The Use of 3-component Seismic Data to Identify Sweet Spots in Fractured Bakken Reservoirs*

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Abstract

Differences in the seismic image of shear waves over producing wells vs. dry holes in the Bakken Formation are a key for drilling success in the Bakken. The Middle Bakken Formation in the Williston Basin has eluded detailed imaging from conventional surface-seismic methods for two reasons:

- Its thickness, typically between 15 and 60 ft., at 8,000 ft., is well below resolution of conventional seismic methods, and
- The P-wave response of seismic energy in the fractured vs. non-fractured rock is virtually identical.

Prevailing wisdom on drilling successful Bakken tests has been locating wells near subtle structural flexures where expectations that higher density natural tectonic fractures exist. The Middle Bakken Formation in Mountrail Co., ND is a tight, brittle, dolomitic siltstone with little or no native porosity or permeability. Fractures are required for reservoir to exist. Two types of fractures exist: Tectonic fractures resulting in HTI anisotropy. Difficult to see on seismic images, tectonic fracturing, manifested on tonal and landform lineaments is correlative with better Bakken production. Another fracture mechanism in the Middle Bakken, proposed by Meissner, Price, and others is hydraulic. The Bakken Petroleum System is self-sourced, and the combination of a uniquely closed petroleum system, a high thermal gradient and volumetric expansion of the Upper and Lower Bakken kerogen into oil has resulted in high potential for creating in situ fractures parallel to bedding planes. This mechanism causes horizontal fractures resulting in VTI anisotropy. The edge of the natural secondary porosity in the Middle Bakken is geographically coincident with the thermal maturity boundary. In early 2009, Vector Seismic formed a consortium to evaluate the seismic signature of fractured reservoirs in the Middle Bakken. A high-resolution converted-wave (3C) seismic profile was acquired through the Behm Energy Edwards 1-34BH Well in T154N, R88W, in Mountrail County. The line tied the dry Behm Well with Bakken producing wells in Parshall Field. The seismic signature of the waveform on the converted-wave, (P-Sr) image shows marked differences that can be correlated to natural fractures in the Bakken Formation and better production. The strong relationship between the converted-wave seismic signature and Bakken productivity suggests that polarized surface seismic data can play an important role in the successful exploitation of this play.

Discussion

In October 2008, Vector acquired and processed an experimental 2D seismic line in Mountrail and Ward Counties ND. In recent years, several operators have been successful drilling long-lateral horizontal wells in the Middle Bakken using surface seismic only loosely for approximate structural control. The efficacy of conventional surface seismic data has largely been discounted for identifying stratigraphic sweet spots in the fracture reservoirs of the Middle Bakken Formation. The seismic signature needed for delineation of Middle Bakken fracture reservoirs was beyond the resolution limits of conventional surface seismic data. Furthermore, differentiation between prolific production in the Parshall Field and the Sanish Field to the west and a dry hole was difficult. As a result, little stratigraphic quality seismic has been recorded and very few wells have been drilled with logs that allow correlation of the seismic signature with production since the discovery of Parshall Field. The Behm Edwards 1-33BH in NW NW S33 T154N R 88W, a dry Middle Bakken test drilled in February 2008, provided the opportunity for Vector to create a cross-township view from the Behm well through productive wells in both fields. Furthermore, lack of logged well control and the engineering focus on the Bakken alone may have resulted in bypassed and missed pay in shallower horizons within both fields. The Vector Parshall-Sanish test line, about 27 miles long was recorded and processed to image the transition between the dry hole on the east, the Middle Bakken production in the center of the profile and prolific production in the Sanish facies on the west.

The Bakken Petroleum System consists of a brittle dolomitic siltstone sandwiched between two excellent, kerogen-rich marine shales. An extremely slow deposition and subsidence history during the early Mississippian and an anomalously high thermal maturation gradient has resulted in a unique system where much of the oil in the Bakken Formation is self-sourced, in-place and trapped in natural fractures in the Middle Bakken. Recent official estimates from the USGS place as much as 4.3 billion barrels of recoverable oil plus 1.8 trillion cubic feet of natural gas in the Middle Bakken alone. Leigh Price, a prominent geochemist with the US Geological Survey in 1999 estimated reserves as high as 500 billion barrels from the Middle Bakken.

The Middle Bakken matrix in the fields is a very tight dolomitic siltstone and must rely on fractures to support economic accumulations of oil. Two mechanisms are responsible for the creation of natural fractures in the Bakken: Tectonic fracturing caused by lateral stress (wrench faulting) has created substantial localized vertical fracture complexes in the Middle Bakken. While generally difficult to see on surface seismic images, these can be mapped in a gross way using satellite imagery and tonal and landform lineaments. Examples of these are well known regional lineaments such as the Nesson Anticline, Wild Rose Lineament, Antelope Field, the Brocton-Froid Lineament, and a pair of NE trending lineaments bounding the core of Parshall Field. The only expected seismic expression of these features is subtle flexures or thickness variations across the faults. As most of the displacement is lateral, vertical expressions require very high resolution seismic to identify. The second fracture mechanism, and likely more prevalent is the dramatic super-lithostatic pressure increase due to chemical conversion of the in-situ kerogen into oil. This mechanism is extensively analyzed by Price (1999), LeFevre and Meissner, among others. Kerogen in the world-class marine shales comprising the upper and lower Bakken Formation have densities on the order of 1.40 g/cc, whereas the oil resulting from high thermal gradient of the kerogen is about 0.82 g/cc. (Price, 1999). The resultant ~70% volumetric increase provides huge potential energy for creation of horizontal and vertical fracture swarms in the brittle Middle Bakken.

The implications for imaging gross porosity anomalies in the Middle Bakken with seismic then are:

- Vertical fractures will likely be invisible to surface seismic. However, attributes such as azimuthal anisotropy may be useful in inferring fracture presence and orientation. Small errors in predicted seismic velocity will provide some indirect evidence of vertical fractures.
- Horizontal hydraulic fractures should be evident in subtle variations in frequency, velocity and waveform. The degree of abnormality clearly depends upon seismic resolution – both from the standpoint of acquisition parameters and processing methods. Therefore, there is a need for high-resolution, fine temporal and spatial sampling and very close velocity control. There is also a requirement for high signal-to-noise ratio.

The current state-of-the art was sufficient for most structural mapping objectives, but inadequate for stratigraphic imaging. Thus, Vector proposed a "total quality approach" including a different acquisition and processing methodologies to improve the technologies and produce a superior image.

By using a radically different approach to acquisition and processing, Vector determined to push the state of the art and make the seismic detection of Middle Bakken reservoirs feasible. To this end, a dual-source, 3-component, high-resolution 2D seismic line was recorded in TWP 152-153N, RGE 87-92W, in Mountrail and Ward Counties, ND. The line, shown on the map below (Figure 1), was designed to tie the Behm Energy Edwards 1-33BH well near the east end and track across the bulk of Parshall and Sanish Oil Fields to the west. Dozens of wells are proximal to the line, including some very prolific discoveries made after the recording of the production line, but most notably:

- Behm Energy Edwards 1-33BH NW NW S33 T154N R88W (Dry)
- EOG Wayzetta 6-12H S SE S12 T153N R90W
- EOG Wayzetta 4-16H NW SE S16 T153N R90W
- Whiting O&G Braaflat 11-11H NW NW S11 T153N R91W (IP 2669 BOPD)
- Three Forks1 Bartleson 44-1H SE SE S1 T152N R93W(IP 104BOPD, 96MCFG)
- EOG Herbert 1-26H SW SE S26 T153N R90W (IP 1267BOPD)
- Whiting O&G Liffrig 11-27H NW NW S27 T153N R91W (IP 2247BOPD, 1700MCFG)
- Fidelity E&P Annala 11-36H NW NW S36 T153N R92W (IP 1009BOPD)

The 2D line was extended east of the Behm Edwards 1-33BH well (dry hole) by approximately 5 miles in order to measure the seismic response in an area thought to be east of the productive extent of Parshall Field and to insure that a full spread and fold is available to tie this well.

The acquisition parameters used to meet the objectives above were Dual-source (Vibroseis and Dynamite), 3-component recording, 1-ms sample rate, point source, and point receiver.

Prior to the acquisition of the production profile, a comprehensive dual-source source test was conducted near the Behm well. Comparative tests were made with variable charge sizes, hole depths, and sweep parameters.

P-wave seismic profiles as seen in Figures 2 and 3 below show virtually no seismic character change between the image at the dry Behm Energy well and the producing wells in Parshall Field. However, converted wave processing and the subsequent common conversion point (CCP) stacks (seen in Figures 4 and 5) show a distinctive seismic character change in the vicinity of the fractured Middle Bakken.

The eastern edge of the Middle Bakken production has been popularly called the Bakken Thermal Maturity Boundary and is defined by the limit of self-induced hydraulic fractures created by the conversion of Kerogen to oil. This boundary can be clearly seen on the converted-wave seismic data recorded on the Vector Parshall-Sanish Test line.

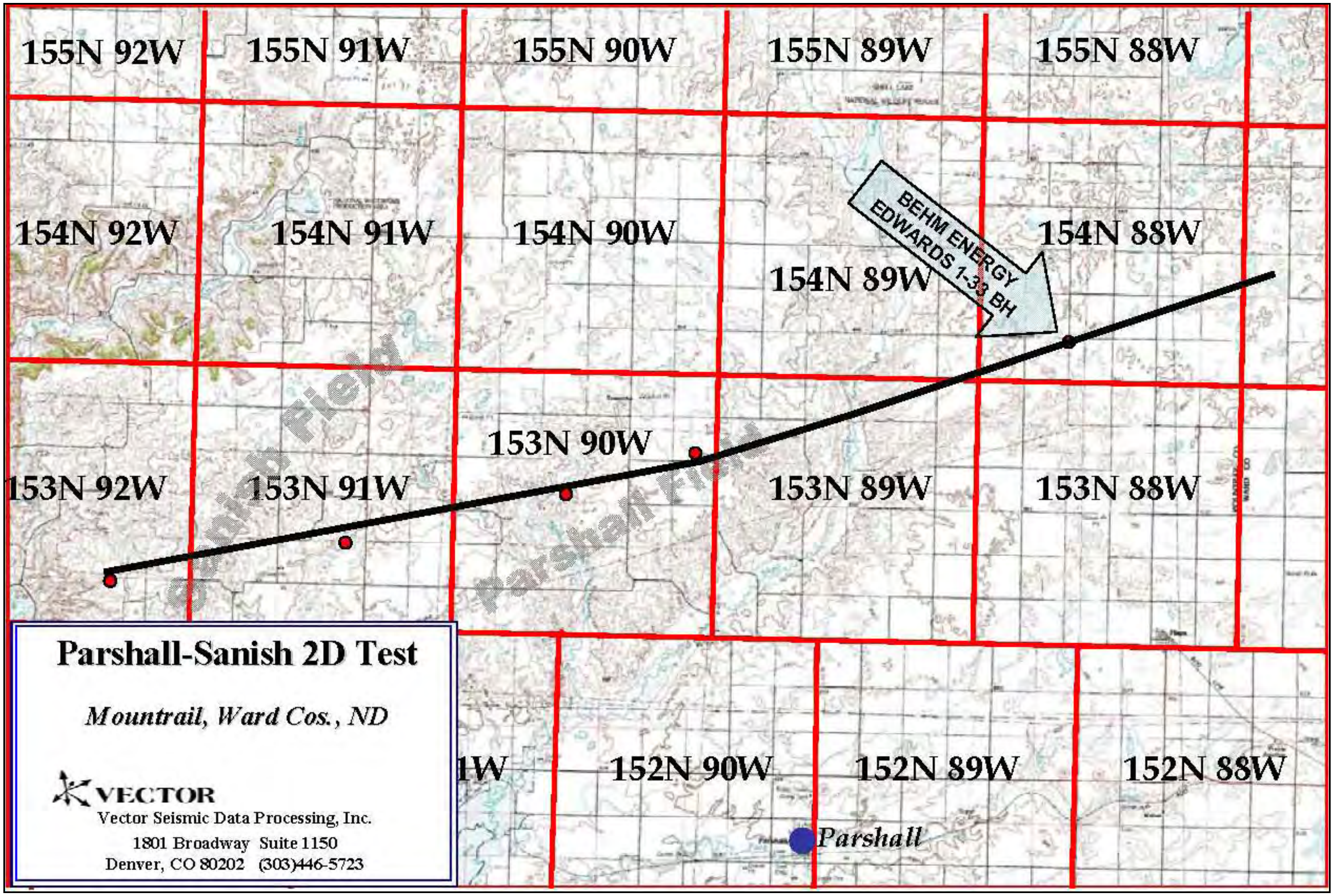

Figure 1. Approximate location of the Parshall-Sanish 2D/3-component Seismic Test. These data were acquired using both shot hole and Vibroseis sources and tied the dry hole with production in Parshall and Sanish Fields.

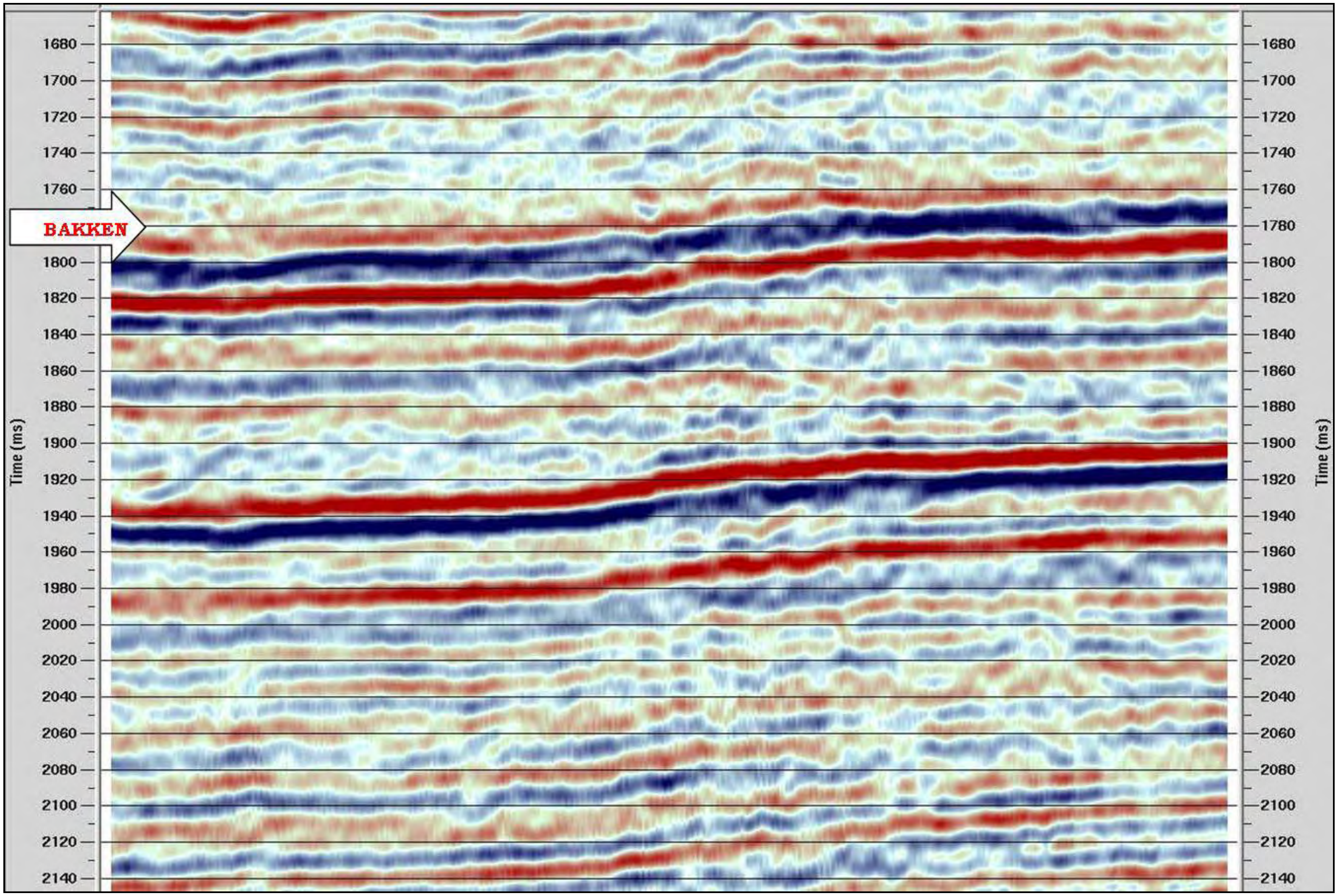

Figure 2. Dynamite P-wave seismic data near the Behm Energy 1-33BH well. This was a dry hole where no natural fractures were found in the Middle Bakken Formation.

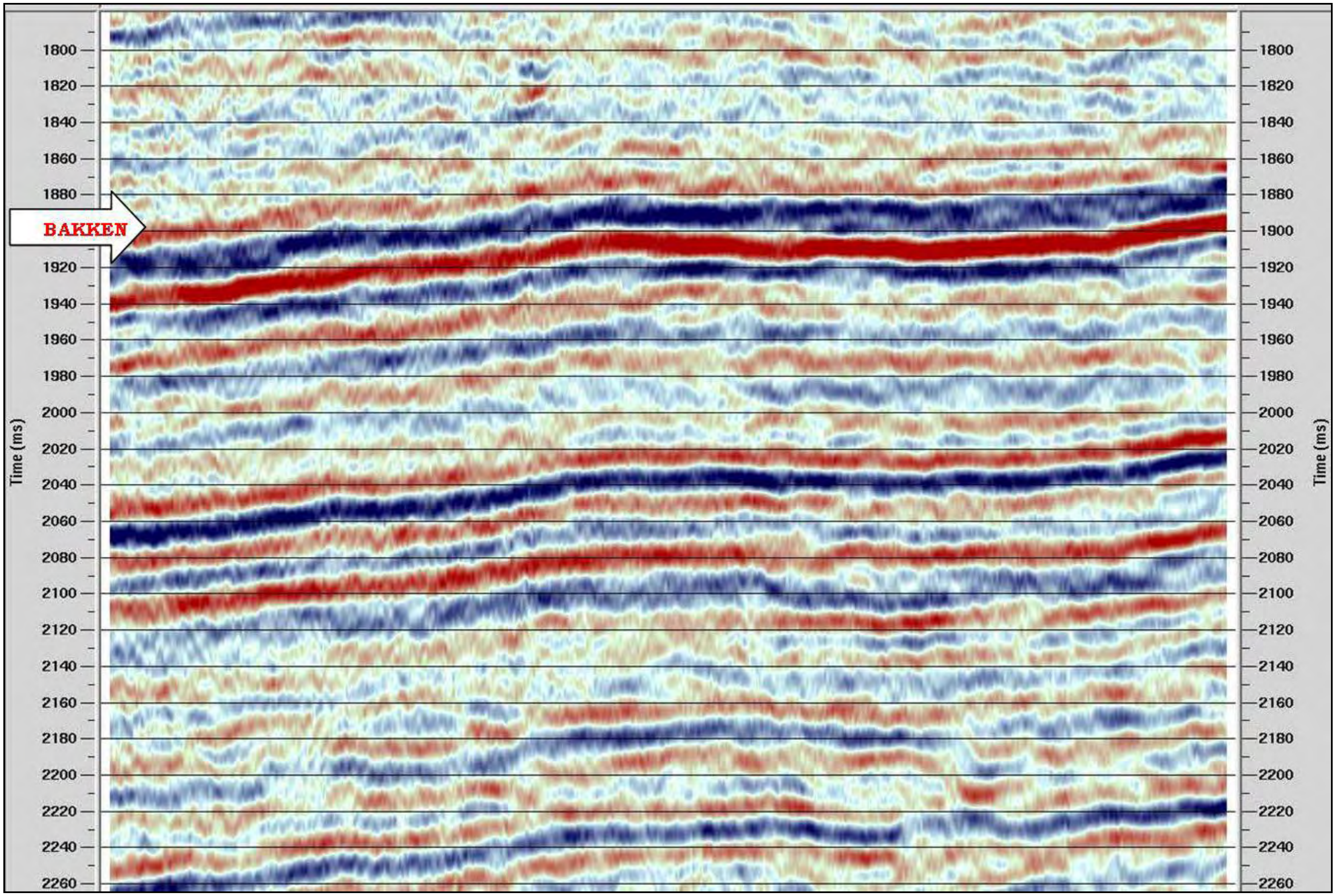

Figure 3. Dynamite P-wave seismic data from the core of Parshall Field. Note the similarity of the structural and stratigraphic image to that shown in Figure 2. This segment is proximal to a 1,250 BOPD producing well.

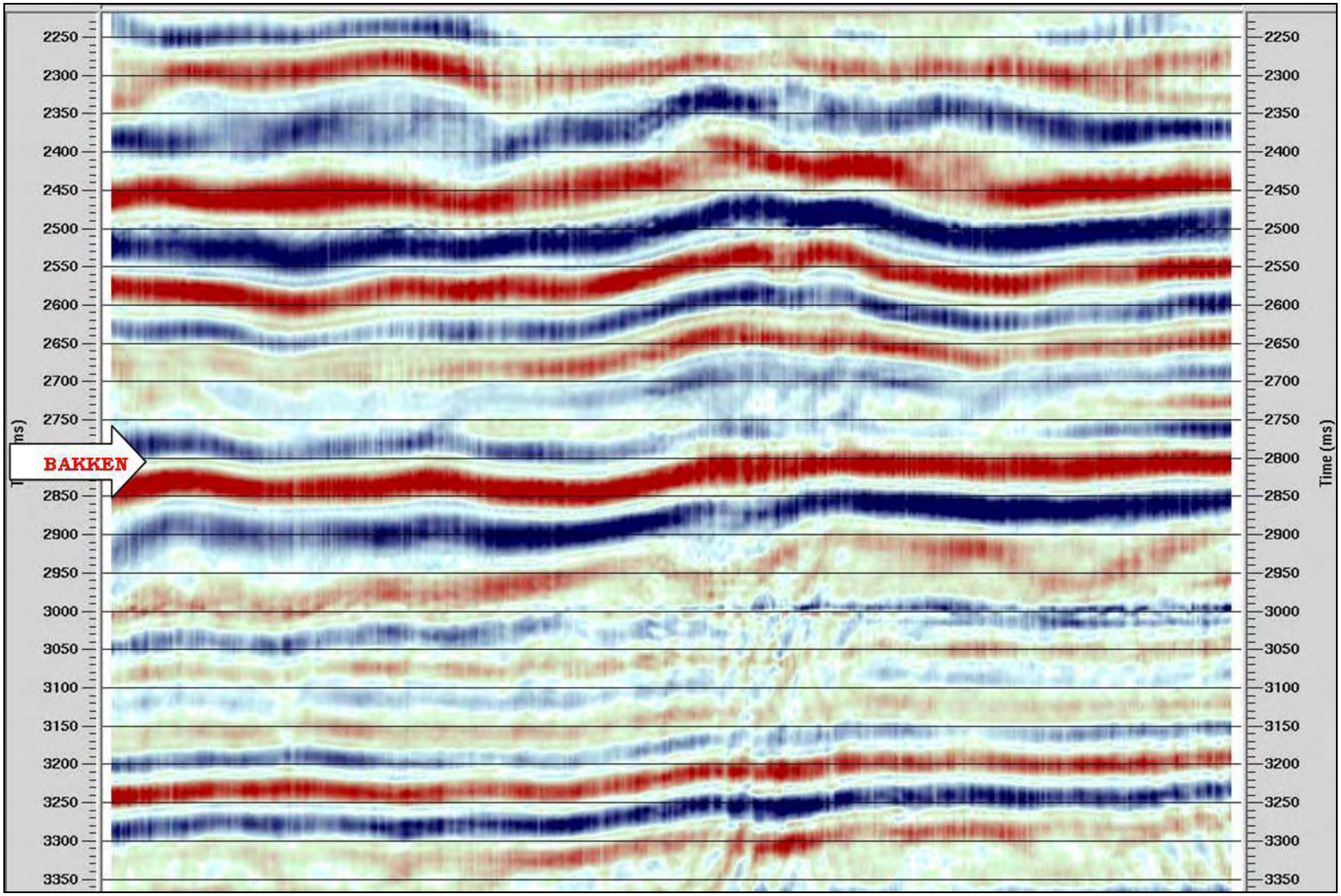

Figure 4. This is the dynamite converted-wave (radial shear) image corresponding to the P-wave section seen in Figure 2 above. Note the continuity of the Bakken reflector indicating the absence of hydraulic fractures.

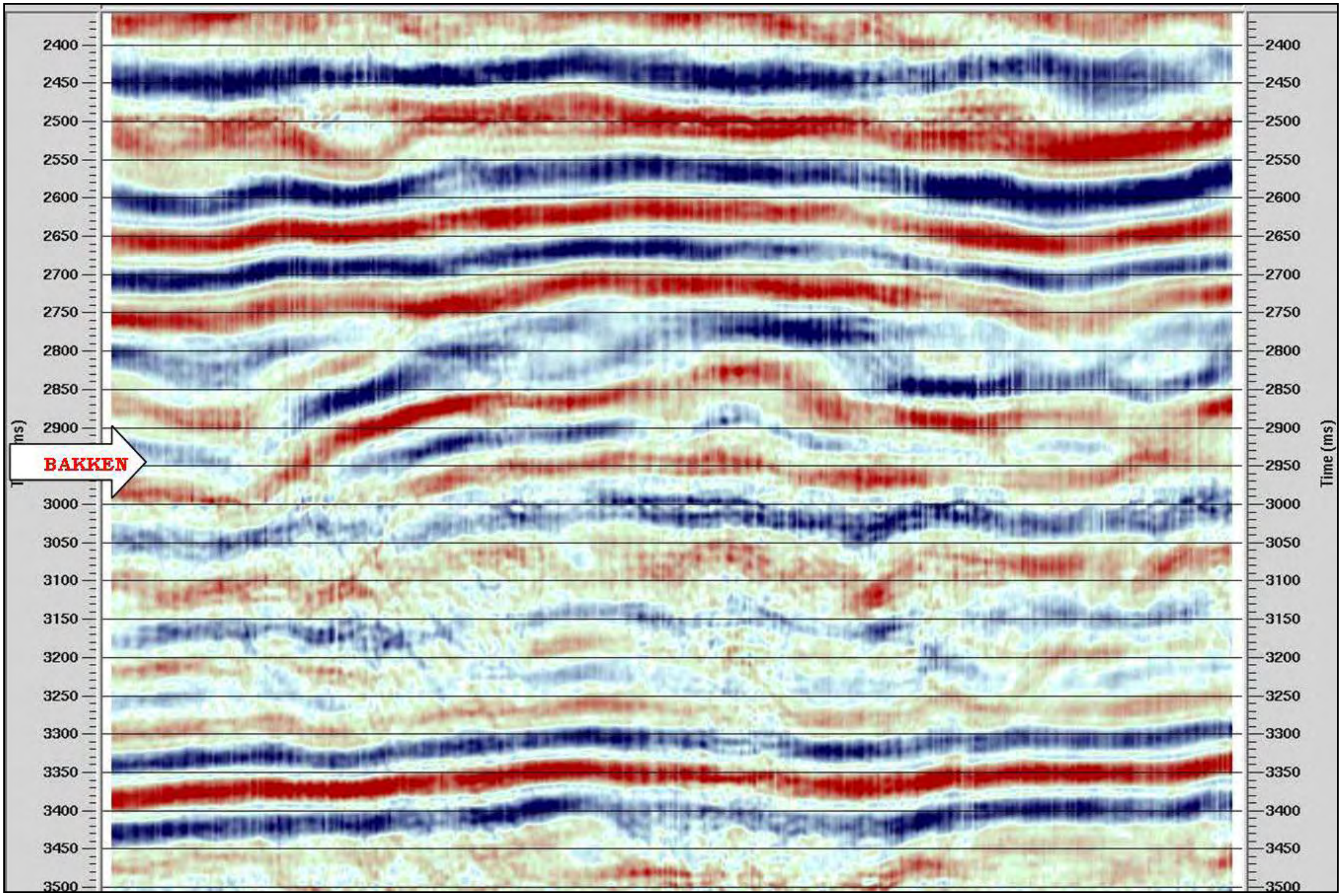

Figure 5. Dynamite converted-wave (radial shear) image corresponding to the P-wave section seen in Figure 3 above. The acoustic "time structure" is a manifestation of the rock mechanics in the presence of fractures.