Velocities of deep water reservoir sands

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Summary

In deep-water sedimentary processes, compaction is a major force for porosity reduction, which incorporates sediment texture such as grain size and sorting. Measured data suggest that porosity, fluid saturation and differential pressure are main parameters to affect velocities of weakly cemented deep-water sands. Geological compaction and possible weak cementation can reduce porosity from 35% to less than 25% and increase rock frame modulus, especially shear modulus. This causes an increase of dry modulus with decreasing porosity associated with an increase in burial depth. However, water saturation effect on bulk modulus from dry state tends to be less dependent on porosity. This is consistently different from the sorting effect on the velocities observed on artificial samples made by sand and glass bean mixture (Zimmer, et al., 2002).

Introduction

Exploration and production of hydrocarbons in deepwater environments face complex technical and economic challenges. Deep-water reservoirs are located off the continental shelf with water depth ranging from 1000 m to more than 3000 m and are often associated with overpressure build up, early hydrocarbon charge and seal with retarded diagenesis. Deep-water sands maintain the shallow properties even at great depth such as near 18,000 ft. However, these weakly cemented sands with progressive compaction and cementation history are different from surface sediments. Current techniques based only on log and seismic data have proved insufficient and risky. We need to carefully investigate properties of the deep-sands and its interaction with fluid in order to build a foundation for seismic interpretation of rock and fluid properties.

Spencer *et al.* (1994) has showed that the acoustic properties of loose sands are controlled by grain contacts. Han (1994) has showed that the shear wave velocities are particularly sensitive to weak cementation. Han (1986), Marion, et. al, (1992) and Yin (1992) have systematically investigated porosity and velocity of mixture of loose sands and clays. The results have revealed gradual effect of clay content on porosity and velocity of shaly sands and sandy shales. Recently, Zimmer et. al.(2002) have studied velocities of packed sands, glass beads with different sorting combination. Data have shown significant pressure effect on velocities, and sorting effect on porosity. However, without sediment compaction, the general applicability of these results to deepwater rocks is questionable.

A suite of sand samples from the Gulf of Mexico was used for the study. Although samples are limited, current results are significant. In this abstract we summarize measured results and reveal the application for DHI techniques.

Texture of deep-water sands

Core samples come from two wells with the water depth of 4000 ft and two reservoir formations at depths of 12000 ft (shallow) and 17700 ft (deep) respectively. Porosity, bulk and grain density were measured as shown in Figure 1. Data shows that there are three groups of samples, separated by porosity: 8 shallow samples have very high porosity (VHP) of 30 to 35%; 17 deep samples have high porosity (HP) ranged from 24 to 30%. The low porosity samples are silt and shale, which is not focus for this study.

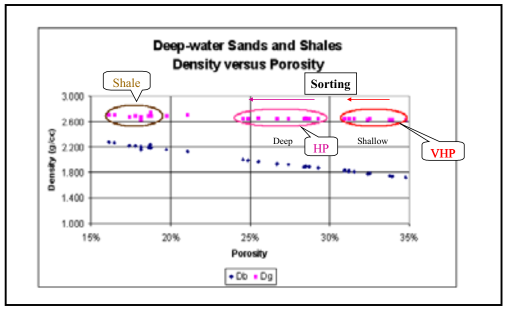

Figure 1. Dry-bulk and grain density as a function of porosity for the shallow and deep sands.

Grain density is 2.65 gm/cc, typical for clean sands. Measured gas permeability ranged from 100 to 1000 md. All the samples are relatively clean, fine grain sands as shown in Figure 2. Data reveal that the deep samples with low porosity suggest more compaction and cementation than those of the shallow samples. Range of porosity may relate to sorting.

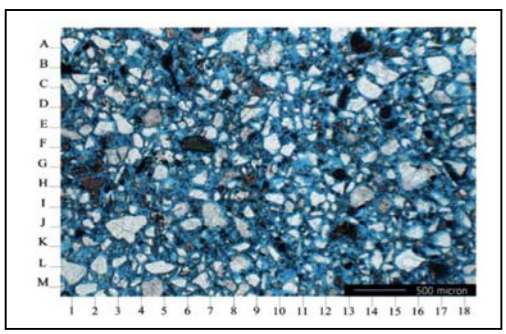

Figure 2. Thin section for a deep-water clean, unconsolidated fine sand sample.

Weakly cemented sands show a relatively large porosity compaction and hysteresis during pressure up-loading and downloading. Our data show that after conditioning pre-pressure to that in situ, pressure cycle effect is limited, especially on velocities.

Dry Velocities

We measured velocity on room-dried samples. Dry P- and S-wave velocity as function of pressure is shown in Figure 3. Both Vp and Vs tend to increase with increasing pressure. Velocity increment with pressure transits from high derivative at low pressure to low at high pressure.

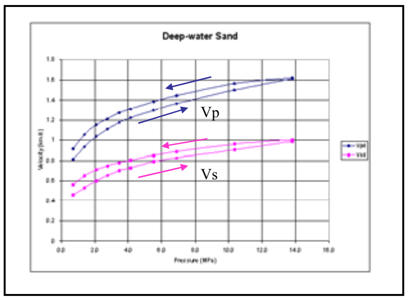

Figure 3. Dry Vp and Vs versus cycling pressure.

Pressure effect on velocities can be modeled by the power law

$$V_p = a * P^b \qquad (1)$$

where a is velocity at unit pressure and b is exponent.

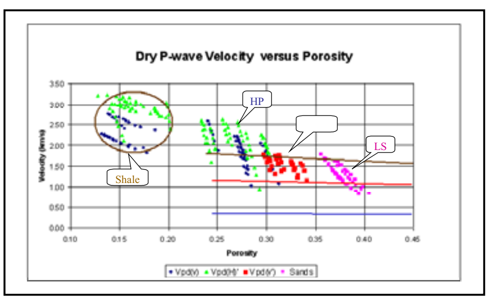

Figure 4a. Measured dry Vp versus porosity.

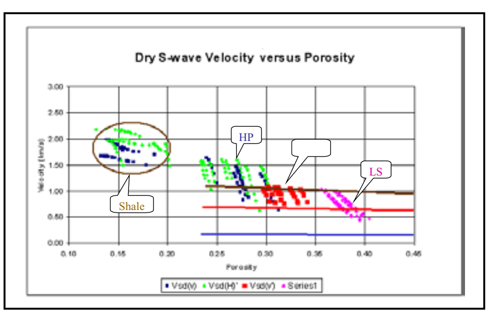

Figure 4b. Measured dry Vs versus porosity

Dry P- and S-wave velocity as function of porosity is shown in Figure 4a and 4b. Data also include repackaged loose sands (LS) and data lines cover porosity from 24 to 40% and differential pressures of 0.05, 3.45 and 20 MPa for loose sand and glass beans (LGS) (Zimmer et al., 2002). P- and S-wave velocities of shallow sands are significantly lower than those of deep-sands, although up-limit of pressure is 13.8 MPa for the shallow sands and 27.6 MPa for the deep sands. Both the Vp and Vs of the VHP sands data show remarkable consistency with data of the LS sands and the LGS lines. But porosity compaction of the naturally compacted VHP sands is much smaller than those of repackaged samples. It suggests that the VHP sands are in early compaction stage, velocity is not sensitive to porosity, similar to the LGS sands. However, the HP sands with more compaction (low porosity) in deep show significantly high velocity trend (take off the pressure effect). S-wave velocities of the VHP sands show less relevance to porosity and have value around 1.0 km/s, which is significantly less than those for deep sands. Significant separation in shear velocity of the VHP (shallow) from HP (deep) sands suggests that effects of compaction and cementation are mainly to stiffen sand rigidity for deep sands as validated in Figure 5.

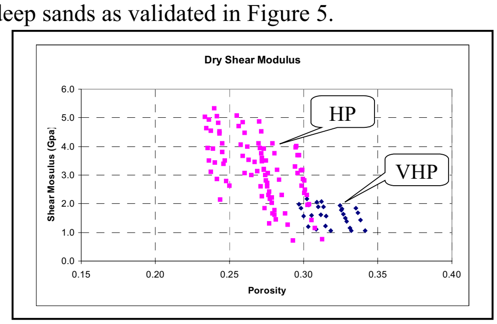

Figure 5. The HP (deep) sands have much higher shear modulus than those of the VHP (shallow) sands.

Measured data show that velocities of the VHP sands are less pressure dependent in comparison to those of the HP (deep) sands. That may not represent in situ condition but possibly induced by core damage during coring. With high pressure in situ, rock frame is stronger due to additional cementation (but less stressed). When pressure is released during coring, weak cement can be fractured due to extensional residual stress caused by relaxation of grain deformation. These induced fractures can cause high-pressure effect on velocities. But this is not the case for loose sand samples.

Brine Saturated Velocity

Water saturated sands and shales represent background properties of sedimentary basin. Understanding velocity in water-saturated sands will help to calibrate DHI in hydrocarbon reservoirs. We have measured velocities on brine-saturated samples to examine the fluid saturation effect.

First, we test fluid saturation effect on shear modulus. Data suggest that shear modulus remains a constant with water saturation for the sand samples as predicted by Gassmann's equation (1951). We have compared calculated P-wave velocity with measured data on water saturated sands. Calculated data are slightly lower than those measured. We conclude that velocity dispersion is minimal for those porous sands.

Fluid saturation effect is mainly on bulk modulus as shown in the simplified Gassmann's equation (Han and Batzle, 2004)

$$K_s = K_d + G(\phi) * K_f \qquad (2)$$

Here G (ϕ) is the gain function, which is a dry rock frame property. Figure 6 show dry and brine saturated bulk modulus at a high pressure.

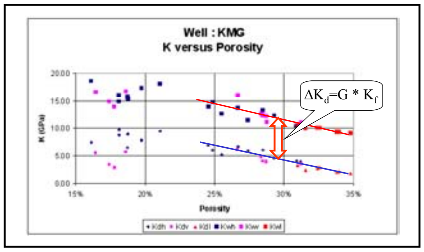

Figure 6. Dry and water saturated bulk modulus.

Data show dry bulk modulus increase significantly with decreasing porosity and fluid saturation effect causes a significant increase of bulk modulus. However, the increment of ΔK tends to be a constant and not sensitive to porosity. We can use increment in bulk modulus ΔK_d to calculate the gain function.

$$G(\phi) = \Delta K_d / K_f \qquad (3)$$

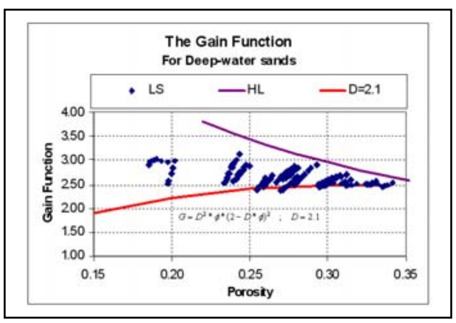

Figure 7. The gain function for deep-water sands

The gain function for the shallow and deep sands is shown in Figure 7. The gain function for deep-water unconsolidated sands is distributed in narrow range: high bound derived from the Reuss bound, and low bound around a constant of 2.5. The gain function decreases with increasing pressure and seems more sensitive to pressure for the HP sands (core damage effect?) than the VHP sands. The low bound of the gain function seems consistent with

$$G = D^2 * \phi * (2 - D * \phi)^2; \quad D = 2.1 \quad (4)$$

The gain function for the loose sands is significantly higher than those of consolidated reservoir sandstones (Han and Batzle 2003).

Brine saturated velocity show less dependence on porosity as shown in Figure 8. We have developed an empirical model based on Reuss bound to model velocities. The Reuss bound of P-wave modulus is

$$M_{Reuss} = \frac{M_0}{1 + (M_0 / K_f - 1) * \varphi} \qquad (5)$$

We can derive velocity as

$$V = (M/\rho)^{0.5} = \left(\left(\frac{M_0}{1 + n * \varphi}\right)/\rho\right)^{0.5} \qquad (6)$$

where M_0 is P-wave mineral modulus. We assume M_0 is equal to 83 GPa. The coefficient n is used to simulate different pressure effect on velocities. This formulation is purely empirical and may be used to describe velocity-pressure-porosity relations. The n value can be calibrated locally.

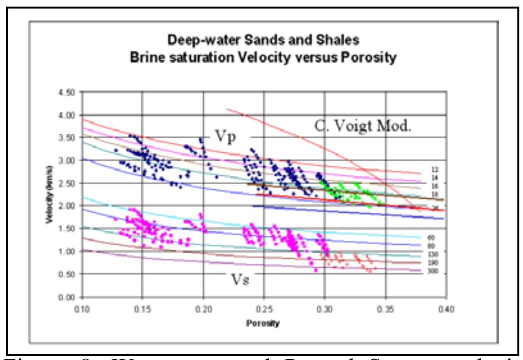

Figure 8. Water saturated P- and S-wave velocity versus porosity with modeled velocity-porosity trend.

Zimmer et. al.(2002) has used the modified Reuss model (Dvorkin and Nur, 1996) to simulate the sorting effect on dry velocity-porosity relation for packaged sand samples. We found that their method is not proper for our data because compaction effects also affect the dry velocity-porosity relation of deep-water sands. Dry velocities of deep-water sands are significantly higher than those of lab packed sands. However, water saturated data actually more or less follow the Reuss trend and is less dependent on porosity. Our data show that increment of bulk modulus caused by brine saturation for deep-water sands is almost a constant (constant gain function). Zimmer's data suggest that large water saturation effect associated with lower porosity sands may be due to lack of geological compaction.

P-wave and shear modulus relation

Dry P- and S-wave (shear) modulus are related to V_p/V_s ratio as follows:

$$\frac{M}{\mu}=\frac{V_p^2}{V_s^2} \qquad (8)$$

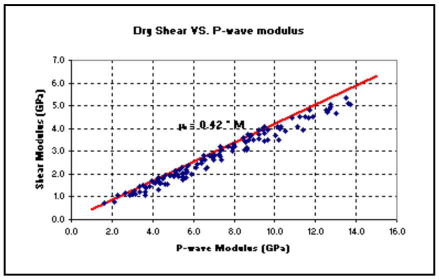

Figure 9. Shear and P-velocity modulus relation.

Figure 9 shows cross plot of shear and P-wave modulus. At high-pressure condition shear modulus is proportional to P-wave modulus as shown by red line in Figure 9 with ratio of 0.42. This ratio is equivalent to k/μ ratio of 1.05. This value tends to increase with decreasing pressure. This tight relationship of dry bulk and shear modulus provide internal constrain on fluid saturation effects on velocity.

Conclusion

Deep-water reservoir sands with unique sedimentary processes show progressive effect of compaction and cementation on porosity and frame velocities, which also incorporates the grain texture and fluid migration.

1. Compaction is a major driving force. Poor sorting will provide room for low initial packing porosity and more potential for continued compaction.
2. For deep-water sands, over pressure and early charge of hydrocarbon often block pore fluid flow to minimize the cementation effect.
3. With increasing depth and age, porosity reduces and dry velocity increase. Fluid saturation effect for deep-water sands can be described by the constant gain function of 2.5 and fluid modulus.
4. Velocity dispersion of deep-water sands is relatively small.
5. Compaction and weak cementation increases shear rigidity more than bulk modulus.
6. P and S-wave velocities of water sands tend to follow the Reuss trend and shows less dependence on porosity.
7. Pressure effect on velocity of VHP sands is relatively small. With weak cementation, pressure effect on velocity increases, which may be caused by core damage.
8. Dry shear modulus at high pressure is proportional to p-wave modulus.

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