Squeezing Every Last Drop Out of a Coarse 3D Oil Sands Dataset for Refining 3D Survey Design – A Case History*

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Abstract

The Alberta oil sands form one of the largest bituminous hydrocarbon reserves in the world (ERCB 2011). Most of the oil sands properties are too deep for traditional open mining techniques and require the application of in-situ thermal recovery processes such as Steam Assisted Gravity Drainage (SAGD). In SAGD, 8 to 10 pairs of horizontal wells, 100m apart and a kilometer long, are drilled parallel to each other. The well on the top of the pair is used to inject steam, which melts the bitumen by heating. The bitumen seeps down towards the bottom producing well, which pumps out the bitumen to the surface. As bitumen is produced, a steam chamber grows around the well pair. The growth of the steam chamber is non-uniform and mainly controlled by the stratigraphy of the reservoir (mud bodies acting as baffles or barriers), the pre-existing structural framework (faults, joints, etc.), the respective fluid saturations and mobility, and the local in-situ stress field. To understand the geological setting, the burial history, and to characterize the reservoir and monitor the growth of the steam chambers, 3D (and 4D) seismic surveying is the method of choice.

Numerous papers have been published regarding the extraction of the petrophysical properties of the oil sands reservoirs from seismic data (Xu and Chopra 2009, Gray 2011, Roy et. al., 2008, Solano and Schmitt 2004), the very near surface effects (De Meersman, 2011), or the geomechanical effects of the thermal recovery processes (Kendall and Wikel, 2012). However, limited material has been published regarding the design of 3D and 4D seismic surveys in the oil sands. In this case history, we demonstrate the cyclical process of seismic survey design, data acquisition, data processing and quantitative interpretation, followed by a survey design refinement.

Geological Setting

The project is a commercial SAGD scheme in the Athabasca oil sands, Alberta. The geology at the site is very complex, and can be divided horizontally into five sections with section 1 being the topmost: 1) thick Quaternary section that forms most of the overburden, 2) Cretaceous section that is very muddy and acts as the cap rock, 3) Cretaceous McMurray oil sands reservoir, 4) Devonian carbonates, and 5) pre-Cambrian basement (Figure 1). The Quaternary is made of glacial tills (mostly sands, gravels, silts and clays), buried channel systems and former glacial lakes. It was subjected to multiple glacial and interglacial intervals, periodically covered with an ice-sheet that carried and deposited glacial drifts. At the base of the Quaternary, a major unconformity corresponds to a period of erosion of the Cretaceous sediments from the late Cretaceous to the early Quaternary. Below this unconformity, the Clearwater and Grand Rapids formations are mostly shaley, and form the cap rock. Under this cap rock lays the notoriously complex McMurray reservoir that comprises interbraided channel systems and inclined heterolithic stratifications (I.H.S.) that vary from clean sand beds to silty muds. At the base of the reservoir, there is a major unconformity that spans more than 200 millions years, resulting in an extremely rough weathered surface with paleo-topographic highs and lows that are riddled with sinkholes (Altosaar, 2013). This geological setting is difficult enough to image, but to complicate matters further the structural framework of these formations includes duplexes, collapse features, compaction induced faulting, etc.

Acquisition Parameters of the Legacy 3D Dataset

The legacy 3D survey, shot in 2000, covers a rectangular area of about 14 km^2 and has an orthogonal geometry with the following acquisition parameters: The source line and receiver line spacing are 90m; the source station and receiver station spacing are 30m. The dynamite source has a charge size of 1/8kg at a depth of 9m. The patch consists of 10 lines x 28 receiver stations (900m x 840m). The receiver stations are made of a string of six Oyo 30CT, 10Hz geophones clumped together (no array). The sample rate is 0.5ms. The fold taper is standard i.e. a quarter of the patch size. The migration aperture includes the fold taper. The CMP bin is square and its size is 15m x 15m.

The Devonian unconformity at the base of the McMurray Reservoir is at a depth of 300 to 350 meters. Fold is extremely low in the shallow part of the section with only two or three traces per bin, while at the Devonian unconformity it is about 23 traces per bin. Assuming an average velocity of 2200m/s, for this bin size the maximum un-aliased frequency is around 73Hz for a minimum opening angle of 30 degrees (diffraction energy). When this survey was acquired, it was considered a very dense survey. Unfortunately, the frequencies that are required to achieve the resolution that we desire today are much higher. To make matters worse, the velocity profile is atypical i.e. it does not continuously increase as a function of depth and shows strong velocity inversions within the Quaternary (Figure 2), which will affect velocity model building and reservoir characterization. These velocity inversions are likely due to the transport and deposition of faster material by the ice sheets during the period of glaciation.

Time and Depth Imaging

In the study area, all of the geological layers are within the first 400 milliseconds of the seismic sections. In the past, these 3D datasets were processed with a post-stack migration flow. They were reprocessed in 2012 with an amplitude friendly multi-azimuth pre-stack data processing flow, in both the time and depth domains. The goal of the reprocessing was to assess whether pre-stack imaging, including 5D interpolation to emulate a much denser acquisition, could improve the resolution of the seismic volumes. Although the differences between post-stack and pre-stack volumes are subtle when looking at in-lines and cross-lines, they are more pronounced on time slices and attribute volumes. In particular, on the pre-stack volume, the topography of the Devonian unconformity is more detailed than on the post-stack volume. This is of primary importance as the SAGD horizontal well will be located just a few meters above it. The improvement in imaging of the pre-stack depth migration volume over the pre-stack time migration volume is also clear. Not only do the wells tie in depth at the cap rock and at the Devonian unconformity, but the structural positioning and definition is better. The depth migration is multi-azimuth and anisotropic, with the data being migrated from the base of the weathering layer (Charles et al 2008). Because different types of anisotropy (Figure 5) may be present in the data and are spatially variable, evaluating the anisotropic parameters was very difficult for this dataset.

However, the improvement in spatial resolution from post-stack to pre-stack was minimal, despite the 5D interpolation having reduced the bin size to 7.5m x 7.5m. Much greater spatial resolution improvements were evident on the high-resolution 2D lines described below. Decimation tests performed on one 2D line showed that, when the receiver spacing is kept constant, the resolution slightly decreases as a function of the fold. Since both the coarse 3D and the high-resolution 2D lines have almost identical source and geophones characteristics, this dramatic improvement in seismic resolution is predominantly controlled by the source and receiver spacing as well as the source line and receiver line spacing. In cases where heterogeneities in the subsurface have not been well illuminated, 5D interpolation, cannot recover the perturbations in the wavefield caused by these heterogeneities. Although 5D interpolation is a very useful tool to interpolate un-aliased data, regularize the seismic data coverage and reduce migration artifacts (Trad 2009, Downton et. al., 2012, Cary and Perz, 2012), it is clearly not a substitute for high density, high resolution, seismic data acquisition in this geological setting. It is simply not possible to obtain, or even come close to, the imaging quality of the high-resolution 2D lines using current processing technology on the existing sparse 3D acquisition data.

High-Resolution Test Lines

Last year, we acquired several high-resolution 2D lines in the study area to assess the Earth response, and determine what acquisition parameters would be required to achieve the desired resolution. For these lines, the source and receiver spacing are both 5m, with sources located at the receiver midpoints. All receivers were single 3C geophones. Some lines were shot live three times, with source depths of 6m, 9m, and 12m. Test shots were fired at both ends of one line with varying charge size and depths (examples are shown in Figure 4).

Comparing shot records, stack sections and spectra, 1/8kg at 6m was considered the best source for this line. As expected, increasing the charge size shifted the dominant frequency of the source wavelet towards the lower end of the spectrum (Figure 4). The frequency notch due to the source ghost is at about 125Hz for the 6m shot points, at about 95Hz for the 9m shot points, and at about 80Hz for the 12m ones. The higher frequency notch is more desirable. A technique for combining shots to mitigate ghost effects and to increase the energy on the low frequency component of the wavelet was tested, but has not yet been finalized. Decimation was used to assess the degradation of the seismic image as the source and receiver spacing increases. FK spectra (Figure 6) illustrate aliasing wraparounds of the most powerful events for different receiver spacing. As expected, when the source and receiver spacing were both 30m, the resolution deteriorated to an image that is similar to the left panel of Figure 3, the existing 3D.

The converted wave results were of limited value. The PS section, scaled to the PP section, is of much lower spatial and temporal resolution. The existence and location of the conversion points varied along the reflectors making the registration and statics estimation challenging. Attenuation on the S-waves was clearly visible but difficult to compensate for. We concluded that the requirement for acquiring adequately sampled 3C data at the study area would be extremely costly and leave an unacceptable environmental footprint.

Numerous papers have been published regarding the seismic reservoir characterization of the oil sands (Xu and Chopra 2009). It has been established that there is a strong correlation between the gamma ray logs (related to the proportion of clay) and density logs (as opposed to S-Impedances) which may imply that the reservoir may behave more like a slurry than an elastic medium (Xu and Chopra 2009, Gray 2011). Oil sands facies are often defined by their percentage of clay or mud. Most published papers focused therefore on the differentiation of sands, shales, sandy shales and shaley sands. In addition, it has also been shown that the sharp velocity contrast between the oil sands reservoir and the underlying Devonian carbonates makes the extraction of AVO/AVA properties toward the base of the reservoir extremely difficult (Gray et. al., 2012). Our pre-stack deterministic inversion tests concur with all of these aforementioned findings. We found, however, that the lower frequencies are relatively weak for 1/8kg and it is therefore difficult to avoid having the inversion results not dominated by the well-driven background model.

New Acquisition Parameters

3D seismic survey design is the result of a value of information problem that makes a necessary compromise between the desired area, the achievable resolution at the primary target, the environmental footprint, and the economic constraints. Finding the right balance between these contradicting factors can be very challenging and will vary from operator to operator. We propose the following acquisition parameters for the study area: the source is dynamite, 1/8kg at 6m (minivibs where dynamite is not allowed, see Sun F., 2012 for details). Source and receiver spacing are 10m, source and receiver line spacing are 40m. The receivers are 3C phones. The minimum patch size is 25 lines x 100 stations. The migration apron is 500m. The fold taper is a quarter of the patch size.

Conclusions

The reprocessing of this legacy 3D dataset and of the high resolution 2D lines was extremely valuable not only for improving the seismic image and for identifying issues that are critical for reservoir characterization, but also for refining the survey design of future 3D seismic data acquisition at the study area. Independently of the sampling issues, complex wave-propagation phenomena occurring within the Quaternary and the McMurray reservoir prevent the multi-component data to be exploited to their full potential for reservoir characterization. Multi-component data may be used for other purposes however. Finally, 5D interpolation at processing is NOT a substitute for high density, high resolution, seismic data acquisition - it is only by investing in such surveys that the true nature of the Devonian interface can be mapped to enable more accurate and lucrative SAGD recovery.

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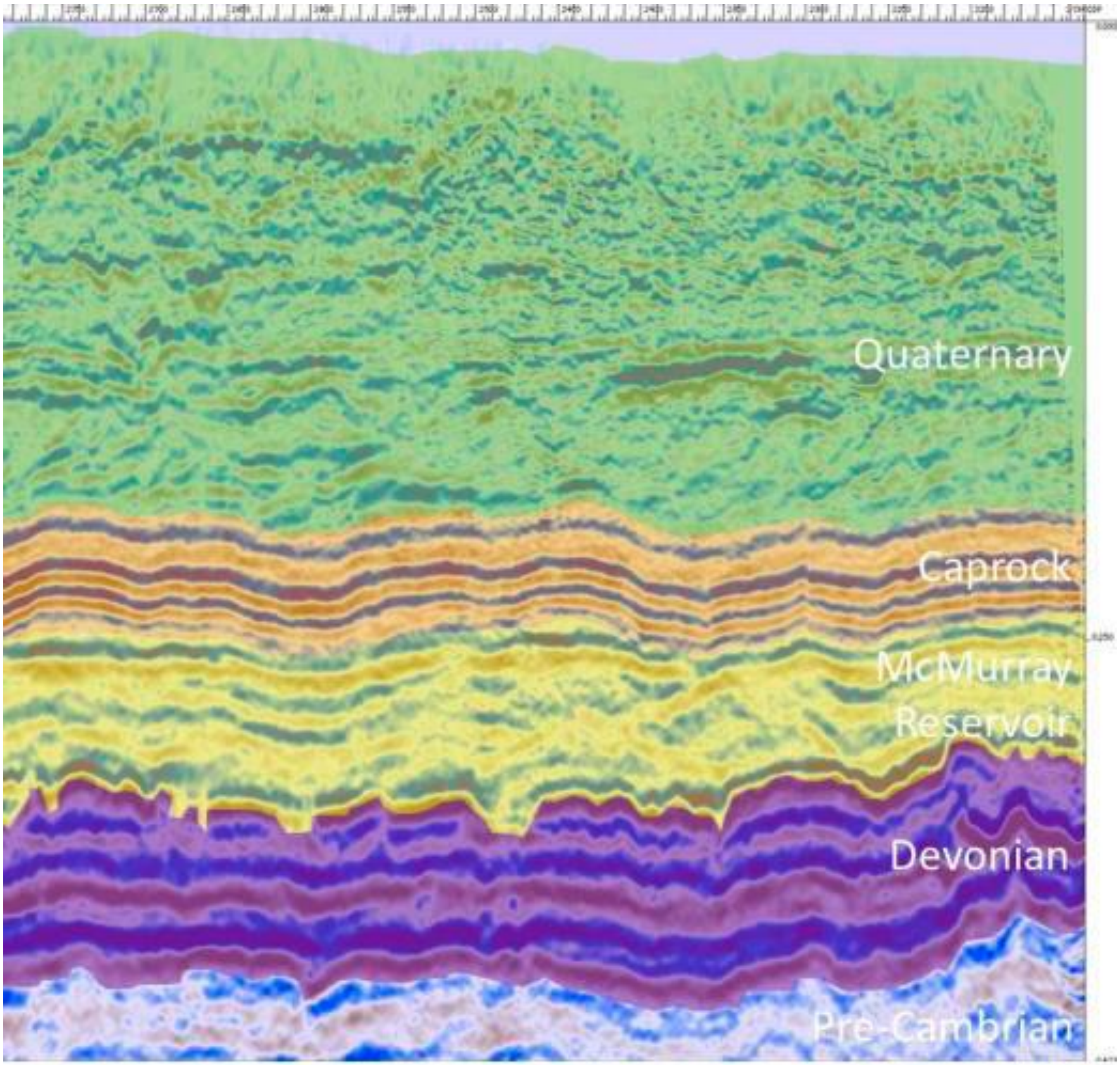

Figure 1. Main geological packages.

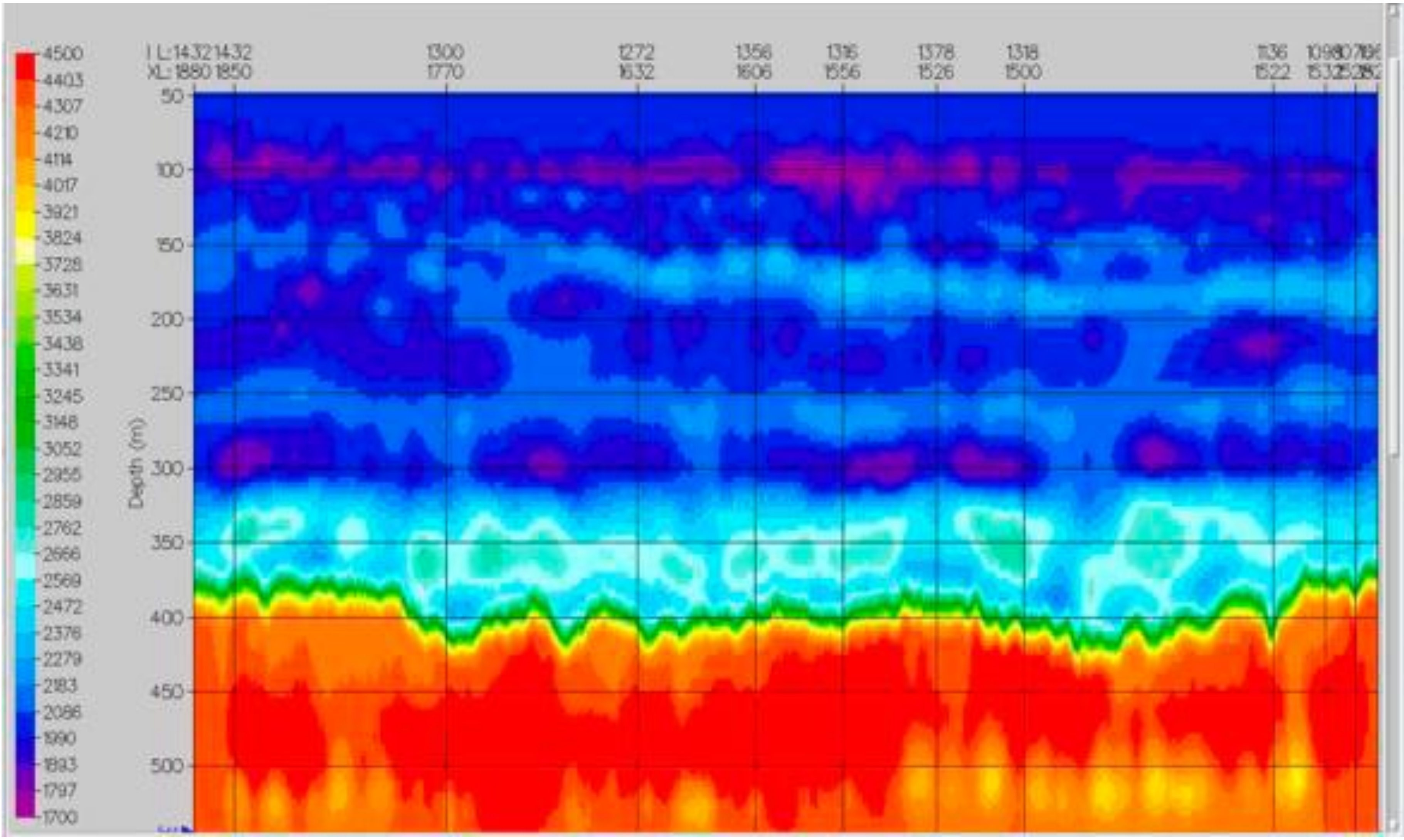

Figure 2. Velocity model along a traverse.

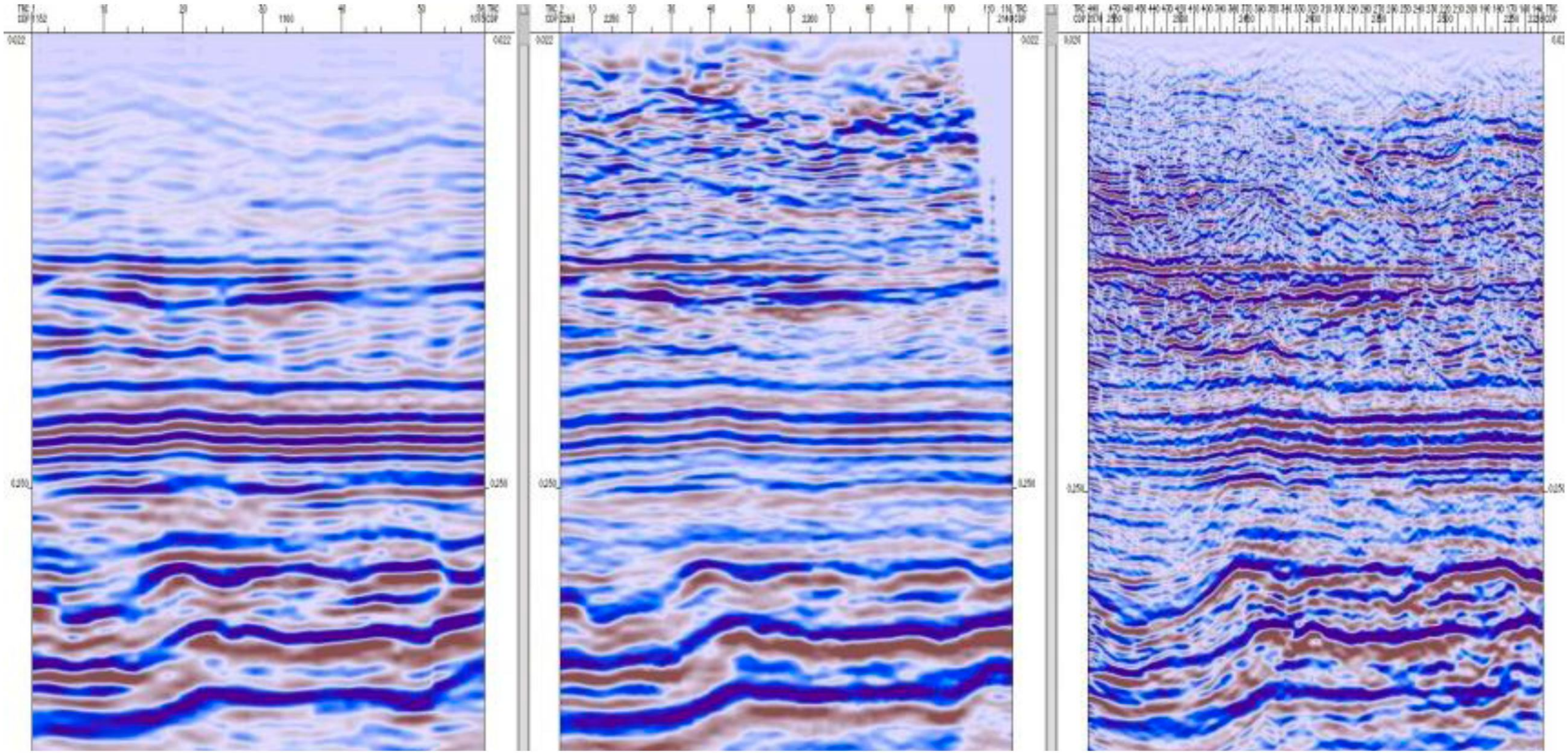

Figure 3. From left to right, 3D post-stack time migration, 3D pre-stack time migration (20 fold), 2D pre-stack time migration (60 fold).

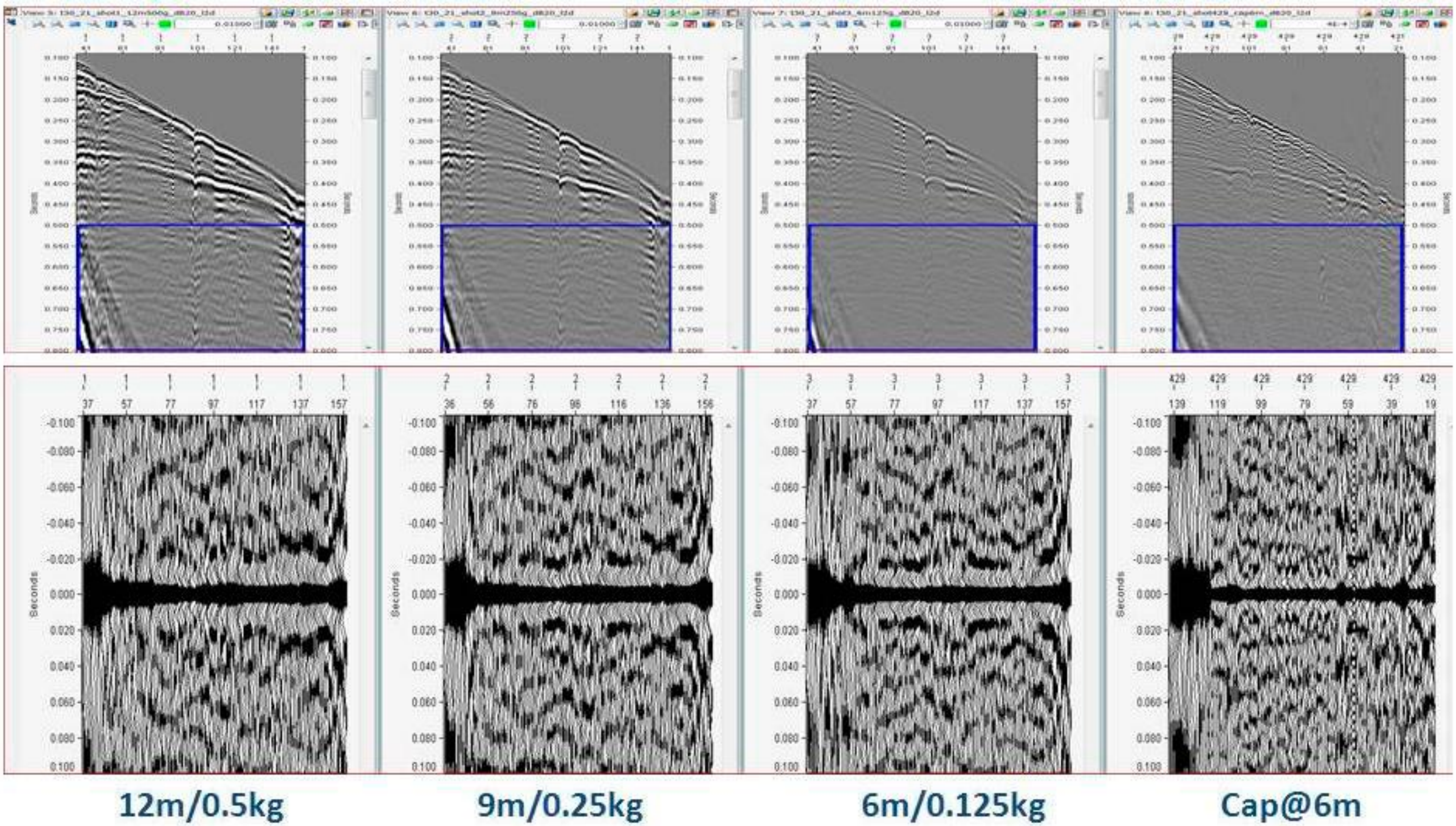

Figure 4. Test shot gathers and autocorrelation plots from a deep time window.

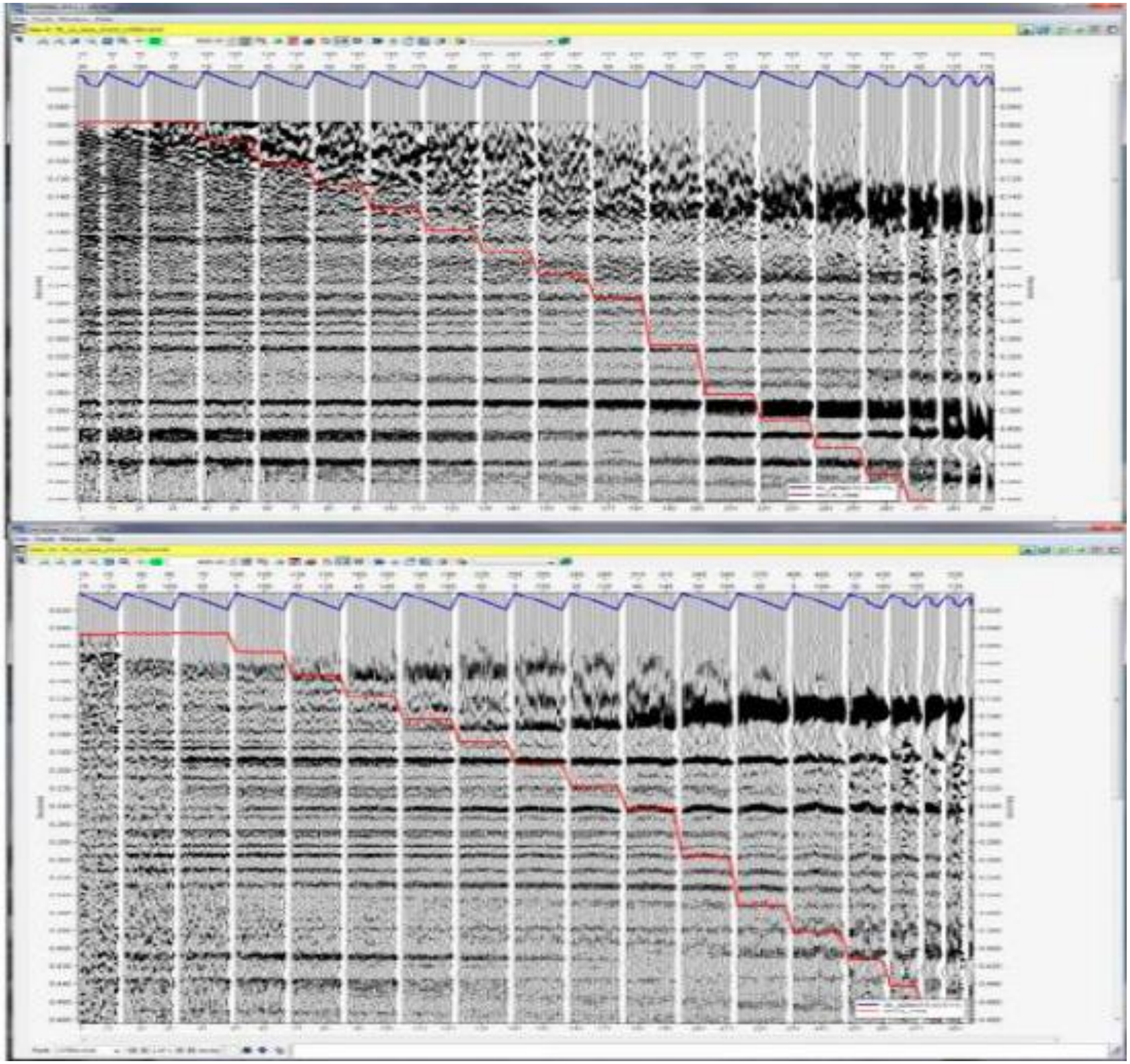

Figure 5. COCA plots at two different locations: very different azimuthal responses due to velocity and/or anisotropy spatial variations.

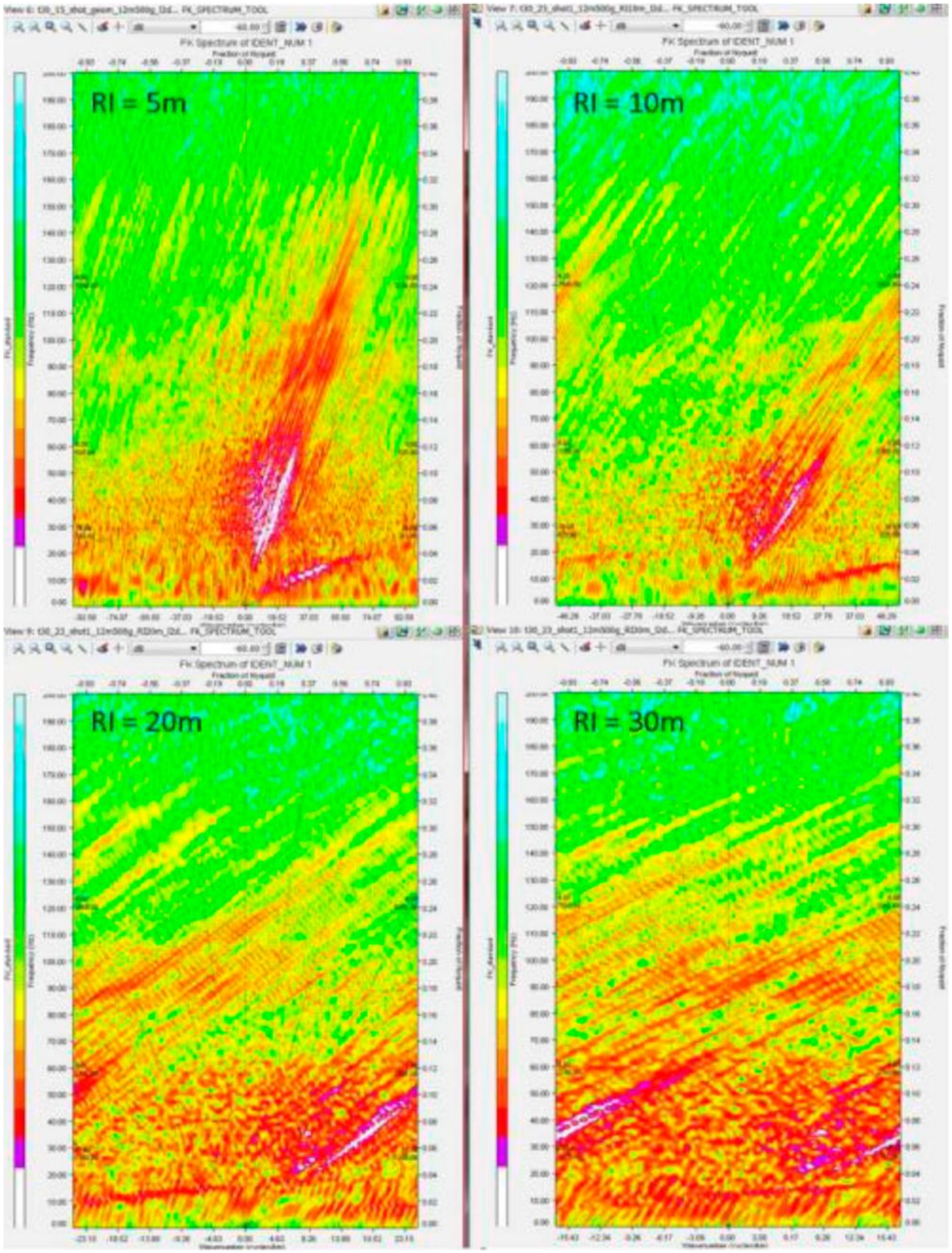

Figure 6. FK spectrum for different receiver spacing.