

**Fault displacement analysis form 3D seismic data: A case study from offshore Nova Scotia, Scotian basin**

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**Summary**

This study deals with the fault displacement analysis carried out for the major fault, located in the Penobscot prospect of the Scotian basin. Initially a fault enhancement filtered (FEF) seismic volume is prepared from the original seismic, which is taken as input for the fault surface generation and throw values calculation from the Cretaceous formations. The calculated throw values of the major fault are then plotted against time and distance. The plotted graphs decipher the degree of tectonic activities and deformations taken place during the Cretaceous period. This helps in understanding the growth and evolution of the major fault as well as its implications in modulating the Cretaceous formations of the study area. Such analysis also provides inference about the fault linkage, depositional compartments and trapping zones for hydrocarbon accumulation.

**Introduction**

The growth of major faults in a basin generally happens through the integration of smaller faults with time (Lohr et al., 2008). This led to strong undulation and stress perturbations, which finally increases the displacement across the offsets. This complex interaction between smaller faults needs to be dealt through fault displacement analysis. As these interactions provide important information regarding the positions of juxtaposition beds, which controls the sealing and permeability across faults. It also gives some inference about the fluid transport, placement of wells and estimation of tectonic activity in the region.

In this study, an integrated analysis is executed for the enhancement and computation of the throw values of the major fault from the 3D seismic dataset of Penobscot prospect. This prospect lies in the Scotian basin, which is rifted in nature. Basin is characterized by several normal faults, step faults and horst-graben structures. The major fault, considered for this displacement analysis, has effectively

intruded the prospect. This analysis is limited to the Cretaceous formations (Wyandot, Dawson Canyon and Logan Canyon) that are regarded as prospective zones for oil and gas exploration (Campbell et al., 2015; Mandal and Srivastava [Personal Communication]).

The analysis comprises of three step process: (1) seismic data conditioning, (2) well to seismic tie and (3) fault surface generation and computation of throw values across the offset. To enhance the quality of fault systems and improve the structural visibility, the seismic data is conditioned. It involves application of different kind of structural oriented filters (SOFs). On completion of data conditioning phase, well to seismic tie is carried out which places the formation tops at proper seismic reflectors. Once the seismic data is successfully tied fault surface of the major fault is constructed. This fault surface eases the correlation of seismic reflectors on opposite sides of the fault offsets and helps in proper calculation of throw values across it. The computed throw values are then plotted w.r.t distance and time.

Such type of approach demonstrate the degree of tectonic activities as well as loading and unloading of sediments within the basin. Study also explains the development of several geologic structures (e.g., minor faults, fracture networks, folds) within the Cretaceous formations that makes it structurally more complicated in comparison to the underlying formations.

**Geology and Dataset**

Penobscot prospect located southwest of the Nova Scotia in the Scotian basin, covers an area of 87 km<sup>2</sup> with sediment depth reaching up to 12 km, is a storehouse of Mesozoic-Cenozoic sediments (Wade and McLean, 1990; Kettanah, 2013) (Fig. 1). It lies over the Lower Paleozoic basement rocks. Several authors have presented a detailed geology of the basin (Wade and McLean, 1990; Wade et al., 1995; Albertz and Beaumont, 2010; Campbell et al., 2015).

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However, a brief overview focusing on the cretaceous formations of the study area is described below for completeness.

In the Cretaceous phase (which is the focus in this study), the basin has witnessed the deposition of sandstones, shale units, marls and chalky carbonates, resulting in the Logan Canyon formation (LCF), the Dawson Canyon formation (DCF), and the Wyandot Formation (WF) (McIver, 1972; King et al., 1974). These sequences are mainly deposited along the eastern Nova Scotia Shelf region. All these formations are intruded by a major fault and has several grabens, half-grabens, horst structures and regularly spaced fractured zones as a result of tectonic activities that started after the break-up of Pangea when the North American plate began to separate from the African plate.

The 3D Pre-Stack Time Migrated seismic data volume (acquired in 1991) (CNSOPB, 2008) used in the present study has following information:

- Data coverage: 66 sq.km (5.5 km by 12 km grid), 60-fold coverage and 2 ms sampling rate.
- Record length: 6 sec.
- 600 inlines (Line no. 1000 to 1600) and 481 crosslines (Line no.1000 to 1481).
- Petro Canada/Shell Penobscot L-30 (drilled to a depth of 4,237, reaching the Cretaceous succession) and Petro-Canada/Shell Penobscot B-41 (drilled to a depth of 3,414m, reaching the Jurassic succession).

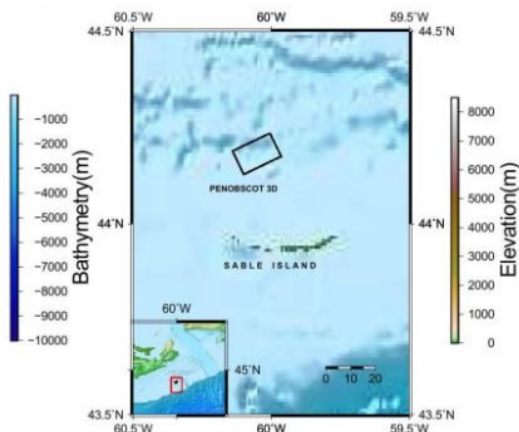


Fig. 1: Location map of the Penobscot prospect. The study area is marked using black square.

## Methodology

The methodology adopted for this study is divided into three phases: **(a)** data conditioning phase, **(b)** well to seismic tie and **(c)** fault surface generation and throw values calculation. These phases are illustrated through a workflow given fig. 2.

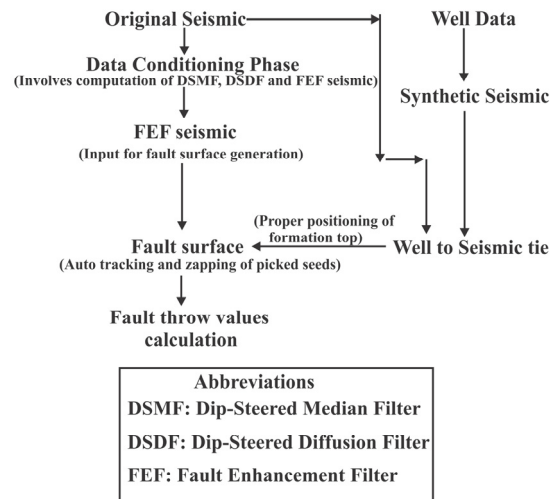


Fig. 2: Workflow used for this study.

**(a) Data conditioning phase:** This phase aims in amplifying the seismic events and differentiate between the dip-azimuth of the seismic reflectors and the overlying noise in the seismic data (Chopra and Marfurt, 2007). It removes the random noises from the original seismic data and enhances the lateral continuity of the seismic events. This leads to a sharp definition of geological structures like faults, fractures in the seismic. In a nutshell, these filtering is done by the set of structural oriented filters (SOFs) as discussed below:

- Smoothing of the seismic reflectors through dip-steered median filtering (DSMF).
- Fault positions enhancement through dip-steered diffusion filtering (DSDF).
- Producing a fault enhancement filtered (FEF) seismic data through logically merging the first two steps.

**(b) Well to seismic tie:** Before picking of seeds and zapping of the major fault an important step need to be carried out is to tie the available well with seismic data. This removes the mismatch between time and depth domain. To carry out this phase in our data,

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first a statistical wavelet of 120ms is extracted from the reference seismic volume within the time ranging from 0 to 1500ms. Based on the available density and sonic logs of the wells, acoustic impedance and reflectivity logs are computed which is then convolved with the extracted wavelet to generate the synthetic seismic traces. The synthetics are then compared with composite seismic traces extracted from the seismic data nearer to the well locations. In this process, a match is tried to be established between the identified reflections from the seismic volume with that of the corresponding geological marker of the wells. It was observed that the well L-30 presents a reasonable correlation (Fig. 3) as compared to well B-41. During this tie, cross-correlation coefficients of 0.77 between Wyandot and Dawson, 0.92 between Dawson to Logan, and 0.84 between Wyandot and Logan formations was obtained.

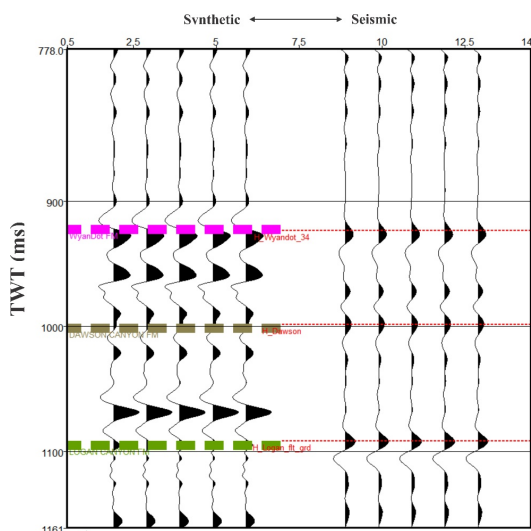


Fig. 3: Well to tie seismic for L-30. The well Litho-markers, i.e. Logan, Dawson and Wyandot are represented by green, grey and pink dotted lines respectively

**(c) Fault surface generation and throw values calculation:** In this phase, FEF data is displayed in z direction and the major fault, which is clearly visible, is auto tracked by picking the seeds. This process is carried out up to where the major fault runs in the seismic data. At the end, all the seeds are zapped to create a curvilinear fault surface. This fault surface is then viewed in the corresponding seismic sections for the calculation of throw values in each Cretaceous

formation (Fig. 4). The throw acts as an approximation for real displacement (McLeod et al., 2000; Walsh et al., 2002). Then the computed throw or displacement values are plotted against distance and time.

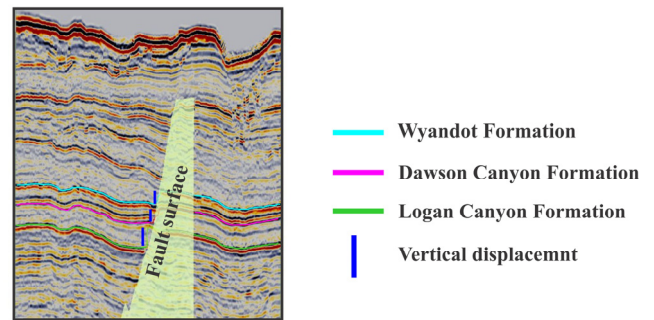


Fig. 4: Major fault intruding the cretaceous formations.

## Results

The computed structural filtering on the original seismic data (Fig. 5a) has effectively removed the random noise and has preserved the lateral continuity with sharp definition of the fault and fracture networks (Fig. 5b and 5c). It has illuminated not only the major fault but also the subtle discontinuous features in the seismic data.

These conditioned seismics has eased the Fault displacement analysis. This analysis has been carried out to explain the tectonic deformations that took place due to rifting of North American mainland from the Pangea. It includes formulation of two graph profiles: a) time vs different throw values and b) profile distance vs throw displacement.

On viewing the FEF seismic in vertical section perpendicular to the fault surface, the throw values are calculated across the offset in millisecond (ms) for each Cretaceous formation. By using the average P wave velocities based on their composition (For Logan's sand-shale units 2400 m/s, for Dawson's marine shale 2600 m/s and for Wyandot's bioturbated chalks 2200 m/s [Avseth et al., 2005]) in a step of 125 m the throw values in ms are converted into meters (m). Then their weighted averages are computed using the normalize profile distance as weight factor and are summed to achieve the cumulative throw values for each formation. Then these values are back-stripped

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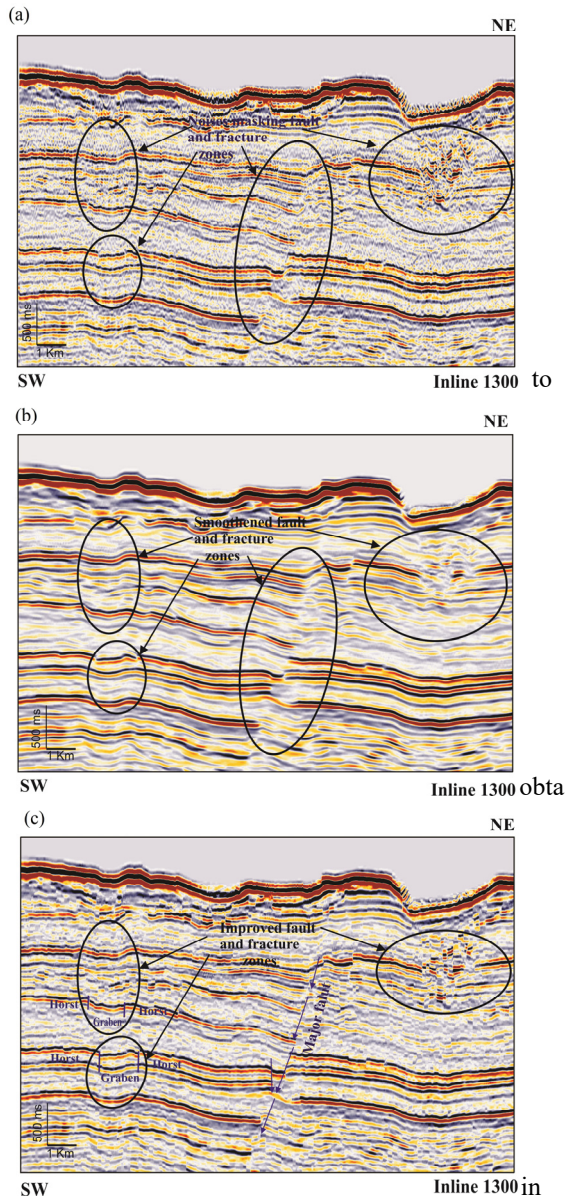


Fig. 5(a) Original seismic for inline 1300. Heavily masked geologic structures with noisy reflections. (b) DSMF seismic for the same inline. It has improved the data quality on removing random noises and maintaining the lateral continuity of the seismic events. (c) FEF seismic for the same inline. The sharpness of the geologic structures gets preserved and enhanced (see the black ovals for differentiating the seismic sections).

from the overall throw accumulated corresponding to each formation period.

These throw values (e.g., 10.42m and 18.21m for Aptian to Cenomanian and Cenomanian to Coniacin ages, respectively) are then plotted against time in million years (My). The throw value experienced a sudden jump of ~51.79 m within the Coniacian to Campanian age. The throw further extended to about 79.33 m and continued within the Tertiary period (Fig. 6). Such large throw build-up through different ages (geologic time) explains the degree of tectonic activities and sediment loading unloading encountered by the basin.

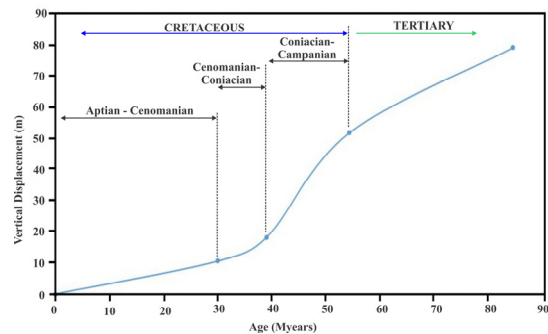


Fig. 6. Illustrates cumulative throw of the geologic formations (Cretaceous to Tertiary) with respect to geologic age (M years).

Displacement-distance profiles are computed to know the changes in throw values along the length of a fault (Long and Imber, 2010; Childs, 2003; Bergen and Shaw, 2010). This helps in understanding the growth of fault in spatial scale. The throw values of the major fault system are measured perpendicular to the fault strike. The throw or displacement values to distance profile of the Cretaceous formations are illustrated the following significant features.

The profile of LCF indicates that the fault suffers a smooth increment of throw values in western portion of the formation then a sudden zone of displacement from ~ 20.42m to 58.20m is encountered at a distance between 500m to 625m. However, towards the eastern part of the formation, the displacement decreases and dies out (at about 4.75 km along the strike direction) but in between, the fault suffered a maximum displacement of 118.81m at about 2.5 km along the strike. This maximum throw value along the strike direction represents the core of the fault segments that coalesced over time to generate the fault. A bell-shaped pattern of displacement-distance profile over the Logan Canyon formation is seen which

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demonstrates the variation in the tectonic activity (Fig. 7a). In DCF, the fault suffers a step-wise increment of throw from western portion of the formation and then encountered a sudden displacement of 18.86 to 34.89 m at a distance of 750 m to 875 m. The maximum displacement of 100.53 m in the Dawson is found at a distance of 3.25 km. Displacement further continued and were tapered off at 4.75km towards the eastern part of the formation (Fig. 7b). The overlying WF also experiences similar type of gradual increment in the throw of the fault along the strike and attains a sudden increment, i.e., from 49.11 to 79.11 m at a distance of 875 m to 1 km. At a distance of 3.25 km, the fault suffered a maximum displacement of 87.22 m. Similarly, as explained above the throw continued and were ended at about 4.75km towards the eastern part of the formation (Fig. 7c).

These throw/displacement vs distance plots for the three Cretaceous formations illustrate both the growth history of the fault and about the tectonic impact of faulting activity within the formations. It explains the severe tectonic impact over the Logan Canyon formation during the Aptian to Cenomanian age, which led to the displacement of about ~ 118.81m in vertical dimension. However, it is observed that the Dawson Canyon and Wyandot formations have experienced lesser throw compared to the Logan Canyon formation. This explains the cumulative build-up of throw as one goes down with the formations. Such faulting scenario have also demonstrated the development of several other geologic structures (e.g., minor faults, fracture networks, folds) within the Wyandot formations, making it structurally more complicated in comparison to the underlying formations.

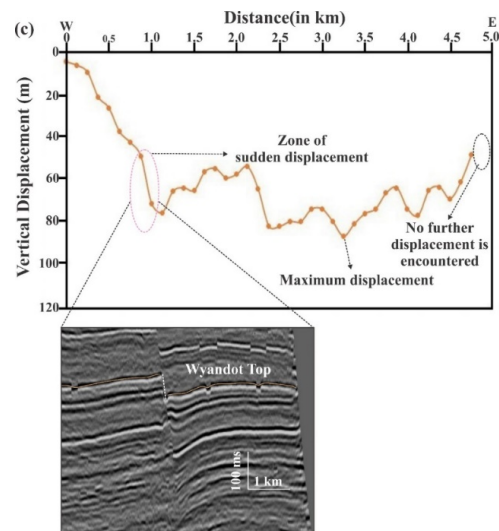
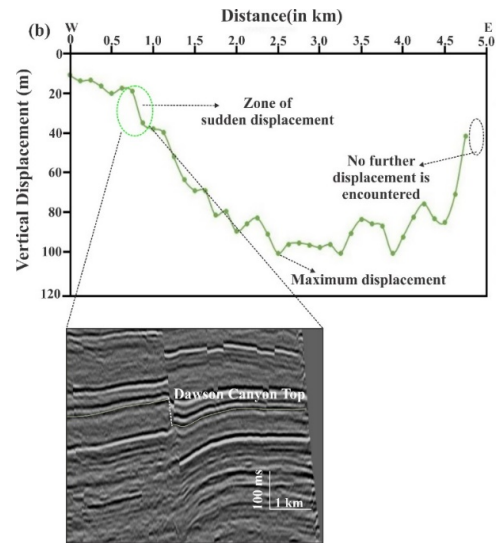
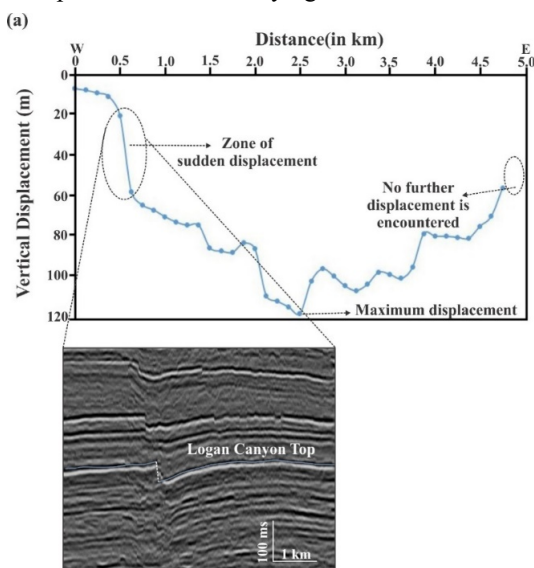


Fig.7: Displacement-distance profile for the Cretaceous formations (a) Logan canyon, (b) Dawson canyon and (c) Wyandot. Zone of sudden displacement is indicated using dotted ovals. Maximum throw is also shown is observed at a distance of 2.5 Km for LCF and 3.25 km for DCF and WF.

### Conclusions

The conditioned volumes have subtly enhanced and clearly differentiated all the geologic features present in the Cretaceous formation of the prospect. Fault growth and evolution studies carried out for the major fault support the intense and cyclic events of tectonic deformations within the Cretaceous

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formations. It explains the coalescence of the fault segments that led to the formation of major fault and reveals the different depositional compartments with trap closures. The large throw values of the major fault caused by the fault linkages. This fault linkage builds an add-on strain that eventually provides large accommodation space for the hydrocarbon bearing sediments to get deposited. Thus, the study provides significant inputs to understand the evolutionary history of the Cretaceous formations.

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