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Seismic feasibility tests in the Williston Basin to improve reservoir characterization

In this case study George El-Kaseeh, Niranjan Banik, Adam Koesomadinata, Mark Egan* and Antoun Salama, WesternGeco, demonstrate the benefits of a point receiver land acquisition system and dedicated processing to achieve improved resolution in a complex shale reservoir setting.

The Bakken resource of the Williston Basin produces from thin heterogeneous reservoir zones with rapidly varying lithology. Improving seismic resolution to better image these complex reservoirs is a key objective of Bakken operators. Feasibility tests have been performed to investigate the extent to which modern acquisition and processing technologies can improve the temporal and spatial resolution of seismic data in the area. The results indicate that point receiver systems can deliver data with broader bandwidth and higher signal fidelity than conventional acquisition methods. Estimations of rock properties from the inverted test data correlate with measurements from three producing wells close to the test line. Although focused on the Williston Basin, the techniques outlined in this paper are believed to be relevant to any complex onshore reservoir requiring improved resolution at either or both ends of the seismic bandwidth spectrum.

The Williston Basin is a large sedimentary basin situated approximately in the middle of the North American continent. The basin, which covers parts of Montana, North Dakota, and South Dakota, contains the largest undeveloped oil play in the USA. It also extends into the southern Saskatchewan region of Canada.

The Bakken resource resides in complex shale reservoirs containing interbedded sands, silts, dolomites, and limestones of Upper Devonian and Lower Mississippian age at depths ranging from about 7000–10,000 ft. Oil is produced from several levels, but the most notable reservoir is a dolomite layer that resides within the Middle Bakken shale formation. The Middle Bakken is usually of the order of 50 ft thick, and the dolomite layer is considerably thinner.

First production from the Bakken was in the 1950s and it peaked in 1986, after which low oil prices and low levels of production caused a decline. The 2000s saw significant increases in production thanks to rising oil prices and improvements in horizontal drilling technologies. Apart from the Middle Bakken, matrix permeability is typically low; however, optimally placed horizontal wells can intersect natural fractures that provide conduits for the oil. Artificial (hydraulic) fracturing is also frequently applied to create new fractures and widen natural fractures around a well.

The pay zone is highly heterogeneous, with lithology changing rapidly both vertically and laterally. These variations are often at subseismic scale, so despite the fact that overall seismic data quality has historically been considered to be fairly good in the Williston Basin, improving resolution is one of the industry’s key objectives. Most efforts to date have concentrated on improving temporal resolution; however, lateral resolution is also important for identifying the spatial extent of reservoirs. Indeed, as discussed by Egan et al. (2010), lateral resolution and temporal resolution are closely interrelated.

Project objectives

The key objectives of the seismic feasibility tests in the Williston Basin were to investigate the extent to which point receiver acquisition, combined with a broadband seismic source, broadband receivers, and modern data processing algorithms could improve temporal and lateral resolution relative to conventional acquisition systems. Another objective was to accurately determine porosity from the seismic data, a focus of many operators in the Bakken. An additional objective was to see if Young’s modulus could be extracted from the seismic data in order to estimate how brittle the reservoir rocks were. Brittle rocks are more prone to natural fracturing, and more conducive to artificial fracturing, than ductile rocks. They are therefore likely to deliver higher permeability.

Data acquisition

A 12 mile 2D line was acquired in late August 2009 using a lightweight, portable version of the Q-Land central recording system tailored for noise tests, proof-of-concept projects, and small surveys in difficult imaging areas. Key acquisition parameters are shown in Table 1. The line passed close to three well locations. Logs from these wells were made available to WesternGeco as a part of the study. One of the challenges was to see if well-to-well variations in production could be explained.

Improving resolution not only requires recording and maintaining high frequencies; it also benefits from extending the low frequencies. Maximizing the low-frequency signal

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content is also critically important for accurate inversion of the seismic amplitude information. To put more low-frequency energy into the ground, the seismic source used the maximum displacement sweep (MD Sweep), which delivers a predetermined vibrator output power spectral density function at the low frequency end of the sweep. The sweep started at 4 Hz.

The broadband seismic signal was recorded by geophone accelerometers (GACs), which are designed to preserve signal with less distortion of low frequencies compared with velocity geophones that are typically used for surface seismic recording. The GACs were deployed as closely-spaced point receivers, with the data from each accelerometer recorded as a separate trace. To comply with permitting constraints, the accelerometers were laid out in an inline linear fashion. Receiver spacing was 10 ft, probably denser than what was expected to be necessary. The objective of oversampling spatially was that this would enable decimation tests to be performed in the processing centre to determine an appropriate spacing for future 3D surveys. Dense sampling of point receiver data enables a wide variety of noise types (including, for example, ground roll) to be effectively attenuated by data processing algorithms, so it was not considered necessary to shoot with multiple vibrator sweeps. Therefore, a single sweep was acquired at each shotpoint location.

The raw point receiver data (Figure 1) exhibit considerable variation in noise levels between one trace and the next. This noise was generally at high frequencies. The seismic line traversed fields full of tall crops (Figure 2) and the data were acquired during a period of strong winds. It is believed that the high frequency noise is largely due to the strong winds blowing through the crops. Whatever the case, the high density of phones eventually proved to be valuable in the various digital group forming (DGF) strategies that were tried. Most of these strategies weighted the point-receiver traces that exhibited higher signal-to-noise ratios favourably.

Managing intra-array variations
Conventional seismic surveys are acquired with arrays of geophones hard-wired together to provide one recorded trace. This is a simple and robust way of reducing some types of noise, but can severely impact the quality of the
recorded signal. Intra-array statics – variations in the time of a reflection measured between one geophone to the next – represent a major threat to seismic resolution. The first stages of the processing sequence for point receiver data are designed to address these static variations.

The top panel of Figure 3 shows a window from an example point-receiver shot record that captures the main targets of interest—including the Middle Bakken. A time-dependent gain function has been applied to compensate for geometrical spreading losses, but otherwise, this is a raw record. Undulations in the reflection curves clearly show the presence of near-surface static anomalies. Indeed, some of the undulations have wavelengths that are almost as short as the array lengths used in conventional surveys, which are typically 165-220 ft [50-67 m]. The times of the point receiver first breaks were automatically picked and fed into a refraction statics program. The middle panel of Figure 3 shows the same record after application of static corrections to the point receiver data.

A study was performed to quantify the potential impact of intra-array statics on bandwidth, and hence resolution, using various simulated acquisition geometries. A synthetic hyperbolic reflection was computed for the Middle Bakken reservoir using a 4-120 Hz Klauder wavelet to simulate the correlated sweep that was used in the field. The exact geometry of the field record was mimicked in the modelled record. The statics computed from the real data were then induced into the synthetic hyperbola. The bottom panel of Figure 3 shows the synthetic reflection – with statics – that corresponds to the real data windows above it. A zoom of a portion of the synthetic reflection is displayed in Figure 4. It is evident that the statics fluctuations between these traces, which are 10 ft apart, are significant with respect to the broadband nature of the wavelet.

Group forming without intra-array corrections was applied to simulate shot records from three different acquisi-
As pointed out by Egan et al. (2010), although point receiver recording successfully preserves bandwidth through the acquisition and data conditioning steps, that represents just one link in the resolution chain. In order to maintain temporal and spatial bandwidth all the way through to the final product, care must also be taken to preserve frequencies throughout all the subsequent data processing steps. This includes using suitably small bins in the imaging steps so that the anti-alias filtering precautions that are internal to migration algorithms do not throw out the hard-earned high frequencies. Typically, adequately small CMP binning is not a problem in point receiver surveys. As an example, Figure 6 shows a VTI pre-stack Kirchhoff time migration of the test line. In this case, the receivers were digitally group formed (after correcting for intra-array effects) to 40 ft intervals, so the CMP bin spacing was 20 ft.

Inversion and estimation of rock properties
The low-frequency model was created from well data upscaled to 6 Hz and from horizons picked on the stacked

fig5.png

Figure 5 The influence of intra-array statics on a stacked trace.

fig6.png

Figure 6 VTI prestack Kirchhoff time migration of the Q-Land 2D test line.

fig7.png

Figure 7 Acoustic impedance from inversion of the Q-Land test line.

fig8.png

Figure 8 Young's modulus derived from the Q-Land test line.
data. Inversion to acoustic impedance (Figure 7) of a near-angle stack was then performed using the ISIS suite of reservoir characterization technology – a simulated annealing procedure. The Middle Bakken formation was resolvable, and hints of the dolomite reservoir within it were tantalizing.

Rock physics models subsequently enabled dynamic Young's modulus (Figure 8) to be computed (Banik et al., 2010) as well as other attributes. Analysis of these results offered a plausible explanation of why the three wells had different production rates, namely that lithology and porosity were not the only controlling factors, but brittleness was also important.

Other seismic field data owned by Williston operators were also provided to WesternGeco. These data were reprocessed and inverted as part of this study. Such data sets provided useful information because they were acquired with different acquisition geometries, different source efforts, and at different times of the year – when noise characteristics were different. The impacts of these variables on inversion and reservoir characterization are currently being analyzed.

Final remarks
The objectives of this study were to investigate the extent to which point receiver acquisition, combined with a broadband seismic source, broadband receivers, and modern data processing algorithms could improve the resolution and integrity of reservoir characterization in the Williston Basin. The results proved to be quite favorable for describing better the Middle Bakken formation and even hints of its internal layering.

In the process of the investigation, useful lessons were learned concerning the seasonal nature of the environmental noise and the variable degree of source effort, receiver spacing, and methods of DGF that would be required to address that noise in subsequent 3D surveys.

The situation discussed here represents work that is still in progress. Analyses of depth imaging considerations, prestack inversions, candidate rock models, and the other field experiments provided by Williston operators are all active projects that are nearly finished. The same is true concerning the modelling of data that would be provided by competing survey designs. The collective result is being crafted into an integrated 3D seismic workflow that is expected to deliver the next level of geo-solutions sought in the Williston Basin.

References