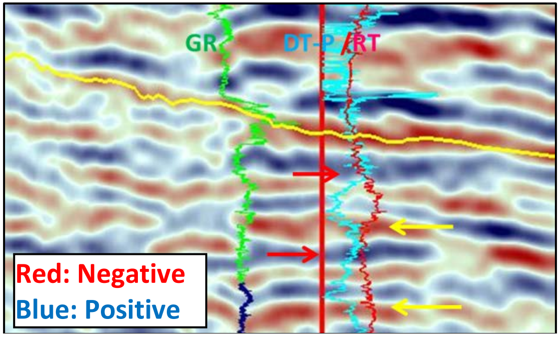


Fig. 6 TOC rich zones on seismic.

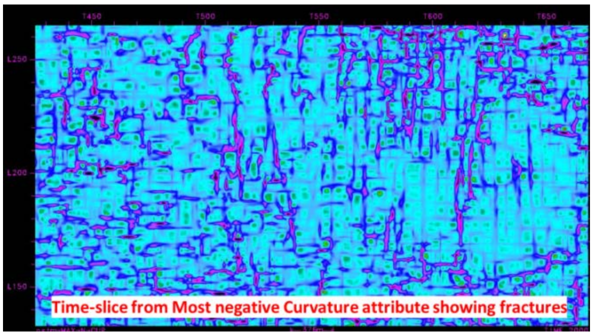


Fig. 7 Fractures from volumetric curvature attribute.

E. Petroleum system Modelling

Out of the many elements of petroleum system model, generation, migration, trap formation, accumulation and preservation, mainly, generation and retention are important for shale gas reservoir. Generation potential is analysed mainly by geochemical methods and retention potential comes from log and seismic data as discussed in sections C and D. Characteristics of good source are already summarised in section of source rock properties.

F. Identification of drillable locations

Identification of drillable location for shale-gas reservoir also requires fracture and brittleness mapping, in addition to integration of all the studies mentioned above. Natural fractures can provide pathways for permeability. Fracture can be mapped through post-stack attributes, e.g., coherency, dip-azimuth and curvature (**Fig. 7**). Pre-stack processes such as AVO etc. help in mapping of fractures. Brittleness is mapped by estimating Lame's constants, λ and μ and elastic constants Young's Modulus and Poisson's Ratio. After having known all the properties and parameters, drilling plan and stimulation scheme may be initiated.

Discussion and results

Having theoretical knowledge of characteristics of unconventional reservoirs and their expected log and seismic responses, the same data was interpreted to identify shale-gas reservoirs. Image enhanced seismic volume converted in COSIN of Phase attribute helped in better correlation. TOC-rich zones are identified by the sonic-resistivity overlay and authenticated by existing geochemical studies. Identified zones from logs are well-recognized on seismic data and can be mapped away from the wells with seismic guided log property mapping. Class-IV type AVO is found in TOC-rich zone from synthetic modelling. The AVO and pre-stack inversion provide brittleness property. The fracture mapping is demonstrated with post-stack attribute (curvature).

Conclusions

The customized workflow was applied in an area where source-potential is well-established from earlier geochemical and sedimentological studies. Customized interpretation of log and seismic responses has enhanced the geologic understanding and has indicated good unconventional shale-gas resource potential. TOC-rich matured zones indicated by sonic-resistivity overlay, seismic attributes and AVO reasonably match with zones directly interpreted from geochemical methods. Like in conventional plays, all shaly zones may not have favourable properties for shale-gas.

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