Niobrara Fracture Prospecting Through Integrated Structural and Azimuthal Seismic Interpretation, Silo Field Area, Wyoming*

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Introduction

A large multi-client, full-azimuth 3D seismic survey of almost 800 square miles acquired by Global Geophysical Services in southeastern Wyoming is the basis for a regional structural interpretation and azimuthal analysis of the Niobrara in the area of the Silo Field, in the northern end of the Denver Basin. The unconventional Niobrara oil and gas play has been compared to the Bakken in North Dakota, but variable well results have long plagued operators. Silo Field has produced about 10 million barrels of oil since 1981, but well rates can vary drastically over a short distance. The goal of the study is to illustrate how advanced geophysical technologies will permit better understanding of risk through an integrated, regional understanding of structural setting, seismic rock properties, and fracture prediction.

The Niobrara Formation or Niobrara Chalk in the Denver and Raton basins was deposited from Northern New Mexico to southern Wyoming in the Late Cretaceous Western Interior Seaway that extended from Western Canada to the Gulf of Mexico. The Niobrara, a self-sourcing unit of alternating chalk and shale is the source rock for the billion barrel Wattenberg field as well as the Silo field in SE Wyoming. The formation is overpressured and has open natural fractures providing a permeability network in a generally low-permeability section. Porosity is generally between 5-10%. Well costs are typically half those of the Bakken Formation in the Williston Basin (Montana and North Dakota). Typical weight percent values for TOC (Type II kerogen) in the Niobrara are 2-3 %; considerably leaner than the Bakken and somewhat leaner than the Eagle Ford. Typical drilling depths in the study area are 7500-8500 feet.

Natural fracturing in the Silo Field area is a major factor influencing well performance and ultimate recovery of Niobrara oil. The cause of fracturing is widely debated and has been attributed to many variables: basement faulting, salt dissolution, lithology variations, compaction over basement highs, hydrocarbon expulsion, strike-slip faulting, uplift, and the present-day stress regime. Our approach to understanding the Niobrara fracturing is to integrate:

1) seismically derived rock attributes;
2) well and production data; and
3) regional structural interpretation.

Our preliminary results are presented below.

Seismic Rock-Property Analysis

Full azimuth imaging and analysis for this large 3D survey is providing better data for interpreting the deep structural framework and improved regional insight into the variability of the Niobrara - offering clues to optimal well placement (Figure 1). Rock-property analysis of the Niobrara involved processing the 3D to address both layer and azimuthal anisotropy, creating gathers with reliable far offset amplitudes for an elastic inversion. Initial analysis of the layer anisotropy was performed on isotropically migrated gathers using a simultaneous picking tool for velocity and VTI (vertical transverse isotropy). VTI information was then used to update traveltimes and begin scanning for HTI (horizontal transverse isotropy). The approach used to define the HTI involved migrating the gathers approximately 100 times to test the impact of small changes in azimuthal anisotropy (as expressed by elliptical migration operators). The migration scanning result was used to once again update 1-D travel times feeding a second full Kirchhoff pre-stack time migration of the entire Silo 3D. Azimuthal anisotropy was mapped using vectors created from (Vfast-Vslow)/Vfast and Azimuth of Vfast volumes (Figure 1). Stress-field changes apparent from azimuthal migration scanning show a rotation of the regional background stress field from a Vfast azimuth of 140 degrees in some portions of the Silo 3D to 40-50 degrees in other parts. Open fractures should parallel these azimuthal anisotropy anomalies. Ongoing work is combining the azimuthal anisotropy results with analysis of the regional structural framework and stress field.

Well Data and Elastic Inversion

The migrated gathers were then used for an elastic inversion of the Silo 3D. Limited well data has made the initial inversion of Silo more of an attribute volume than a calibrated rock-property prediction – but useful trends appear to be present in the data. Figure 2 shows one well tie from the inversion, highlighting rock-property variations within the primary target interval – the Niobrara B1-->B2 section. The inversion shows zones that appear less ductile (more brittle) in the B1-B2 interval using a cross-plot-derived attribute based on LambdaRho and MuRho inversion products. Mapping of this package across a portion of the Silo 3D shows areas of more brittle rock – areas one would expect to have greater fracturing (Figure 3).

Structural Interpretation

Preliminary interpretation of the Silo 3D suggests that presence, direction and causes of fracturing in the area are variable and no single explanation applies to the whole region. An Archean-Proterozoic fold and thrust belt is imaged below the Niobrara in the Silo area. Paleozoic through Tertiary reactivation of these basement faults shows three major trends: NW-SE; NE-SW; and N-S (Figure 4). These basement fault trends are reflected in the younger stratigraphy, including the Niobrara.

In some parts of the study area basement faulting appears to have been active after the deposition of the Permian salt, causing widespread deformation of the salt/evaporite layers. A period of basement quiescence is reflected in the constant layer thickness of Cetaceous-age

Dakota and Niobrara Formations. Laramide-age shortening deformed both the cover and the basement in the area, creating the broad high, NW-SE-trending uplift, related to the Silo field and north-south-trending anticlines on the western edge of the 3D area. Some of the faults that cut the Niobrara can be directly linked to underlying reactivated basement faults (Figure 5b), whereas other Niobrara faults (Figure 5a) appear to have no direct correlation with the basement. The large NW-SE-trending strike-slip fault zone that goes through the Silo Field is a reactivated basement fault that may have controlled the location of the Permian salt basin and was later used as an accommodation zone linking shortening along N-S-trending basement thrusts with NW-SE-trending basement thrusts.

Future Work

Our results to date suggest that the Niobrara has been a difficult play because fracturing is highly variable and may not be caused by a consistent set of variables everywhere. By understanding the structural segmentation of the area and combining that with rock-property analysis, azimuthal-anisotropy results and well data, we are in an excellent position to understand past well performance and predict areas of future potential.

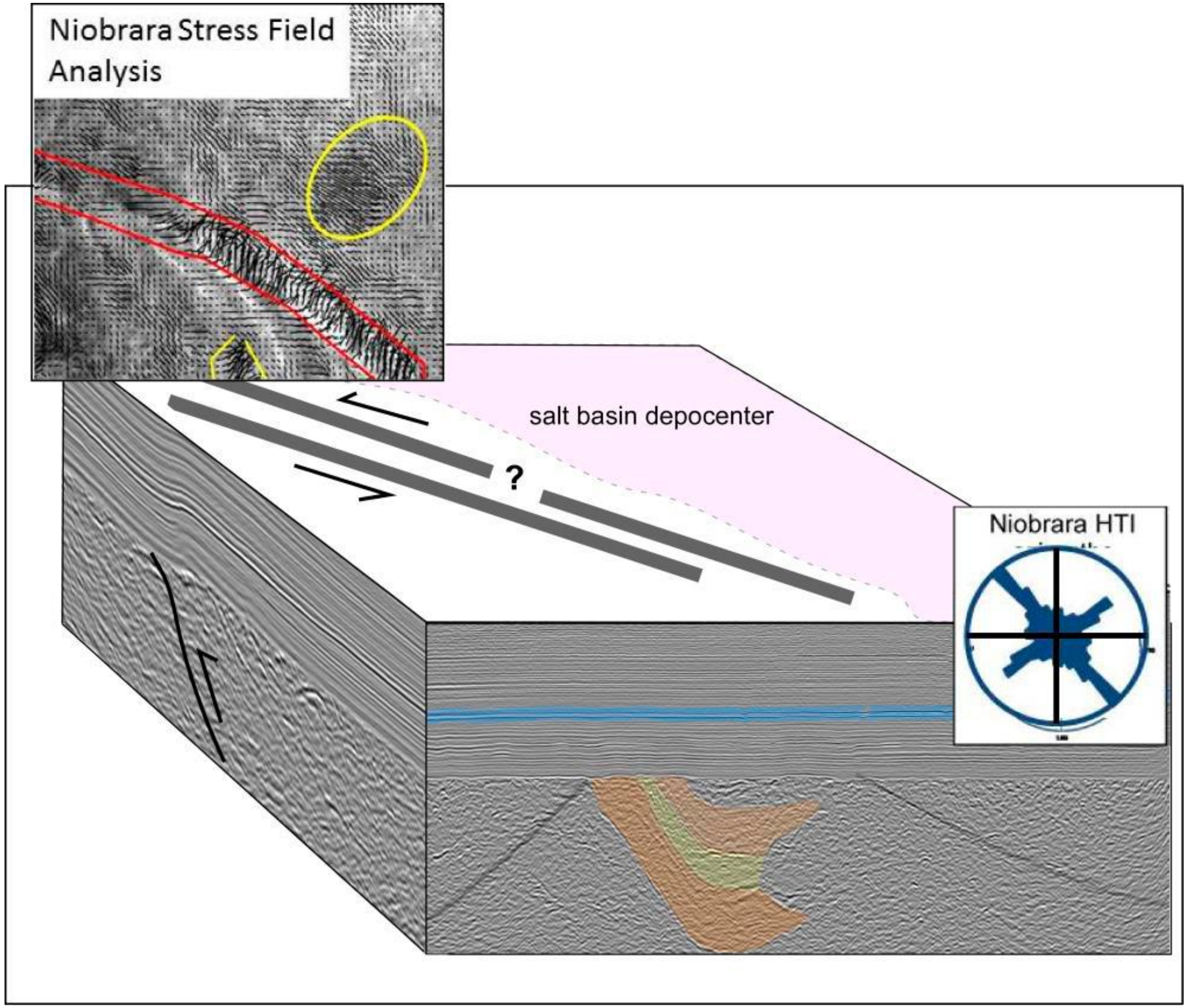

Figure 1. The multi-client 3D survey offers the potential to combine azimuthal-anisotropy results with an analysis of the regional structural framework, basement and salt deformation, and stress field.

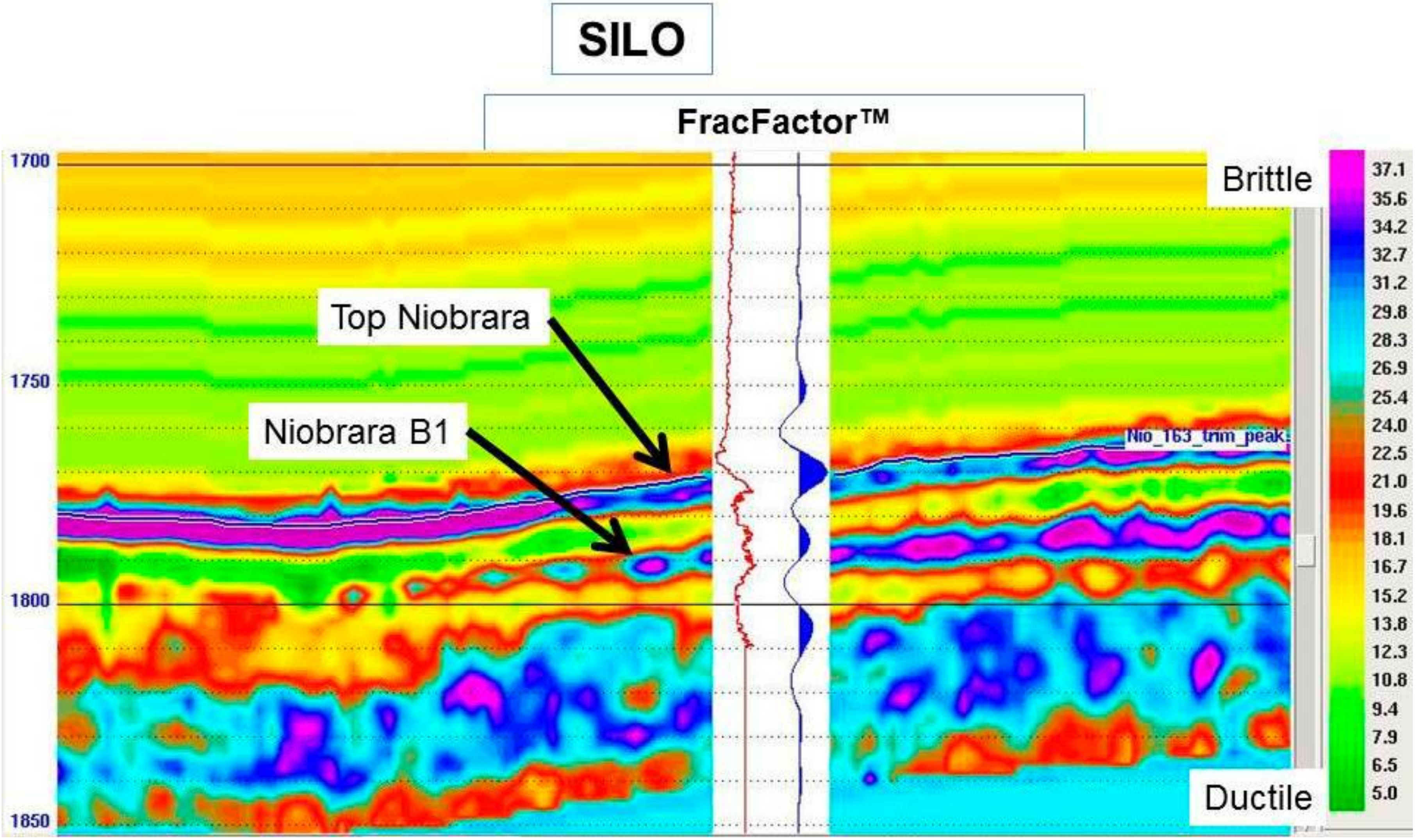

Figure 2. Well tie synthetic and inversion result illustrating spatial changes in the Niobrara B1 (and B2) approaching Silo field from left to right. The stronger purple colors from the inversion indicate increasing brittle rock predicted from a LambdaRho-MuRho inversion product called FracFactor.

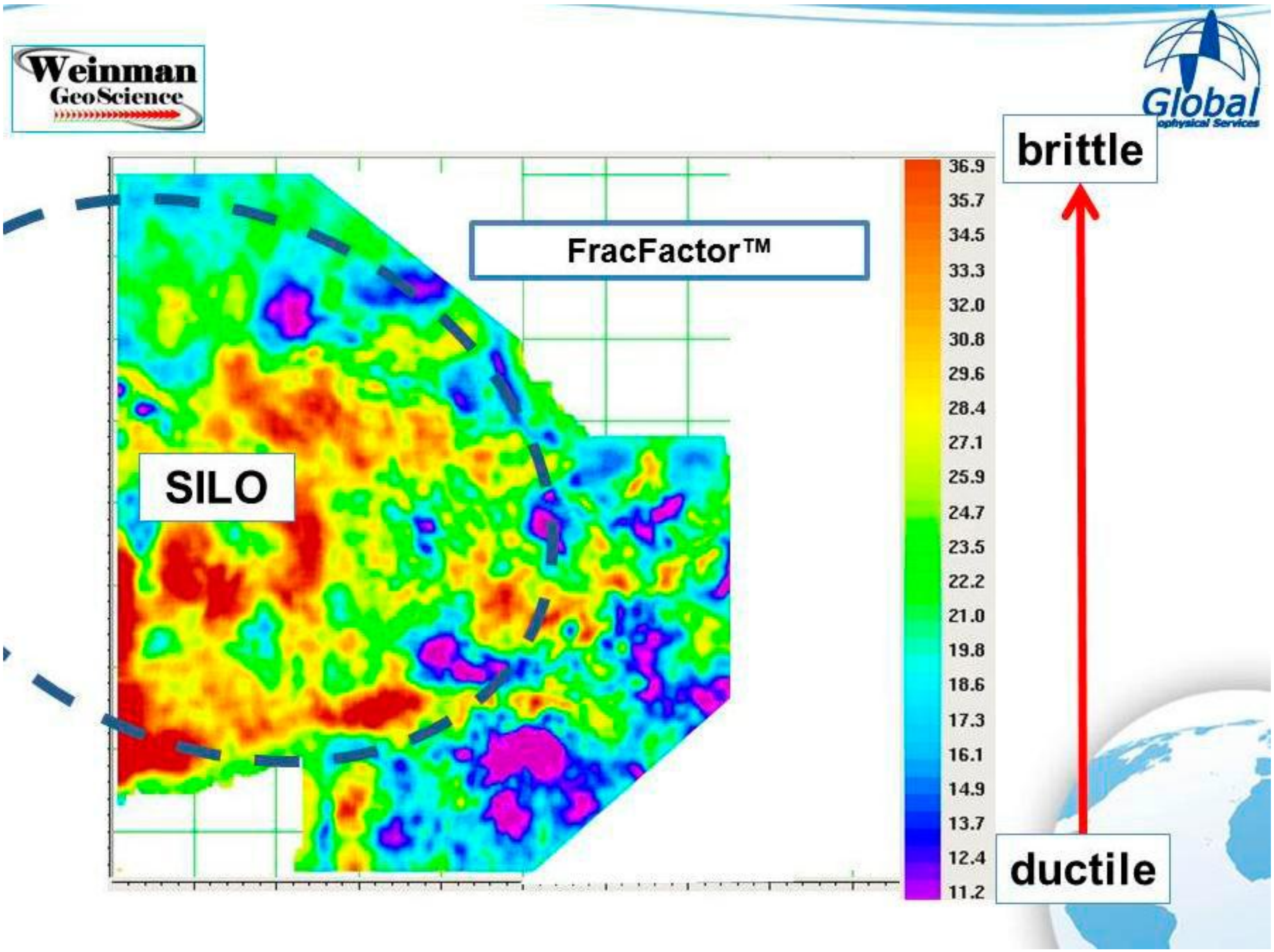

Figure 3. Approximately 60-80 mi^2 portion of the Silo 3D inversion on the edge of Silo Field, illustrating spatial changes in the Niobrara B1 and B2 interval. The hotter colors correspond to areas of greater brittle character.

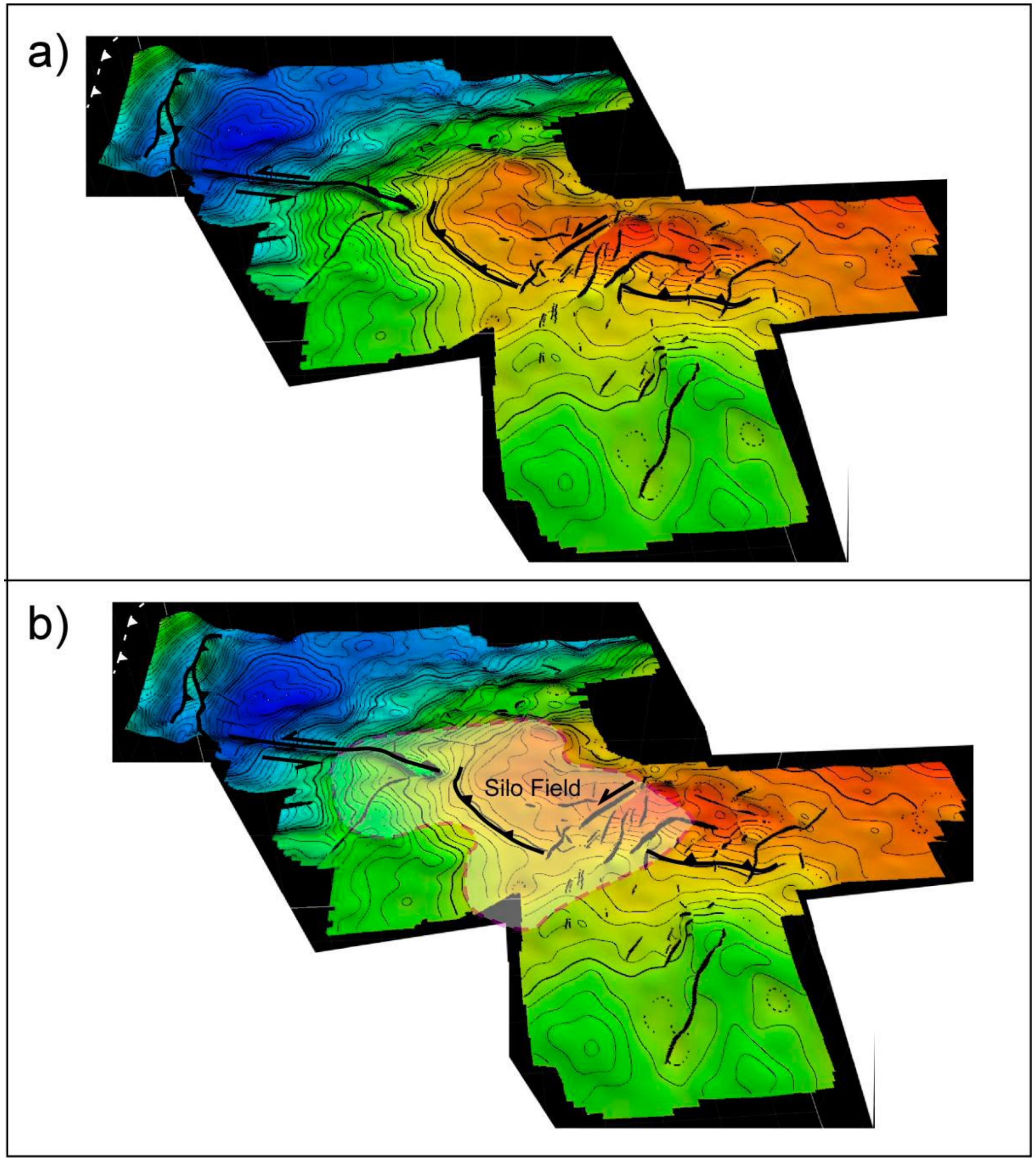

Figure 4. Perspective view of a time-structure contour map on the top of the Archean-Proterozoic basement in the Silo area (red areas are high). a) Mapped basement faults were reactivated in the Late Paleozoic or Tertiary, causing deformation in the overlying stratigraphic section. The major basement fault orientations are N-S, NW-SE, and NE-SW. b) The large strike-slip fault that cuts Silo Field connects the Silo Field basement high with a N-S-trending series of basement thrusts. The Silo Field area overlies the NW nose of a large basement uplift.

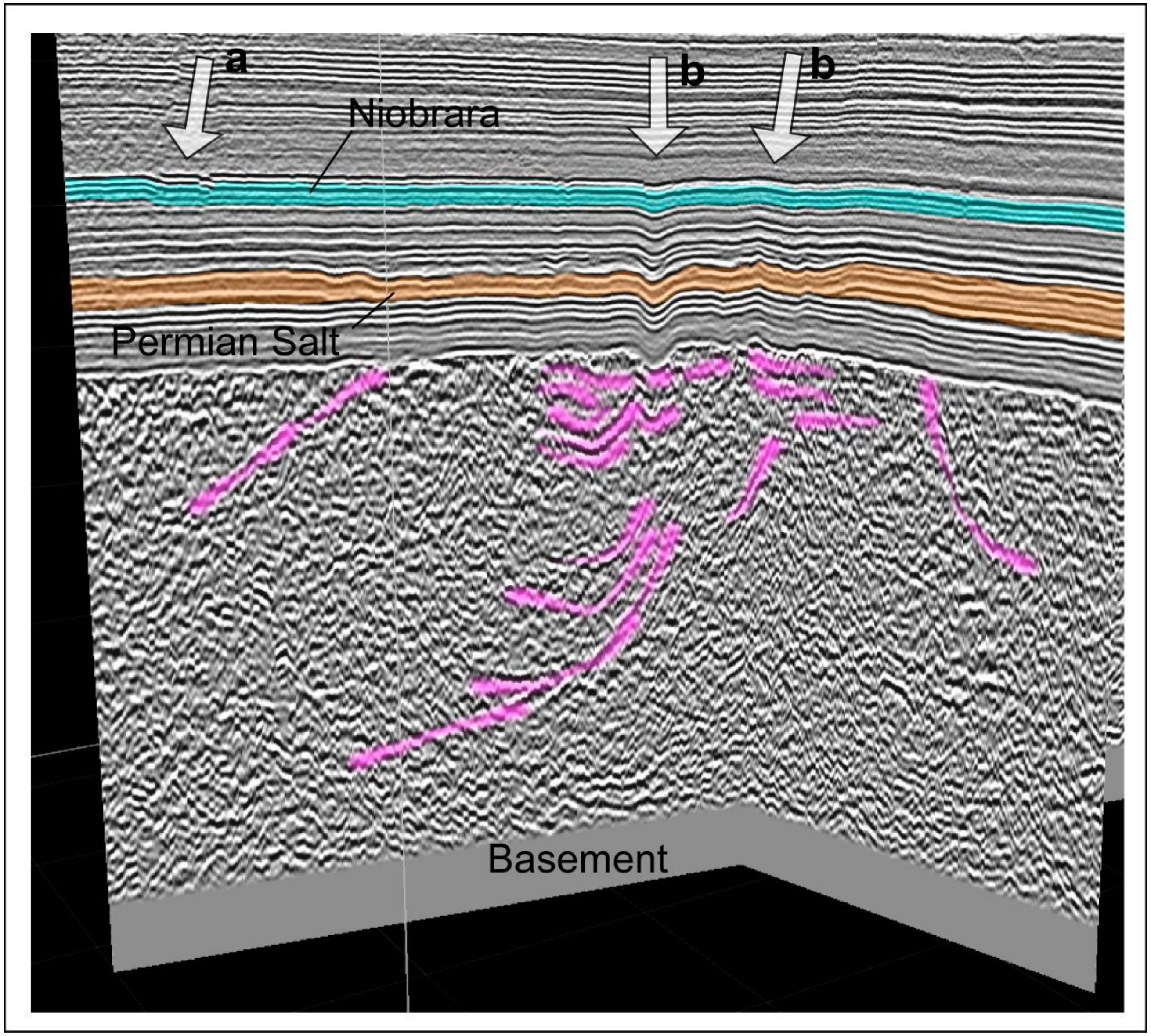

Figure 5. Two intersecting vertical sections from the 3D survey show basement faults highlighted in pink and their effect on the overlying stratigraphy. Some basement faults were active at the end of the Paleozoic, causing widespread folding in the Permian salt/evaporate section. Renewed basement faulting during the Laramide Orogeny caused faulting and folding in the overlying Niobrara Formation. Some areas of Niobrara deformation can be linked to underlying basement faults ("b") whereas other areas show no direct correlation ("a").