



# Using dual-azimuth data to image below salt domes

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## Introduction

In complex geological areas, subsurface illumination is largely determined by the acquisition geometry. More recently, multi-azimuth and wide-azimuth surveys are increasingly being used to maximize subsurface coverage, but these can present new challenges; for example, how to combine the images from different azimuths into a single migrated image for use by the interpreter.

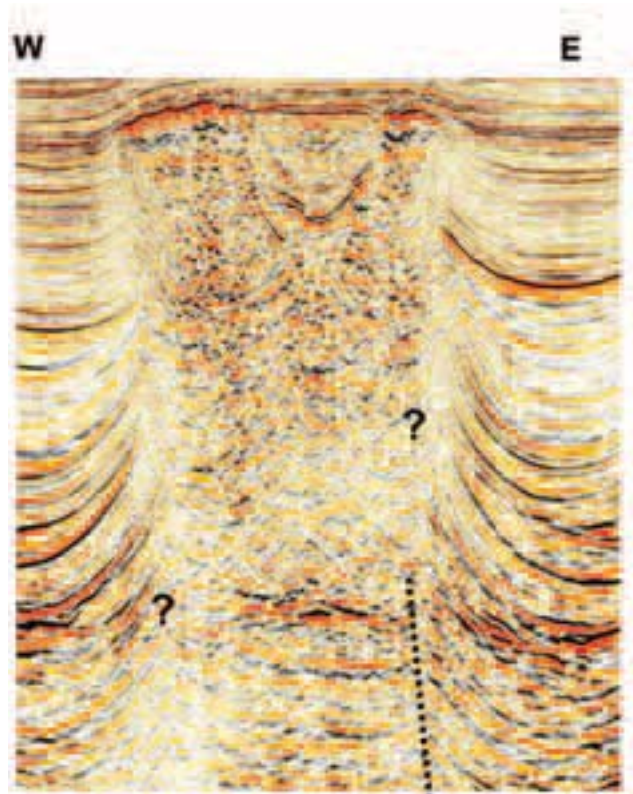
Traditionally, the common practice is to ignore potential azimuthal velocity variations and build a single vertical velocity model, in some cases incorporating VTI anisotropy. Data from different azimuths are pre-stack migrated separately, but with a single velocity model usually derived from one azimuth, and then combined into a single image after application of residual move-out corrections. We present a case history of building a single velocity model for pre-stack depth migration of dual-azimuth data in the southern North Sea. The dual-azimuth data gave us enhanced illumination of the target zone, but somewhat to our surprise, it also showed strong azimuthal velocity variations in the overburden. We devised a methodology and built a single velocity model that incorporated these azimuthal velocity variations so that all events are migrated to their correct position. When the data sets are combined, primary events are reinforced while noise cancels out to give one optimal data set.

## Dutch North Sea salt dome

Many gas discoveries are associated with salt structures within the pre-Zechstein fairway of the Dutch North Sea. Within our survey area lies a large square salt dome with significant prospectivity, both beneath the salt and in the steeply dipping sediments on the salt flanks. The initial interpretation was based on low-fold seismic data acquired in 1990, with 3000 m streamers. Despite pre-stack depth migration processing carried out in 1999, the structure remains poorly defined particularly below the salt overhangs and against the flanks of the salt body. As shown in figure 1, improved imaging was required to identify and delineate fault blocks within the main subsalt structure, optimize the location of wells, and firm up additional prospects. (Dewey et al., 2004)

## Data acquisition

Due to the steep dip of the salt flanks and large velocity contrasts between the salt and surrounding sediments, much of the seismic energy was dispersed, resulting in poor illumi-



**Figure 1** E-W line across the centre of the large square salt dome. Data were acquired in 1990 and depth imaged with the original 1999 pre-stack time migration velocity model. Steep dips against the salt flanks are not imaged. Below the salt overhangs, poor illumination makes fault interpretation uncertain.

nation of the pre-salt section. Figure 2 shows the results of a ray-tracing study around the salt diapir, for reflection from the target Top Rotliegend (base salt) horizon. The pictures show maps of the estimated offset range for E-W acquisition on the left and N-S acquisition on the right. Blue colours show that a limited range of offsets were successfully ray-traced from the target horizon indicating areas of poor illumination. Red colours, on the other hand, show a wide range of successful offsets, indicating areas of good illumination.

In 2003, a new 3D survey was acquired with long offsets (5100 m streamers). The main acquisition direction was E-W in the direction of the prevailing geological dip, but two additional swaths were acquired in the N-S direction, parallel to the salt dome and to a linear salt ridge to the east, as shown in Figure 3. Both datasets were acquired using two sources and

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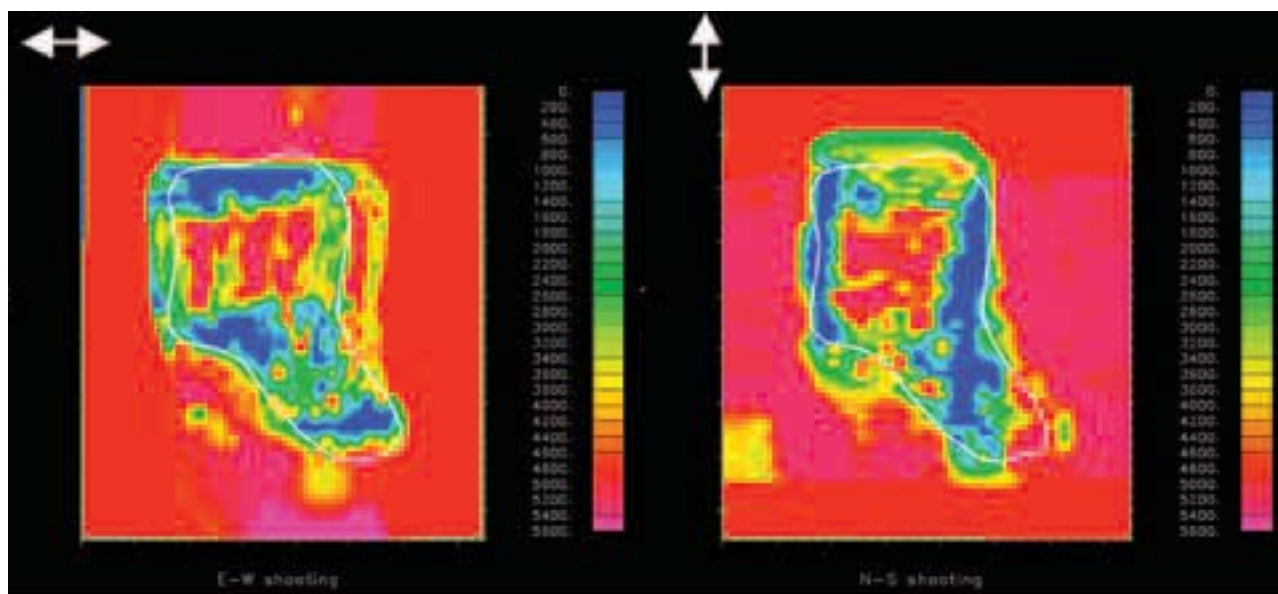


Figure 2 Ray-traced illumination maps for E-W acquisition (left) and N-S acquisition (right)

six streamers resulting in 68-fold data with a 25 m crossline spacing. The shooting pattern was chosen to minimize waiting for tides and to maximize feathering matching.

### Time processing

The orthogonal datasets were processed simultaneously through pre-stack time migration (PrSTM). Extensive noise attenuation, removal of direct arrival energy, and high-resolution demultiple were included in the preprocessing sequence. To optimize the image quality, the PrSTM velocity fields for each dataset were picked independently. Interestingly, significant differences in the vertical velocity fields were observed, resulting in steep dips being migrated to slightly different positions.

Consequently, simple addition of the orthogonal datasets resulted in smearing of the steeply dipping reflectors (Figure 4). For interpretation purposes, three final datasets were generated: one for the E-W acquisition, one for the N-S swaths,

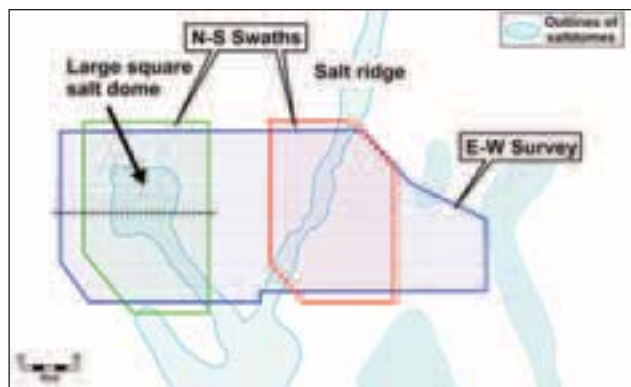


Figure 3 Plan view of surveys overlain on salt structures. The location of the example seismic sections is indicated with a broken black line.

and one combined volume. While pre-stack time migration works well in simple geological settings, it cannot handle the complex raypaths surrounding the salt feature. To correctly image below the salt, depth migration is required, which will allow for refractions at the main geological layers and can handle multiple raypaths.

### Velocity variations with azimuth

For optimum depth imaging and correct positioning of events, we needed to build an accurate velocity depth model, taking into account variations in velocity due to azimuth while discriminating between azimuthal variations and effects caused purely by local heterogeneity. Choosing the appropriate velocity updating method was critical to this process. We used reflection tomography (either layer-based or gridded), with residual move-out picks based on a migration with an initial model. We picked residual move-out for both azimuths separately and input all picks, for both azimuths, into a single tomographic inversion, but with appropriate ray tracing performed for each azimuth. In Figure 5, we show the results of three velocity updates of a mid-Tertiary horizon, output from tomography using picks from each azimuth separately and then both together.

The picture on the left was derived using residual delay picks from the E-W survey only, the picture in the middle from the N-S survey only, and the picture on the right was derived using picks from both surveys. East and west of the salt dome, the E-W survey shows faster velocities than the N-S survey, but slower velocities to the north and south of the salt dome. Similar velocity differences were observed after both pre-stack time migration and pre-stack depth migration over large depth ranges, from the shallow Tertiary all the way down to the Top Zechstein. The main units affected appear to be the chalk and shale sections. The precise cause



Figure 4 Kirchhoff pre-stack time migration. Left picture shows the E-W survey only, middle picture shows the N-S survey only, right picture shows both surveys combined. Note the smearing of events on the combined data set.

of this is still not known, but it is probably related to radial stress fractures induced by the salt diapirism. Figure 6 shows a coherency cube time slice through the Tertiary with evidence of radial faulting around the salt dome. The observed velocities are consistent with this pattern, slow velocities normal to the faults and fast velocities parallel to them.

**Velocity model building for depth imaging**

Multi-offset (walkaway) VSP data from three wells were analyzed for intrinsic and effective VTI anisotropic parameters. The analysis showed azimuthal variations and also confirmed strong VTI anisotropy for the Lower Tertiary and the Cretaceous. This meant that a combination of VTI and azimuthal anisotropy was present, which in order to treat correctly, required an orthorhombic anisotropic solution. However, this could not be parameterized using data from only two azimuths.

A Horizontal Transverse Isotropy (HTI) solution was also ruled out, both by the limited azimuths and by the complexity of the anisotropy. Our solution used the limited range of azimuths to our advantage and adopted a practical model-building flow; it used a single vertical velocity model and independent VTI anisotropic fields for each azimuth (Whitfield et al., 2005). We termed this approach ‘dual ani-

sotropy’. The velocity model was built in a top-down fashion using layers, with each layer having its own independent properties such as velocity, gradient, and spatially varying anisotropic parameters, delta and epsilon, appropriate for each azimuth.

To analyze the data from the two surveys, we compared the gathers from both datasets at the same common image point. Pseudo split-spread gathers were generated, which we termed ‘butterfly gathers’. Figure 7 shows examples of

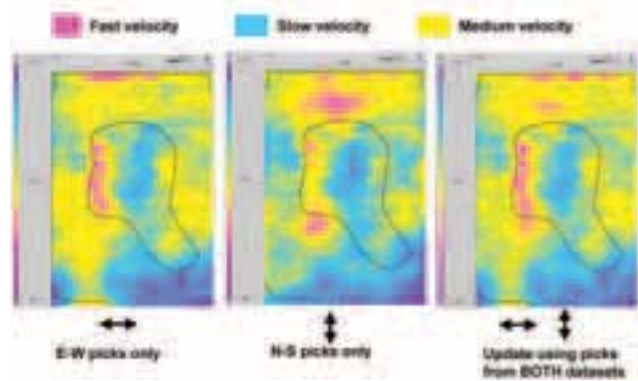


Figure 5 Velocity maps of a mid-Tertiary horizon around the salt diapir after tomography.

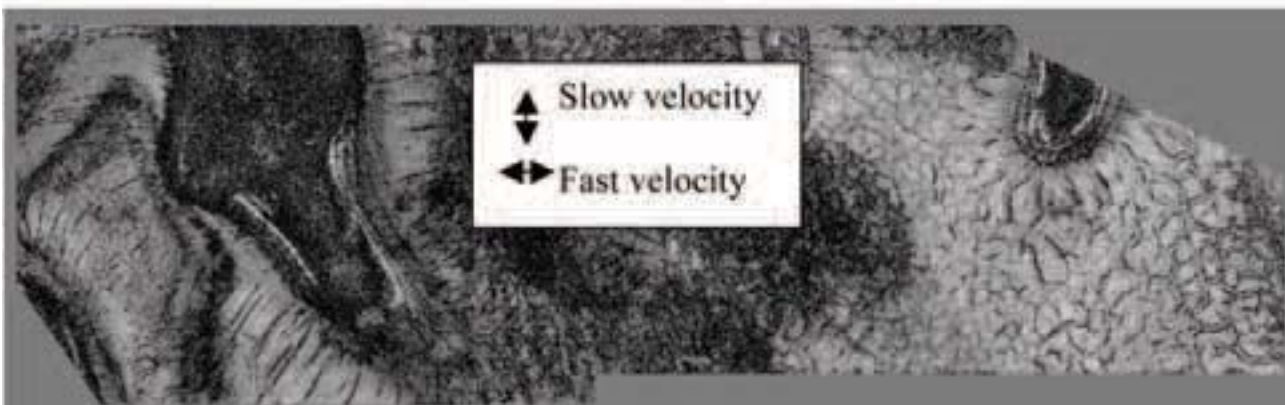


Figure 6 Coherency cube time slice showing evidence of radial faulting around the salt dome.

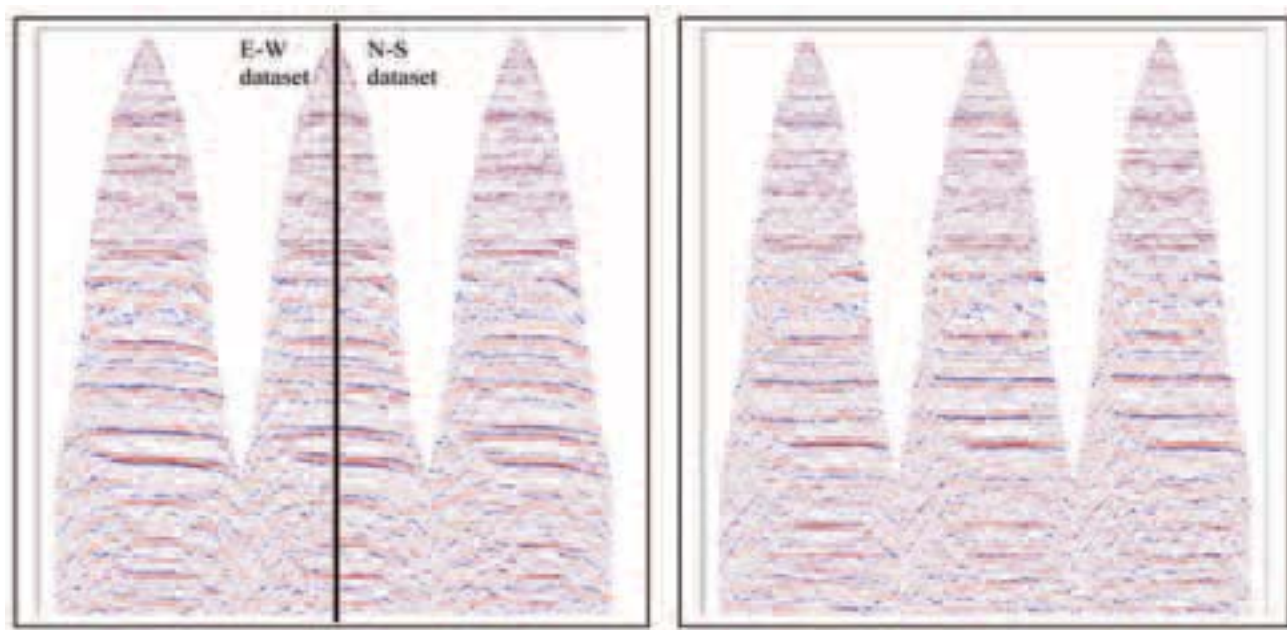


Figure 7 Butterfly gathers from an initial model (left) and the updated model (right).

butterfly gathers - the left panel was migrated with an initial velocity model with no azimuthal correction; the right panel was migrated with our final model with dual anisotropy. At each butterfly gather, the E-W dataset is displayed on the left with negative offsets and the N-S dataset on the right of the split-spread. In this particular example and for the data migrated with the initial model on the left, events from the E-W dataset are nearly flat, but the N-S dataset appears under-corrected suggesting that the velocity is too fast. This initial model was derived from the older dataset, which was also acquired in the E-W direction, so it seems we have chosen the correct velocity for that azimuth on both the older and the new datasets, but we were obviously unaware that velocities varied with azimuth. These gathers are situated just to the west flank on the salt dome, so the observed velocity variation fits with our idea of radial faulting, being responsible for these variations. Once the correct vertical velocity field was established and the correct anisotropy parameters applied to each dataset, events on the gathers become flat as shown on the right panel. Note that events in the butterfly gathers meet at the near-zero offset because the azimuthal

component of the velocity variation vanishes. This is used as an additional constraint to QC the velocity model and ensures the combined dataset gives a sharp image.

#### Pre-stack Kirchhoff depth migration

By ray tracing through the velocity model and taking into account the rapid changes in velocity, the pre-stack Kirchhoff depth migration provides a better image of the subsalt reflectors than the straight ray time migration. However, the Kirchhoff algorithm has limitations in imaging below complex salt overhangs and under tall and steeply dipping salt flanks. In these areas, it tends to introduce migration noise, which remained present even after the two orthogonal datasets were summed and obscured the real image (Figure 8).

Kirchhoff migration was adequate for most of the model-building phase as it allowed rapid generation of target lines to be output for QC and structural updates.

#### Wave equation migration

Wave equation migration is a better-suited algorithm for imaging around and beneath complex salt bodies, not only because it can handle multiple raypaths, but because it gives an inherently more stable image in the presence of severe velocity contrasts than the Kirchhoff ray-based approach. Both datasets were migrated with the Kirchhoff-derived velocity model in VTI mode using the shot profile wave equation algorithm. The improved image quality allows for a more accurate interpretation of the salt/sediment interface. On completion of the velocity model to base salt, a wave equation migration was run to refine the top salt interpretation. Gravity modelling was also used to aid and confirm the shape of the salt bodies.

Due to the near vertical salt flanks, a small change in interpretation had a noticeable effect on the final image.

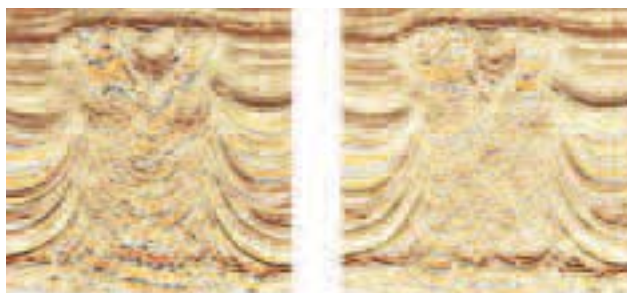
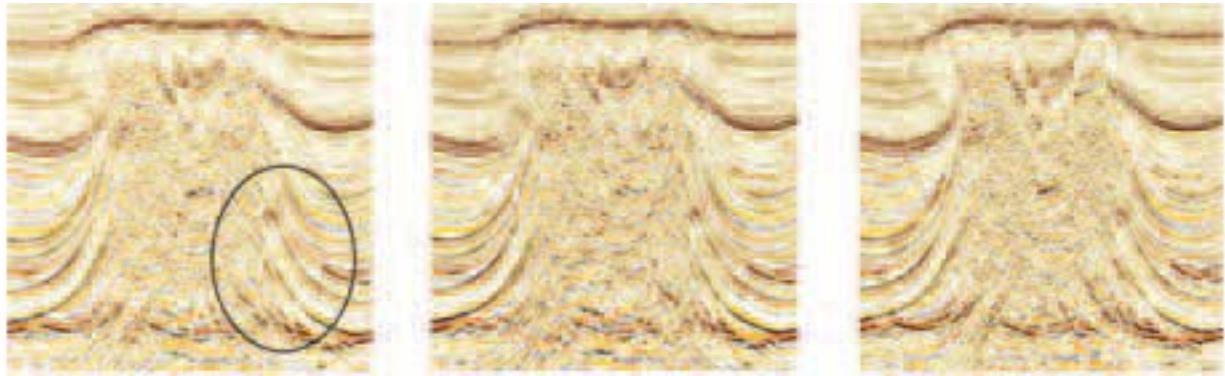


Figure 8 Kirchhoff depth migration. Left: E-W acquisition, Right: N-S acquisition.



**Figure 9** Final wave equation migration datasets. E-W acquisition (left); N-S acquisition (middle), and both datasets summed (right).

We found that several iterations of model updating, including refinements to the interpretation, were crucial for a good image. With increased computer power and a corresponding decrease in the cost, using wave equation migration as part of the model-building processing flow has now become a viable option.

The orthogonal datasets were migrated separately using the wave equation migration and then summed (Figure 9). The results showed imaging differences due to varying illumination resulting from the different acquisition directions. Summing the wave equation migration datasets sets gave the best image from both surveys and increased the signal to noise ratio.

### Conclusions

In areas of complex geology, multi-azimuth datasets improve illumination of the subsurface. However, to optimally combine these datasets, any azimuthal velocity variations must be taken into account. We have observed strong azimuthal velocity variations in both steeply dipping shale sequences and fractured chalk in this southern North Sea dataset, which were confirmed by VSP data.

We have developed a practical methodology to take into account azimuthal anisotropy variations in the velocity model, for a limited number of azimuths. This allows each dataset to be optimally migrated so that they can be summed to give one final dataset for interpretation.

In the southern North Sea, rapidly changing lithologies (shale to chalk to sandstone with intermittent salt bodies) require a detailed velocity model comprising of typically eight or more units. Despite automated delay picking tools

and tomographic velocity updating, generating and optimizing an anisotropic velocity model, consistent with well data, is still a time-consuming process, typically taking up to a year to complete. While the increased computer power now allows computational processes such as wave equation migration to become part of the model-building workflow, more effort is still needed to speed up the generation and fine tuning of the velocity models. As the number of azimuths acquired for each dataset looks likely to increase, more effort must be put into automated processes that can distinguish between the vertical and azimuthal component of velocity so that detailed anisotropic models of the earth can be constructed for imaging. The ultimate aim would be to construct velocity models incorporating orthorhombic anisotropy without increasing the turnaround time.

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