SUBMARINE CANYON-FILL RECONSTRUCTION FROM INTEGRATED SEISMIC-STRATIGRAPHIC ANALYSIS – APPLICATION TO BANQUEREAU FORMATION, SCOTIAN BASIN – OFFSHORE CANADA.

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ABSTRACT
Building geological models (integrating stratigraphic, structural and paleo-environmental 3D models) that allow the interpretation of sand bodies deposited by turbidity currents along submarine canyons or channels, is one of the most useful tools used by geoscientists for the definition of new drilling opportunities in both exploration and development phases. In this context, the integration of methodologies such as sequence stratigraphy and seismic attributes, together with well-log and core information, outline the basis for the interpretation of sand-body lithostratigraphy and chronostratigraphy. Similarly, these models allow the interpreter to reconstruct the depositional environment and deformation history of a sedimentary basin [1]. Based on a series of chronostratigraphic stages, this paper proposes a 3D model for the sedimentation history of the Banquereau Formation. This model is based on the integration of seismic stratigraphy, seismic attribute interpretation and well-log analysis. Also, a set of system tracts and corresponding transgression and regression phases were identified for the sedimentary interval of interest. The available dataset provided the information to identify the geometry and changes in the sedimentation patterns of the stratigraphic sequences from the Tertiary to the present, thus defining a 3D model for the sedimentation history of the Banquereau Formation.

This model was used to map the geometry and changes in the sedimentation patterns of the stratigraphic sequences from the Tertiary to the present, thus defining a 3D model of the sedimentological and structural architecture of this interval. Last but not least, the resulting 3D stratigraphic model made possible the identification and description of an amalgamated channel complex filling a submarine canyon associated with a fluvio-deltaic setting. This sort of analysis might be used as an analog for similar reservoirs, providing key insights and vital information for decision making.

KEYWORDS / PALABRAS CLAVE
Seismic Attributes | Sequence Stratigraphy | Well Logs | Submarine Canyon.

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RECONSTRUCCIÓN DEL RELLENO DE UN CAÑÓN SUBMARINO A PARTIR DE ANÁLISIS SISMOESTRATÍGRÁFICO INTEGRADO – APLICACIÓN A LA FORMACIÓN BANQUERAU, CUENCA ESCOCIA – COSTA AFUERA CANADÁ

RESUMEN
La construcción de modelos geológicos que permitan la interpretación de cuerpos de arena depositados por corrientes de turbidez a lo largo de cañones o canales submarinos, es una de las herramientas más utilizadas por los geocientíficos para la definición de nuevas oportunidades de perforación en las fases de exploración y desarrollo.

En este contexto, la integración de metodologías como estratigrafía de secuencias y atributos sísmicos, en conjunto con información de registros de pozo y de núcleos, esbozan las bases para la interpretación litoestratigráfica y cronoestratigráfica de cuerpos de arena. De la misma manera, estos modelos permiten al intérprete reconstruir el ambiente de depósito y la historia de deformación de una Cuenca sedimentaria. Basado en una serie de etapas cronoestratigráficas, este artículo propone un modelo 3D para la historia de sedimentación de la Formación Banquereau. Este modelo se basa en la integración de estratigrafía sísmica, la interpretación de atributos sísmicos y el análisis de registros de pozo.

También, se identificó un conjunto de system tracts and sus correspondientes fases de transgresión y regresión para el intervalo sedimentario de interés. Los datos disponibles proporcionaron la información para identificar la geometría y los cambios en los patrones de sedimentación de las secuencias estratigráficas desde el Terciario hasta el presente, definiendo así un modelo 3D de la arquitectura sedimentológica y estructural de este intervalo. Por último, pero no menos importante, el modelo estratigráfico 3D resultante hizo posible la identificación y la descripción de un complejo de canales amalgamados llenando un cañón submersino asociado con un entorno fluvio-deltaico. Este tipo de análisis podría ser usado como un análogo para reservorios similares, proporcionando información clave y vital para la toma de decisiones.
1. INTRODUCTION

The study area is located in Offshore East Canada, more specifically in the Nova Scotia Basin (Figure 1). Now, extended works have improved understanding of the Nova Scotia basin since the 1960s [2]–[3], in order to find the most profitable plays. In this context, approximately 180 exploration wells have been drilled on the shelf of the Scotian basin [3], as well as another eight wells on the slope (4). Most of the discoveries made on the Scotian Shelf relate mainly to gas or condensate [3]. These discoveries have been principally encountered in the Cretaceous and Jurassic Formations in the Scotian Basin [5]. The main target of this paper is the Banquereau Formation, which is a Late Cretaceous to early Quaternary stacked series of prograding sequences that downlap unconformably onto the Wyandot Formation [6].

The palaeoecology and stratigraphy of the Scotian Shelf and the Sable Sub-basin have been described in several papers [6]–[8], but due to the lack of prospectivity for hydrocarbons, little attention has been paid to the structure of the Banquereau Formation, its implications for paleogeography and relative sea level [10]. McIver [6] also stated that the mudstone of the Banquereau Formation is a Late Cretaceous to early Quaternary stacked series of prograding Tertiary delta complexes. More specifically in the Banquereau prograding Tertiary delta complex.

While most of the previous work done on the Banquereau Formation was based on limited information (well-logs separated from seismic data), the scope of this paper is to show how the integration of these sorts of information through different advanced geological and geophysical data interpretation techniques led to the generation of a robust sequence stratigraphy model that accounts for the characterization of the submarine channels and valleys found in the Penobscot Block (Figure 1), more specifically in the Banquereau Formation.

According to Wash and Mosher [16], Cretaceous sediments and the transgressive sedimentary succession above the Wyandot Formation are designated the Banquereau Formation. Marine shelf mudstones, sandstones and conglomerates of the Banquereau Formation were

2. THEORETICAL FRAME

All the reported Formations of the Sable Sub-basin are shown on the stratigraphic column in Figure 2. In chronological order, the Formations are Abenaki, Mississauga, Logan Canyon, Dawson Canyon, Wyandot and Banquereau. Abenaki Formation is Jurassic in age, while Mississauga, Logan Canyon, Dawson Canyon, and Wyandot Formations are all from the Cretaceous. Banquereau Formation is Late Cretaceous to early Quaternary in age [13]. Mississauga Formation is mainly sandstone with some minor shale beds. This Formation is commonly broken into an Upper and Lower unit, with the “Base O-Marker”. The member Base O-Marker is a regional stratigraphically correlatable unit, which is easy to identify on seismic data and comprises mainly sandstone, minor carbonates and shale [14]. Mississauga Formation can broadly be defined as comprising fluviodeltaic sediments [15]. Logan Canyon Formation has several members with variable percentages of sandstone and shale, but the main component is a thin shale succession, interpreted as a marine transgression above the Mississauga Formation [15]. Dawson Canyon Formation is mainly shale, while Wyandot Formation is chalk-dominated. Highly bioturbated, with minor amounts of marl and shale [13]. In fact, palaeontological evidence indicates there is a hiatus associated with the top of the Wyandot Formation [6] above which lies the Banquereau Formation. As mentioned before, Banquereau Formation is mudstone-dominated, with minor amounts of siltstone and sandstone in a prograding series of clinoforms [6], [8].

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influenced throughout the Cenozoic by several major unconformities related to sea level fall [16]. Unconformities are noted during the Paleocene, Oligocene and Miocene intervals where fluvial and deep-water currents eroded largely unconsolidated sediments, subsequently depositing them on the abyssal plain [7], [17]. Winnowing and reworking of deep-water sediment by bottom currents began in the Oligocene [18], providing the earliest evidence of thermohaline circulation. Sediment distribution of Miocene successions were strongly influenced by the Western Boundary Undercurrent with periods of intensified bottom current activity also occurring in the Late Pliocene [19]. Unconformities are noted by widespread gullying cutting in the Early Pleistocene. During the Quaternary to recent, several hundred meters of glacial and marine sediment were deposited on the outer shelf and slope [7], [17], [20]. Wach and Mosher [16] also argues that on the Scotian Shelf and Grand Banks, the widespread hiatus eroding either the upper part or all of the Oligocene is marked by a regional unconformity; the nature of which includes canyon formation. Canyon incision at the shelf edge initiated during the Eocene and was extensive by the Oligocene [6]. Pe-Piper and Piper [23] noted that although Oligocene strata are absent on the Scotian Shelf and Grand Banks, they are present both on the Labrador Shelf [24] and on the New-Jersey margin where small hiatuses are correlated with the global eustatic 1887 sea-level curve of Hay [25], [26]. Wade and MacLean [28] attributed the missing Oligocene strata on the eastern Scotian Shelf to a broad southeasterly trending canyon associated with a sea-level Lowstand, although Grüt and Zentilli [30] argued for thermal inversion in the Late Cretaceous to Early Cenozoic, based on results from apatite fission track analysis.

Figure 1. Location of the study area. (Modified from Google Earth)
3. EXPERIMENTAL DEVELOPMENT

In this paper, a stratigraphic sequence model, as defined by Catuneanu, Hancox, Cairncross, and Rubidge [31] (Figure 3), will be used to generate all the sequence stratigraphic analysis and to build a system tracts model.

The principal data of this study is a high-quality 3D PSTM from the Penobscot block, located in Nova Scotia Offshore of Canada (Figure 4). The dataset consists of 2 wells with a set of well logs, time to depth tables for the seismic well tie process and the seismic volume mentioned previously (Figure 4). Figure 5 shows the workflow applied to the dataset to obtain the final model. All steps and partial results are illustrated and briefly described in the following sections. It is worth mentioning that this study was conducted in a non-prospective interval. Nevertheless, this methodology may be applied to seismic surveys that image similar geological features. All dataset interpretation was performed in Petrel & Opendtect software packages.

WELL-LOG INTERPRETATION

Following the workflow illustrated in Figure 5, data processing began with well log data interpretation. Figure 6 illustrates the available well logs for one of the correlation wells (Gamma ray [GR], P-Sonic [DTp], and Deep resistivity [ILD]). The first step in the well log interpretation was the definition of the Vshale model, following Asquith and Krygowski [32], using the Gamma ray [GR] and the Equation 1. In this context, Figure 8 illustrates the resulting Vshale model. The next step involved the interpretation of the facies model based on both the Vshale model defined in this study and neural networks as proposed by Bhatt and Helle [33]. By using neural networks, one can associate as many well log properties as there are available, thus finding clusters of points in a crossplot that share similar ranges of the rock properties used as input data. Therefore, one of the clusters defined during the application of neural networks in classification mode would represent a specific lithology with a given range of porosity, shale fraction, density, P-wave etc.
Additionally, the classification of different types of claystone may also be performed by applying neural networks. Figure 7 shows the resulting crossplot of the facies modeling where 3 different lithologies were interpreted as sandstone, claystone and shale. Electrofacies were interpreted, enabling the definition of the sedimentary environments per interval, which correlates with the facies model defined herein (Figure 8). Now, with the sedimentary environments interpreted, the next step was to carry all the information from the 1D models to the 3D scenario. In order to achieve that, seismic-well tie was performed in the correlation wells using the P-Sonic ([us/ft] and Density ([g/cc] logs available. Figure 9 shows the resulting synthetic seismogram from which the depth-time model was obtained to take the 1D stratigraphic information generated (facies, electrofacies and sedimentary environments) to the 3D seismic information.

**Figure 7.** Final crossplot for the facies modeling obtained by applying neural networks and Vshale. Crossplot (a) shows the range of values of Vshale and P-sonic and crossplot (b) illustrates the facies classification for Banquereau Formation.

**Figure 8.** 3D Facies model for the correlation wells obtained by applying neural networks and Vshale.

**Figure 9.** Synthetic seismogram resulting from the seismic-well tie process on one of the correlation wells.

### SEISMIC IMAGE ENHANCEMENT & INPUT DATA FOR SEQUENCE STRATIGRAPHIC INTERPRETATION

After tying the correlation wells to the seismic, the interpretation of the 3D seismic data began with enhancement of the seismic image. This process included reflector relative dip estimation and the enhancement of reflector continuity. Based on the reflector relative dip attribute known as Dip Steering (which was calculated using Opendtect) an amplitude filter (Dip Steered Median Filter, DSMF) was applied to the original PSTM image so that the reflector continuity could be enhanced [34] (Figure 10) and thus facilitate the manual interpretation of stratigraphic surfaces. In this context, using the methodology proposed by Oiolo, Ezepuekwu and Doki [34], a fault enhancement filter (FEF) was also applied so that the fault surfaces could be easily interpreted using geometric seismic attributes based on the result of this fault filter (Figure 11). Following the manual interpretation of the main stratigraphic surfaces and faults in the entire seismic volume, a set of about 240 horizons were automatically tracked in the interval of analysis using the main unconformity horizons and faults as constraints. These horizons neatly follow the reflectors and therefore represent timelines that will be used in the following steps. It is worth mentioning that this set of horizons is truncated if they approach each other up to a certain distance defined by the interpreter, therefore making it even easier to interpret stratigraphic features such as sub-aerial unconformities.

This 3D horizons framework, combined with attributes such as thickness variations, make it possible to define time attributes for the bounding surfaces.

Using both the enhanced seismic data and the 3D horizons framework it is possible to interpret the palaeo-geomorphology of the entire seismic volume and identify stratigraphic features such as erosional events, non-depositional hiatuses [35], submarine canyons, debris flows and most importantly turbidites. Figure 12 illustrates the enhanced seismic image and the corresponding 3D horizons framework for an Inline of the seismic survey. The prograding delta deposits during the late Cretaceous and Tertiary is incised by recent submarine channels and valleys, which is adequately represented by the horizons framework generated in this study.

### RESULT

#### SEQUENCE STRATIGRAPHIC INTERPRETATION

Based on the horizons framework, the corresponding reflector terminations and seismic facies interpretation (Figure 13), a complete set of stratigraphic surfaces was defined that was later used to interpret the systems tracts (Figure 14). Using the
stratigraphic surfaces and the reflector terminations defined in Figure 14. The seismic data was transformed to Wheeler domain where erosion events and non-deposition hiatus were interpreted (Figure 15). The wheeler diagram, together with the well-log interpretation, made it possible to interpret the system tracts associated with each interval and to propose a base level curve for the study area (Figure 16).

Following the interpretation of the base level curve, system tracts were interpreted in the entire 3D seismic survey, thus creating a 3D sequence stratigraphic model calibrated with well log information (Figure 17). In Figure 16 (b), from bottom to top, it can be seen that the package bounded by the purple (WyantDot Chalk Fm) and the light green surfaces show a downlapping stacking pattern, which can also be seen in the Wheeler domain (Figure 15). It can also be seen that, in the correlation wells, the purple surface represents the top of the WyantDot Chalk Formation and on top of it there are fining upward electrofacies associated with the base of the Banquereau Formation (Figure 13). Therefore, the light green surface represents the end of the transgression and so it is interpreted as a maximum flooding surface (MFS). This package also corresponds to a set of prograding clinoforms with a gentle dip that downlaps the WyantDot Chalk Formation. Additionally, this package consists of semi-parallel reflectors with low to moderate amplitude and low
Moreover, this package consists of semi-parallel reflectors with moderate to high continuity, and was interpreted as seismic facies 4 (SF4) and also exhibits an irregular electrofacies sequence in the correlation wells (Figure 13). This package was interpreted as a HST based on the characterization mentioned previously.

The youngest package interpreted in this section, between the red and sea floor surfaces, relates to a prograding stacking pattern which is being invaded by a prominent submarine valley that eroded down to the last HST. This package consists of semi-parallel reflectors with moderate to high amplitude and moderate to high continuity, which was interpreted as seismic facies 3 (SF3). Additionally, this package is characteristic as it exhibits truncation reflector termination and submarine channel sedimentation (purple dashed lines in Figure 18).

For the following package, between the dark blue and the red surfaces, it can be seen in the Wheeler domain (Figure 15) that the cliniforms start retrograding which means that the base-level is rising again. Moreover, this package consists of semi-parallel reflectors with moderate amplitude and moderate continuity, which was interpreted as seismic facies 4 (SF4) and also exhibits an irregular electrofacies sequence in the correlation wells (Figure 13). This package was interpreted as a HST based on the characterization mentioned previously.

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The study area is located in the continental shelf of the Sabine sub-basin. According to Wach and Mosher [16], marine shelf mudstones, sandstones and conglomerates of the Banquereau Formation were influenced throughout the Cenozoic by several major unconformities related to sea level fall. As mentioned before, sediment distribution of Miocene successions was strongly influenced by the Western Boundary Undercurrent with periods of intensified bottom current activity also occurring in the Late Pliocene [19] – [20], followed by widespread Gully cutting in the Early Pleistocene. These events of bottom current activity and Gully cutting in the Early Pleistocene probably marked the beginning of the formation of the canyon being analyzed. Later, during the Quaternary, several hundred meters of glacial and marine sediment were deposited on the outer shelf and slope [17] [21] [22]. Wach and Mosher [16] also argues that on the Scotian Shelf and Grand Banks, the widespread hiatus eroding either the upper part or all of the Olispocn, is marked by a regional unconformity: the nature of which includes canyon formation. Canyon incision at the shelf edge was initiated during the Eocene and was extensive by the Olispocn (B). These erosional events are seen in the seismic information where after the base level fall, thick sandstone sequences (200 – 400 [ft]) were deposited on the shelf at the end of the FSST (Figure 20). In this context, the sedimentation within the canyon occurred in stages where the energy of the source of sediments, and therefore the grain size, varies according to the stage.
It is highly recommended that stratigraphic columns generated from the description of core and cuttings samples be used as input to calibrate all of the interpretations of lithologies made based on neural networks or any other methodology, since well logs represent an indirect measure of the physical properties of the rocks while having a rock sample from the interval of interest is priceless. Since the 3D seismic stratigraphic model proposed by this methodology is mainly based on seismic data, it needs to have a good S/N (signal/noise) ratio so that the automatic horizon tracking can produce a horizon framework where the resulting horizons will not cross seismic reflectors. Another way to improve the quality of the horizon framework used for sequence stratigraphic analysis is to incorporate as much possible number of horizons as constraints, calibrated with stratigraphic analysis performed with core data and well logs. The more guidelines the algorithm has to perform the automatic tracking of the horizon framework, the better the resulting horizon framework will be. Now, the constraints horizons need to be interpreted based on stratigraphic analysis and preferably, sequence-bounding surfaces, thus the interpreter will have control of how the automatic tracking of the horizon framework would turn out.

Referring specifically to system tracts interpretation from the base level curve (Figure 16), it could be argued that right after the Falling Stage System Tract (FSST) an almost completely eroded Transgressive System Tract (TST) might be interpreted following the high negative amplitude above the Maximum Regression Surface (MRS) at approximately 550 ms (Figure 18).

Besides just having a basic 2D sequence stratigraphic model, this methodology provides the interpreter with a 3D geological model that incorporates 3D sequence stratigraphy, structural geology and sedimentation history, thus allowing the extraction of geobodies from the seismic facies associated with a specific system tract that has the highest probability of sandstone discovery. Together, these work as a tool that helps the interpreter when it comes to well placement decisions.

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La presencia de depósitos de residuos impiden el cumplimiento de la normativa de prueba de filtración en frío (cold soak filtration test). La literatura ha mostrado ampliamente que estos depósitos son resultado de la precipitación de Haze que aparece en los tanques de producto o de sus clientes y que impiden el cumplimiento de la norma de prueba de filtración en frío (cold soak filtration test). La literatura ha mostrado ampliamente que estos depósitos son resultado de la precipitación de Haze que aparece en los tanques de producto o de sus clientes y que impiden el cumplimiento de la norma de prueba de filtración en frío (cold soak filtration test).