DRIVING THE FUTURE OF SEISMIC EXPLORATION

Risto Siliqi, CGG, France, explains how the largest multi-client ocean bottom node survey in the UK Central North Sea will deliver unprecedented seismic data quality to identify remaining reservoir potential.

With the exponential increases in computing power and the recent development of data-driven processing technologies raising the bar for quantitative imaging of complex subsurface geologies, acquiring seismic data with ocean bottom nodes (OBNs) offers the right solution to match current industry expectations.

Addressing imaging challenges

Building highly precise images of the subsurface requires illumination of the geological detail. How accurate these images are depends on the survey design and layout of both the seismic sources generating the acoustic signals and the receivers capturing the encoded information carried back from the propagation of the seismic wavefield throughout the subsurface.

Each ‘pixel’ of the image is built by collecting all the reflected energy produced at that location by the seismic acquisition. To be able to evaluate this reflected energy, it is first necessary to estimate the parameters characterising the subsurface. This important imaging step is known as velocity model building. Today, as a result of considerable progress in computing power, it is possible to accurately invert the recorded wavefields for a subsurface model that is sufficiently detailed to simulate data, which closely match the recorded seismic data.

This data-driven approach, known as full-waveform inversion (FWI), goes beyond techniques that use only the seismic data arrival times (traveltime kinematics), by incorporating more information provided by the amplitude and phase of the seismic waveform. FWI is considered to be the most promising data-driven tool for building velocity models without the intrinsic bias of subjective structural interpretations. Many successful applications of FWI have been reported to update the model of shallow sediments, gas pockets and mud volcanoes (e.g. offshore Brazil, the Gulf of Mexico and the North Sea). All emphasise the need for data with a superior signal-to-noise ratio for the low frequencies, as the latter are critical for the FWI modelling process.

Reverse time migration (RTM) is commonly viewed as the current state-of-the-art for imaging. Its basic aim is to accurately evaluate the image 'pixels' by searching for reflection events, thus correlating the wavefield simulated by the forward-propagation of the source signal with the wavefield obtained through the backward-propagation of the measured data using the same velocity model. However, when the geology is highly complex, and even when RTM is applied, the images often suffer from migration artifacts (artificial noise), uneven amplitudes, and limited resolution. Least-squares RTM (LSRTM) was proposed to overcome these issues. Unlike RTM, LSRTM is a data-driven imaging approach: the final calculated subsurface image represents the reflectivity model, which can accurately regenerate seismic data matching the actual recorded seismic traces through forward modelling. This closed-loop approach ensures self-consistency and mitigates any artificial noise or amplitude effects that do not correspond to the data recorded in the field.

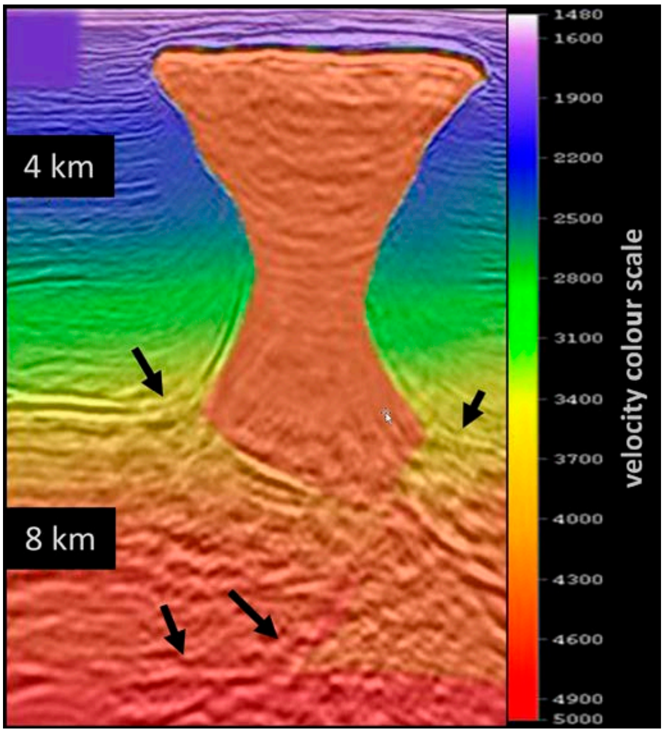

Figure 1. *Marine towed-streamer data. Conventional velocity model superimposed with the generated image. Arrows indicate unresolved imaging challenges.*

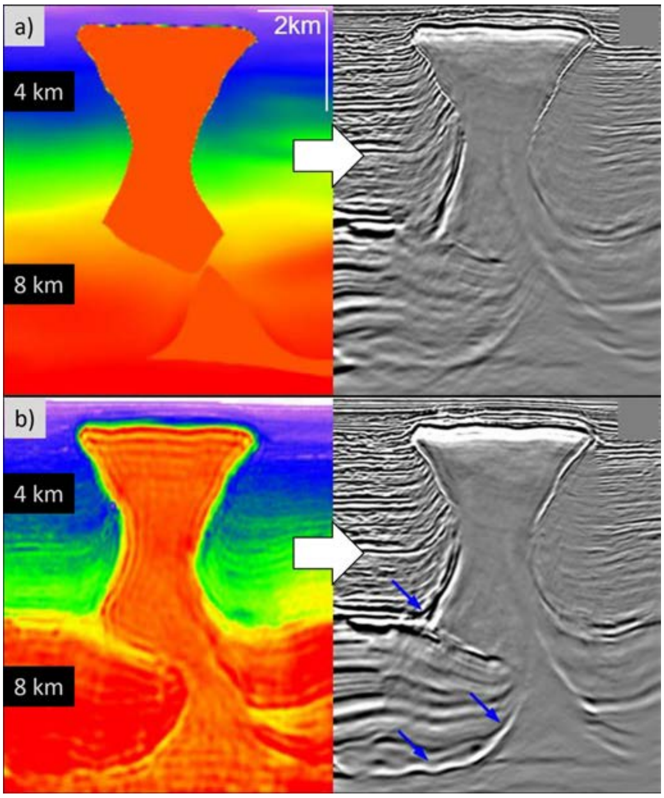

Figure 2. *OBN data. Velocity model on the left and generated image on the right for a) conventional velocity model building and b) TL-FWI. Blue arrows indicate the imaging benefits.*

The use of data-driven algorithms, such as FWI and LSRTM, is setting a new paradigm in seismic imaging. The output velocity and reflectivity models are both capable of generating synthetic seismic data that fits the recorded data from the field. This novel way of validating the subsurface image against the original recorded data is testament to the quality of these new technologies.

Acquiring OBN data to match today's imaging expectations

When data is placed in the driving seat of the imaging process, having the right data becomes fundamental. The more complex the subsurface, the more complex the propagated seismic wavefield. The directions and distances from the source to the point at which the reflected energy is recorded become unpredictable. The distribution of source-receiver patterns with uniform azimuths and offsets is crucial for data-driven imaging and model building algorithms. The best way to achieve these requirements in the field is to disconnect source and receiver deployment, which is exactly what OBN acquisition geometries do. The enhanced signal-to-noise ratio required for high-resolution images can be achieved with their higher trace density per square kilometre of full-azimuth data. Meanwhile, the reliability of the low-frequency component of OBN data is assured by the natural deghosting based on multicomponent recording of pressure and particle motion.

OBN imaging and FWI technology have become hot topics in the industry, with published case studies describing applications in areas where complex salt overburdens obscure the reservoir, such as the Gulf of Mexico (Atlantis, Green Canyon, Mad Dog, Stampede, Herschel) and offshore Brazil (Santos Basin). In addition, several test surveys have been carried out to evaluate the right node density for resolving the geological challenges of the North Sea.[1]

Data-driven model building for complex geology

Standard FWI algorithms have limitations in the presence of strong velocity contrasts, such as shallow salt diapirs or dense carbonate layers. Cycle-skipping and amplitude discrepancies between the modelled and recorded data can in these circumstances confuse the algorithm and lead to biased and unrealistic velocity model results. CGG recently introduced a new technology called Time-Lag FWI[2] or TL-FWI, which is specifically designed to overcome these issues, and therefore gives better results in complex salt environments compared to conventional FWI algorithms. The technology considers both diving waves and reflections for modelling, allowing it to provide deeper model updates than standard FWI implementations. The time-lag aspect specifically refers to the strategy that it uses to mitigate the problems of cycle-skipping and amplitude discrepancies, making it more robust.

OBN imaging of the Herschel field in the Gulf of Mexico is an excellent example of how this technological leap can overcome the complex challenges posed by salt. The delineation and interpretation of salt boundaries in existing seismic images is very difficult and subjective. The low acoustic impedance contrast with the surrounding high-velocity Cretaceous carbonates makes it uncertain. In addition to the complex salt geometry, poor illumination beneath a large salt canopy makes it very challenging to deliver a clear image of the steep events truncated by the salt. These issues are difficult to resolve using existing streamer data and conventional imaging technology (Figure 1).

However, the use of an appropriate data-driven model building algorithm, such as TL-FWI, with the right OBN data can unlock the details of the salt complexity. As seen from the model comparison in Figures 2a and 2b, the technology was able to correct the initial salt misinterpretation and add precious velocity details that would be impossible to achieve using conventional tomographic or manual interpretation methods. The significant contrast between shallow, slow sediment and the deep super-fast Cretaceous is accurately modelled and the salt can now be easily interpreted. The image on the right-hand side of Figure 2b, produced using this detailed velocity model, has capitalised on the benefits of TL-FWI. In terms of the value to interpretation, there is significant uplift for a number of important features. There is no longer distortion of the Oligocene layer (6 to 7 km) and the truncations in the steeply-dipping Cretaceous layers against the salt are greatly improved (below 8 km).

Data-driven imaging for complex geology

Structural imaging of the Herschel field is not the end of the story. The RTM images still suffer from irregular illumination and migration artifacts originating from both the salt canopy and the small areal extent of the survey, causing edge effects. An imaging process using a new LSRTM approach[3] was implemented to better handle these challenges. This approach estimates the inverse of the forward modelling operator (i.e. the imprint of the migration process on the imperfect dataset), then applies this for different structural dips, frequencies and offsets to compensate for frequency-, angle- and offset-dependent illumination effects. Compared to the RTM, LSRTM further improves the image with more balanced amplitudes, improved resolution, and an enhanced signal-to-noise ratio (Figure 3). Figure 4, representing the extracted amplitude along an interpreted horizon at a depth of approximately 5 km, shows the extent to which the loss of illumination around the salt body observed in the RTM image (4a) is compensated for in the LSRTM (4b).

Large-scale OBN surveys in Central North Sea

The latest generation of broadband towed-streamer surveys have revealed additional insight into the remaining potential of the Central North Sea (CNS). CGG has regularly drawn on its experience in this region to apply its latest acquisition and processing technologies in order to improve the imaging of its challenging geology. Currently, a contiguous data volume of over 35 000 km^2 of recent streamer data is being imaged using a Q-Tomo, Q-FWI, and Q-RTM. This compensates for absorption effects (Q) and is designed to provide more reliable images and attributes for quantitative interpretation (QI). Regional pore pressure prediction and quick-look AVO attributes have been derived from this data to provide insight for reservoir development and near-field exploration. The images of the deeper high pressure high temperature (HPHT) reservoir targets have been enhanced with 8600 km^2 of dual-azimuth coverage data obtained with orthogonal passes of towed streamers.

The right data

Despite the uplift in subsurface images brought about by dual- and multi-azimuth streamer surveys and the latest imaging technology, there are specific scenarios where the technical limitations of what can be achieved within the geometrical constraints of towed-streamer data have likely been reached. Overcoming the toughest challenges of the CNS, such as complex salt diapirism or deep reservoir characterisation in structures beneath the Base Cretaceous Unconformity (BCU), requires the next step in seismic acquisition. If designed appropriately, OBN acquisition is now the right technology to make that next step. The goal is to target the remaining reservoir opportunities below the BCU as well as any potential upside hydrocarbon volumes in existing Tertiary discoveries around salt diapirs (Figure 5).

OBN represents the best way forward to sample the subsurface with a uniform distribution of offset-azimuths and a rich bandwidth, especially with noise-free low frequencies. Proven data-driven model building technologies, such as TL-FWI, will then reap the full benefit of the recorded wavefield that has densely sampled every corner of the subsurface. The technology will properly address misinterpretation of the strong velocity contrasts of Quaternary channels in the very shallow subsurface as well as contourites present in the shallow Tertiary section, and possibly highlight some inter-bedded sand injectites. By resolving any existing misinterpretation of strong velocity contrasts and velocity details in the overburden, imaging through LSRTM will then increase the resolution and recover the amplitude of target horizons impacted by various artefacts originating from the rugose top chalk and BCU surfaces, or from sand injectites and shallow polygonal faults. In addition, the increased fold gained with OBN will provide a much cleaner image.

Reasonably well sampled OBN datasets result in better removal of strong propagation effects. Advanced demultiple and deghosting algorithms benefit from receiver positioning on the seafloor. In addition, the anisotropy of the subsurface, which often skews and slightly distorts images, will be more accurately taken into account due to the full-azimuth sampling of the wavefield in all directions. The tailored processing of OBN surveys in the CNS will generate data that is intrinsically suitable for

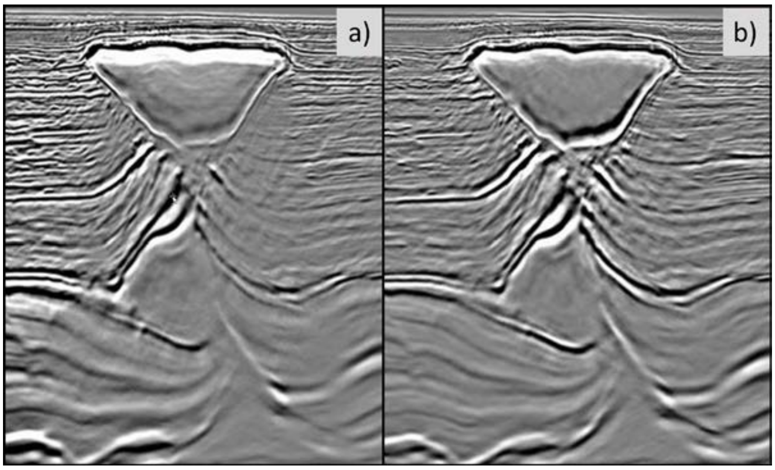

Figure 3. *OBN images generated by a) conventional RTM and b) LSRTM.*

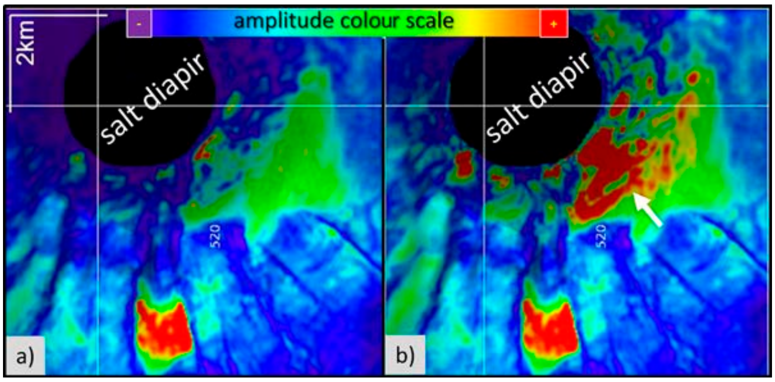

Figure 4. *OBN amplitude image along an interpreted horizon (5 km depth) for a) conventional RTM and b) LSRTM. White arrow indicates the amplitude recovery near the salt.*

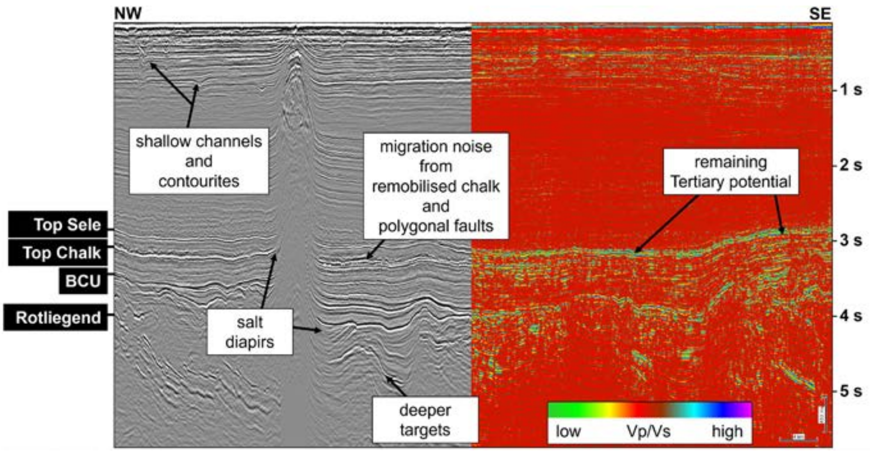

Figure 5. *Seismic line along the CNS superimposed with the inverted Vp/Vs attribute. The arrows indicate the most difficult challenges driving the need for OBN data.*

Figure 6. *Large OBN multi-client survey in the CNS designed to provide exceptional imaging of deep HPHT reservoir targets obscured by salt diapirs.*

QI studies for reservoir development and near-field exploration as well as for 4D production monitoring.

Since the receivers are coupled with the seabed, OBN systems record not only the pressure but also the particle motion, where the horizontal component measures the shear modes. This provides a second S-wave image of the subsurface, which complements the P-wave image and helps to constrain rock and fluid properties.

The right time for the CNS

OBN acquisition has historically only been considered for a small proportion of the total number of seismic surveys conducted by the industry despite highly attractive aspects of the solution. Node surveys have generally been more expensive than streamer surveys because of the large amount of time spent deploying and retrieving nodes on the seafloor. For this reason, surveys have been limited to focused reservoir imaging and monitoring applications.

OBN contractors have responded with a new focus on resolving the factors limiting the efficiency of the seabed seismic solution, both on the source and receiver side. In the last few decades, the efficiency of OBN technology has improved with longer node battery life and faster deployment/retrieval methods.

Ongoing engineering efforts, combined with operational innovation, have increased the potential to achieve a step-change in seabed seismic efficiency and cost effectiveness, e.g. the number of seismic traces acquired per day by OBN surveys in the Gulf of Mexico has tripled over the last 20 years.[4] OBN is entering a new phase of maturity and has now been adopted globally as a leading imaging technology in a variety of settings.

Large-scale OBN – the right strategy for future CNS development

When the objective for the OBN data is to achieve high-resolution images of complex structures, the size of the survey is no longer comparable to the standard node patches deployed for 4D monitoring. The imaging of complex salt diapirs requires an extended shooting area around the deployed nodes. However, with a reasonably well sampled, large-area node survey it is possible to efficiently acquire larger source-receiver offsets (and therefore imaging apertures) and achieve more efficient acquisition per square kilometre through an economy of scale. By including adjacent geological targets and increasing the survey size, OBN surveys become more competitive than the typical small patch surveys generally acquired on a proprietary basis. In addition, a more comprehensive analysis of the lateral extension of complex structures joining up specific targets provides a wider geological context.

This is why CGG Multi-Client, in conjunction with Magseis-Fairfield, have designed the Cornerstone OBN programme to deliver subsurface images of unprecedented quality in the most challenging areas of the UK CNS. The first phase, which started in March 2020, will provide approximately 2500 km^2 of full-azimuth data suitable for field development and near-field exploration (Figure 6).

The maturity of commercial OBN technology for large-scale, dense exploration surveys is a key enabler behind this strategic shift. Specifically for the shallow waters of the North Sea, the development and maturity of efficient node-on-a-rope (NOAR)/node-on-a-wire (NOAW) acquisition systems using reliable autonomous long-duration nodes ensures the productivity required to make such a survey economically viable. In this specific case, the use of ZNodal OBN technology will make it possible to acquire high-quality seismic data with minimal HSE risk. The system is lightweight, making deployment faster and economical, with no troubleshooting required while recording.

This multi-phase, multi-client programme covers reservoir targets in HPHT areas where multiple complexities in the sedimentary overburden pose challenges for seismic imaging using existing streamer data. OBN data will complement the existing high-quality Cornerstone streamer data. Mastering the cutting-edge data-driven processing of OBN data will raise the bar for the coming years in the North Sea.

Note

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