

Sub-salt overpressure detection before drilling using wave equation migration technologies

Morgan P. Brown* and Joseph H. Higginbotham, Wave Imaging Technology Inc.

Summary

Unexpected zones of high pore pressure present the most significant risk—financial and health—to sub-salt drilling operations in the Gulf of Mexico. Below-trend P-wave velocity is an imperfect, but oft-used pore pressure attribute. We present two technologies to measure velocity under salt. The first infers sub-salt sediment velocity from normalized base of salt (BoS) amplitude. The second computes time-shift focusing information from a wave equation depth migration (WEM) and converts the focusing information to deviations from the migration velocity. Both techniques are tested successfully on the BP Velocity Benchmark Model, providing quasi-independent verification of the low-velocity zones under salt.

Introduction

Sub-salt oil deposits likely represent the USA's most significant remaining conventional oil resource base. However, a variety of geotechnical risks and engineering challenges make recovery of this resource anything but conventional. Chief among the geophysical risks: high pore pressures directly under salt that pose a safety and drilling hazard. Even if a well is not "killed" or sidetracked due to pressure issues, an unplanned casing string may doom the completion of the 30,000-foot holes which have become more common. With sub-salt Gulf of Mexico drilling costs regularly exceeding \$100 million, operators have a keen financial interest in mitigating the added costs of encountering unexpected sub-salt overpressure.

Techniques which use walkaway vertical seismic profile (VSP) data have shown value in predicting pore pressure ahead of the bit under salt (Leaney et al., 2004). The disadvantages of these techniques are a) high acquisition costs and lost rig time, and b) a commitment to the existing drill path, unless a sidetrack is made. Sub-salt pore pressure prediction over a wide area, performed *before* the well spuds, is therefore a very desirable complement to VSP-based technologies.

In this abstract, we introduce a hierarchy of cost-effective, pre-drill seismic imaging technologies for the detection of sub-salt overpressure. These innovations complement the more expensive VSP-driven overpressure detection schemes, and can be used to reconnoiter many potential drill paths, months before the well spuds. Both techniques use below-trend P-wave velocity as a proxy for overpressure. While the connection between velocity and overpressure is far from definitive, velocity is nonetheless

the most commonly-used wide-scale overpressure attribute (e.g., Dutta and Khazanehdari, 2006).

We prove the efficacy of our two-stage sub-salt overpressure detection methodology on the well-known BP velocity benchmark model, which contains sub-salt low-velocity zones that were likely intended as zones of overpressure.

Method

When salt forms a geometric "four-way" closure, pore pressure may rise inside sediments truncating against the base of salt. Dipping layers exacerbate the effect. Seismic overpressure detection schemes do not measure pore pressure directly. Low effective stress inside overpressured sediments normally lowers the sound velocity (and more generally, raises the V_p/V_s ratio). Therefore, below-trend sound velocity measurements from reflection seismic data have been used successfully as a proxy for overpressure detection (e.g., Dutta and Khazanehdari, 2006). Figure 1 illustrates the pore pressure problem under salt—low relative velocities against the base of salt are the trouble zones.

Under salt, however, conventional velocity estimation technology which has aided pre-drill pore pressure estimation away from salt may not succeed. Wave equation depth imaging (WEM) technology has shown considerable value in imaging beneath salt, but until recently, this technology could not be used to produce velocity estimates, and thus, overpressure estimates. While many recent WEM velocity estimation technologies have been recently introduced (for example: Flidner and Bevc, 2008; Wang et al., 2008; Vigh and Starr, 2008), no obvious winner has emerged at the time of writing.

In this paper, we introduce a hierarchical two-step approach using a suite of WEM technologies for pre-drill overpressure estimation. The two methods may be used independently or preferably, in conjunction with one another, providing quasi-independent measurements of seismic velocity under salt.

The first technology uses full-wave simulation, followed by wave equation depth migration (WEM) to correct—more rigorously than raytrace solutions—the base of salt reflection for overburden effects. To first order, BoS amplitude is controlled primarily by the velocity of the sub-salt sediments. The radical focusing and defocusing induced by top of salt rugosity and other overburden effects leaves a strong imprint on the BoS amplitude. By

Wave Equation Migration Velocity Focusing Analysis

correcting for these effects, we make the BoS amplitude more lithologically interpretable. The first technique runs rapidly, and thus is suitable for wide-scale reconnaissance. Moreover, the correction factor can be applied any available depth image—in cases where multi-client data is required, no expensive tape copy is needed.

The second technology measures sub-salt velocity with a previously introduced WEM focusing analysis technique (Brown et al., 2008; Higginbotham et al., 2008). It enables the direct calculation of velocity under salt, rather than a relative measure of velocity. Used in conjunction with the first technology, the second approach provides a quasi-independent confirmation of overpressure.

Wave Equation Normalization of BoS Amplitudes

For a P-wave reflected at normal incidence from an interface, the reflection amplitude is controlled by the P-wave velocity and density in the two layers. The velocity and density of salt are well known (about 4,500 m/sec and 2.17 g/cm³). If the density of the sub-salt sediments is assumed constant, then the reflection amplitude is controlled mainly by the velocity of the sub-salt sediments. High reflection amplitude on the base of salt therefore implies a low sub-salt velocity, which implies high pore pressure.

Unfortunately, base of salt amplitudes are not so easily interpretable. Complex salt geometry causes the image to focus and defocus, independent of any pore pressure effects. We use a two stage procedure to correct the base of salt amplitude for these illumination effects, and therefore make the amplitude a valid proxy for pore pressure:

- Construct a migration velocity model which contains a salt body and a “trend” velocity below salt (see Figure 2), then solve the acoustic wave equation to simulate shot records. By migrating the simulated shot records, we obtain an image of the base of salt (overlay in Figure 2). We then convert the image amplitude to a normalization function (bottom panel of Figure 2).
- Robustly divide the image of the field data by this normalization function. After normalization, the high amplitudes on the base of salt are conformal with the low velocity anomalies (see Figure 3).

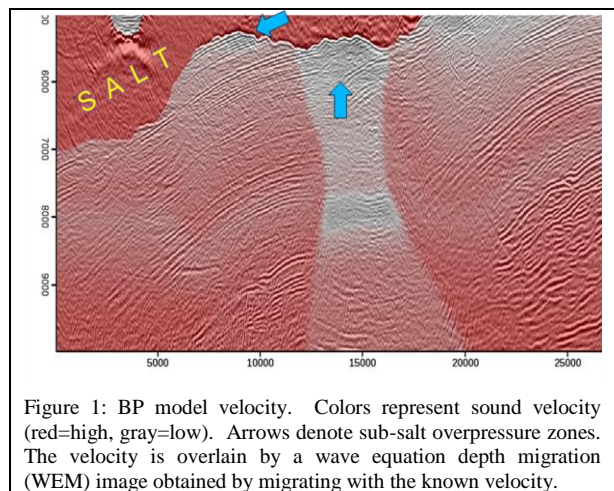
This methodology can be run relatively rapidly, in a wide-area reconnaissance mode. Moreover, no seismic data is required, reducing costs. The normalization function can be computed and applied to any existing seismic image.

Wave Equation Migration Velocity Focusing Analysis

We use a shot record WEM algorithm and the time-shift imaging condition to produce estimates of velocity error. Image focusing as a function of a migration time-shift parameter is measured at many (x,y) locations. The optimal time shift is related to a root-mean-square velocity error. The theory underlying the conversion of optimal focusing time shift into velocity error was given by Higginbotham et al. (2008). Because our method uses WEM to obtain the velocity information, it handles the wavefield focusing caused by salt naturally.

We test potential drill paths using our Migration Velocity Focusing Analysis technique. The data are migrated with the “best” migration velocity—usually obtained by multiple iterations of reflection tomography and one or more “salt flood” sequences. Such a migration velocity might resemble Figure 2—well-defined above-salt velocity and salt geometry, but no velocity structure below salt. The analysis requires the presence of sub-salt reflectors.

We tested four potential drill paths on the BP Velocity Benchmark model (see Figure 4), migrating the data with the migration velocity shown in Figure 2. Migration Velocity Focusing Analysis produces energy clouds in the depth/velocity plane; the peaks of maximum energy represent the measured velocity. We infer an overpressure risk at drilling locations where the known velocity is lower than the migration velocity. Notice that at two such locations (9,000 m and 12,250 m), the analysis indicates a velocity lower than the migration velocity (implying overpressure) and consistent with the known velocity (indicating accuracy).



Wave Equation Migration Velocity Focusing Analysis

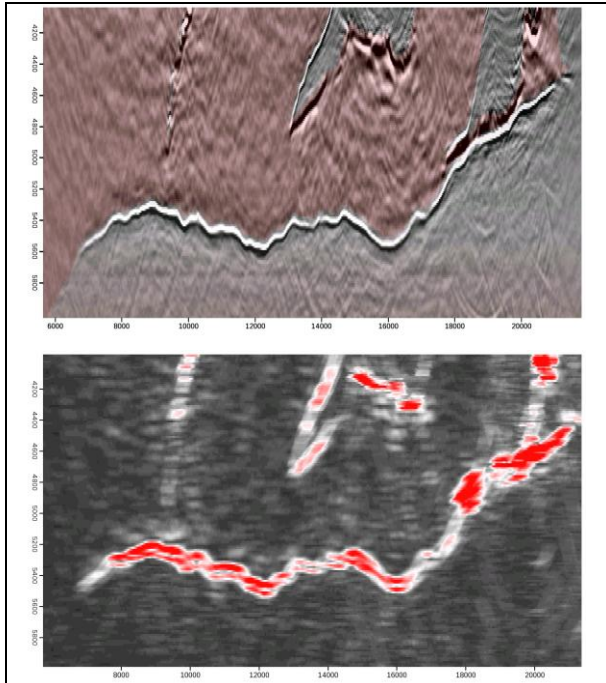


Figure 2: (Top) Image of 400 shot records modeled in a “best guess” velocity consisting of a known sediment velocity to the base of salt, known salt geometry, and a $v(z)$ trend inserted below the salt. Reflection strength on the base of salt in this image is primarily dependent on the overburden illumination effects, but not on sub-salt velocity. (Bottom) We seek to normalize the image of the field data by these illumination effects. The bottom panel shows how image amplitudes are conditioned to produce a robust normalization function. Notice the obvious variations in field strength along the BoS.

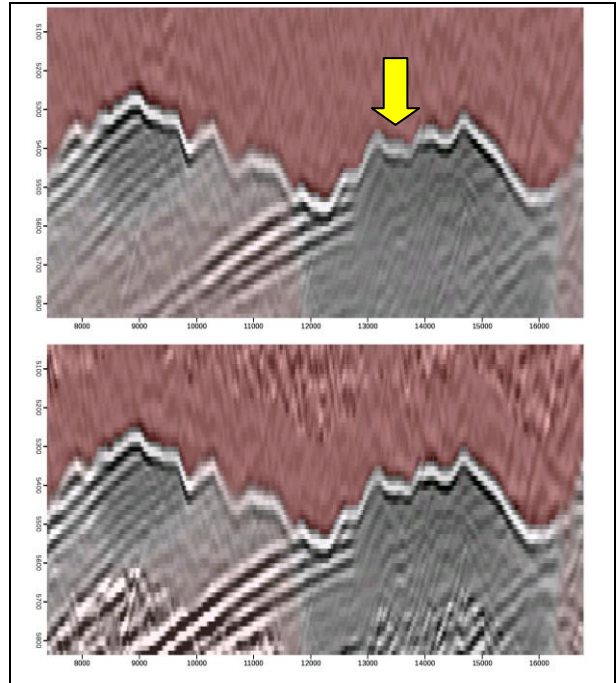
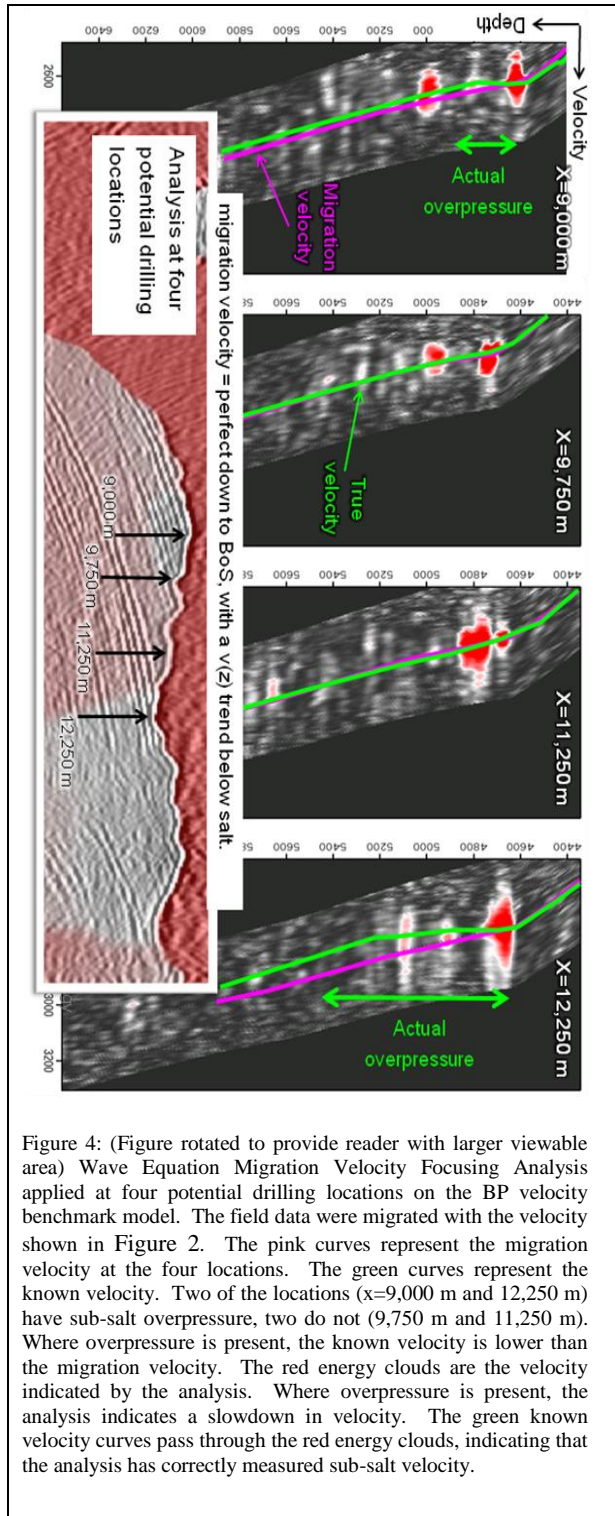


Figure 3: Images of field data around base of salt reflection before (top) and after (bottom) normalization by full-wave illumination function. Yellow arrow denotes region with overpressure which was “missed”. After normalization, this region has been boosted in amplitude and the reflection strength as a whole is conformal to the low velocity anomalies.

Wave Equation Migration Velocity Focusing Analysis



Conclusions

We proposed a two-stage approach to the pre-drill detection of overpressure beneath the base of salt by using sub-salt seismic velocity as an overpressure proxy. This methodology complements VSP-based overpressure detection technologies. The first stage of our approach uses the relative base of salt reflection amplitude as a velocity proxy, with a crucial step of simulation and imaging to normalize base of salt amplitude for salt-related focusing effects. The second stage uses a relationship between WEM time shift and migration velocity error to directly measure the velocity in sub-salt layers. Because it uses WEM, this technology does not run into the same troubles as techniques which work well *above* salt, such as ray-based reflection tomography. We successfully tested the two-stage overpressure detection methodology on the BP Velocity Benchmark model.