Coming to terms with subsalt

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With offshore Brazil, the Gulf of Mexico (GoM) and Africa all containing subsalt discoveries, operators today are facing some of the world's most complex geologies but not always with the most effective exploration tools.

While there have undoubtedly been marked developments in seismic technologies over the last few years, seismic continues to struggle in the imaging and interpretation of salt body geometries, in creating clear subsalt images, and in generating a robust earth model around salt bodies.

Seismic and reverse time migration provide a good definition of top-salt interfaces (where a large portion of the seismic energy is reflected due to the high seismic impedance contrast) but are often only able to provide a partial definition of salt flanks and the base of salt and subsalt.

All too often the seismic wavefield in base and subsalt is distorted, illumination is irregular and velocity distribution is complex. Furthermore, the highly irregular (rugose) structures and many interchanging layers of salt and other rock types generate complex wave propagation, multiple internal reflections and scattering. This leads to incomplete ray distribution, a suboptimal velocity model and limited seismic depth imaging.

3-d csem inversion overlain with 3-d seismic

FIGURE 1. The 3-D CSEM inversion is overlain with 3-D seismic. Black lines represent the salt top and base interpreted from seismic. The 3-D CSEM inversion result showed a salt root that was not previously mapped. (Source: EMGS)

A complementary exploration technology—3-D controlled-source electromagnetic (CSEM) acquisition—is providing crucial additional structural information to seismic interpretation and delivering salt bodies for improved seismic imaging and velocity models. In many cases, these techniques also can be applicable to sub-basalt imaging as well.

Growing influence

In CSEM surveys, a powerful horizontal electric dipole is towed about 30 m (98 ft) above the seafloor with the dipole source transmitting a carefully designed low-frequency electromagnetic (EM) signal into the subsurface. Grids of seabed receivers measure the energy propagated through the sea and the subsurface. Through a numerical inversion process, a 3-D resistivity volume of the subsurface is constructed. CSEM can then be used to improve seismic imaging by incorporating such resistivity information into the velocity models.

How can CSEM complement seismic as well as generate information from subsalt that seismic can't? First, since salt is very resistive in contrast to sediments, EM methods are well suited for imaging subsalt sediment structures. The EM energy is also rapidly attenuated in conductive sediments but is attenuated less and propagates faster in more resistive layers such as basement structures. An intelligent, well-constrained attribute correlation between inverted resistivity and compressional velocity in sediments can be used to refine the seismic velocity model and produce better seismic imaging for basement structures.

Second, CSEM measures different rock properties to seismic and is subsequently unperturbed by the scatter and refraction that causes seismic difficulties. Through EM, the base of the salt is accurately picked out in depth by the change of resistance and applied to the velocity model to improve the quality of the migrated image. Low-frequency magnetotelluric data also have a large penetration depth and are able to delineate deep basement structures.

The result is that both the structural information and the resistivity distribution recovered through EM methods can be used to update and improve the velocity model for seismic depth imaging.

salt body

FIGURE 2. Based on CSEM data it is obvious that the salt body extends further to the side and that the base of the salt is a large 'drop' shape. (Source: EMGS)

CSEM offshore Mexico

One example of how CSEM is complementing seismic is a 3-D CSEM inversion survey recently acquired in the deepwater GoM by EMGS for PEMEX. In this case, conducting a resistivity survey through EM and then incorporating the reinterpreted geobodies back into the seismic via migration reaped dividends.

The survey targeted a salt diapir with potential hydrocarbon reservoirs at the flanks where 3-D seismic was available and where the approximate location of the salt diapirs were known. There was a need to identify amplitude vs. offset anomalies and provide an improved structural definition of the target area.

Through the acquired CSEM data along with additional data such as well logs and previously acquired CSEM, a robust initial resistivity model for 3-D CSEM anisotropic inversion was established. The model was defined by a vertical and horizontal resistivity grid with salt bodies based on seismic data interpretation included in the initial model to enhance convergence in inversion.

Figure 1 shows the result of the 3-D CSEM inversion overlain with 3-D seismic with the vertical resistivity component shown and the black lines representing the salt top and base interpreted from seismic. The 3-D CSEM inversion result showed a salt root that was not previously mapped based on seismic data alone.

In addition, the geometry of the salt flank was seen to vary in places from the original interpretation, changing the prospectivity of the salt flank. In Figure 1, for example, it's clear that the overhang of the salt is larger.

A horizontal cross-section of the inversion results also indicated a connection in the northeast between the two main salt bodies in the survey area—separate bodies, according to the original seismic interpretation. The resistivity within the central salt body as well as between the different salt bodies in the survey area also varied significantly, helping the operator better understand the composition and internal structure of the salt—higher clay content in pinch-out structures and in the salt root, for example.

Figure 2 illustrates how the larger resistivity associated with the salt body extends further to the side and that the base of the salt is associated with a large "drop" shape rather than the simple convex shape indicated by seismic.

anisotropic 3-d csem vertical resistivity

FIGURE 3. Anisotropic 3-D CSEM vertical resistivity without regularizing the anisotropy ratio (on the left) is compared to a sample using the anisotropy regularization function (on the right). Black lines show the seismic interpretation and indicate how the additional information contributed by the regularization leads to an improved structural reconstruction. (Source: EMGS)

Based on the combined CSEM and seismic data, a more appropriate interpretation seems to be the green line. Where the seismic data are strong (such as on the left), the resistivity information confirms the seismic interpretation. Where the seismic data are poor, EM provides an improved interpretation. It's through the cross-referencing and interconnectivity between the two datasets that a complete picture of the subsurface can be generated.

Since salt is expected to be nearly electrically isotropic on the length-scales of the measurement and to constrain the range of anisotropy, it was also necessary to introduce a new regularization function to mitigate the sensitivity difference between horizontal and vertical resistivity components. This was achieved through the inclusion of *a priori* information about anisotropy.

Figure 3 compares anisotropic 3-D CSEM vertical resistivity resulting from inversion without regularizing the anisotropy ratio (on the left) and using the anisotropy regularization function (on the right). In this case, the black lines represent the salt top and base interpreted from seismic, with the results indicating how the additional information contributed by the regularization leads to an improved structural reconstruction without sensitivity artifacts in the vertical resistivity model. It is this regularization that ensures that the salt body geometry is reconstructed realistically in both the vertical and horizontal components of resistivity, thereby improving the definition of geometrical details.

The imaging results from the GoM demonstrated that CSEM data have the potential to enhance interpretation in complex salt-affected areas, with the incorporation of the resistivity data into the seismic velocity model-building workflow enhancing the resolution of seismic subsalt imaging. In such cases, a 5% to 10% improvement in the imaging of the structure post-migration can have a huge impact on future drilling and appraisal decisions and the accompanying costs.

Power of integration

The industry is still at an early stage in the full integration of seismic and EM data. Yet even where geobodies are being reinterpreted and incorporated into the seismic migration, powerful changes in the geometries of the fault lines are already being seen.

What is clear is that by interconnecting and cross-referencing between seismic and EM and by fostering a closer integration between different measurements, a more complete picture of subsalt surfaces can be revealed.