Applicability of Density Inversion in Defining Reservoirs

Yongyi Li, Paradigm Geophysical, Calgary, Canada

2005 CSEG National Convention

Summary

Seismic density attributes, density reflectivity and density properties, that inverted from prestack data are useful in defining a reservoir. Understanding density attributes and pros and cons of density inversion techniques may reduce the risk in reservoir characterization. In this paper, we discuss the causes of density variation, the correlation of density with other seismic rock properties, and other factors that help in forming density anomalies. Examples from unconsolidated sand, tight sand and conglomerate reservoir are presented. A workflow in using density attributes to define a reservoir is suggested.

Introduction

P-wave velocity, S-wave velocity and density are three basic seismic rock properties. Similar to velocities, density is directly related to porosity, fluid type and fluid saturation, and mineral composition. Consequently it can be used in defining a reservoir. Seismic density contrast or density refelectivity can be inverted from prestack P-wave or converted data. A section or a volume of density reflectivity can also be inverted into density properties. The techniques inverting density reflectivity from P-wave data are based on three term AVO inversion (e.g., Kelly et al., 2001; Downton, 2001). For converted wave data, two term AVO equations are often used (e.g., Jin et al., 2000).

In comparison with velocities, density is considered as a much simpler rock property. As the density attributes are attracting more attention, the related issues need to be re-examined. One of commonly asked questions is when and where density attributes are applicable. In other words, when would density attributes provide additional or crucial imformation on a reservoir.

In this study, we examine various influences on density properties, including the effects from porosity, fluid, and mineral composition. Density and velocity correlation is then discussed to demonstrate whether density provides the information that velocities do not. To demonstrate the usefulness of density attributes in reservoir characterization, examples from oil sand, tight sand, as well as conglomerate reservoirs are given. The goal of this study is to understand the causes of density anomalies, and to analyze the pros and cons of the methodologies that are currently used in density attribute inversion.

Rock physical background

1) Petrophysical aspects

A general equation for calculating rock density is $\rho_b = \sum_{i=1}^{n} V_i \rho_i$, where V_i and ρ_i are volume fraction and mineral density, respectively. For clastic rocks, we often use $\rho_b = \rho_{ss}V_{ss}(1-\phi) + \rho_{sh}V_{sh}(1-\phi) + \phi\rho_w S_w + \phi\rho_{fl}(1-S_w)$, where ϕ and S_w are porosity and

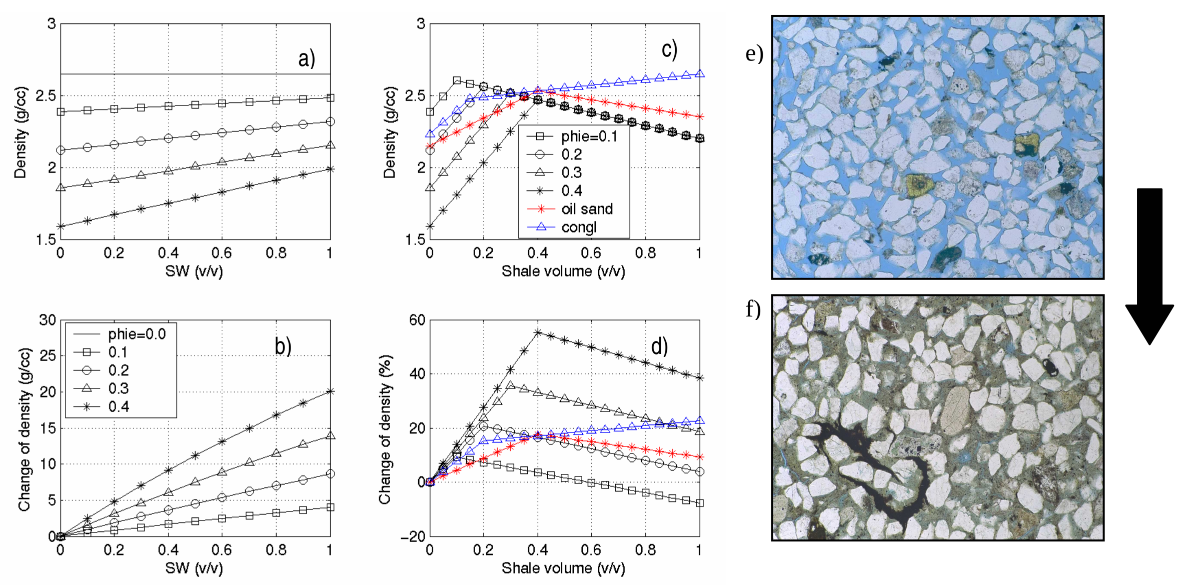

Figure 1. Density properties and their relationship with water saturation and shale volume.

water saturation, and the index ss, sh, and fl represent sand, shale and fluid. This relation demonstrates that density is a function of porosity, fluid type, water saturation, and mineral composition.

Figures 1a and 1b show how the density of sand is influenced by water saturation, where the density of gas is assumed as 0.0 g/cc. The observations from Figures 1 a and 1b include 1) density is linearly increasing with water saturation; 2) a 20% increasing in density may be resulted for sand with a porosity of 40%; and 3) the tight sand with porosity of 10% only results in a 5% density increase.

Volume fraction of shale in sand has a more significant effect on density than water saturation. We calculated this effect using density 2.65g/cc for zero porosity sand, and 2.2 g/cc for the shale (Figure 1c and 1d). When entire pore space is filled with shale the sand with porosity of 40% has a density increase as three times as that due to water saturation (approximately 60. For tight sand and sands with medium porosity the increase is also doubled. Two special cases, unconsolidated oil sand and conglomerate were also studied (Figures 1c and 1d). Using 1.3 g/cc for the density of heavy oil, the change in oil sand density is approximately 20%. Using density of 2.35 g/cc for the clean conglomerate with porosity of 15%, and 2.60 g/cc for the shale that fills the pore space in the conglomerate, it also results in a 20% change in conglomerate density. For a given porosity or a rock type, we see a turning point with increasing shale volume. The turning point indicates where pore space is completely filled by shale. After the turning point, the density of sand decreases due to lower shale density. For the conglomerate, however, its density experiences a continuous increase due to the shale density is higher than the density of the conglomerate. Figures 1e and 1f show two thin sections, a clean sand and a sand filled with shale.

2) Density-velocity correlation

Gardner's equation, $\rho_b = aV_p^b$, is widely used in calculating density from velocity, where a and b are lithologically related coefficients. This relation revealed a fact that density and velocity are correlated. However, many exceptions exist in reality.

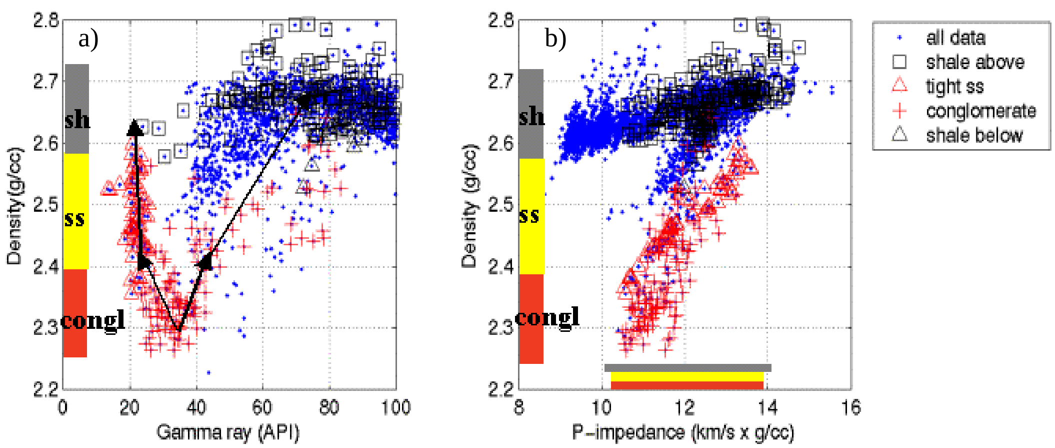

Figure 2. Effect of lithological mixing in density

Figure 2 shows an example in which density has complex relations with other rock properties. The log data is from a conglomerate reservoir, where the conglomerate mixes with sand and shale. In Figure 2a, conglomerate density increases due to sand or shale filling pore space. The turning points are observed from conglomerate to clean sand or to shale. This is similar to what we have observed in Figure 1 except that two opposite trends are now shown, to the left for sand and to the right for shale. Figure 2b shows the cross-plot of density and P-impedance. We may notice that Gardner's equation does not hold here. We also notice that the density contrasts between the tight sand, the conglomerate, the shale above and the shale below are good. In comparison, the impedance contrasts between these lithological units are poor. We may thus consider this play as a candidate in using density attributes to identify reservoirs.

3) Case studies

Porosity, water saturation and mineral composition as well as density-velocity correlation are not necessary the only factors that lead one to use density attributes in defining a reservoir. One should consider using conventional post and prestack seismic attributes first. This is because these seismic attributes may already answer the questions. In addition, extra effort in data acquisition and processing are required in order to obtain correct and high resolution density information. Therefore, the usefulness of density attributes depends on how effective of other seismic attributes are. To illustrate this, two examples, one from an oil sand play and the other from a conventional sand play, are shown in Figure 3. In Figure 3a, we see that P-impedance and P- reflectivity provide similar information as their counterpart density. In this play one may not need to pursue in using density attributes to define the reservoir. For the sand reservoir case we see the density reflectivity clearly indicates the reservoirs. P- and S-impedances, however, do not have the contrasts as density has and also the P- and S-reflectivities are rather difficult to interpret. As a result, the usage of density reflectivity may be recommended.

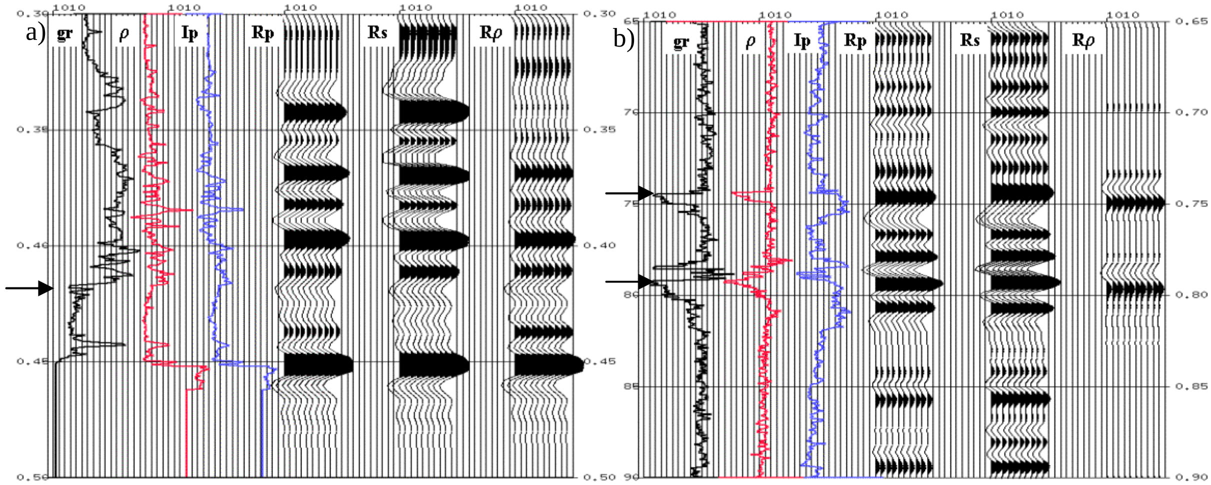

Figure 3. P-reflectivity, S-reflectivity, and density reflectivity of an oil sand reservoir and a conventional sand reservoir.

Density Inversion

Density reflectivity $\Delta\rho/\rho$ can be inverted through using P-wave data or converted wave data. For P-wave data, the inversion is based on three-term AVO equation and P-reflectivity, S-reflectivity and density reflectivity can be inverted. Two commonly used equations are Fatti's (Fatti et al., 1994) and Gidlow's (Gidlow et al., 1992) (Equation 1).

$$R_{pp}(\theta) = R_p \sec^2\theta - R_s 8\gamma^2 \sin^2\theta + 4\gamma \sin^2\theta^2 - R_\rho \tan^2\theta \,. \qquad (1)$$

For converted wave data, S-reflectivity and density reflectivity can be solved using Equation 2.

$$R_{ps}(\theta_i) = c(\theta_i)R_s + d(\theta_i)R_\rho\,, \qquad (2)$$

Where

$$c(\theta_i) = -\frac{Vp\tan^2\theta_j}{2}\left[1 + 2\sin^2\theta_j - \frac{2Vs}{Vp}\cos\theta_i\cos\theta_j\right],$$

$$d(\theta_i) = \frac{Vp\tan^2\theta_j}{2}\left[4\sin^2\theta_j - \frac{4Vs}{Vp}\cos\theta_i\cos\theta_j\right].$$

A more rigorous approach can be taken in solving P-wave, S-wave and density reflectivity called simultaneous P-P and P-S inversion. Simultaneous inversion is considered as having potential in obtaining a more stable estimation of density reflectivity. A synthetic example of P-wave and converted wave CMP gathers, and P-, S- and density reflectivity is shown in Figure 4. Again, we see density reflectivity provide different information in comparison with P- and S-reflectivities. The peak and trough pairs in density reflectivity do correspond with three sand units at this well location.

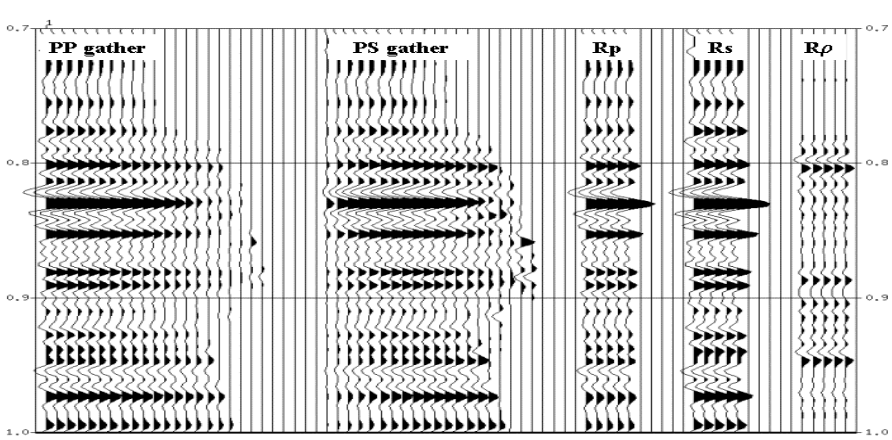

Figure 4. PP and PS CMP gathers, and inverted P-, S- and density reflectivities.

Conclusions

Density is a fundamental seismic rock property and can be used in defining a reservoir. Seismic density attribute can be inverted from P-wave or converted wave data or through a joint inversion scheme. The usefulness of seismic density attributes is closely related to porosity, water saturation, mineral composition and local geology. As the inversion of density attributes needs additional effort in data acquisition, processing and interpretation, understanding the applicability of density inversion is of great importance. A procedure involving log analysis, zero-offset density and AVO modeling, feasibility studies should be followed. Most importantly, the usage of density inversion should be pursued at the circumstances where other seismic attributes have demonstrated the inability in providing the required information.

References

Kelly, M., Skidmore, C., and Ford, D., 2001, AVO inversion, Part 1: Isolating rock property contrasts: The Leading Edge, **20**, 320-323.

Downton, J., and Lines L., 2001, Constrained three parameter AVO inversion and uncertainty analysis: 71st Ann. Internat. Mtg.: Soc. Of Expl. Geophys., 251-254.

Jin, S., Cambois, G. and Vuillermoz, C., 2000, Shear-wave velocity and density estimation from PS-wave AVO analysis: Application to an OBS dataset from the North Sea: Geophysics, **65**, 1446-1454.

Fatti, J. L., Smith, G. C., Vail, P. J., Strauss, P. J. and Levitt, P.R., 1994, Detection of gas in sandstone reservoirs using AVO analysis: A 3-D seismic case history using the Geostack technique: Geophysics, **59**, 1362-1376.

Gidlow, P.M., Smith, G.C., and Vail, P.J., 1992, Hydrocarbon detection using fluid factor traces, a case study: How useful is AVO analysis?: Joint SEG/EAEG summer research workshop, Technical program and Abstracts, 78-89.