Resolution Enhancement and Reservoir Characterization of a Wattenberg Field Through Wavefield Re-Datuming and Inversion

Jyoti Behura[†,*], *Pete Smith*[‡], *& Oscar Quezada*[§]

[†]*Seismic Science LLC*, [‡]*formerly Encana Corp. and currently at Geosmith Inc.*, [§]*Anadarko Petroleum Corp.*

Corresponding author's email: jyoti.behura@seismicsciencellc.com

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Abstract

Knowledge and utilization of in-situ stress and fracture distributions in the subsurface determine the operational success in most unconventional plays. Besides stress and fracture distributions, seismic attributes derived from amplitude-variation-with-offset (AVO), velocity, and attenuation analyses play key roles in the characterization and development of these plays. In this case study of the Vogl area, we use only the surface seismic data to decipher the stress distribution from azimuthal velocity analysis, fracture orientation and rock properties from azimuthal AVO inversion, and fault properties through attenuation inversion. Since the robustness and accuracy of the above attributes are extremely sensitive to the overburden effects, we utilize a novel re-datuming technique to eliminate all effects of overburden. The re-datumed common-offset common-azimuth (COCA) gathers clearly show azimuthal moveout (related to in-situ stress distribution). The re-datuming also generates high-resolution gathers and enhances the signal-to-noise ratio which should help in geo-steering and in possibly distinguishing Niobrara and Codell formations. The azimuthal velocity analysis yields the direction of V_{fast} that corresponds to the direction of maximum stress. The study shows that this direction for the Niobrara-Codell formations in the Vogl area is predominantly W-E and WSW-ENE. The attenuation attribute shows that the regional fault oriented N-S within the Vogl area is of significantly lower attenuation compared to the surroundings. The most likely explanation for such low attenuation is that the fault has undergone calcite mineralization and is therefore sealing. Such an inference has major implications for not only field development but also for environmental impact of hydraulic fracturing because this regional fault would not conduct hydraulic-fracturing fluids to the surface. The AVO attributes show a distinct change across the regional fault which again points to the possibility of the fault being sealing. Such a contrast might arise from differences in pore-pressure or in lithology. Moreover, the AVAZ attribute is similar to the V_{fast} direction which indicates that the dominant fracture direction coincides with the in-situ maximum horizontal stress direction.

Introduction

The Wattenberg Field is a part of the Denver-Julesberg Basin and is located in Colorado. The Vogl seismic data used in this study comes from the Wattenberg area.

The Niobara and Codell formations are the main producing intervals in the Wattenberg Field. These formations are tight, i.e, their permeability and porosity are quite low because of which horizontal drilling followed by hydraulic fracturing is the preferred completion strategy used in these formations. Natural fracture systems in these formations contribute significantly to the permeability. Also, the geometry of the induced fractures from hydraulic fracturing are controlled by the existing natural fractures and also the present-day in-situ stress state. It is clear from multiple case studies that knowledge and utilization of in-situ stress and natural fracture distributions in the subsurface determine the operational success in most unconventional plays. The aim of the work presented here is to extract natural fracture parameters and in-situ stress state in this area *accurately* using surface seismic data. In addition, we aim to extract rock properties derived from AVO, velocity, and attenuation analyses that play key roles in the characterization and development of these plays.

In this case study of the Vogl area, we use only the surface seismic data to decipher the stress distribution from azimuthal velocity analysis, fracture orientation and rock properties from azimuthal AVO inversion, and fault properties through attenuation inversion. The 3D seismic data used in this work has excellent fold coverage as well as azimuthal distribution which makes it an ideal candidate for wide-azimuth processing and interpretation.

Since the robustness and accuracy of the above attributes are extremely sensitive to the overburden effects, we utilize a re-datuming technique to eliminate all effects of overburden. The re-datuming process also enhances the resolution and signal-to-noise ratio of the seismic data. For the above reasons, the re-datumed data is ideal for traveltime and amplitude inversion. We perform azimuthal velocity analysis (assuming Orthorhombic anisotropy), interval attenuation analysis, and AVO/AVAZ inversion on the re-datumed gathers.

Processing

Minimal processing of the raw gathers is conducted so as to preserve amplitudes. The processing steps include

- shot-strength correction
- datum statics corrections
- noise suppression

The seismic data is a merge of two different surveys which necessitated the application of a scalar to correct for the amplitude discrepancy. Receiver amplitude scaling was not necessary.

All elevations of shots and receivers were equated through the application of datum-statics corrections using a replacement velocity of 1300 m/s. The data were thereafter binned using a CMP bin radius of 70.7 m and a bin spacing of 100 m in both X- and Y- directions.

Since our aim was to preserve amplitudes, we performed a conservative noise suppression that eliminated most of the high amplitude energy in the near offsets and most of the random and cultural noise. The noise suppression algorithm is based on a time-frequency domain thresholding operation. We chose parameters to ensure that the reflection amplitudes near the target zone (Niobrara and Codell reflection) were not affected.

Re-datuming

Mulder (2005) states that, "Redatuming is an operation on seismic data that accounts for translations of the positions of sources or receivers, or both. It can be used for various purposes, for instance, to improve the result of imaging algorithms that require regular acquisition geometry or to remove the effects of irregular topography from the seismic data. Another application is the simplification of the processing and interpretation of data recorded in areas with a complex near-surface geology." Multiple re-datuming methodologies exist that achieve the above-mentioned goal; almost all of them, however, need the knowledge of the velocity field to do an accurate re-datuming. Therefore, re-datuming is a complicated process especially when the overburden is laterally heterogeneous, anisotropic, and attenuative. If not properly accounted for, the hundreds of feet of overburden, with its complicated anisotropy, scattering effects, and attenuation, can leave a significant footprint on the attributes derived from seismic data. Here, we eliminate the overburden effects using a *velocity-independent wavefield re-datuming technique* that simulates a virtual acquisition at a user-chosen datum. The benefit of this re-datuming technique is that it does not require any material properties of the overburden.

For the Vogl data, we simulate a virtual acquisition at the base of the Pierre Shale which is a reflector at 1.4 sec and forms the new datum (Figure 1).

The output data are in the form of common-offset common-azimuth (COCA) gathers at each CMP location. A COCA gather consists of traces sorted according to increasing offset; for each offset, traces corresponding to azimuths 0° through 180° are displayed. In the presence of azimuthal anisotropy, a sinusoidal moveout is expected with azimuth for every value of offset (traces within any two consecutive vertical lines). Moreover, the sinusoidal moveout will get accentuated with increasing offset. If the subsurface is azimuthally isotropic, there should not be any azimuthal moveout.

The geometry parameters of the generated COCA gathers are

- Minimum offset: 5 m,
- Offset increment: 5 m,
- Azimuth range: 0°-180°, and
- Azimuth interval: 5°.

From the output COCA gathers at Vogl we observe that

- the re-datumed gathers clearly show azimuthal moveout (related to in-situ stress distribution), and
- the re-datumed data is of higher resolution which should help in geo-steering and in possibly distinguishing Niobrara and Codell formations.

It is worth noting that this powerful technique minimizes processing costs, is completely data-driven, does not require any velocity information, is robust, and generates high-quality pre-stack gathers.

Inversion of COCA gathers

The high signal-to-noise ratio of the re-datumed data along with the enhanced resolution makes them ideal for both traveltime and amplitude inversion.

Prior to amplitude inversion, we extract velocity parameters using semblance analysis. In order to honor reflection coefficient changes with offset, we adopt the AVO-sensitive semblance scheme initially proposed by Sarkar *et al.* (2001) and extended by Yan & Tsvankin (2008) to wide-azimuth data. The AVO-sensitive semblance algorithm yields reliable estimates of anisotropic moveout velocities which we then convert to interval velocities. Tsvankin (2005) and Tsvankin & Grechka (2011) are of the opinion that naturally-fractured media most likely have Orthorhombic symmetry (or lower symmetry such as monoclinic). Vertical transverse isotropy (VTI) and horizontal transverse isotropy (HTI) are too simplistic models to describe these fractured formations. We, therefore, assume that the Niobrara and Codell formations have Orthorhombic and use the moveout equations derived by Vasconcelos & Tsvankin (2006) and Xu & Tsvankin (2006) in our semblance analysis. The azimuthal velocity anisotropy is sensitive to both in-situ stress and existing fracture systems.

Following interval anisotropic velocity inversion, we invert for AVO attributes of intercept and gradient and also for the anisotropic attenuation coefficient. Again, we assume Orthorhombic media for amplitude inversion and extract azimuthally-variant gradient which should be insensitive to the in-situ stress but sensitive to the difference in natural fractures across interfaces. Therefore, bed-bound fractures could be deciphered from the azimuthally-variant AVO gradients.

We also invert for interval Orthorhombic attenuation anisotropy parameters (Zhu & Tsvankin, 2007) from the

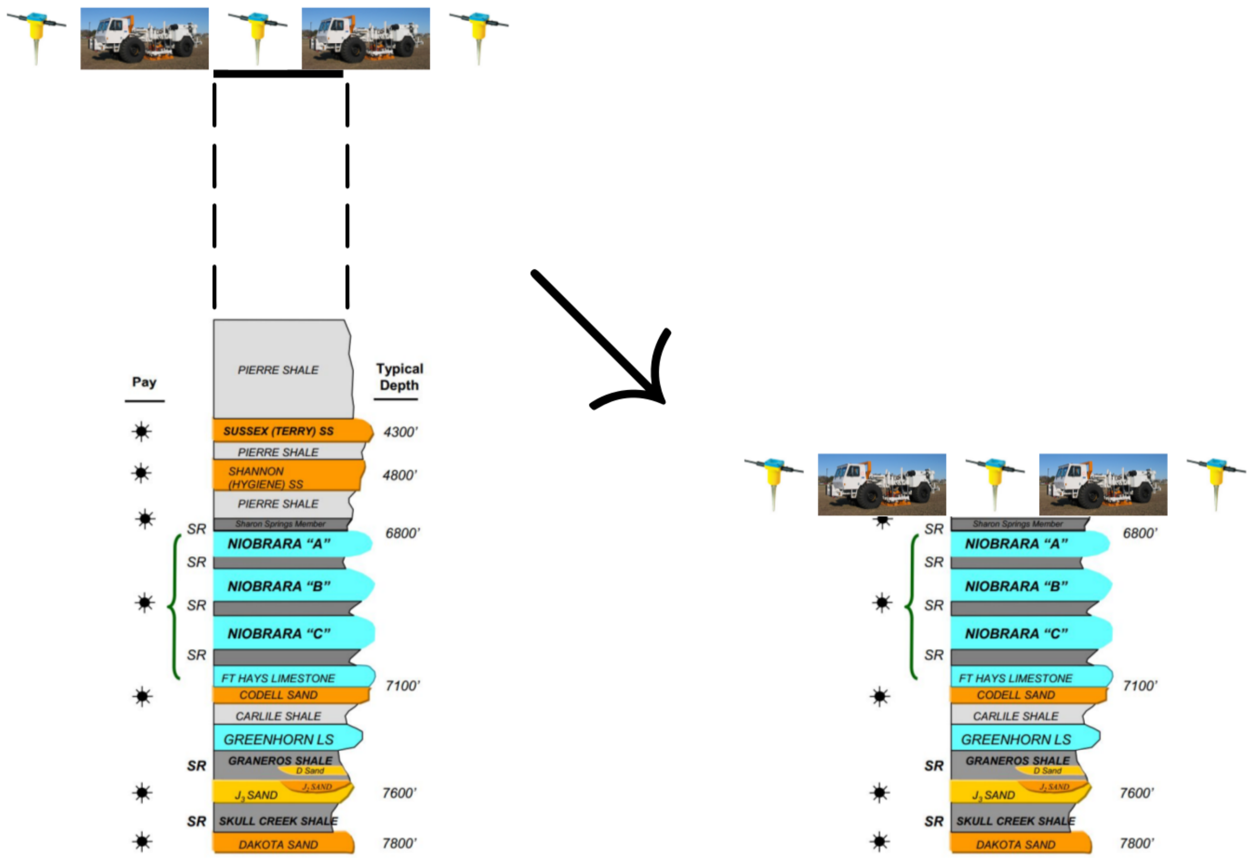

Fig. 1: Cartoon of the original datum and the new datum used for the Vogl seismic data. The original surface seismic data is re-datumed to the base of the Pierre Shale. The stratigraphic section has been modified from Sonnenberg (2013).

COCA gathers. Attenuation is closely related to the lithology as well as the presence of fluids. As discussed below, attenuation and attenuation anisotropy for the Vogl data are closely related to lithology changes in fault zones.

Results and Conclusions

The velocity and amplitude inversion results are summarized below.

- Azimuthal Velocity: The azimuthal velocity analysis yields not only the V_{nmo}^{fast} and V_{nmo}^{slow}, but more importantly the direction of V_{nmo}^{fast} that corresponds to the direction of maximum stress and fracturing. The study shows that this direction for the Niobrara-Codell formations in the Vogl area is predominantly W-E and WSW-ENE.

- Attenuation: The attenuation attribute shows that the regional fault oriented N-S within the Vogl area is of significantly lower attenuation compared to the surroundings. The most likely explanation for such low attenuation is that the fault has undergone calcite mineralization.

  Multiple lab measurements show that shales have much higher attenuation than less shaly rocks. Mineralization of the fault zone between Niobrara and lower-Pierre would make it less shaly and thereby lower the attenuation. Even if the fault zone were fractured, it is reasonable to expect that the fractures in the vicinity of the fault zone are mineralized as well, also resulting in lower attenuation. Moreover, if our interpretation of fault mineralization is correct, we would expect the attenuation anisotropy to be negligible, i.e. we should observe isotropic attenuation in this zone. That is indeed the case, where the attenuation anisotropy parameter is close to zero in the fault zone.

  The shales, on the other hand, exhibit strong attenuation anisotropy as expected. Moreover, the anisotropy parameter should be negative for shales (multiple published lab studies) and that is exactly what we observe on field data.

  Fault mineralization would also imply that it is sealing. Such an inference has major implications for not only field development but also for environmental impact of hydraulic fracturing because this regional fault would not conduct hydraulic-fracturing fluids to the surface.

- AVO and AVAZ: The intercept and gradient attributes for the Niobrara reflection show a distinct change across the regional fault which again points to the possibility of the fault being sealing. Such a contrast might arise from differences in pore-pressure or in lithology. Moreover, the AVAZ attribute is quite similar to the V_{nmo}^{fast} direction which points to the possibility that the dominant fracture direction is similar to that of the in-situ maximum horizontal stress direction.

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