Delineation of Complex fault network North Slope, Alaska using seismic attributes
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Introduction
The North Slope, Alaska has a complex fault system in the subsurface due to different episodes of tectonics. The most producing reservoirs are fault controlled. Our study area lies in the south of the well-known Prudhoe Bay and Kuparuk River oil fields. The Triassic-aged Shublik Shale, which is the most prominent source rock, has gone through three stages of extensional tectonic activities during the Jurassic, Cretaceous, and Eocene. To understand the complex fault system, we computed an ensemble of volumetric seismic attributes, including coherence, curvature and aberrancy, and studied them along the Shublik Shale surface. In this study, we have divided the structures into three types based on seismic signature, 1. significant fault throw on vertical seismic section, 2. insignificant fault throw but clearly visible flexure, 3. insignificant fault throw and very weak flexure. We observed type 1 faults on the vertical seismic section, and seismic attributes which trends in WNW direction, these faults have large lateral extent. The type 2 faults have similar orientation as type 1. The type 2 faults are clearly visible on the curvature and aberrancy attributes. Although, the type 3 structures have no visible throw on vertical seismic, but, it can be seen as two fault lineation (which are orthogonal each other) on curvature and aberrancy attributes. Based on our attribute analysis and regional geologic understanding, we believe that, the type 1 and type 2 fault sets are of Jurassic age, whereas the two faults of the type 3 were formed in Cretaceous and Eocene with an orientation of nearly east-west and north-south orientation. These type 1 faults display cross cutting, single-tip and double-tip abutting relations with the older west-north-west striking faults.

Summary
The North Slope, Alaska has a complex fault system in the subsurface due to different episodes of tectonics. The most producing reservoirs are fault controlled. Our study area lies in the south of the well-known Prudhoe Bay and Kuparuk River oil fields. The Triassic-aged Shublik Shale, which is the most prominent source rock, has gone through three stages of extensional tectonic activities during the Jurassic, Cretaceous, and Eocene. To understand the complex fault system, we computed an ensemble of volumetric seismic attributes, including coherence, curvature and aberrancy, and studied them along the Shublik Shale surface. In this study, we have divided the structures into three types based on seismic signature, 1. significant fault throw on vertical seismic section, 2. insignificant fault throw but clearly visible flexure, 3. insignificant fault throw and very weak flexure. We observed type 1 faults on the vertical seismic section, and seismic attributes which trends in WNW direction, these faults have large lateral extent. The type 2 faults have similar orientation as type 1. The type 2 faults are clearly visible on the curvature and aberrancy attributes. Although, the type 3 structures have no visible throw on vertical seismic, but, it can be seen as two fault lineation (which are orthogonal each other) on curvature and aberrancy attributes. Based on our attribute analysis and regional geologic understanding, we believe that, the type 1 and type 2 fault sets are of Jurassic age, whereas the two faults of the type 3 were formed in Cretaceous and Eocene with an orientation of nearly east-west and north-south orientation. These type 1 faults display cross cutting, single-tip and double-tip abutting relations with the older west-north-west striking faults.

Geology of the Study Area
Our study area, which is Storms 3D seismic survey area is located south of the well-known hydrocarbon producing field in the North Slope, Alaska. The nearby fields Milne Point, Kuparuk River, Sag River Oil Pool, have been producing oil and gas since 1970s from the Lisburne, Ivishak, Kuparuk, and other deep reservoirs. Most of the well-known producing oil-fields are related to the Jurassic aged Beaufortian rifting (Houseknecht and Bird, 2011).

The Barrow Arch, which is an east-west trending rift in the north, and the Brooks Range, which is an east-west trending thrust and fold range in the south, structural highs bound the Colville Basin (Figure 1). The sedimentary rock deposits of the North Slope has been divided into three major tectono-stratigraphic events, including Ellesmerian, Beaufortian, and Brookian (Figure 2). The Ellesmerian rifting sequence consists of Carboniferous to Triassic passive-margin deposits. In this the extensional settings normal faulting took place. The Lisburne Group consisting primarily of carbonates of and Shublik formation consisting primarily of Shales are part of Ellesmerian sequence. The Beaufortian rifting sequence was deposited in Jurassic to Early Cretaceous (Bird, 1985). Normal faulting took place due to this rifting the faults were south dipping. The Barrow Arch came into picture due to this rifting. The Brooks Range resulted during the Brookian orogeny, when continent-continent collision took place in Cretaceous and Cenozoic (Nixon et al., 2014).
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Seismic and Well Log Data

The Storms 3D seismic survey area is approximately 280 mi². This survey was acquired in 2005 with 5s record length, and with a maximum offset range of 14,500 ft. The nominal fold of this survey was around 40. The data were later processed with a bin size of 11x110x110 ft (Division of Oil and Gas, 2017). There is one well inside the survey area. Figure 3 shows the seismic amplitude section vertical section and the Shublik Formation time-structure map.

Seismic Attribute Analysis

Structural curvature

Structural curvature of seismic reflectors illuminates its curvedness of the bending and folding. Opposed to one in 2D, two principal curvatures are required to characterize the 3D structures. One of the two can be, the most positive principal curvature (k1), which displays anomaly around the crest of the anticline. Whereas the other one can be most negative principal curvature (k2) which display anomaly around the trough of the syncline (Chopra and Marfurt, 2007). In this paper, we have used the most negative curvature, because it illuminates lineation. Curvature is a vector, where the magnitude of the curvature measures the amount of curvedness and the direction of curvature is the direction of the lineation (Guo et al., 2016).

Aberrancy

Aberrancy is defined as the third derivative of a curve or a surface (Figure 4). As the curvature measures the lateral changes in dip, aberrancy measures the lateral changes in curvature. Aberrancy illuminates the center of the curved bed. In the case of a fault with very small throw, the reflectors show a continuous signature without any significant change in the waveform shape. In such cases, coherence attributes (e.g. coherency, eigen structure coherence, Sobel filter similarity) does not identifies such faults, whereas aberrancy can highlight these faults quite well (Qi and Marfurt, 2018).

In the case of a fault, the total aberrancy magnitude anomalies (high values) appear at the fault plane, whereas the total aberrancy azimuth indicates the direction of the downthrown side.
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### Discussions

The faults in the northern part of the survey has a predominant strike of WNW, shows significant amount of throw, displayed as number 1 (type 1) seismic cropped section on Figure 5b. Coherence (Figure 5a) was able to detect these faults. For number 2 (type 2) location (on Figure 5b) coherence shows, small incoherency. Curvature (Figure 5b) as well as aberrancy (Figure 6a), display strong anomaly for this flexure. Notice on the Figure 5b, the strike (of k₂) or the fold axis of this flexure is around N 105° (purple color). For number 3 location (with type 3 faults), the vertical seismic section shows, very little flexure, these flexures remain undetected on the coherence map, whereas strong lineation can be seen on coherence as well as aberrancy image. These lineation are at 90° to each other, and they strike in N175° and N85 °, Nixon et al. (2014) discussed about single tip and double tip abutting of the younger faults on the preexisting faults. Figure 7 indicates that the two younger (type 3) faults single tip/double tip abutting against the (type 1 and type 2) older basement related structure.

![Diagram of dip, curvature and aberrancy](image)

**Figure 4.** Top- The concept of dip, curvature and aberrancy on a curve (modified after Qi and Marfurt, 2018). The red circle indicates peak, and the blue circle indicates trough. Bottom--small offset faults, are seen as a continuous reflector by seismic with a little flexure. So, such faults are not visible on the coherence, but are clearly seen on curvature and aberrancy.

![Coherence and curvature images](image)

**Figure 5.** (a) Coherence and (b) the most negative curvature (k₂) strike modulated with most negative curvature magnitude slice along the Shublik surface. In the southern part, impression of faults are barely visible in coherence, whereas very clearly seen curvature. The magenta arrow shows basement related fault structure. Interpreted structures on the Shublik surface with most negative curvature (k₂) attribute. As per orientation, three dominant types of faults can be observed on the attributes, including basement-related WNW-oriented Faults and two faults striking nearly N-S and E-W. Note the picture shows three type of faults, type 1- significant throw (yellow arrow), and type 2-smaller throw but visible flexure(magenta arrow), and type 3-insignificant throw and very weak flexure.
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Conclusions

Coherence attributes were not useful in illuminating the flexures and faults with sub-seismic throw, whereas the aberrancy and curvature were able to detect the two sets of faults along NS and EW (striking N170° and N85°). Since, these two sets of faults are crosscutting, single tip and double tip abutting against the long faults with significant throw (striking N105°), indicates that these faults are younger in age. Based on the regional geologic understanding, the WNW-oriented faults are the oldest (Jurassic), followed by EW-oriented faults (Cretaceous), and NS-oriented are the youngest (Eocene).

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Figure 7. (a) Total aberrancy azimuth modulated with total aberrancy magnitude along the Shublik Shale surface. (b) Cross cutting, single tip abutting, and double tip abutting faults. In Figure 7a, the bright areas indicate high flexure or aberrancy values. The two sets of faults (NWN and NEN), are cross cutting across the older basement-related WNW faults (white arrow). Also, you can notice, the single tip abutting of younger set of faults (yellow arrows) (modified after Bhattacharya and Verma, 2019). Relatively high values of aberrancy can be seen near the abutting tips due to localized strain development.
REFERENCES


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