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# Direct detection of oil using Lambda-Rho and Mu-Rho AVO attributes in under compacted clastic sediments

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## Abstract

Pore fluid and lithology prediction are the two major objectives in AVO analysis and Inversion. Traditionally, AVO is used for identification of Gas reservoir. The identification of oil saturated zone is difficult to decipher from conventional AVO attributes such as Intercept and Gradient. The main objective in this paper is to search for oil saturated zones in under compacted clastic sediments using suitable AVO attribute. The Fluid Factor, Poisson's Ratio, Elastic Impedance, Lambda-Rho and Mu-Rho are some of AVO derived attributes used for pore fluid discrimination. Lambda-Rho is found to have been more affected by fluid and less due to compaction whereas Mu-Rho is more affected due to lithology.

To understand the effect of fluid in under compacted sediments, a forward modeling was first attempted and found that Lambda –Rho is more sensitive to fluid compared to other AVO attributes like Intercept, Gradient, fluid factor elastic impedance and Poisson's ratio. It is further demonstrated from modeling study that Lambda-Rho and Mu-Rho can even discriminate oil zone from gas bearing zone. This is very crucial finding and it will go a long way in direct detection of oil saturated zones in basins with high rate of sedimentation leading to under compaction such as Niger delta, Gulf of Mexico , East coast of India and other such basins around the world.

The above finding has been extended to full AVO Inverted Lambda-Rho and Mu-Rho seismic volume to test the efficacy of the technique and establish its applicability/predictability in time and space within the given geological setting.

**Key words:** Under compacted sediments, Detection of oil and Lambda-Rho Mu-Rho

## Introduction

AVO attributes are conventionally applied for the detection of gas zone which involves cross-plotting of Intercept and Gradient (Foster et al., 1993; Verm and Hilterman; 1995,Castagna et al., 1998). For a given lithologic composition, seismic velocities in rocks are influenced by many factors such as porosity, pore shape, pore fluid saturation, confining pressure and temperature.

Because of large variation in P wave velocity by all these factors, discrimination between fluid and lithology with the help of P wave velocity is difficult. With the inclusion of S waves the difficulties do reduce to some extent, which is in terms of Vp/Vs. However, in case of unconsolidated sands, only Vp/Vs does not help much in discriminating fluid and lithology.Therefore, other AVO attributes must be tried for fluid identification.

Fluid Factor (Smith and Gidlow, 1987), Poisson's Reflectivity (Verm and Hilterman, 1995) Elastic Impedance Reflectivity (Shuey's approximation) and Lambda-Rho and Mu-Rho Reflectivity (Guillaume, 2000) are the four attributes being frequently used in pore fluid discrimination. It is always debated that one is better than other. Since the sensitivity of the AVO attributes for pore fluids vary from basin to basin depending upon the rock texture (mineralogy) i.e. Fluid Factor ($\Delta$F) is an effective pore-fluid discriminator in tertiary unconsolidated sediments in the Gulf of Mexico and Poisson's reflectivity (PR) in North Sea of Paleozoic consolidated sediments. These attributes are very efficient in diagnosing gas saturated zones especially in Tertiary sediments but real challenge is to find the suitable AVO attributes which best separates oil saturated zones from Gas saturated zones. The task becomes difficult when DHIs associated with oil (higher APIs) looks similar to that of gas zone in tertiary un-compacted sediments of Niger Delta. This work is based on the offshore part of Niger Delta, West Africa and it is expected that the work can be extended to the other basins under similar geological setup i.e. East coast of India.The success of the fluid identification from AVO inversion depends on how well one understands the depositional facies in the area of interest.

## Geological Background

The Niger delta is situated in Gulf of Guinea on the west coast of Africa shown in Fig.1a. It is world's one of the most prolific petroleum producing Tertiary delta.The Niger delta is large arcuate wave and tide dominated delta having sediments of age Eocene in north and Quaternay in south.Its formation started with breakup of Africa –South America in Mesozoic. The rifting started in Late Jurassic and continued into middle Cretaceous and almost subsided in late Cretaceous (Lehner and De Ruiter ,1977). The Cretaceous Benue-Abakaliki trough represents failed arm of the rift triple junction associated with opening of South Atlantic Ocean. Marine sedimentation began in the trough (Benue trough) during middle Cretaceous and true delta development commenced in Late Eocene/Paleocene (Doust and Omatsola, 1990). The main sediment supplier in the basin is Niger river along with Benue and cross rivers Fig.1a. The Niger delta is a regressive sequence of clastic sediments developed in series of offlaping cycles. Stratigraphically, the base of the sequence is massive and monotonous marine shales (Akata Shales) grading upward into shallow marine fluvial sands, silts and clays (Abgada Formation-main reservoir rocks).The uppermost part of the sequence is massive non marine sequence as shown in Fig.1b. The depositional environment of the area under study is coastal belt of barrier bar which is the cleaner and coarser sands due to longshore currents along the coastline and Mouth bars deposited at the mouth of distributaries. In both the situation the vertical arrangement of sands deposited is coarsening up. The porosity (23-30%) and permeability (1000-2000 md) of the sands is very good and these sands form excellent quality of reservoir for hydrocarbon accumulation in Agbada Formation. The interbedded marine shales within the Abgada formation act as a good seal.

After rifting ceased, gravity tectonism became the primary process of deformation in Niger delta basin. First shale diapirs formed from loading of poorly compacted, over pressured , prodelta and delta slope clays (Akata formation) by higher density delta front sands (Agbada formation). Secondly,the slope instability occurred due to lack of lateral, basinward support for under compacted delta slope clays. From Eocene to present, the delta has prograded southward (seaward) forming depobelts .Each depobelt is a separate unit bounded landward by growth faults and seaward by large counter regional fault or growth fault of next seaward depobelt (Doust and Omatsola, 1990). For any given depobelt, gravity tectonics was completed before deposition of Benin formation. Five major depobelts are recognised in Niger delta basin. These depobelts form one of the largest regressive delta in the world. Roll over anticlines, collapsed growth fault crest, back to back features, steeply dipping closely spaced flank faults and Shale diapirs are some of complex structures exhibited in the Niger delta basin. The faults are rootless and flatten into detachment planes near top of the Akata formation.

The Niger delta province contains only one identified petroleum system referred as Akata-Agbada petroleum system. The most of this petroleum are found in the fields that are onshore or on the continental shelf in water depth less than 200m. The range of Oil API is 35-40 deg regionally.

## Procedure

The Niger delta is a basin having fast rate of sedimentation. Due to rapid sedimentation and very less compaction, the velocity contrast between sand and shale is very less. In most of the cases, it is observed that the impedance of water sand (very clean sands) is somewhat less/equal or little more than that of encasing shale i.e. the velocity contrasts between water sand and shale is very little and this trend prevails up to depth of 2500m as shown in Fig.2a. Since mechanical and chemical compaction governs acoustic properties of rocks and in general velocity increases and porosity decrease with depth. The, overall trend of P wave velocity in the study area is gradual increase with depth as shown in Fig.2a.There is no sign of abrupt increase of P wave velocity with depth indicating absence of any chemical compaction. There are three pay sands in well X namely sand1 (20m oil column with 3m gas cap), Sand 2 (Gas zone) and Sand 3 (gas zone). Sand1 and Sand 3 are selected for the modelling study. If analysis holds good for these two sands, then it should hold good for other sands as well as including Sand 2.

The nature of seismic amplitude can be understood if we know rock property and its link with depositional environment. Based on log motif analysis, Sand1 interpreted to be massive beach sand and Sand3 is the prograding and retrograding shoreface sand as shown in Fig.2d. Though this type of sands are very clean in nature but it is necessary to understand the rock type (consolidated or unconsolidated) along with mineralogical arrangement within it. Therefore, to understand all the factors, Dvorkin and Nur in1996 introduced Rock physics diagnostic tool. This is a tool to infer rock type, clay volume, digenetic trend and texture in velocity-porosity plane as shown in Fig.2b.They introduced two theoretical model for clean sands: First the Friable sand model (unconsolidated line) and second the Contact cement model. The Friable sand model (unconsolidated line-mechanically compacted) assumes porosity reduction from the initial sand pack value due to deposition of solid matter away from the grain contact and represented by modified Lower Hashin-Shtrikman bound model which connects the critical porosity and the mineral points as shown Fig 2b.

The Contact cement model (consolidated line) assumes the decrease of porosity from the initial sand pack is due to deposition of the cement layer on the grain surface Fig 2b. Another theoretical model for moderately compacted sediment is given by Constant Cement Model (Avseth et al. in 2000), which assumes that the sands of varying porosity all have the constant cement and porosity decrease is due to pore filling material away from the grain contact Fig 2b.

Fig.2c shows sand and shale interval obtained from well X, when plotted in velocity-porosity plane, follows the trend of Friable Sand Model (unconsolidated line) having clay volume ranging dominantly between 20-30%. The main take away from velocity- porosity relation are the sediments are clean and unconsolidated, mechanically compacted, and contrast between water sand and shale in terms of reflectivity will be very low because sand and shale velocities are overlapping. Effective rock frame for unconsolidated sands is derived from modified Lower Hashin-Shtrikman bound model which includes Hertz Mindlin theory. The sensitivity of AVO attributes depends on the effective rock frame stiffness i.e. stiffer the rock, lesser porosity and in turn lower fluid response in terms of AVO attribute.

In case of friable sand model, the effective frame is very weak and porosity is very high, wherein fluid effect is greatest in terms of AVO attributes and also confirmed by Gassman fluid substitution. The modelled AVO attributes such as Intercept, Gradient, Lambda-Rho impedance and reflectivity, Mu-Rho impedance and reflectivity and Elastic Impedance (30 deg.) is shown in Fig 2d. Here Sand 2 and 3 are gas bearing whereas Sand 1 is oil bearing (20m) with 3 m Gas cap.

In the Well X, the average porosities are 30% for sand 1 and 24% for sand 3. In 3-Dimentional space, porosity may not remain the same throughout. Therefore, the responses of AVO attributes like Lambda-Rho and Mu-Rho Impedance, Acoustic Impedance (AI), Elastic Impedance (EI at 30 deg.) have been modelled for a range of porosities(10%-40%). Here clay volume is kept at 25%(~equivalent to calculated in Sand1 and Sand3 Fig 2c) .The modelled fluid effects are shown in Fig 3.In all the model curves expressed in moduli vs porosity plane, it is observed that the response due to gas does not change much whether the gas saturation is 70% or 20%. But when the zone is replaced by oil, it does show sensitivity to the saturation change i.e.it falls almost in the middle of water and gas response when saturation is 70% but for under saturation(So=20%), the oil response starts moving towards water. These results are, however, for different types of impedances( i.e. Lamda-Rho, Mu-Rho, EI and AI), but it can be easily inferred that, even in reflectivity domain, the expected response will be the most negative in case of gas and for oil zone it will fall almost in the middle of gas and water for reasonable saturation. The sensitivity of impedances on oil saturation can be further exploited for its prediction in the reservoir.

Further, it is clear from modelled AVO attributes such as Acoustic Impedance (AI) and Elastic Impedance (EI) that the spacing between oil, gas and water curves decreases with decrease in porosity (Fig 3c&d) whereas for Lambda-Rho, oil, water and gas response curve remain almost equally spaced irrespective of porosity decrease (Fig 3a). Now this is an important finding from the study and it can be conveniently told that Lambda-Rho has very little effect of compaction .The Mu-Rho curve for oil, gas and water, overlap each other (Fig 3b) indicating its insensitivity to presence of fluid type. Therefore, Lambda-Rho attribute can be used as better fluid discriminator (especially oil zone with respect to Gas zone) than other attribute.

## Analysis on Seismic Data

Here, the objective is to discriminate oil from gas anomaly using most sensitive AVO attribute Lambda-Rho. In full stack section shown in Fig.4a, the anomalous amplitude in dotted red polygon looks like oil driven anomaly similar to sand 1(proven oil zone).The same amplitude in Lambda-Rho reflectivity section shown in Fig.4(b) has vanished and the amplitudes associated with three pay zones(Sand1,Sand2 and Sand3) remains almost un-affected. Therefore, it can be said that the amplitude in full stack section in dotted red polygon is lithology driven.

The Prospect A is a proven oil zone with gas cap shown in Fig 5. The root mean square (RMS) amplitude extracted along the interpreted horizon at sand1 from Lambda-Rho reflectivity volume, exhibits that in prospect A, the range of oil anomaly(green) ,which can be seen in scale bar, falls almost in the middle of background (water saturated sand/shales) and gas anomaly. This result is in good agreement with the modelling result of Lambda-Rho attribute from the well. The oil anomaly in prospect A conforms structural closure at oil water contact. Similarly prospects B and D have been interpreted as possible oil zone with gas cap while the prospect C as oil saturated zone only.

The uncertainty associated with study of AVO attributes in terms of reflectivity is that wavelet effect has not been removed, which may cause misinterpretation of the data, especially seismically tuned reflections.

## Conclusions

After analysing, rock properties and associated environment of deposition in under-compacted sediments, it is found that friable sand model is best suited for part of Niger delta basin under study. Different AVO attributes such as Acoustic Impedance, Elastic Impedance (EI) at 30deg, Lambda-Rho and Mu-Rho were calculated from well log and studied in detail for its suitability for discrimination of oil from gas. The Lambda-Rho AVO attribute is found to be most suitable attribute to discriminate oil from gas in this basin because of its less dependency on compaction and more on fluid. Based on the results of sensitivity analysis, AVO inverted Lambda-Rho reflectivity volume, now better discriminates oil zone from gas zone. Besides, it is also capable to differentiate amplitude build up due to hydrocarbon and lithology. Further, this methodology can be used even to get clue on saturation of oil in reservoir zone.

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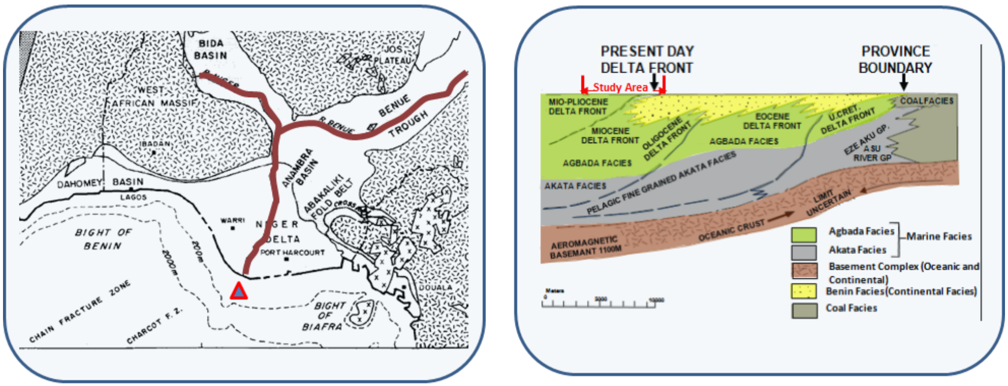
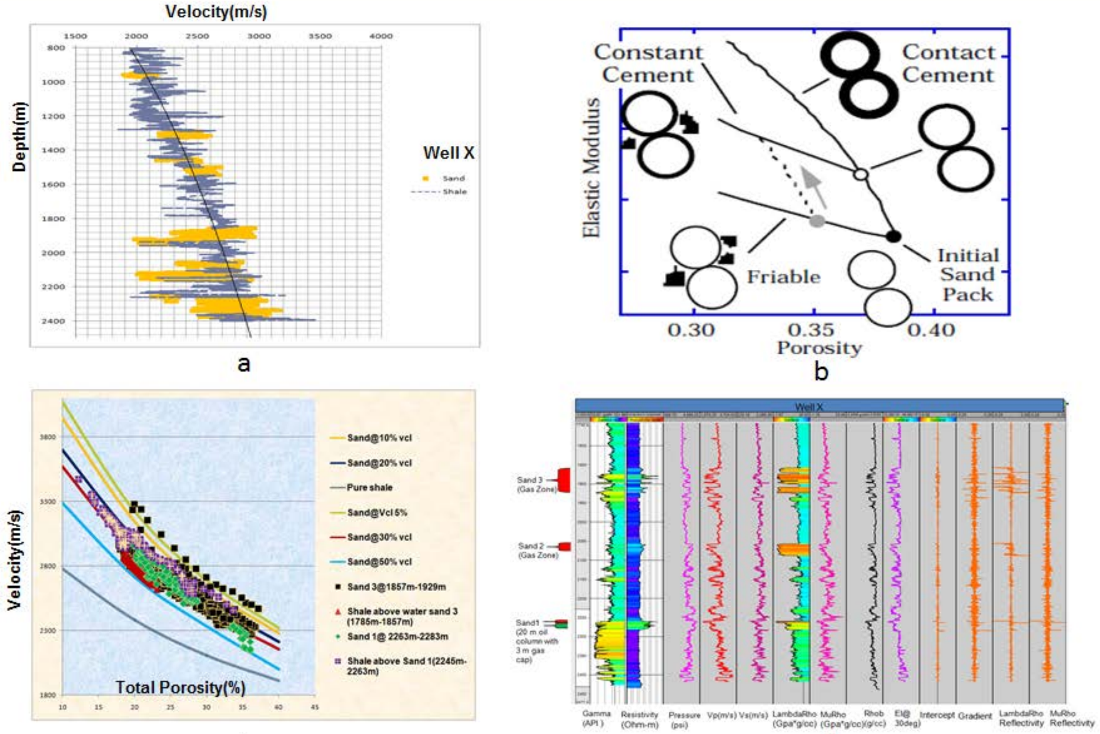


(a) (b)

Fig.1 (a) Simplified geologic map showing drainage into Gulf of Guinea modiified from Whiteman, 1982, Allan 1965) (b) Delatic progradation along the dip oriented profile of the Niger delta



a b

c d

Fig.2(a) showing Velocity depth trends with sands shown in yellow and shales in blue.(b)schematic depiction of three effective medium models in velocity-porosity plane (c) P wave velocity vs porosity for pay zones( as Sand1 and Sand2, and Sand3) with theoretical model curves (d) Modelled AVO attributes

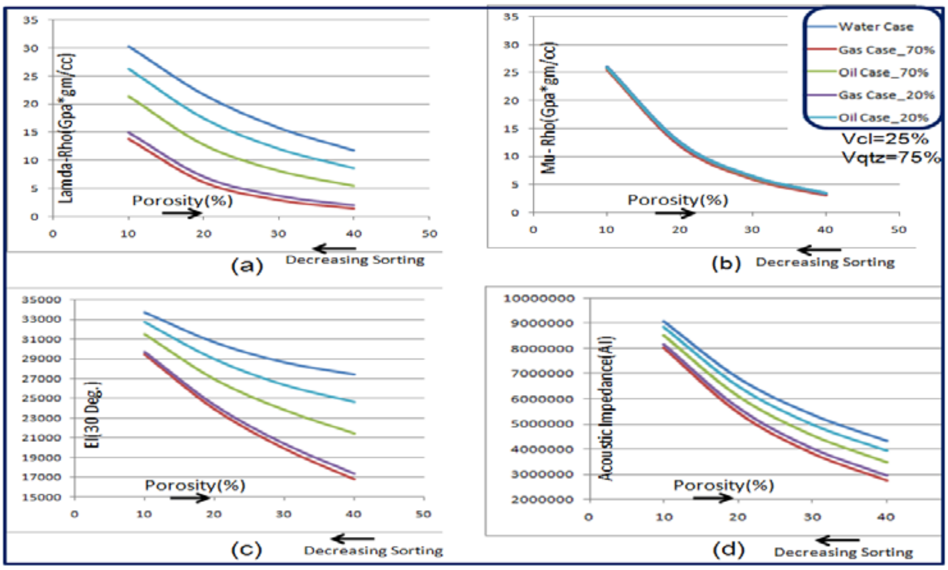


Fig.3 Variation of Elastic Moduli with porosity in Moduli-Porosity planes (a) LambdaRho vs porosity (b) MuRho vs porosity (c)Elastic Impedance vs porosity and(e) Acoustic Impedance vs porosity

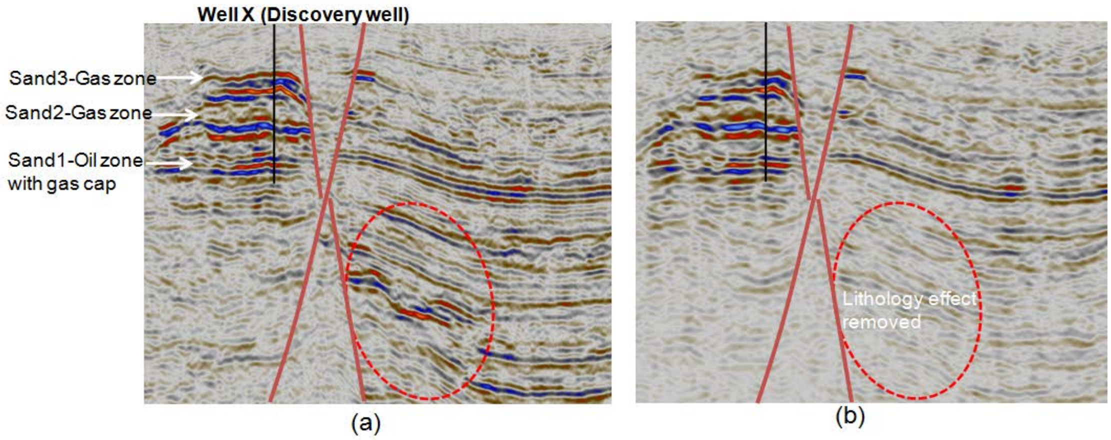


Fig.4 (a) Full stack seismic section (b) Lambda-Rho reflectivity section showing possible lithologic effect encircled in dotted red shown in section (a)

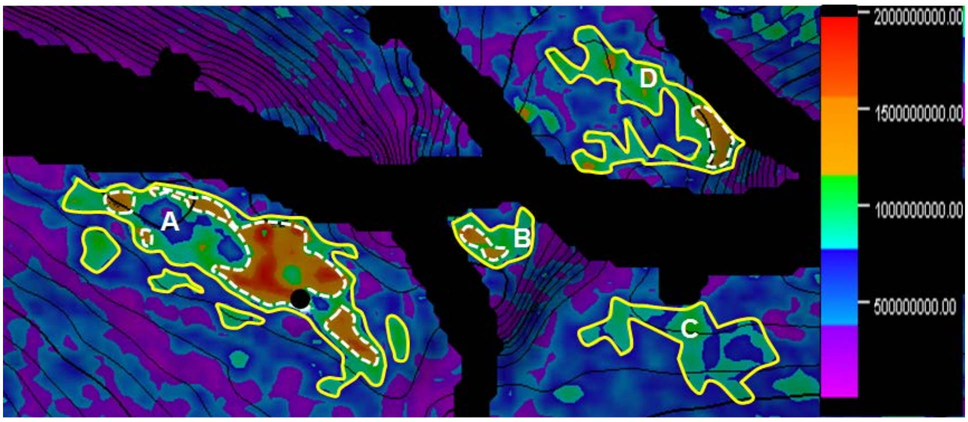


Fig.5 Prospect A is a proven oil zone(20m) with 3m gas cap at wellX displayed as solid circle(black).Solid yellow and dotted white line exhibit possible areal coverage by oil and gas respectively in prospect A,B,C, and D.