

## Subsalt overpressure detection with wave equation depth imaging can save time, cost

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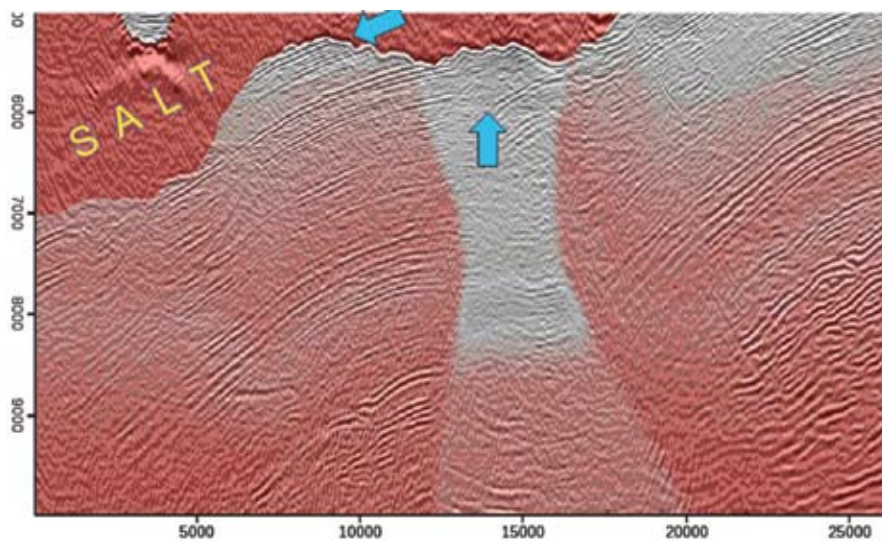
**S**ubsalt oil deposits likely represent the most significant remaining conventional oil resource base for the US. However, a variety of geotechnical risks and engineering challenges make recovery of this resource anything but conventional. Chief among the geophysical risks: high pore pressures directly under salt that pose a safety and drilling hazard. Even if a well is not “killed” due to pressure issues, an unplanned casing string may doom the completion of a 30,000-ft (9,144 m) hole, a depth relatively common for subsalt wells. With subsalt Gulf of Mexico (GoM) drilling costs regularly exceeding \$100 million, operators have a keen financial interest in mitigating the added costs of an unexpected encounter with subsalt overpressure.

Techniques that use walkaway vertical seismic profile (VSP) data have shown value in predicting pore pressure ahead of the bit. The disadvantages of these techniques include high cost, both direct (more than \$1 million) and in lost rig time (several days), and limited options, short of sidetracking from an obvious problem area. Subsalt pore pressure prediction over a wide area, performed before the well spuds is a desirable complement to VSP-based technologies.

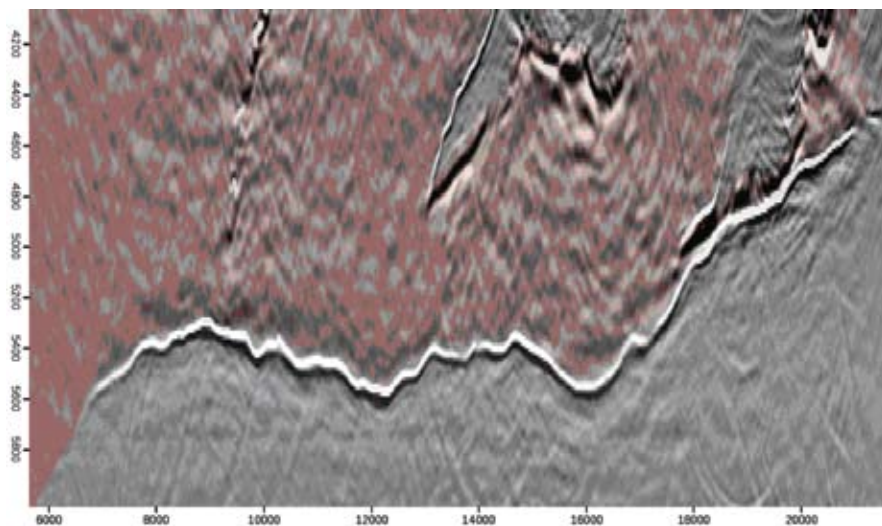
There is a hierarchy of cost-effective, pre-drill seismic imaging technologies for the detection of subsalt overpressure. These complement the more expensive VSP-driven overpressure detection methods, and can be used to reconnoiter many potential drill paths before the well spuds.

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. It runs rapidly, and thus is suitable for wide-scale reconnaissance. Moreover, the correction factor can be applied to any or all images available – no field tape copy or reprocessing required.

The second technology uses a patent-



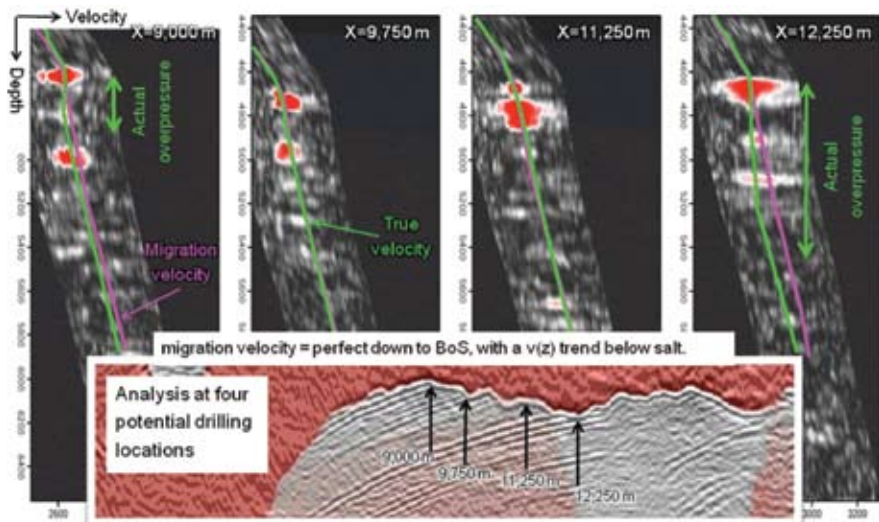
This illustrates the pore pressure problem under salt — low relative velocities against the base of salt are the trouble zones. Synthetic subsalt seismic example provided by BP. Colors represent sound velocity (red=high, gray=low). Velocity within salt is high (4,500 m/sec). Arrows denote zones under the salt with high pore pressure, manifested by below-trend velocity. The velocity is overlain by a wave equation depth migration (WEM) image obtained by migrating with the known velocity.



A migration velocity model which contains a salt body and a “trend” velocity below salt. 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 subsalt velocity. We seek to normalize the image of the field data by these illumination effects.

pending focusing analysis technique for WEM to measure subsalt velocity. It enables direct calculation of velocity rather than a rel-

ative measure of velocity. Used with full-wave simulation, this approach provides a quasi-independent overpressure confirmation.



Migration velocity might be well-defined above salt velocity and salt geometry. Wave Equation Migration Velocity Focusing Analysis applied at four potential drilling locations on the BP velocity benchmark model. The pink curves represent the migration velocity at the four locations. The green curves represent the known velocity. Two of the locations ( $x=9,000$  m and  $12,250$  m, or  $29,527$  ft and  $40,190$  ft) have subsalt overpressure, two do not ( $9,750$  m and  $11,250$  m, or  $31,988$  ft and  $36,909$  ft). Where overpressure is present, the known velocity is lower than the migration velocity. The red energy clouds are the velocity indicated by the analysis. Where overpressure is present, the analysis indicates a slowdown in velocity. The green known velocity curves pass through the red energy clouds, indicating that the analysis has correctly measured subsalt velocity.

**Method**

When salt forms a geometric “four-way” closure, pore pressure rises inside sediments truncating against the base of salt. Dipping layers exacerbate the effect. Seismic overpressure detection does not measure pore pressure directly. Low effective stress inside overpressured sediments generally lowers the sound velocity (and more generally, raises the ratio of compression wave velocity to shear wave velocity, the “VP/VS ratio”). Therefore, below-trend sound velocity measurements (usually obtained by reflection tomography) have been used successfully as a proxy for overpressure detection. Under salt, however, conventional velocity estimation technology may not succeed. Wave equation depth imaging (WEM) has shown value in imaging beneath salt, but until recently, this technology could not be used to produce velocity estimates, and thus, overpressure estimates.

**Wave equation normalization of base of salt amplitudes**

For a P-wave reflected at normal incidence from an interface, 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/cm<sup>3</sup>). If the density of the subsalt sediments is assumed constant, then the reflection amplitude is controlled mainly by the velocity of the subsalt sediments. High reflection amplitude on the base of salt therefore implies a low subsalt velocity, which implies high pore pressure.

Unfortunately, base of salt amplitudes are not easily interpretable. Complex salt geometry causes the image to focus and defocus, independent of any pore pressure effects. A two-stage procedure corrects the base of salt amplitude for these illumination effects to 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, and then solve the acoustic wave equation to simulate shot records. Migrating the simulated shot records gives an image of the base of salt. Then, convert the image amplitude to a normalization function. 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.

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

**WEM velocity focusing analysis**

A shot record WEM algorithm and the time-shift imaging condition 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 using a patent-pending algorithm. Because this uses WEM to obtain the velocity information, it handles the wavefield focusing caused by salt naturally.

Potential drill paths can be tested using Migration Velocity Focusing Analysis. 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 be well-defined above salt velocity and salt geometry, but no velocity structure below salt. The analysis requires the presence of subsalt reflectors.

Four potential drill paths were tested on the BP Velocity Benchmark model, migrating the data with the migration velocity. Migration Velocity Focusing Analysis produces energy clouds in the depth/velocity plane; the peaks of maximum energy represent the measured velocity. An overpressure risk at drilling locations is inferred where the known velocity is lower than the migration velocity. Notice that at two such locations ( $9,000$  m and  $12,250$  m or  $29,527$  ft and  $41,010$  ft), the analysis indicates a velocity lower than the migration velocity (implying overpressure) and consistent with the known velocity (indicating accuracy).

This system proposes a two-stage approach to the pre-drill detection of overpressure beneath the base of salt by using subsalt seismic velocity as an overpressure proxy. This normally costs less than \$1 million and complements more expensive VSP-based overpressure detection. The first stage 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 patent-pending relationship between WEM time shift and velocity error to measure directly the velocity in subsalt layers. Because it uses WEM, this method does not run into the same troubles as techniques which work well above salt, such as ray-based reflection tomography. The two-stage overpressure detection method tested successfully on the BP Velocity Benchmark model. ◉