Imaging Deep Water Salt Bodies in West Africa

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Introduction

The deep offshore of the Gulf of Guinea is a major challenge to seismic processing and imaging techniques, due to the complexity of the salt body structures (figure 1). Even though Kirchhoff prestack time migration (preSTM) can image the top of salt and the wider, simple sedimentary basin reflections, it fails elsewhere.

Strong surface related & interbed multiples and mode conversions at the top of salt are difficult to identify and eliminate, which makes stacking velocity or tomography inversion for sediment velocities difficult. The geometry of the salt bodies makes time processing assumptions *a priori* invalid.

Using synthetic elastic finite difference (FD) modeled data (Levander 1988, Don Larson, pers. comm.) we show that compared to Kirchhoff 3D preSDM, wave equation 3D PreSDM is necessary to properly image target sedimentary reflectors in between and below salt domes. However, this is true only for synthetic data using an exact model. In practice, the difficulty of deriving a proper model of sediment velocities drastically reduces the difference between the two algorithms.

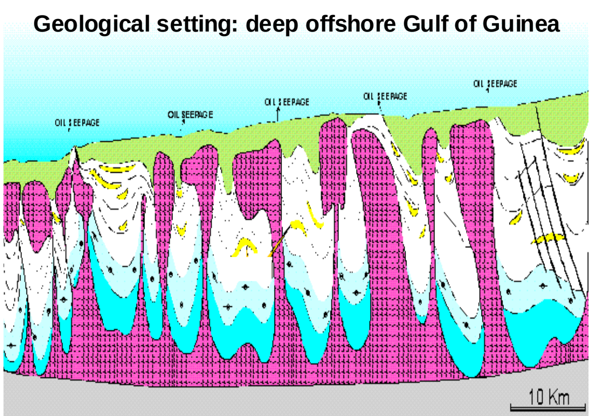

Figure 1 The difficulties associated with this deep offshore environment include: a dipping sea floor, complex coalescing salt structures overhanging prospective mini basins, proximity of the top of salt to the sea bottom.

Methodology

To devise the best methodology for producing high quality images in this area, we created a set of synthetic data using elastic finite difference forward modelling with a model of appropriate complexity: two salt bodies overlying narrow basins with turbiditic complexes (figure 2).

A gridded model, representative of deep water salt tectonic environments was used. This included density, Vp and Vs grids. In order to represent gas hydrates near the seabed, very low S-wave velocities were present in the model (180m/s). The lowest P-wave velocity (in the hydrates) was about 1200m/s. These low velocities restricted the maximum feasible frequency in the FD modelling.

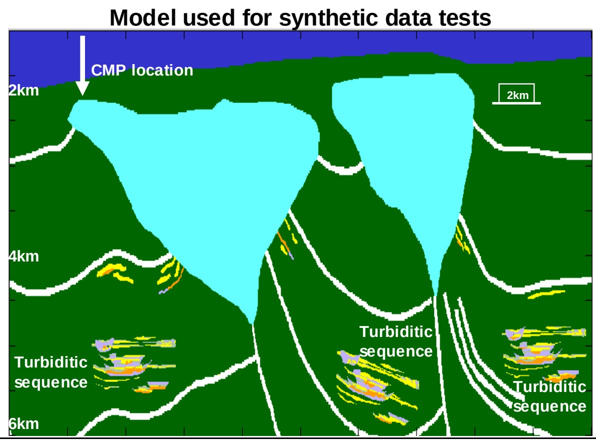

Figure 2. P-wave velocities used. Two salt bodies overlay three turbiditic sequences

Various tests were performed to obtain acceptable results on a data volume created using on a 40-node cluster. The finite difference code used in this study can emulate both acoustic and elastic wave propagation. This is fourth-order accurate in space and second-order in time. It includes absorbing boundaries and, optionally, an absorbing surface to suppress the free surface reflection.

The maximum frequency in the elastic modelled data was 30Hz, and all conversions and multiples were included in this modelling process. Tests were performed for higher maximum frequencies, but given the very low velocities required in the model, it was not feasible to produce higher frequency data. The main limiting factor is related to the memory on the PC clusters used, as to model a single shot record, the amount of memory required is proportional to the square of the maximum frequency (and the run time is proportional to the cube of the maximum frequency).

If we use a grid size that is too large for our maximum frequency (for a given minimum velocity), then the wavefield will become dispersive.

The complexity of the synthetic data can be seen in figure 3. For the near offset (150m) the elastic data show both free surface multiples and interbed salt multiples (3a) whereas the free surface multiples are absent in the acoustic data, which were produced using an absorbing free surface (3b).

Multiple bounces within the salt, of P-to-S conversions (where the conversion occurs at the top salt), can also be seen below the base salt.

Figure 4 shows an elastic CMP from the location indicated by the arrow on figure 2.

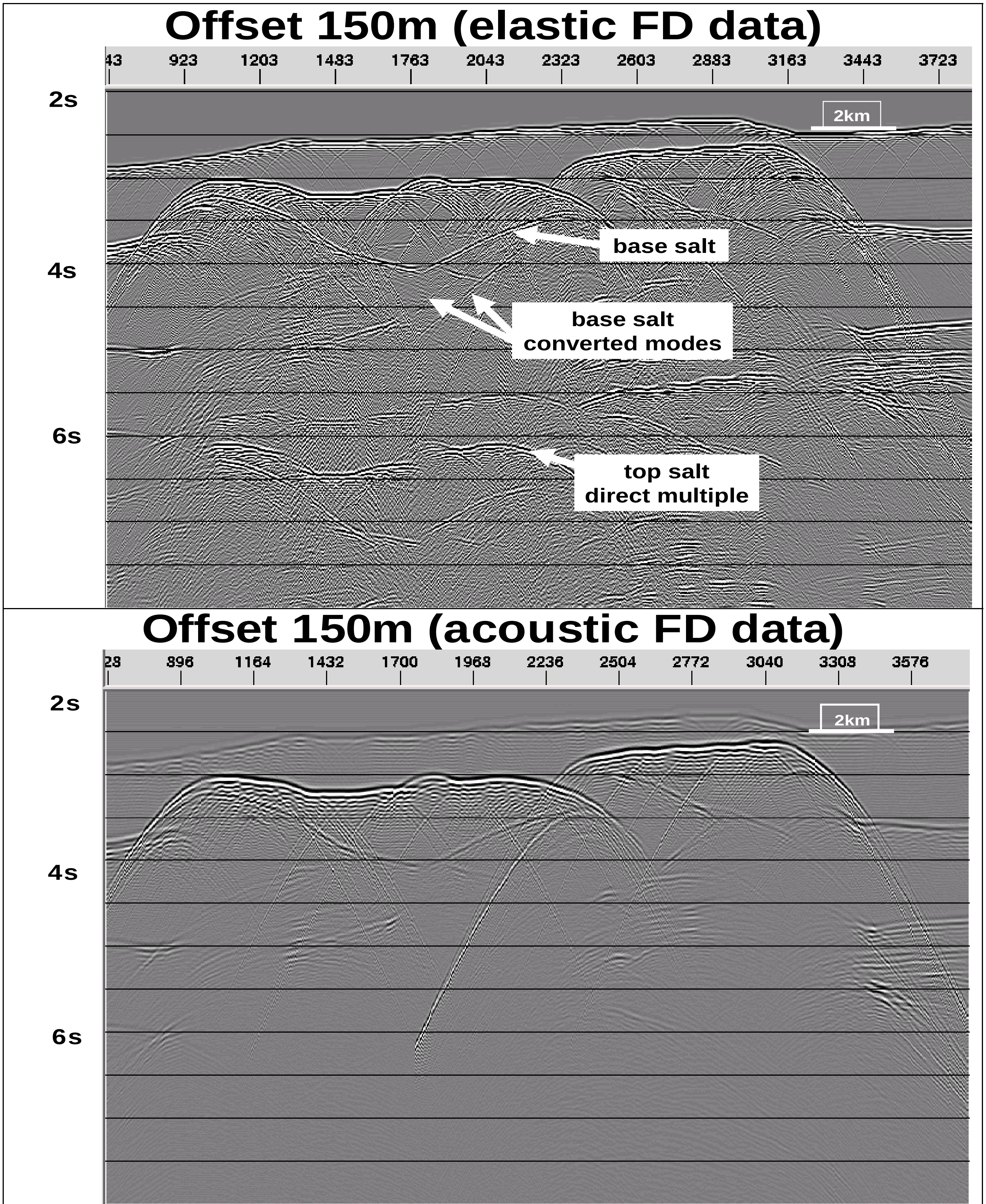

Figure 3: Near offset plane (150m offset) for the elastic data (top) and acoustic data (bottom)

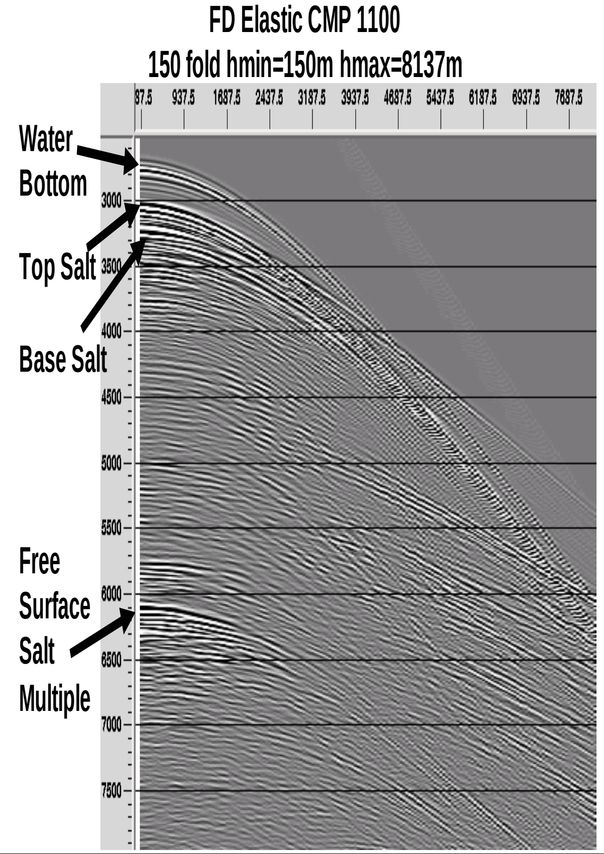

Figure 4. Elastic CMP showing salt reflections and multiples

Depth Migration

The wave equation migration method used in this study is a shot-based approach that employs the phase-shift and split-step Fourier plus interpolation (SSFPI) algorithms for wavefield downward extrapolation. These two approaches are adaptively implemented according to the velocity model structure. Phase shift is used in constant velocity areas (water column, salt bodies), while SSFPI is used in sedimentary strata with varying velocity. The separation of salt (and water in offshore areas) from the sedimentary background greatly reduces the number of reference velocities required in the SSFPI algorithm. In comparison to other extrapolation methods such as the Fourier finite difference (FFD) algorithm, phase-shift and SSFPI do not suffer from numerical dispersion or anisotropy problems and are accurate at wide angles. High angle imaging is further improved by employing a modified imaging condition that compensates uneven energy distribution due to velocity variation and oblique factors in the extrapolated wavefield; thus, providing enhanced amplitudes for steeply dipping events.

The Kirchhoff scheme was amplitude preserving and used the maximum energy single arrival migration method.

The workflow was as follows:

- Generate 2D elastic FD modelled data with 8km offsets using the model supplied by Total
- Generate 2D acoustic FD modelled data with 12km offsets using the supplied model
- Using the known model, migrate the elastic data with:
    - Kirchhoff preSDM,.
    - Kirchhoff preSTM,
    - wavefield extrapolation (WE) preSDM .
- Derive a depth velocity model from the elastic data using:
    - layered tomography and CRP-scan updates,
    - iterative gridded tomography.
    - Hybrid layered & gridded tomography.
- Derive a time velocity model from the elastic data using iterative preSTM CMP-scan updates.
- Migrate the elastic data with Kirchhoff preSDM and preSTM schemes, using the corresponding models.

The acoustic data were also migrated with various combinations of model and algorithm.

Results

Unless otherwise stated, all migrated images have been stacked with a fairly harsh mute after migration, as picked from CRPs along the section. Selection of an aggressive mute was necessary to exclude noise. Initially, multiple and mode conversion elimination were not applied to the synthetic data.

Additionally, the WE migrations have been muted prior to migration with a slightly less aggressive mute. Pre-migration muting is required for common shot migration schemes, as energy is mixed across offsets during imaging.

From inspection of gathers at key locations along the section, we note that most coherent energy appears to die out near the 4km offset. However, for some events (e.g. base salt), we have energy beyond 8km offset.

We conclude that for the quality of data generated in this modelling exercise, it is unclear what the maximum useful offset is. This is because we have various classes of ‘artefacts’ some of which may be legitimate, representing real ‘earth’ effects (e.g. mode conversion, and consequent splitting of events). But we may also have numerical modelling noise (e.g. dispersion) which limits the usefulness of longer offset data.

As part of the assessment of useable offsets, and for investigation of illumination, various ray-trace diagrams were analysed. In practice, rays beyond 4km appear to be lost for most reflections from the undulating sub-salt reflector to the left of the left-most salt body. However, we do retain long offset arrivals for the base salt.

Using the known model, the result of Kirchhoff imaging with the best parameters (maximum aperture, highest ray density) shows that an acceptable image can be obtained of the deeper sedimentary bodies (figure 5). Wave equation migration, however, clearly improves the definition of the western turbidites below the salt flank, and generally produces less noisy images (figure 6).

The WE results were almost perfect. Various Kirchhoff migration results do well in most places, but for the subsalt sediments, including the turbidites, the Kirchhoff results under perform.

Even with the known model, we observed that in both the WE and Kirchhoff images (figures 5&6), the termination of the undulating reflector around 4km against the left salt flank is not imaged at all (indicated by arrow in figure 5). This is in part due to low coverage (illumination issues) but primarily due to low impedance contrasts (even though we have significant velocity contrasts). Impulse response tests showed that it was not an issue of migration response to the model. In a real context, this would probably be misinterpreted as a straight continuation of the sediments up to the salt flank. This effect can be observed on real data imaged on a test zone in the area used to define the synthetic model (shown later).

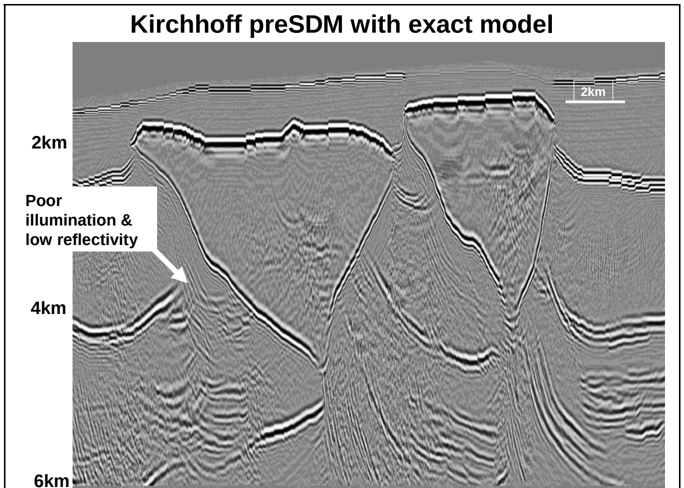

Figure 5 Kirchhoff preSDM using the known model

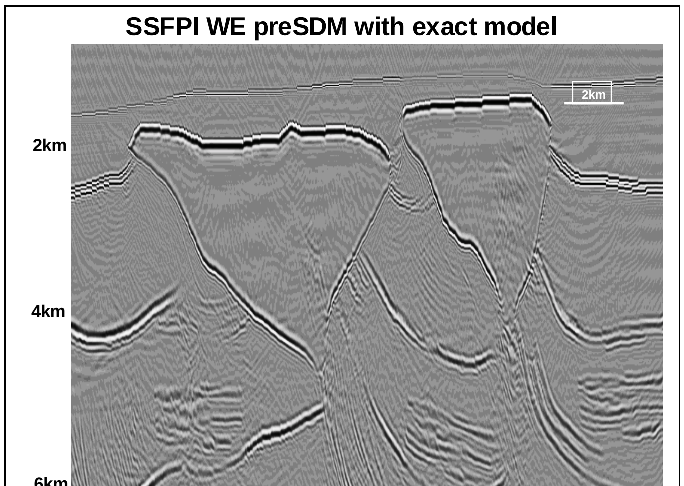

Figure 6 WE preSDM using the known model

Building a Model

After imaging with the exact model, various ‘industrial’ model building routes were followed, whereby a model was derived from analysis of the pre-stack synthetic data themselves using various model update schemes.

However, a major problem of building a velocity model for data such as these, even with hybrid tomography methods, is the estimation of sediment velocities below salt flanks and between salt domes (the shape of the salt and its velocity are not too difficult to derive).

Using various derived models, as in a standard imaging flow of real data, the benefit of wave equation imaging is drastically reduced (figures 7-9). This implies that, in an operational context, the choice of wave equation migration will depend upon the possibility of obtaining an accurate velocity model.

The images resulting from this procedure very quickly degrade, as both multiple and converted wave energy ‘misleads’ the interpreter by yielding false models. To the right of the left-most salt body, the right flank of the base salt can be seen to be a ‘double’ event in the layered ‘derived’ model, as a converted mode is being imaged (i.e. misleading velocities were picked).

Optimal Model building strategy

Based on the results of this study, and other work in complex salt environments, a route for model building tailored for such areas is proposed.

In addition, pre-processing of the input data to suppress both multiple and converted mode energy will be beneficial, both to facilitating elaboration of an accurate velocity model, and for the final migration.

The route proposed below combines layer and gridded tomography for the overburden, turning-ray Kirchhoff preSDM for the overburden and salt-flank imaging, and wavefield extrapolation (WE) migration model building and migration for the sub-salt sediments.

Proposed Model Building Steps:

1. Kirchhoff using smooth sediment flood below sea bed followed by dense autopicking + gridded tomography
2. Updated sediment flood Kirchhoff to pick top salt & remote sediments
3. Sediment + salt flood; turning-ray Kirchhoff for overturned salt pick

4 (discretional). Sediment + salt flood; turning-ray Kirchhoff to refine overturned & base salt pick

5. Wavefield Extrapolation Image Perturbation Scan to update base salt and/or sub-salt sediments

Future Acquisition Considerations

Other work has shown that for complex salt geometry, shooting direction has a profound impact on image quality (e.g. Manin & Hun, 1992, O’Connel et al, 1993, Bernitsas et al, 1997, Etgen & Regone, 1998, de Bazelair, 1999, Jones et al, 2000). Hence, in light of this, and the insights gained during this modelling study, it would be prudent to perform an acquisition planning study prior to any future data acquisition, to assess the possible impact of converted model arrivals and multiples on the imaging and model building.

In addition, illumination studies are recommended to determine the most optimum shooting direction(s) most likely to illuminate the desired target regions.

Conclusions

The deep offshore of the Gulf of Guinea is a major challenge to seismic processing and imaging techniques, due to the complexity of the salt body structures and the omnipresence of mode conversions that mask the primary signal. We have shown that in this context, wave equation 3D PreSDM is necessary to properly image target sedimentary reflectors in between and below salt structures, compared to Kirchhoff 3D preSDM methods.

However, to benefit from this technique requires building a very accurate depth model using hybrid tomography methods. We have demonstrated that one of the problems in building such a model relates to masking of sediment pinchouts against salt flanks by strong mode conversions. These observations from forward modelling are confirmed by images obtained from field data on a test zone (Figure 11).

Acknowledgements

Thanks to Total for kind permission to use their data.

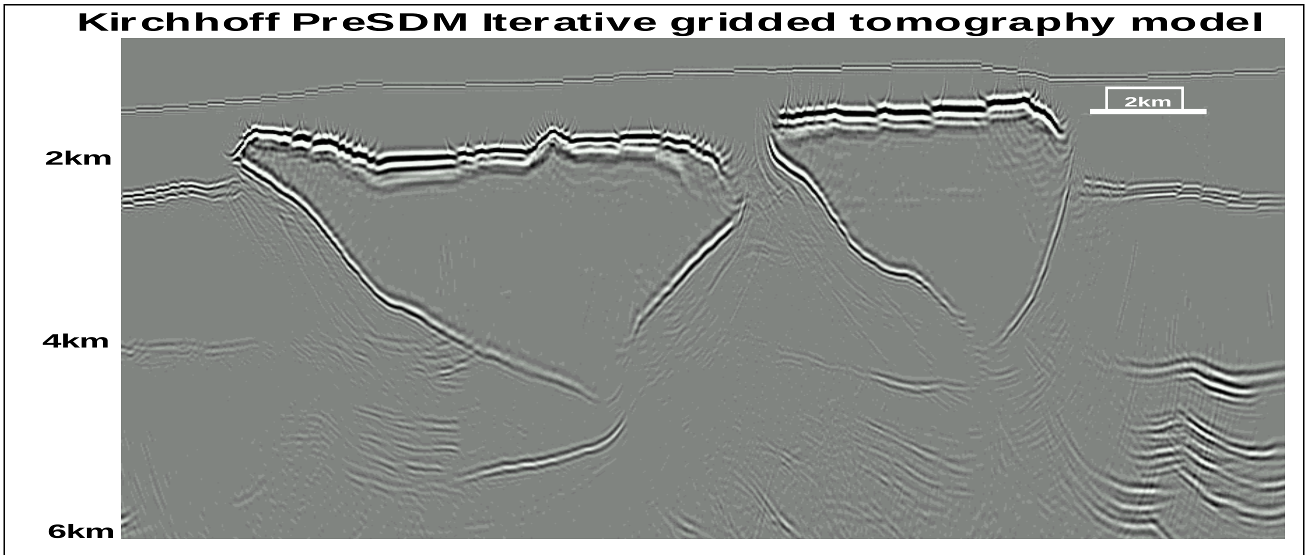

Figure 7 Kirchhoff preSDM using the iterative gridded tomography model

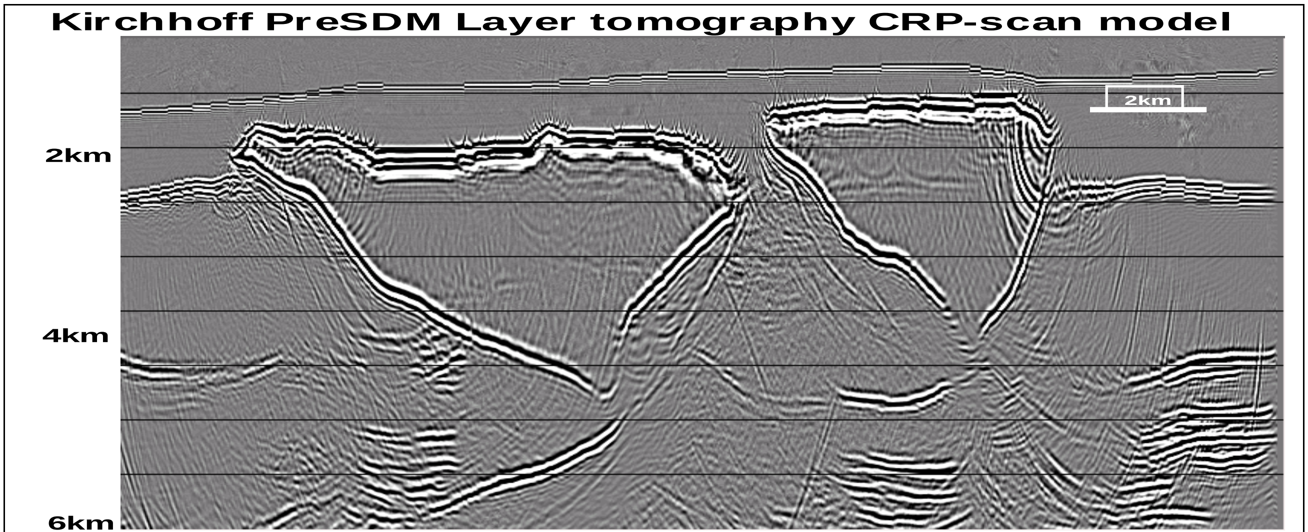

Figure 8 Kirchhoff preSDM using the layered tomography & iterative CRP scanning model

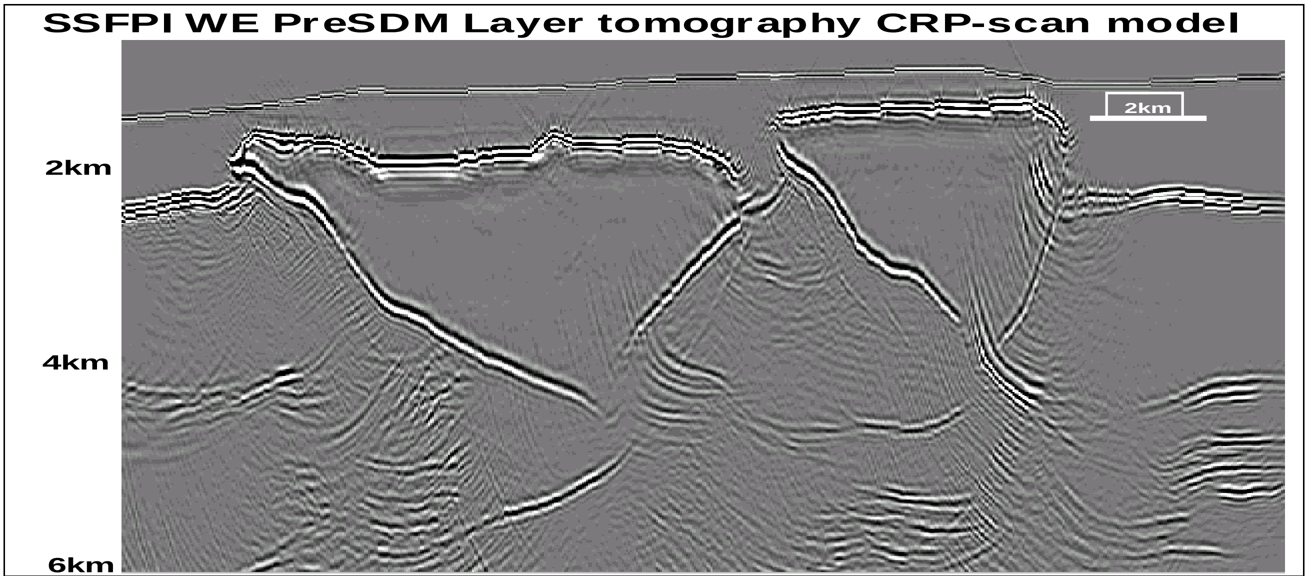

Figure 9. WE preSDM using the layered tomography & iterative CRP scanning model

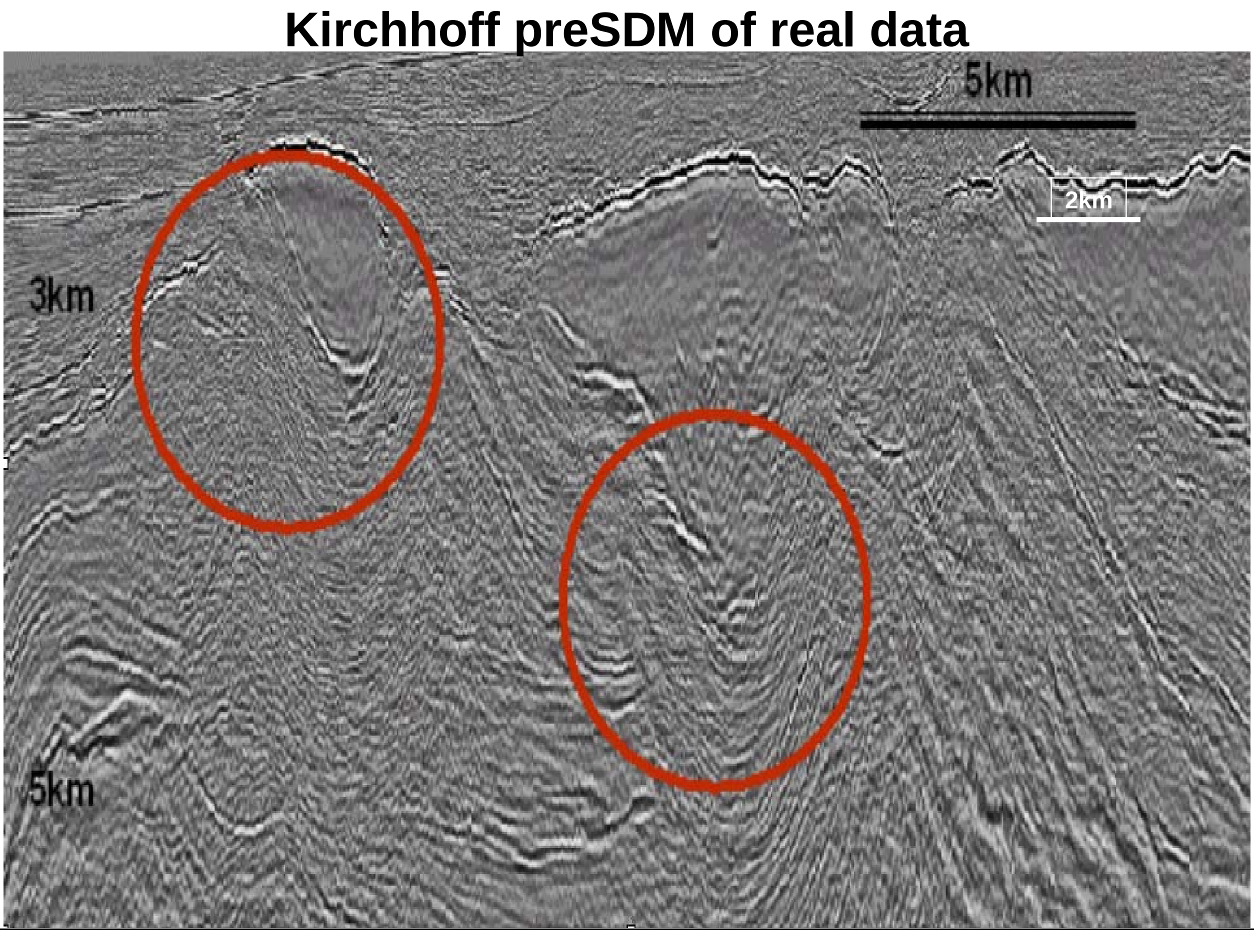

Figure 10. Kirchhoff 3D preSDM of real data used to design the model

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