LUKE TWIGGER, CGG, UK, EXAMINES RECENT ADVANCES IN SEISMIC TECHNOLOGY THAT REDUCE SUBSALT RISK.

Oil and gas exploration, especially in areas of complex geology such as salt provinces, is a risky and expensive endeavour. Gaining access to the best data allows truly informed decision-making when it comes to taking acreage and planning drill campaigns. There has been a step-change in seismic techniques within the past few years, with innovations such as broadband, full azimuth and anisotropy at the heart of new tailored solutions. Increased levels of precision and richer subsurface information from new surveys have prompted the introduction of extra levels of detail within new algorithms and models, making previous simplifications obsolete. All of these advances are available on a proprietary basis, but can also be found in current CGG multi-client surveys.

Continuous exploration innovation

The need for high-quality seismic images in areas of complex and challenging geology has motivated many breakthroughs in acquisition and processing. Along with continued advances in each individual domain, there are also synergistic multi-disciplinary

SEEING SAFELY THROUGH TO THE SUBSALT

solutions, which couple innovative acquisition configurations with custom subsurface imaging techniques, such as the broadband marine seismic solution, BroadSeis™.

This solution utilises Sercel Sentinel® streamers towed in a unique variable-depth profile to provide ghost notch diversity. Broadband deghosting algorithms exploit this diversity to remove ghost effects from the data pre-stack and provide up to 6 octaves of bandwidth. High-fidelity, low-frequency data provide deeper penetration for the clear imaging of deep targets, as well as providing more quantitative reservoir attributes.

Bandwidth is just part of the story. In areas of complex salt geometry, conventional narrow-azimuth (NAZ) or wide-azimuth (WAZ) acquisition cannot always provide the necessary subsalt illumination to successfully perform tomographic velocity model building. This can make it difficult to image features such as steeply dipping salt flanks and subsalt three-way closures.

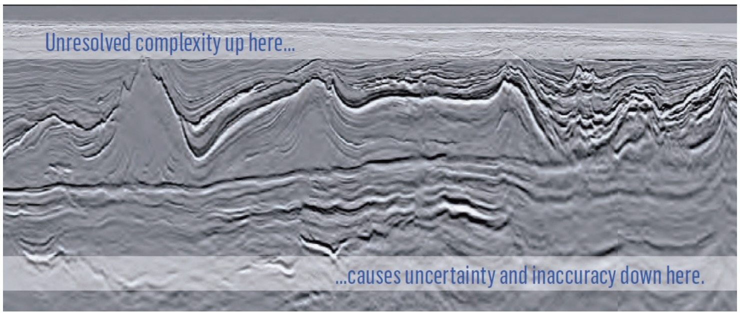

Figure 1. *Before interpreting and exploring the deep areas of interest, shallow complexity must be understood and compensated for.*

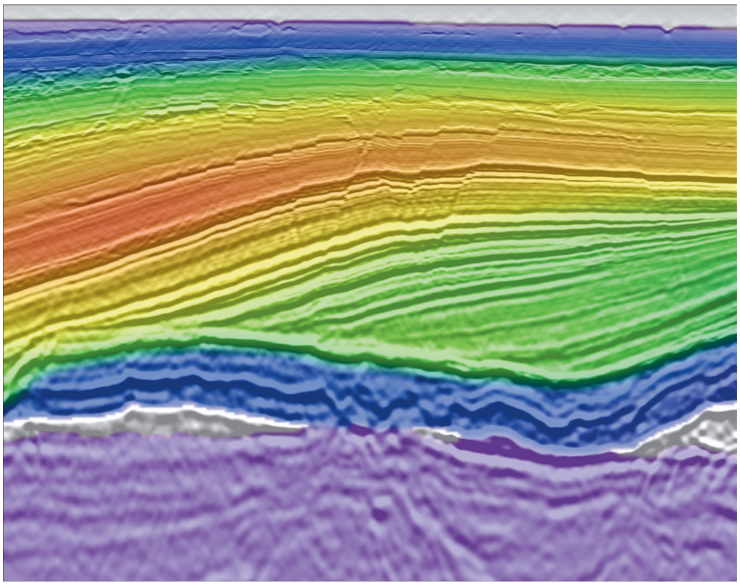

Figure 2. *Full Waveform Inversion performed on this BroadSeis survey in the Kwanza Basin provided detailed models of velocity and anisotropy, such as this line through the epsilon model.*

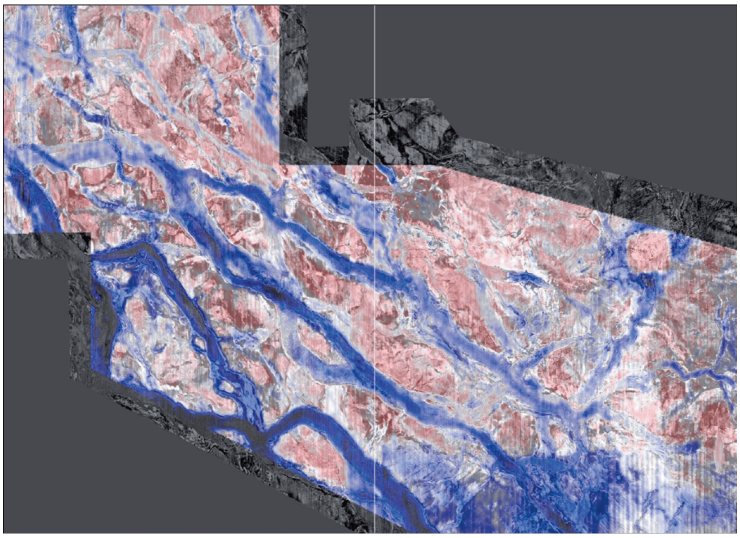

Figure 3. *Dip Constrained Tomography provides detailed 3D velocity models of shallow channels, such as these observed in the CGG Cornerstone survey in the North Sea.*

Combining multiple NAZ and/or WAZ surveys with different shooting directions provides incremental improvements, but this approach is still short on azimuthal coverage and offset range. Tailored surveys using full-azimuth, ultra-long offset and broadband acquisition techniques, such as StagSeis™, are designed to address these challenges.

Meanwhile, reverse time migration (RTM) has matured over the past decade from an academic tool into a production workhorse. Its capabilities have grown dramatically during this time, alongside available computer power. Initial versions of RTM could only output stack data, while migrated gathers are in routine use nowadays. The upper frequency limit continues to rise, from as low as 10 Hz on early results to 70 Hz or more on current projects. Following the recent adoption of broadband deghosting, such operations can now be directly applied within the migration algorithm. Some of the latest research involves proactively using multiples to image the subsurface and enhance conventional images using primaries only, rather than working to remove them prior to migration.

Attention to detail

As seismic acquisition, processing and imaging techniques continue to advance, higher levels of detail and precision are not only made possible but demanded. Old assumptions and shortcuts are no longer necessary or valid. Geophysical properties such as anisotropy require accurate models of a growing number of parameters to fully describe.

The effects of anisotropy, which describes how seismic velocities vary with direction, have been included in seismic processing and imaging for many years. However, simpler forms of anisotropy such as VTI (for horizontal layering) or TTI (for tilted layering) are insufficient to fully describe seismic wave propagation. Tilted, fractured bedding is a potential further complication. In cases such as the Perdido Fold Belt, tilted orthorhombic modelling and imaging provide more accurate images.

Historically, salt bodies have been generalised as homogenous with constant seismic velocity. As salt geometries are imaged with higher levels of accuracy, the effects of internal salt structure can no longer be ignored. The effects of heterogeneities, such as sediment inclusions and interbedded and layered evaporites, have an appreciable impact on the imaging of subsalt events. Ignoring these variations during velocity model building can lead to the degradation of base of salt and subsalt imaging. CGG has developed a range of tools for proper derivation of salt velocity structures, including a unique reflectivity inversion scheme designed for areas with sparsely distributed sediment inclusions within the salt, which has been used to great effect in the Gulf of Mexico.

Resolve the shallow to truly see the deep

Many areas of the world feature highly variable near-surface conditions and complex shallow geology. These cause rapid variation in seismic velocities and related attributes, which can be difficult to model using conventional techniques. Unresolved complexity in the shallow areas causes uncertainty and inaccuracy deeper down, where hydrocarbon targets are often located. CGG has a range of advanced tools to create detailed models of these, which help reconstruct accurate images of the previously obscured targets beneath.

Full waveform inversion (FWI) is a versatile method well suited to many of these challenges, from permafrost to shallow gas clouds and supra-salt carapaces. It updates the velocity model by minimising the mismatch between observed seismic data and synthetic data from the model. FWI can use every aspect of the recorded seismic wavefield, including parts, which are often removed during conventional processing such as direct arrivals. The results are of very high resolution and can potentially be as spatially well resolved as the seismic images.

While most FWI algorithms take anisotropy into account when performing the modelling, it has been common practice to update vertical velocity only, keeping anisotropic parameters fixed during the inversion. The latest FWI methods from CGG now perform a joint update of both velocity and epsilon, thus bringing the benefits of FWI to the anisotropy model. The CGG Kwanza Basin BroadSeis survey, on the front cover of this issue of *Oilfield Technology*, made good use of this technology to clearly image the Kwanza Basin's shallow channels. In fact, the near surface of many marine surveys feature channels, such as large-scale Quaternary channel systems in the North Sea or the dramatic paleo-canyons found in the Para-Maranhao Basin, offshore Brazil. Until recently, the most common method for resolving this was simple 1D updating based on the depth distortion of a horizon picked below the channels. This has now been superceded by dip constrained tomography and FWI when modelling such channels.

Identify, map and mitigate geohazard risk

The greater attention to detail in geophysical models also provides a valuable benefit when it comes to identifying and locating geohazards, such as overpressure zones or gas hydrates. Such features leave a characteristic signature within seismic data. The same advanced tools used routinely for seismic processing and imaging prove equally adept at detecting and mapping these hazardous geological phenomena.

Zones of overpressured sediments with abnormally high pore-fluid pressures can be found directly beneath salt bodies, such as those in the Gulf of Mexico. Such overpressure zones are typically associated with anomalously low seismic velocities, which can be modelled using a technique such as CGG's Salt Exit Velocity Inversion (SEVI). Accurate knowledge of the salt exit velocities also enables the calculation of effective stress, to aid well design.

Gas hydrates can be found in the shallow sediments of many marine areas. They are characterised by strong seismic reflectivity, due to higher-velocity hydrates overlying a lower-velocity free gas interval. Such features strongly attenuate seismic amplitudes, causing dim zones to occur beneath them. Tomographic amplitude inversion is used to derive and validate geologically meaningful Q models. These can be input to Q PSDM to compensate for amplitude and phase distortions within the dim zones. They also provide valuable information on the location and extent of gas hydrate pockets within the survey area.

Case study Brazil

The first case study comes from the Santos Basin, offshore Brazil. This area is well known for its complex salt features. Due to its rugosity and burial beneath a series of reflectors that mimics its undulations, the top of salt can be difficult to interpret. Furthermore, the Santos Basin salt is largely composed of layered evaporites. Not only do these evaporites display significant velocity variation, they are relatively high-amplitude and a source of multiples. An added complication is the presence of volcanic intrusives found primarily in the post-salt section.

An integrated suite of technologies was required to successfully image the pre-salt targets in this area, starting with BroadSeis

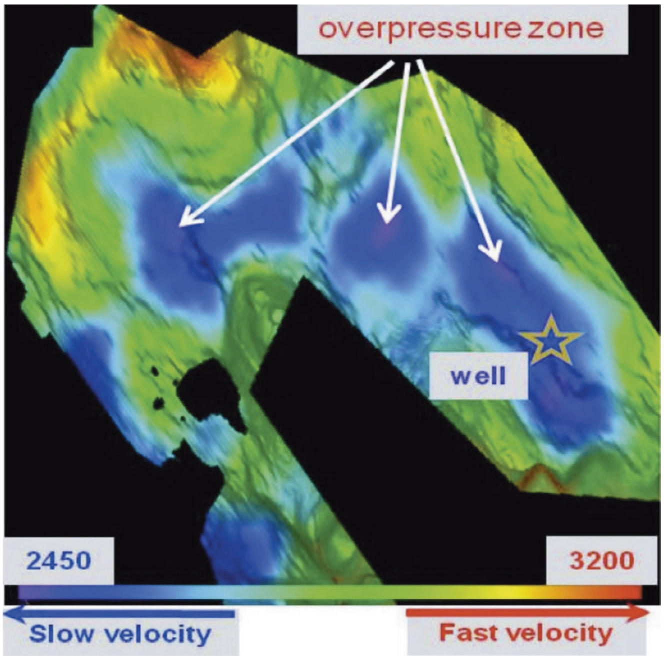

Figure 4. *The detailed models computed using CGG's Salt Exit Velocity Inversion technique not only improve subsalt imaging, but also provide valuable warning signs for overpressure zones.*

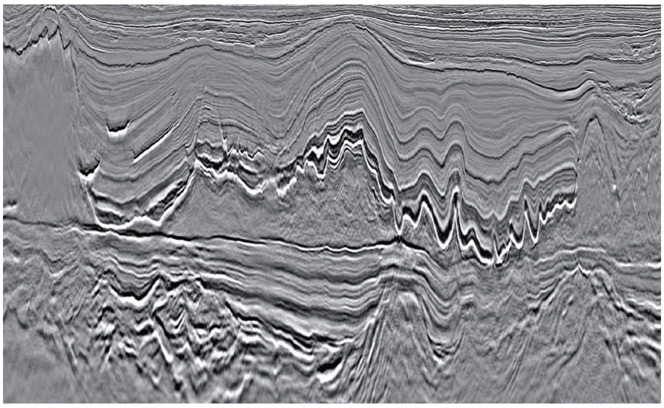

Figure 5. *BroadSeis broadband seismic provides fresh insight to the productive basins offshore Brazil including Santos, Espirito Santo and the Campos Basin shown here.*

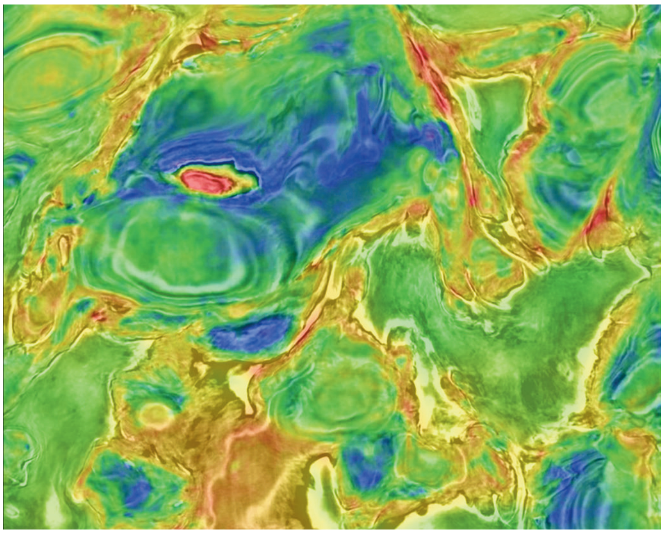

Figure 6. *This depth slice from the Keathley Canyon area of the Gulf of Mexico shows the stunning velocity detail picked out by Full Waveform Inversion making full use of the ultra-long offsets of up to 18 km present in the CGG StagSeis data.*

acquisition. The variable-depth streamer arrangement and broadband deghosting provided low frequencies to penetrate the salt and illuminate the deep targets, along with high frequencies to facilitate a detailed interpretation of the rapidly varying shallow section.

High-resolution tomography was used to derive detailed models of the velocity and TTI anisotropy in the post-salt sedimentary areas. A sequence of iterative scenario tests, evaluated based on pre-salt imaging quality, was used to simultaneously derive the structure of the volcanics, top of salt and base of salt. Tomography was used to perform intra-salt and pre-salt velocity updates. RTM proved invaluable throughout the workflow, both for evaluation of each scenario test and providing 3D angle gathers to the tomography.

This CGG multi-client project integrated cutting-edge acquisition, locally adapted and advanced imaging algorithms and experienced staff to provide the best yet seen images of the *Santos Basin*.

Case study Gulf of Mexico

The second case study is taken from the Gulf of Mexico. Its chief innovation is the StagSeis solution, a multiple-vessel staggered-acquisition configuration, combined with a suite of purpose-built sophisticated subsurface imaging algorithms unique to the company. As in the Santos Basin, the survey also utilised BroadSeis broadband acquisition. Full azimuthal coverage was provided out to 10 km, with ultra-long offsets as great as 18 km. The ultra-long offsets provided invaluable information for the FWI stage and enable derivation of a detailed shallow velocity model.

The main geological challenge is the complex salt geometry hindering the illumination of deeper targets, which StagSeis was specifically designed to solve. The Gulf of Mexico has other geological features related to salt, such as narrow mini-basins and sediment carapace, which require attention to detail and specialist techniques to correctly model and image such as FWI.

The StagSeis multi-client dataset is an innovative tailored solution. It provides hitherto unreached levels of illumination, which give the best yet images of the deep subsalt regions.

Conclusion

Modern exploration challenges require multi-faceted solutions, which combine complementary technologies from many disciplines including equipment, acquisition, imaging and interpretation. This is especially true in environments of complex geology such as deep subsalt areas. Regional challenges can be overcome with local expertise leveraging tailored acquisition configurations matched to specific subsurface imaging technologies and workflows. In the rapidly evolving world of seismic technology, the benefits of such solutions are evident in every image.

Acknowledgements

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