Overpressure prediction using converted mode reflections from base of salt

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Summary

Using Zoeppritz and elastic wave equation models, examples are presented demonstrating the use of P-wave, S-wave, and mode converted amplitudes for overpressure prediction at base of salt. Base of salt primary and mode converted reflections exhibit similar increases in amplitude as subsalt sediments become overpressured. This characteristic behavior may be used to distinguish overpressuring from amplitude anomalies due to fluid and lithologic effects.

Introduction

Overpressured sediments are frequently encountered below salt bodies in the Gulf of Mexico and have caused drilling problems and dangerous well blowouts. Detailed seismic velocity analysis has been employed since the 1960s to predict overpressured sediments prior to drilling by detection of P-wave velocity inversions (Pennebaker, 1968; Aud, 1976; Reynolds, 1970; Keyser et al., 1991; Best et al., 1990). However, in the subsalt case, this technique is not effective because inverted velocities are common at base of salt and not necessarily indicative of high pore pressures. An alternative method of predicting overpressure through seismic analysis is needed in this environment.

Amplitude analysis of both primary and converted mode reflections at base of salt may offer a more definitive means of identifying overpressure directly below the salt body. Differences in the sensitivity of P- and S-wave amplitudes may be utilized to constrain rock properties more accurately than depending only on P-wave amplitudes for information. In particular, S-waves depend more directly on shear modulus than P-waves and are sensitive to lithologic variations such as high porosity. Thus, overpressured sediments which are accompanied by high porosity may be detectable by anomalous behavior of S-wave amplitudes. Mode conversions have the potential to be especially useful for predicting overpressured conditions at base of salt because at this interface they are strong and easily identifiable based on their moveout and AVO (Ogilvie and Purnell, 1996).

Methodology

Zoeppritz and 2D elastic wave equation models were used to test whether changes in V_p and V_s associated with an overpressured zone directly beneath salt show an anomalous AVO or stacked amplitude response which could be used to distinguish these sediments from normally pressured ones. Accurate V_p, V_s, and densities necessary to characterize overpressured sediments in the models could not be directly obtained. This may be related to the hazards involved in drilling through overpressured sediments and the limitations in recording low S-wave wave velocities which may characterize overpressured zones. Log observations with full-waveform acoustic logs require S wave velocities of the sediments to be greater than the compressional velocity of the drilling mud (Tatham and McCormack, 1991). In place of direct in situ measurements of V_p and V_s for overpressured formations, lab measurements at various differential pressures (Domenico, 1984; Domenico, 1977) and VSP data at various depths were used (Lash, 1980).

Modeling results based on lab and field data were similar and results from VSP data are excerpted below. In order to use VSP data from a normally pressured area to approximate overpressured sediments, it was necessary to assume that overpressured sediments do not undergo normal compaction. Their levels of porosity and fluid saturation are similar to those of shallow sediments (Plumley, 1980). Based on this assumption, V_p and V_s from shallow sediments were used to approximate an overpressured zone. Sediments at 1000 and 2000 ft (305 m and 610 m) represent overpressured zones with differential pressures of 500 and 1070 psi respectively. Depths were converted to differential pressures assuming a normal differential pressure gradient of 0.535 psi/ft (Plumley, 1980). These overpressured sediments were compared with sediments at 9000 ft (2743 m) or differential pressure of 5000 psi, characterizing normally pressured sediments.

Velocities from lab and field data and densities calculated using Gardner's relation comprised the input for Zoeppritz and elastic modeling codes. In order for the elastic synthetics to be comparable to the Zoeppritz models, only a single interface was modeled. Primary and shear sources were used to generate P-wave and S-wave sections with PS and SP mode conversions respectively. Elastic P-wave and S-wave shot gathers generated from the modeling code were processed separately for stacking converted and unconverted reflections. In particular, NMO velocities for mode conversions were calculated as a simple average of the P- and S-wave velocities.

Overpressure response experiments

The Zoeppritz equations (Aki and Richards, 1980) were used to calculate reflection coefficients and energy at base of salt for PP, PS, SS, and SP modes. Velocities and densities from VSP data were selected to simulate three pressure regimes appearing in Figure 1.

Overpressuring causes reflection coefficients for all modes

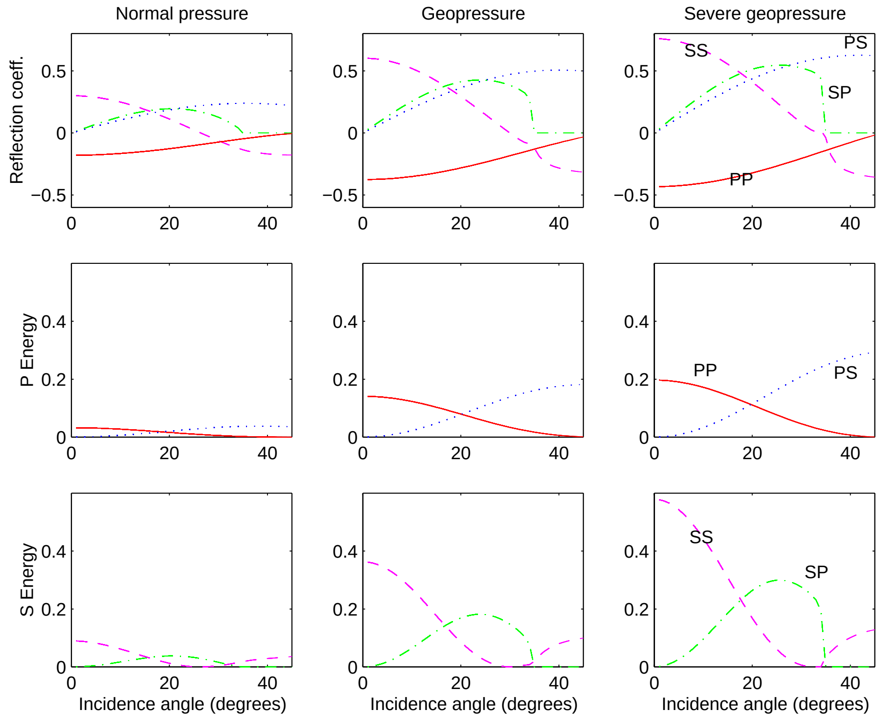

Fig. 1: Reflection coefficients and energy calculated for PP, PS, SS, and SP modes at base of salt. Velocities and densities for sands beneath the salt body simulate various pressure conditions: normal pressure (5000 psi), overpressure (1100 psi), and more severe overpressure (500 psi). All modes show increases in reflection coefficients and energy as overpressuring increases.

to increase. These increases are accentuated in the energy plots which show energy of overpressured sediments between three and eight times larger than normally pressured sediments. The increase in reflection strength is especially prominent for the SS and SP modes which are sensitive to larger drops in V_s than V_p with overpressuring. The overall rise in reflection strength for all modes is a consequence of lower V_p and V_s which create a greater impedance contrast at the base of salt.

While overpressuring creates significant changes in the energy of reflected modes, it does not alter reflection coefficient trends or polarity. In contrast to a gas sand with a class III AVO anomaly which causes the PP reflection coefficient to increase anomalously with offset, overpressured sands simply scale all reflection coefficients. Thus AVO analysis may provide ambiguous results for distinguishing overpressured sediments.

Given the lack of distinct AVO anomalies and the increase in reflection strength with overpressuring, overpressured sediments may be more confidently detected on stacked P-wave and converted mode seismic sections. According to the energy plots in Figure 1, the overpressured sediments should have significantly higher stacked amplitudes than normally pressured sediments. To assess whether such a bright spot would be visually obvious on a stacked seismic section, elastic models were created using the same parameters as the Zoeppritz models.

The three pressure regimes simulated in the Zoeppritz models are combined in stacked seismic sections for the PP, PS, SS, and SP base of salt reflection (Figures 2- 5). Maximum trough amplitudes are tracked above the traces which represent, from left to right, overpressured sediments, normally pressured sediments, and more severely overpressured sediments. Overpressuring causes similar increases in amplitude for all reflection modes: amplitudes double and triple in magnitude for the overpressured and more severely overpressured sediments. These increases are large enough to be discernible on the stacked sections.

Gas sand response experiment

For primary and mode converted reflections at base of salt to have diagnostic value for predicting overpressure, their response must be different than the seismic response due to fluid and other lithologic anomalies. While a base of salt bright spot on a P-wave section may indicate overpressuring, it may also be caused by gas (Figure 6). Mode converted reflections may be used to distinguish a gas-related amplitude anomaly on a P-wave section from one due to overpressuring. In the case of overpressuring, the converted mode section shows a bright spot (Figures 3- 5). In contrast, mode conversions do not increase in amplitude in the presence of gas.

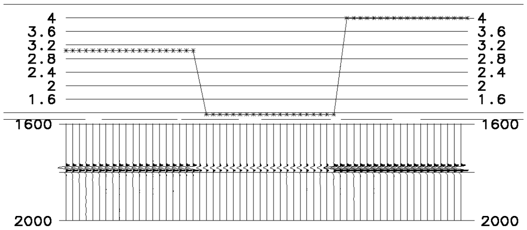

Fig. 2: PP base of salt reflection for overpressured sediments (left), normally pressured sediments (center), and more severely overpressured sediments (right). Maximum trough amplitudes are plotted above the traces. Overpressured and severely overpressured sediments show amplitudes two and 3 times higher than normally pressured sediments.

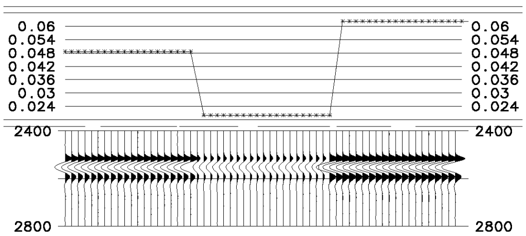

Fig. 3: PS base of salt reflection for overpressured sediments (left), normally pressured sediments (center), and more severely overpressured sediments (right).

Discussion

The advantage of this technique over traditional P-wave velocity analysis for overpressure detection is that it can be applied directly to the base of salt reflection. By utilizing both P-wave and S-wave reflection amplitudes to constrain rock properties, this technique does not rely upon velocity inversions. Further, it is possible to distinguish overpressured sediments from gas sands which have similar amplitude responses on a P-wave section. Converted modes provide the additional criterion to make this distinction. Strong mode conversions may be evident in conventional P wave data to make amplitude analysis of shear events possible. Multicomponent data expands the application of this technique by eliminating the need for a strong impedance contrast.

There are several theoretical and practical considerations which limit the application of this method:

- Lithologic conditions other than overpressuring may cause P-wave and converted mode amplitudes to respond in a similar manner.
- To be seismically detectable, overpressured sediments must have preserved a substantial amount of their porosity. If differential pressures exceeded 2000 psi at any time during burial, porosity is substantially reduced so that changes in pressure conditions only weakly change the elastic properties of the formation.

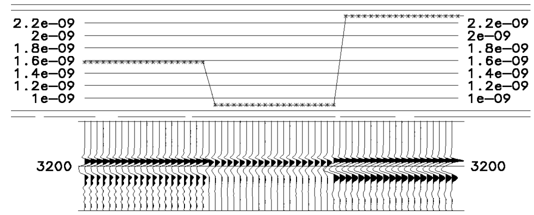

Fig. 4: SS base of salt reflection for overpressured sediments (left), normally pressured sediments (center), and more severely overpressured sediments (right).

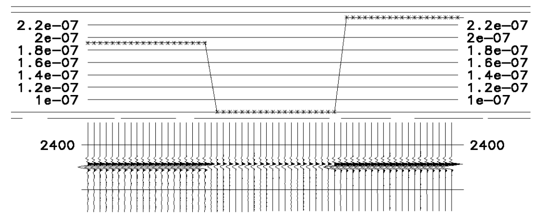

Fig. 5: SP base of salt reflection for overpressured sediments (left), normally pressured sediments (center), and more severely overpressured sediments (right).

- Overpressuring generated at depth (through clay transformation for example) after porosity has been substantially reduced is difficult to detect seismically because it is not accompanied by changes in the properties of the rock matrix.
- Elastic models constructed for this study are very simple and do not take into account the effects of geometry, overburden, and tuning which may cause amplitude anomalies unrelated to changes in rock properties.
- The identification of overpressured sediments may require that normally pressured sediments be present to serve as a comparison.

Conclusions

Zoeppritz and elastic wave equations models were used to examine the effects of varying subsalt velocities and densities in a manner consistent with changing pressure conditions. Amplitude analysis of P-wave base of salt reflections in conjunction with converted mode base of salt reflections offers an alternative method to extract information about pressure conditions beneath salt which would not otherwise be possible with P-wave data alone. In particular, we have shown that the presence of both strong P-wave and converted mode base of salt reflections may indicate anomalously high pressure conditions. While there are numerous other factors which may cause similar amplitude responses, prospect-specific elastic modeling may be used to eliminate some of these factors and uncover the effect of rock properties on seismic amplitudes.

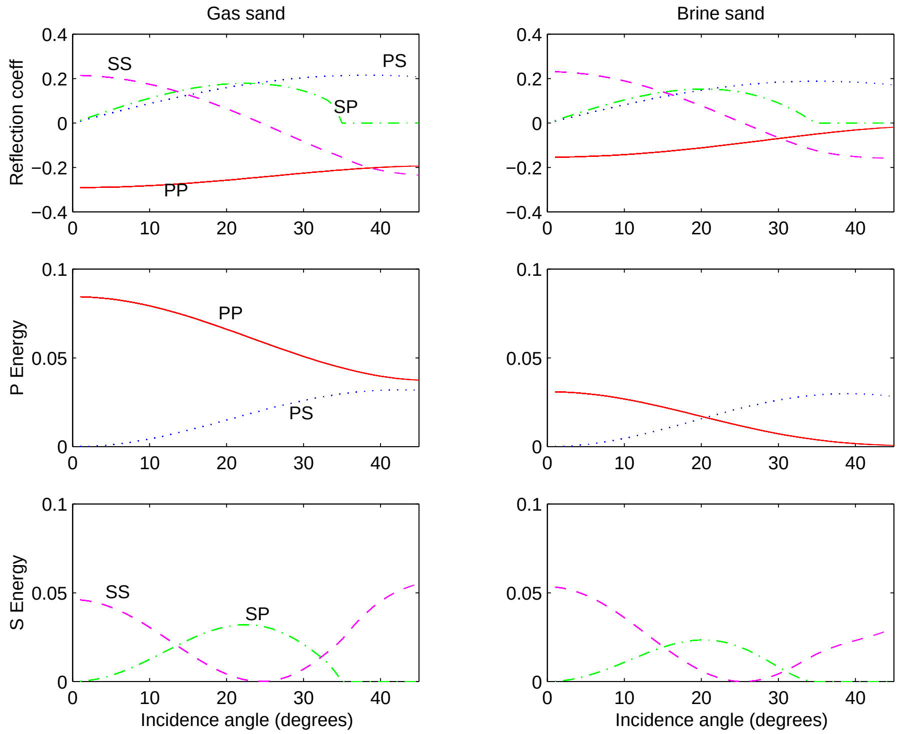

Fig. 6: Reflection coefficients and energy calculated for PP, PS, SS, and SP modes for salt over gas and brine sand reflections. A gas sand is distinguished from a brine sand on the basis of a strong PP reflection. Unlike the example shown in Figure 1, other modes do not show significant changes in response to the presence of gas.

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