Application of high-resolution 3D seismic to mine planning in shallow platinum mines

Eric Gillot[1], Mark Gibson[2], Dominique Verneau[1], and Stephane Laroche[1] **explain how 3D seismic imaging was able to prove an attractive alternative to 'total drilling' in the context of a platinum mining production project.**

Over the last decade 3D reflection seismic has been applied for platinum mining in South Africa. 3D seismic surveys have almost exclusively been conducted in the Western Bushveld where ore extraction depths range between 500 and 2000 m. The ore is mined mainly via vertical shafts and also some decline shafts. In the Eastern Bushveld, the mining targets are at shallower depths of less than 400 m. The challenge set by the mining companies is to obtain high-resolution seismic cubes with maximum vertical resolution at this depth of investigation. The cost of geophysics must also be more attractive than that of the 'total drilling' alternative. Trials were therefore conducted at two mine sites in the Eastern Bushveld.

Exploitation of existing seismic

A 2D test was performed by CGG over a mine in the Eastern Bushveld in 2001 with an explosive source and various vibrator sources. Although the results were encouraging, they did not meet the expectations of the mine operator. The explosive source was rejected due to its cost. The vibroseis source produced results of insufficient quality linked to the frequency content emitted by the vibrators used, such as the M18, and the difficulty in resolving static anomalies. It was therefore decided to change to the new generation Nomad 65 vibrator, which can emit up to 250 Hz, and focus specifically on resolving statics-related problems. As 2D acquisition would not satisfy the client's required image of his mine, it was also decided to move straight onto 3D projects.

Proposed project

A 3D survey test was therefore commissioned by the mine operator to find a solution for his mine planning challenges. The project had two main aims:

- Test the economic viability of the seismic method for mine planning via a gradual decimation of survey parameters, such as design, spread, sweep length, etc., while retaining a financially attractive solution compared with the cost of the 'total drilling' option traditionally favoured by mining operators.
- Obtain a result over a significant surface area of interest to the client, which could then be immediately used for mine planning.

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The location chosen for the first project site (Figure 1) lies in a valley crossed by a hydrographic network (*dongas*) encased in weathered strata, sometimes right up to the level of the hard norite substratum. Part of the challenge was to provide a high-quality seismic image while resolving the difficult static corrections problem induced by this specific geological context in the first 50 m.

The main ore body mined at this location is UG2 (<1m thick). It is a monoclinal structure with slight 2 m amplitude undulations and a wavelength of 30 m. The survey was designed to image at a depth ranging between 100 m and 400 m at a 10° dip and track the disturbance of PGM (Platinum Group Metal) ore bodies (faults, flexures, potholes, etc.) to within 10 m.

Design

A 2.5 x 2.5 m dimension was selected as the smallest bin size that could be technically possible at an economically viable cost.

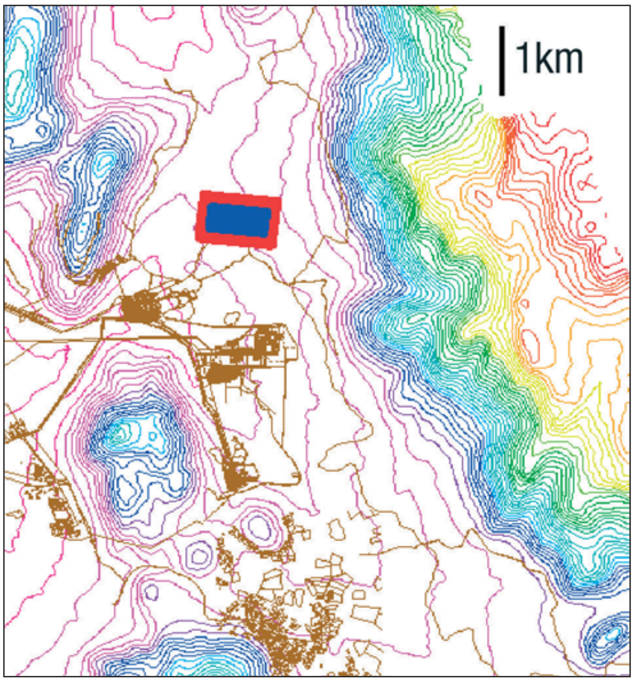

Figure 1 *Topography and location of the 3D survey.*

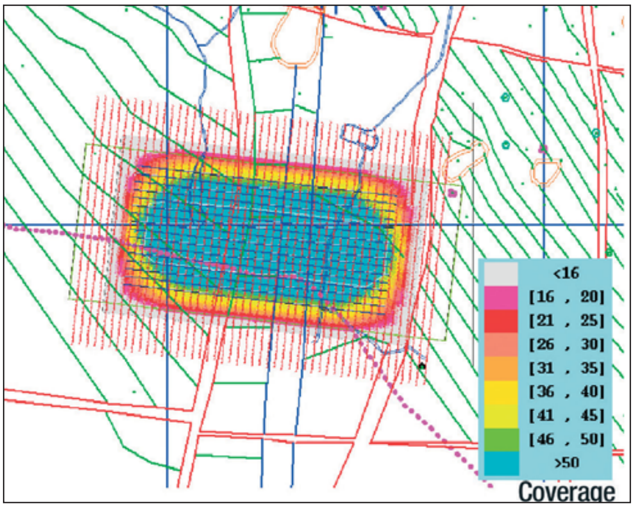

Figure 2 *Significant coverage at < 300m offset.*

Figure 3 *Sercel Nomad 65 (26,700 KN).*

The distance between receiver lines and between vibrator lines was set at 20 m, as short offsets were important because of the shallow target depth (Figure 2).

Acquisition

The acquisition of 3048 VPs was made with a patch of 16 lines of 140 traces. A single N65 vibrator (Figure 3) was deployed using a sweep range of between 40 and 250 Hz with a 50% drive and an adapted sweep to compensate for the loss of groundforce observed between 100 and 150 Hz during individual VP tests made over the entire survey area (Figure 4).

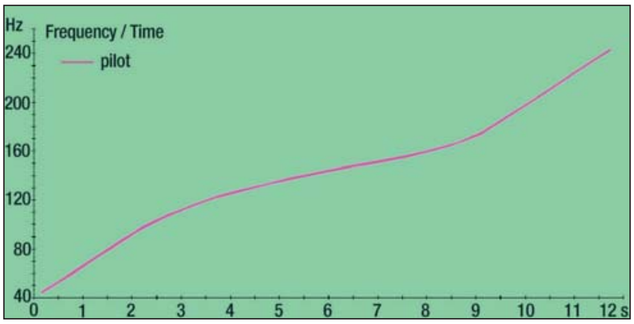

Figure 4 *Ramp of the sweep selected after testing.*

Standard processing

Statics solutions

The preliminary statics were computed with the general linear inversion (GLI) 3D refraction method, designed to pick and interpret first break data, and a two-layer near surface geological model was derived to compute our statics solution (Figure 5). The application of statics to a single VP is shown in Figure 6.

Automatic residual statics computation

Surface-consistent long and short wavelength residual statics were performed with a small, shallow window due to the shallow geological context.

FKx-Ky filtering

A 3D filter was performed in the FKx-Ky domain. The process is conducted on cross-spread gathers after gain recovery and primary static corrections (Figure 7).

Velocity analysis

The stack image obtained at this stage is not very sensitive to velocity variations; it is therefore possible to deliver a correct stack image with a somewhat inaccurate velocity (approximately + or –5%). Figure 8 displays constant-velocity stacks with large steps of 600 m/s per panel, which are required to see visual changes in the stack image.

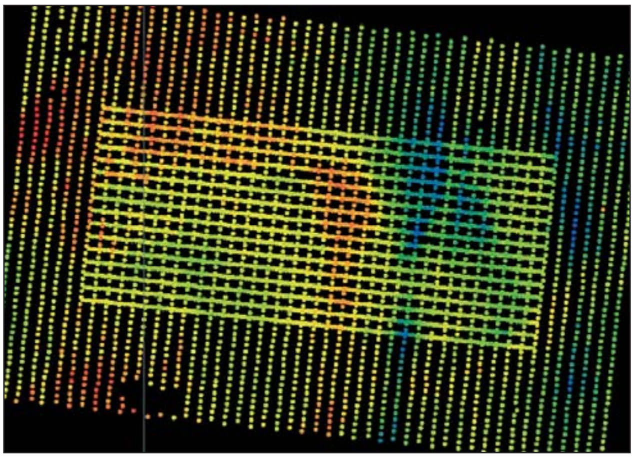

Figure 5 *Static corrections derived from the GLI method (static values ranged from 2.6 to 35 ms).*

An additional problem is posed by the thickness of the weathered layer (WZ), which can be up to 50 m. This is a significant thickness compared to the target depth (100-300 m) and the WZ velocity is therefore expected to have an impact on the RMS velocity.

Frequency content and NMO stack

Once the correct velocity functions had been defined, the usual problem of NMO stretch had to be resolved by definition of a very precise mute function. The NMO stretch problem is particularly acute in this case where the target is at a shallow depth. A test was therefore made on synthetic data to estimate the preservation of high frequencies, which are essential for ore definition.

The input model for this test is a reflection at an apex of 100 ms (twt) and a velocity of 4500 m/s; the wavelet has a bandwidth range of 30-200 Hz (see blue reflection in Figure 9).

During NMO application, the far offset traces are stretched (as in Figure 9 in red). The frequency content of the trace at 240 m offset is reduced by 10 dB at 200 Hz (this can be recovered by a simple whitening process). The resulting stack is shown in Figure 9 in green.

This test clearly demonstrated that the potential loss of resolution induced by NMO was not a critical issue for this hard rock shallow target. However, the WZ was expected to have a much larger impact due to its absorption of high frequencies.

Post-stack time migration

Various post-stack processing techniques were tested prior to the migration and validated to increase the signal-to-noise ratio and the frequency content. These included linear noise attenuation, where a 3D FKx-Ky conical filter was applied in the inline/crossline domain, acquisition footprint attenuation, and finally spectral equalization plus a band-pass filter of between 60 to 180 Hz (central panel in Figure 10).

The limited size of the 3D surface (750 m in length) and the high-velocities resulted in a truncation of the migration operator for most data below 300 ms. It was therefore decided to apply a post-stack time migration to the final stack after linear noise and footprint attenuation. A spectral equalization (60-180Hz) and a dynamic trace equalization (L=200ms) were applied after migration.

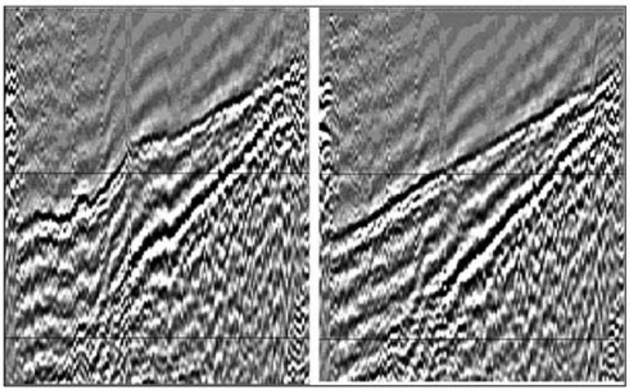

Figure 6 *Raw VP without (left) and with application of the GLI statics (right).*

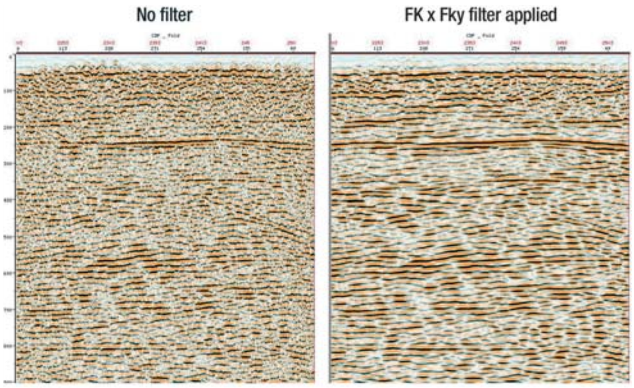

Figure 7 *Application of the FKx-Ky filter displayed on a stack.*

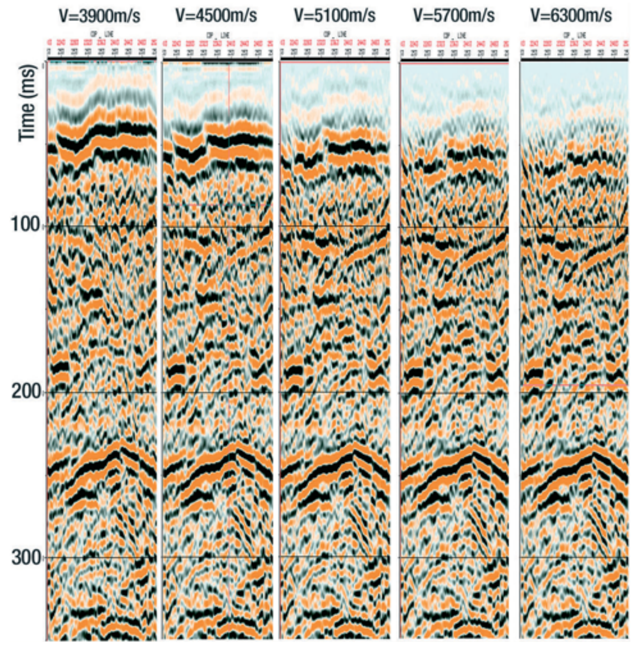

Figure 8 *Constant velocity scans for in-line section.*

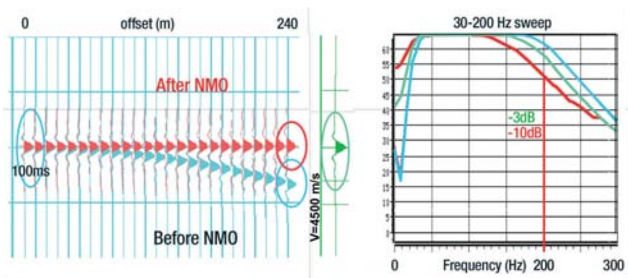

Figure 9 *Synthetic test to estimate the preservation of high frequencies.*

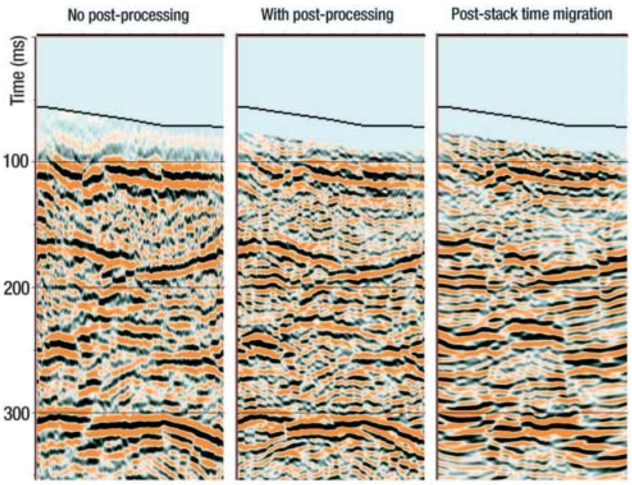

Figure 10 *Final post-stack time migration.*

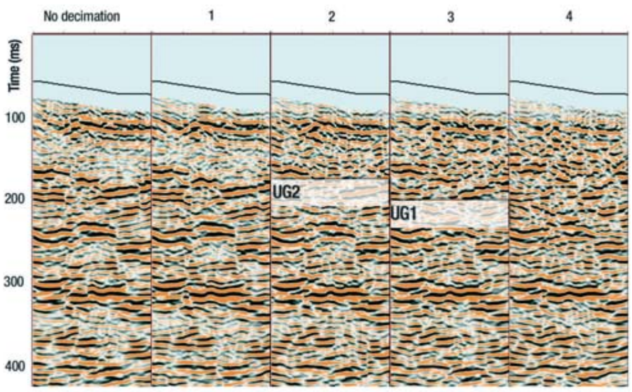

Figure 12 *Post-stack migration with post-processing for the full dataset (far left panel) and four decimations (1 to 4: the higher the decimation number, the stronger the impact of the decimation).*

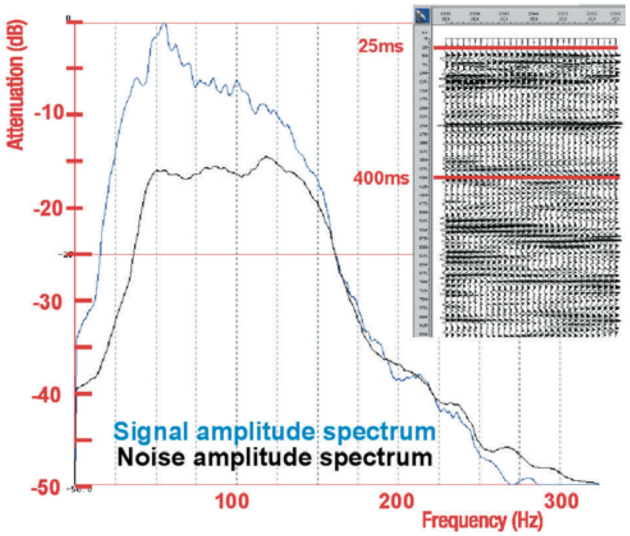

Figure 11 *Signal and noise spectra on stack. The signal and noise spectra were computed on a 25-400 ms time window.*

Conclusions

To image such shallow targets, it is important to select the right offset ranges and mute functions to ensure a high-frequency content. The ratio between the thickness of the WZ layer and the target depth ratio is high, implying that the WZ velocity will impact the stacking and migration RMS velocities.

A reasonably good signal-to-noise ratio was obtained. Figure 11 shows a NMO stack on a central line of the 3D polygon prior to the deconvolution stage together with its spectrum. The stack spectrum was compared with the noise spectrum and a good signal-to-noise ratio was noted up to 150 Hz.

This 3D HR survey was acquired as a feasibility study and the processing results prove that 3D seismic provides a reliable structural image for shallow targets (200 to 300 m below the surface at the first site and up to 50 m at the second test site). The processing results therefore provided a positive geophysical response to the client's expectations.

Decimation and pre-stack time migration

As the second challenge was to ensure the competitiveness of the seismic method, the data was decimated according to four designs (all with a 5 m x 5 m bin) and post-stack migrated. To further improve our processing effort, one of these decimated datasets was selected to run a pre-stack time migration (PreSTM) test.

Decimation

The original survey was performed with a high-density of source points and receivers. The purpose of the decimation is to obtain final results of the same quality as the original survey in terms of resolution and structural image but with sparser acquisition parameters. Comparisons were made and, as can be seen in Figure 12, the UG2 ore body at the relatively shallow depth of 230-330 m is adequately imaged up to decimation 2 while UG1 at a greater depth of 350 m is still satisfactorily imaged by decimation 3.

Decimation 2 was validated by interpreters for targets between 230 and 350 m and, as this depth is the most commonly encountered in the Eastern Bushveld, decimation 2 was chosen to perform the Pre-STM sequence. In addition, it was decided to reserve decimation 3 for targets at depths greater than 350 m. Decimation 1 must be used for targets at shallower depths.

Kirchhoff time migration

CGG's Kirchhoff time migration (known as TIKIM) was performed on pre-stack data. TIKIM outputs a migrated image resulting from the stack of all the individual traces generated

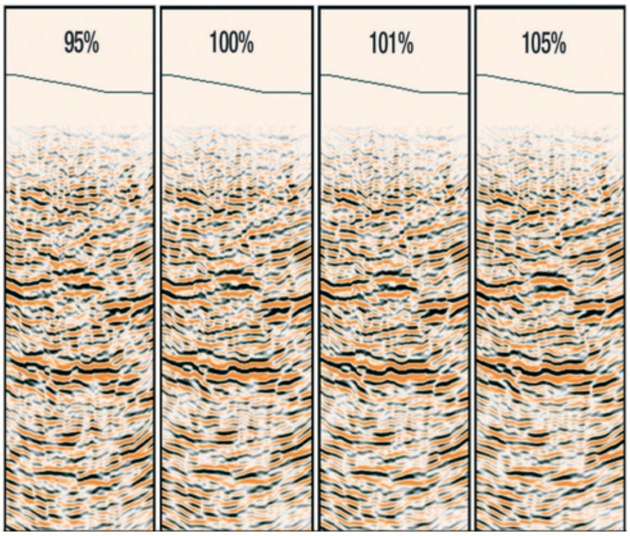

Figure 13 *Post-stack migration with post-processing for the different PreSTM velocity model perturbations (decimation 2).*

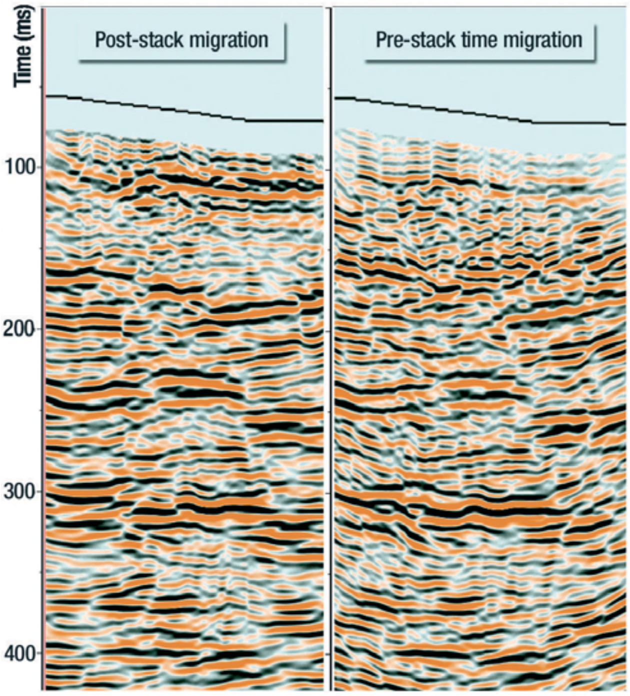

Figure 14 *Stack comparison for decimation 2 between post-stack migration only (left) and PreSTM (right).*

by the algorithm. For the purpose of velocity analysis, it is also possible to separately compute the images corresponding to different offset classes and different velocity model perturbations.

The PreSTM sequence usually runs in two parts. Firstly, the full volume is migrated with an initial (stacking) velocity field. The outputs are stack panels obtained by stacking the migrated CDPs with the perturbed reference velocity field.

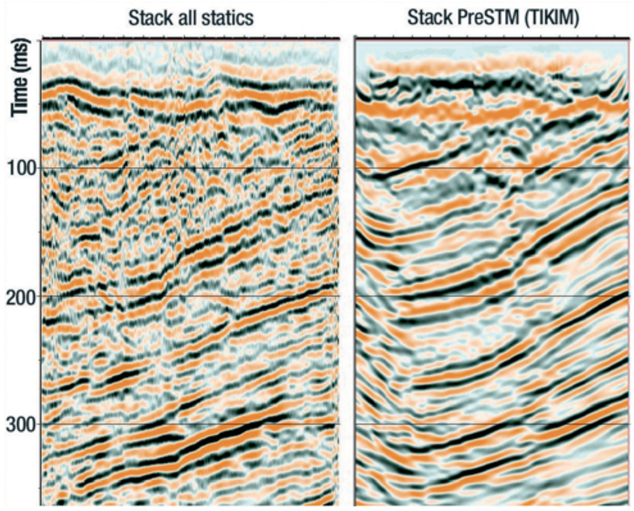

Figure 15 *In-line Stack before (left) and after (right) full PreSTM at a shallower second mine site (UG2 at a depth of less than 100 ms).*

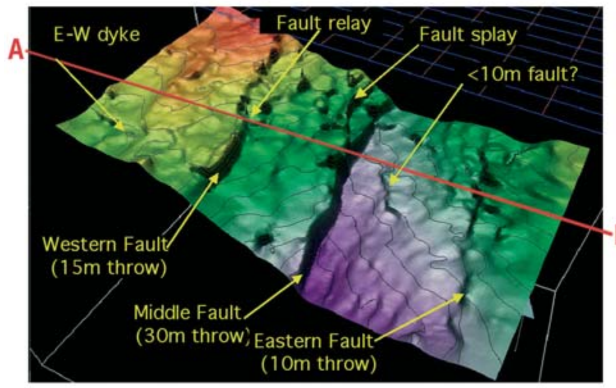

Figure 16 *Visualized UG2 surface with post-stack time migrated data.*

For this sequence, velocity perturbations were made every 1%, from 95 to 105% of the reference velocity field (Figure 13). After review of the stack panels, the client decided to perform the PreSTM with 101% of the reference velocity field. This was because the interpreter considered this percentage to give the best image from a structural point of view.

The same post-migration parameters as for post-stack processing were used to perform the full PreSTM volume (Figures 14 and 15).

Interpretation

Immediately after the acquisition phase, CGG delivered an initial seismic volume to the client, using a first-pass, post-stack time migration performed by a dedicated in-field processing centre, to enable the client to begin interpretation straightaway. Initial results from first-pass time migration (post stack) were structurally sound (Figure 16).

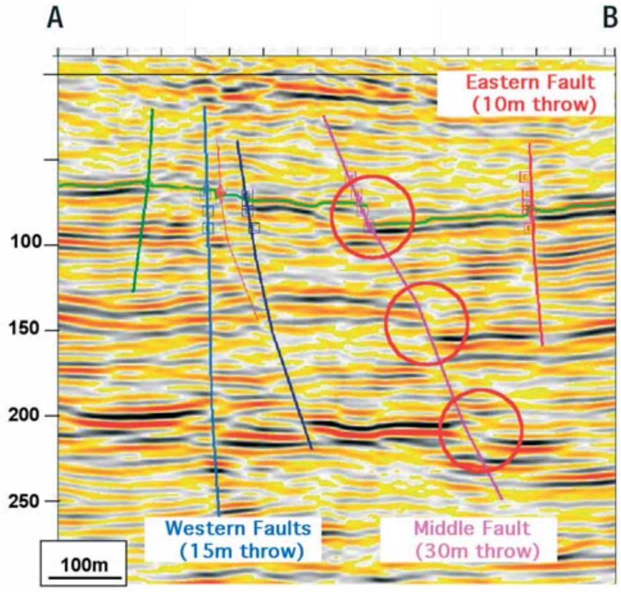

Figure 17 *Post stack time migration in-line (see location of Figure 16).*

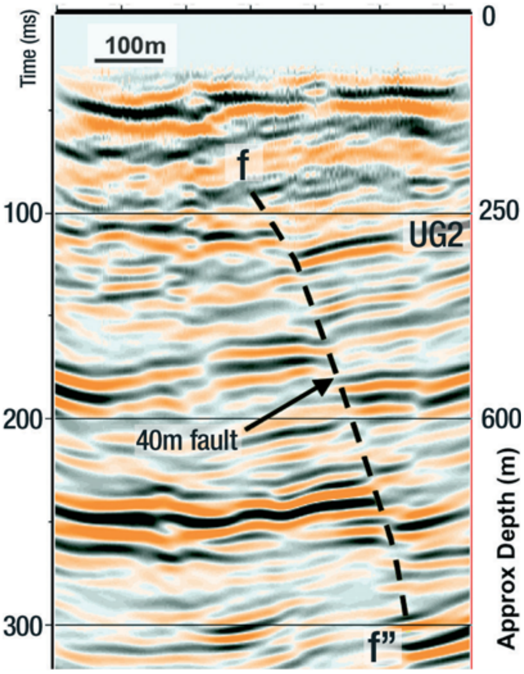

Figure 18 *PreSTM in-line showing better structural imaging.*

The post-stack time migration sequence preserved (Figure 17) a high frequency content allowing the detection of 8-m fault throws, which corresponded to client specifications. However, it did not produce as good a structural image as the PreSTM cube (Figure 18) as some fault diffractions are visible (see red circles in Figure 17).

Both processed cubes are therefore necessary for interpretation.

Final conclusion

These 3D acquisition trials proved the economic (decimations 2 and 3) and geophysical effectiveness (decimations 1 to 3) of such surveys at very shallow depths and their competitiveness compared with extensive drilling campaigns for imaging target depths beyond 150 m. The use of a high-frequency Sercel N65 vibrator contributed greatly to the successful achievement of such a challenge, and computation of the finest static model possible was also a key success factor.

Acknowledgement

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