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Seismic Characters of Pore Pressure Due to Smectite-to-illite Transition

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SUMMARY

In this study, we strive to understand unloading overpressure caused by smectite-to-illite by using shelf well log data from offshore Louisiana. Two trends of smectite-to-illite transition can be categorized, based on their signatures on the sonic travel time and density crossplot. It corresponds to the cases of fluid expansion and fluid escape during the smectite-to-illite. The fluid expansion can arise high magnitude overpressure and tends to happen when the upper formation has been undercompacted and has less sand content. For the fluid escape case, it has relative deeper overpressure onsets and its overlying formation is less undercompacted and has more sand content. From the synthetic seismic gathers, the two trends of smectite-to-illite have different seismic responses, and can be discerned with AVO technique.

Introduction

Overpressure tends to happen once the pore fluid cannot connect and communicate with the pore fluid at the shallow depth (e.g. sea bottom for offshore or water table for onshore). The retardation of fluid vertical and lateral movement is due to low fluid mobility (ratio of the rock permeability to the fluid viscosity), so permeability is the major factor controlling seal behavior. Shales constitute about 70% of sediment rocks, and are characterized by low permeability (from micro- to nano-darcy) due to its fine grain (< 4 μm) particles. Overpressure can occur in shales in the process of mechanical compaction, or expansion of pore fluid from physical or chemical changes, or both (Swarbrick and Osborne, 1998; Dutta, 2002; Mukerji *et al*., 2002). Some common mechanisms include: disequilibrium compaction (DC) or undercompaction, kerogen-to-gas, smectite-to-illite (S-to-I) or clay diagenesis, aquathermal expansion, tectonic uplift or erosion, hydrocarbon buoyancy, and vertical or lateral transfer.

In the northern Gulf of Mexico, overpressure exists extensively, can be caused by various mechanisms, such as disequilibrium compaction, which takes place in young sediments with fast sediment rate, and smectite-to-illite (Lahann *et al*., 2001; Katahara, 2003; Lahann and Swarbrick, 2011, Yu and Hilterman, 2014), which happens in smectite-rich shale at a temperature above 70 °C. In this study, we focus on understanding the process of smectite-to-illite from the wireline logging measured rock properties. Two trends of smectite-to-illite are categorized, fluid expansion and fluid loss, and we discuss the geological conditions to implement either of the transition.

Geophysical responses to overpressure

Velocity and density varies similarly with depth for overpressure caused by disequilibrium compaction. However, the trends of velocity and density deflect from certain depth for overpressure caused by unloading (Bowers, 2002; Ramdhan and Goulty, 2011). In Figure 1, the dashed lines represent normal cases when shales compacts under hydrostatic pressure, and solid curves represent the behaviors of velocity and density when disequilibrium compaction occurs (Figure 1a) and unloading happens (Figure 1b). This is because disequilibrium compaction develops during the compaction loading process. When the sediments buries with a rapid sediment rate, pore water does not have enough time to flow out due to poor permeability of the fine grain sediments, and density is retarded to increase and so is velocity.

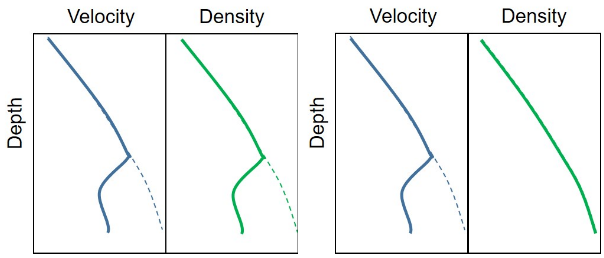

Figure 1 *Velocity and density vary with depth for a) disequilibrium compaction and b) unloading.*

Unloading mechanism (Figure 1b), which refers to the condition that effective stress (difference between overburden stress and pore pressure) decreases while pore pressure increases, resulting from some internal reasons, such as smectite-to-illite, kerogen-to-gas, etc. Because compaction is irreversible, bulk properties like porosity changes little while effective stress reduces. Even though effective stress decreases, increase of density indicates that chemical compaction or diagenesis occurs to decrease porosity. But velocity is more sensitive to the decrease of effective stress than density, because effective stress affects grain contacts and thus frame moduli.

Data and method

We utilize logging data from 320 wells from the shelf of Gulf of Mexico (GoM), offshore Louisiana. The data sets define sandstone as sediments with a shale volume less than 50% and shale with a shale volume larger than 50%. The logging data is averaged on 60m (200ft) intervals, including P-wave velocity, resistivity, and density for sand and shale zone; mud weights, temperature, and overpressure onsets are from the logging run. No high quality pressure measurement is available, so we approximate pore pressure by using mud weights. The hydrocarbon zones have been deleted, so we focus on the water-saturated sediments. Based on the work done by Verm *et al*. (1998), most wells contains overpressure mechanisms of smectite-to-illite in the north of the study area, and several wells contains disequilibrium compaction as the major overpressure mechanism.

Based on velocity and density trends with depth, we sort 37 wells with relatively good-quality data containing overpressure caused by unloading. Specifically, this unloading is caused by smectite-to-illite instead of gas generation, because there is little source rock reported in Pliocene, Miocene and Oligocene formations, where are generally shallower than 5000 m within this area. And smectite-illite transition is common in the GoM, since GoM contains large amounts of smectite-rich shale (expanding clays).

Figure 2 plots density in g/cc against sonic travel time in us/ft of shale from the 37 wells, and depths are color-coded. Two empirical compaction trends of smectite and illite are added in dark and light blue as references (Dutta, 2002; Lahann *et al*., 2001; Gutierrez *et al*., 2006). At shallow depths above 3000m, most of data fall near the Smectite line, while at deep depths below 3000m, most of shale data fall near the illite line. So smectite-rich shale converts to illite-rich shale with increasing depth, and most of the transitions happen between 2500 m and 3500m. However, it is difficult to tell how the transition shifts the rock properties from the smectite line to illite line.

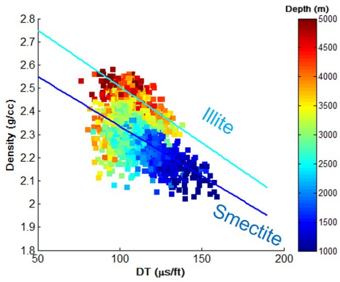

Figure 2 *Shale density against sonic travel time (DT) for 37 unloading wells, and depths are color-coded. Dark and light blue lines are reference loading curves of smectite and illite.*

Two trends of smectite-to-illite

When temperature satisfies, the smectite reacts with ion of potassium, to generate illite and quartz along with free water:

$$\text{Smectite+K-feldspar} \rightarrow \text{Illite+Quartz+nH}_2\text{O} .$$

Due to fine grain and large surface areas, smectite plays the role of load-bearing material. When it dissolves, it leaves a void that resembles a crack. The surrounding grains will tend to collapse into the void, and thereby compress the pore water as well as increasing pore pressure. Since overburden stress transfers from the fine grains to the pore fluid, it is a load transfer process. If the released fluid cannot escape, the rock is overpressured and close to suspension status. If the pore water escapes, the rotation and sliding of the surrounding grains quite possibly occur to achieve the new balance between porosity and effective stress.

By observing individual well data on the density-slowness crossplot, two trends of illitization are categorized: one corresponds to fluid expansion (Figure 3a), and the other corresponds to fluid escape (Figure 3b). Fluid expansion has more slowness change and little density change, while fluid escape has more density change and little slowness change. We hypothesize that trend I tends to takes place, if smectite-rich shales have been overpressured due to disequilibrium compaction, since fluid is hard to escape due to poor connectivity. The overpressure onset (caused by DC) is shallower than the onset of smectite-to-illite. And trend II tends to occur, if smectite-rich shales is normally compacted, and fluid may totally escape due to good pore connectivity. The overpressure onset is deeper than the onset of smectite-to-illite. The dashed lines in Figure 3 indicate some mixed results of fluid expansion and escape.

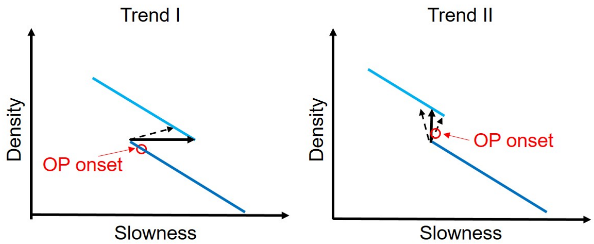

Figure 3 *Sketches of two trends of smectite-to-illite: a) trend I and b) trend II. The solid arrows denote the end-member cases of fluid expansion and fluid loss. The dashed arrows denote some possible mixed cases.*

Single well data and synthetic AVO

Figure 4 demonstrates density and slowness of two single wells containing two trends of smectite-to-illite transition. Well 6841 in the left panel has an overpressure onset of 2600m, and Well 4545 in the right panel has an onset at 2908m. By checking the complete well data, above the overpressure onsets, the sand volume of 12% in average in Well 6841 is much less than that of 55% in Well 4545. These suggest that Well 6841 contains more undercompacted formations and less pore connectivity than Well 4545.

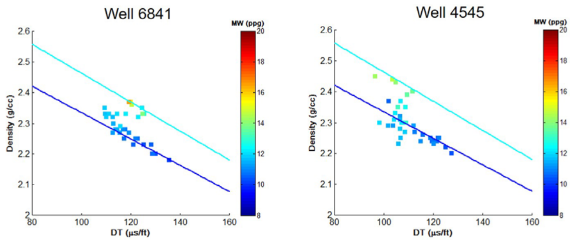

Figure 4 *Density against sonic travel time (DT) for wells with a) trend I smectite-to-illite and b) trend II smectite-to-illite. Mud weights in ppg are color-coded.*

We utilize the 200ft interval density and velocity to generate synthetic seismogram. Mud rock line (Castagna *et al*., 1985) is used to estimate the S-wave velocity, and the anisotropy are neglected. With the P-impedance, we calculate reflection coefficients with Zoeppritz equation. A Ricker wavelet of a central frequency 25Hz is used to convolve with the reflectivities. Figure 5 demonstrates the synthetic AVO gathers, where the horizontal axis is incident angles from 0 to 30°, and vertical axis accords with the well log data sampling. Class IV AVO is identified since negative amplitude decrease with offsets, at the onset of trend I S-to-I with fluid expansion unloading. Class II AVO marks the onset of trend II S-to-I with fluid loss. Class I AVO can be expected for illite compaction because of P-impedance increase. So two trends of illitization have distinct AVO signatures.

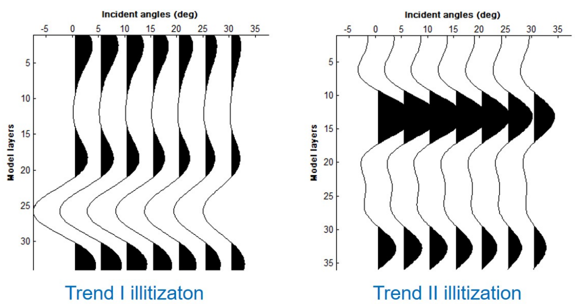

Figure 5 *Synthetic AVO gathers for a) trend I and b) trend II smectite-to-illite.*

Conclusions

Two trends of smectite-to-illite can be observed from the wells with unloading overpressure. Density changes little while velocity decreases for the trend I because of fluid expansion, and density changes more than velocity during the trend II smectite-to-illite because of fluid loss. The formations above trend I tends to have lower permeability or higher clay content than that above trend II. The two trends of smectite-to-illite have distinct seismic signatures, and we may develop some quantitative interpretation relating to fluid pressure and volume during the transition in the future.

Acknowledgements

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