High Resolution Sequence Stratigraphy of the Banquereau Formation, Offshore Nova Scotia

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Abstract

This thesis interprets the sequence stratigraphy and depositional history of the lower Banquereau Formation through describing and interpreting the internal geometry of an interval of clinoforms found in the lower Banquereau Formation. Previous studies have described the lithology of the Banquereau Formation to be mostly mudstone with minor amounts of siltstone and sandstone in downlapping and prograding sequences. Sequence stratigraphy interpretations integrated with high resolution reflection mapping allows for the creation of a depositional model of the offshore Nova Scotia during the Late Cretaceous to early Quaternary. These interpretations provide an in-depth understanding of the internal structure of the prograding sequences at a level of detail not previously known for the Banquereau Formation. Interpretation of seismic data demonstrates that deltaic sized clinoforms prograded to the southeast to combine with the shelf edge during the later periods represented by the thesis data. The seismic data of this thesis represents condensed sections which allows for the creation of an overall relative sea level curve for the area which does not take into account sequence scale sea level changes.

Purpose

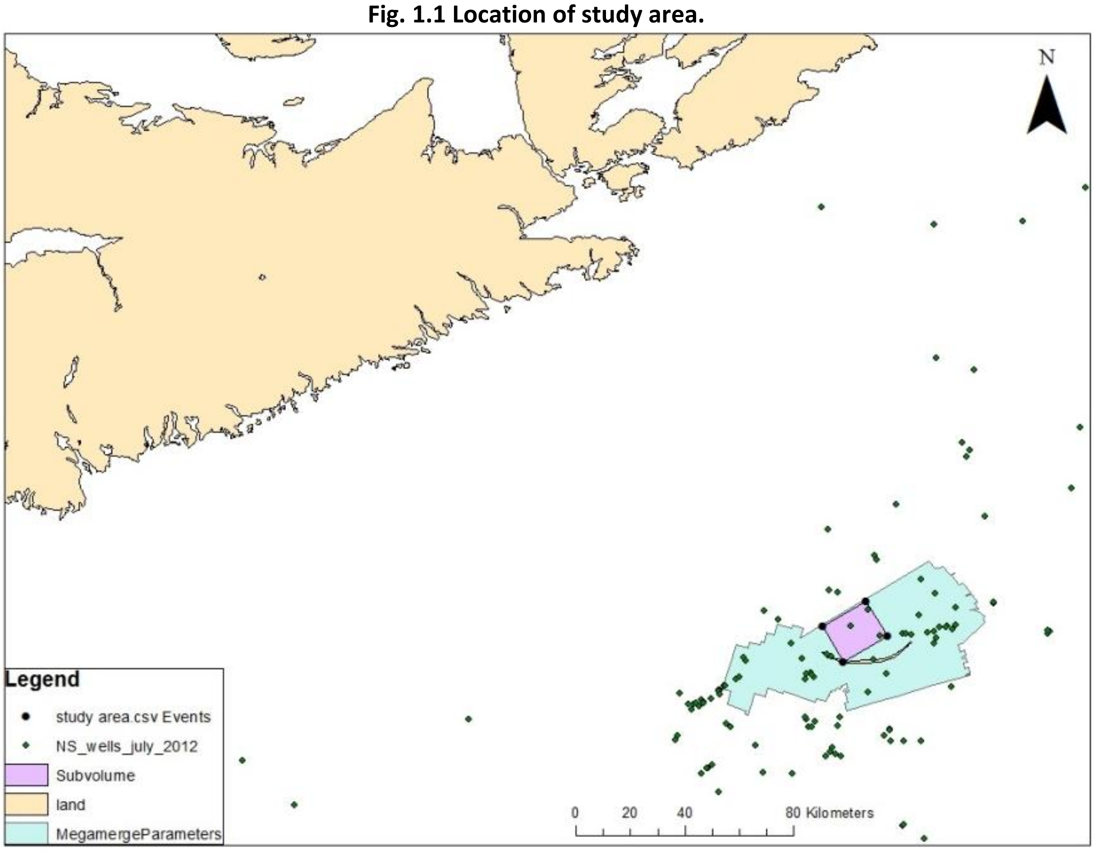
The Late Cretaceous to Late Neogene/early Quaternary Banquereau Formation in the Scotian Basin, offshore Nova Scotia, is a stacked series of prograding sequences that downlap onto the Wyandot Formation. The Banquereau Formation unconformably overlies the Wyandot Formation and ranges in depth from 165 to 1355 m below the seafloor, reaching the thickest point of 1500 m in the Sable Sub-basin, north of Sable Island. Due to low potential for hydrocarbon exploration in the Banquereau Formation within the Sable Subbasin, it has been accorded little scientific attention. There have been studies published describing the general lithologies found within the Banquereau Formation and describing the clinoform shape of the prograding sequences of the formation but the focus of this thesis is to perform sequence stratigraphic analysis on a sub-volume of the Sable Megamerge dataset in order to provide a better understanding of the depositional environment of these clinoform shapes. The high resolution seismic data available for this thesis was donated by ExxonMobil and allow for interpretation of the clinoforms at a highly detailed scale. Through the use of sequence stratigraphy and a new software by OpendTect the goal of this thesis is develop a depositional model for the lower portion of the Banquereau Formation and understand changes in relative sea level associated with this model.

Chapter 1: Introduction

1.1 Regional Location

The setting of this study is the Scotian Basin offshore Nova Scotia (Fig. 1.1), an area of 300,000 Km^2 (Hansen et al., 2004), subdivided into several sub-basins. These sub-basins from northeast to southwest are the Laurentian, the Abenaki, Sable, Shelburne, and the Georges Bank (Mukhopadhyay et al., 2003). The sub-basin in this thesis is the Sable Subbasin. Offshore Nova Scotia is separated into three oceanographic regions, the shelf: up to 200 m water depth, the slope: 200 to 4000 m water depth, and the abyssal plain: greater than 4000m water depths (Colletta et al., 2011). The focus of this study is the Banquereau Formation which is Late Cretaceous to early Quaternary in age and lies on top of the Wyandot Formation (McIver, 1971).

Fig. 1.1 Location of study area.



1.2 Previous Work

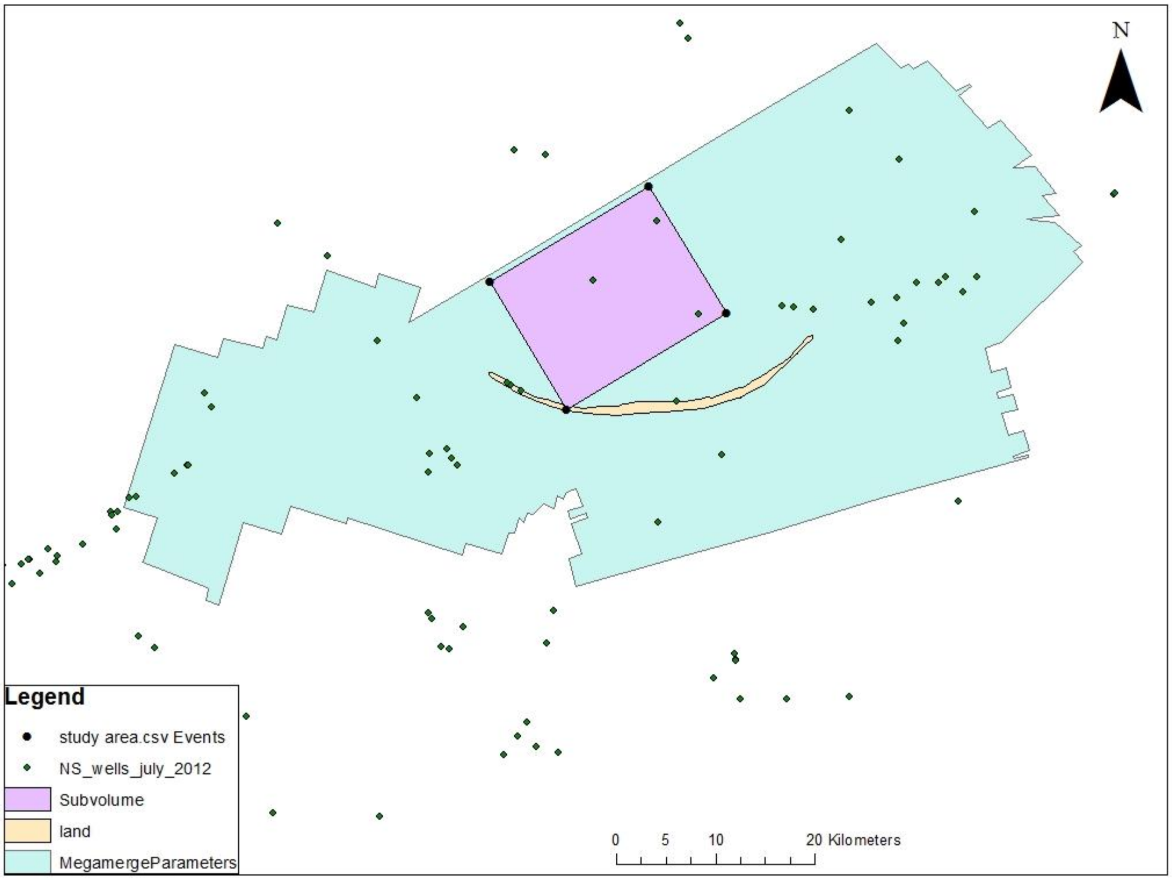


Fig. 1.2 Sable Mega-Merge dataset in blue and thesis sub-volume in pink.

Offshore Nova Scotia has been explored since the 1960s. Approximately 180 exploration wells have been drilled in the Scotian Basin (Mukhopadhyay et al., 2003) on the shelf (Fig. 1.2) and eight wells drilled on the slope in the range of 1000m water depth (Colletta et al., 2011). Discoveries on the Scotian Shelf have been gas or condensate (Mukhopadhyay et al., 2003). These discoveries are mainly found in the Cretaceous and Jurassic formations in the Scotian Basin (Cummings et al., 2005). The geology of the Scotian Shelf and the Sable Sub-basin have been studied previously and the stratigraphy has been identified in several papers (e.g. McIver 1971; Wade and MacLean, 1990; Fensome et al., 2008; Campbell, 2012), but little attention has been focused on the structure of the Banquereau Formation and its implications for paleogeography and relative sea level due to the lack of prospectively for hydrocarbons. McIver (1971) described the lithologies of the Banquereau Formation as most commonly mudstone with lesser amounts of silt and argillaceous sand which is found in increasing amounts in the upper half of the formation. McIver (1971) also stated the mudstone of the Banquereau Formation is commonly burrowed or highly reworked. The sand of the Banquereau Formation is very fine to fine grained and is finely laminated to highly burrowed with channel features identifiable in the upper portion of the formation (McIver, 1971). The lithology is detailed, but due to poor well control at the time of publication McIver (1971) does not mention the internal geometry of the Banquereau Formation. Fensome et al. (2008) describes the lithology Banquereau Formation as sandstone topsets of clinoforms with mudstone fore- and bottomsets. According to Fensome et al. (2008) the lower interval of the Banquereau Formation is a "prograding deltaic clinoform units that built basinward".

1.3 Background Geology

The formations of the Sable Sub-basin are found on the stratigraphic column of Figure 1.3 These formations from oldest to youngest are the Abenaki, Missisauga, Logan Canyon, Dawson Canyon, Wyandot and Banquereau. The Abenaki Formation is Jurassic in age, whereas the Missisauga, Logan Canyon, Dawson Canyon, and Wyandot formations are all of Cretaceous age. The

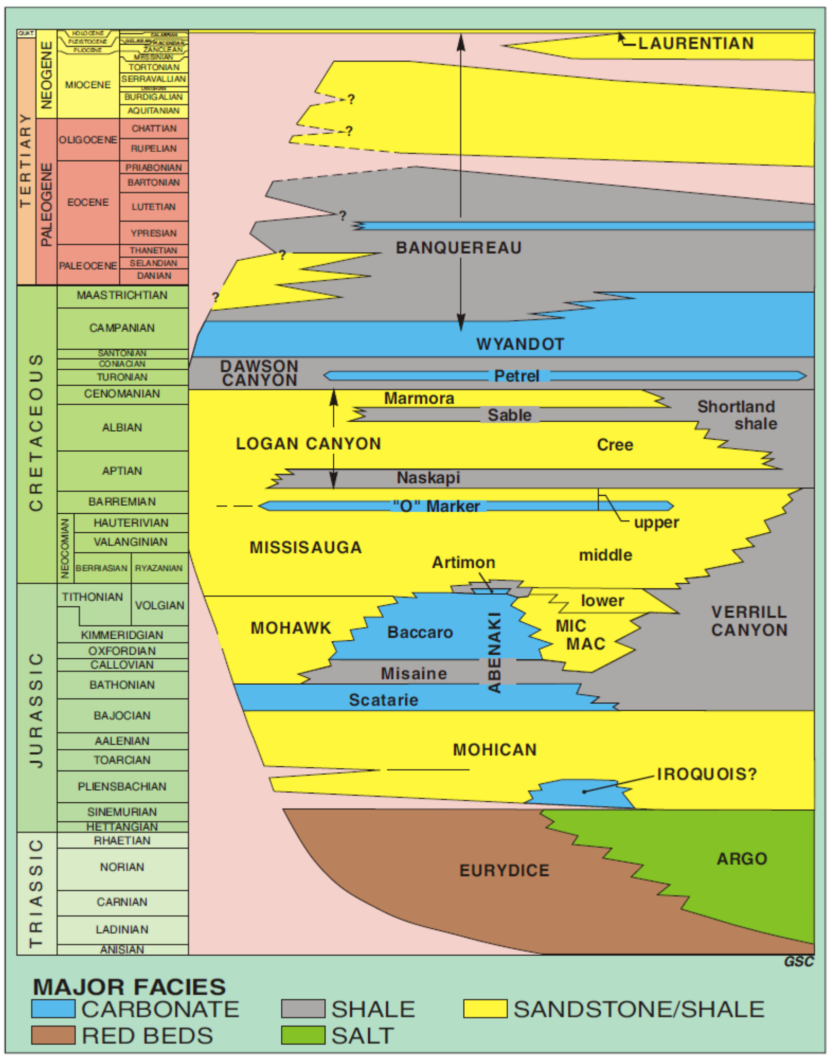


Fig. 1.3 Stratigraphic column for the Sable Subbasin (Modified from MacLean and Wade, 1993; in Fensome et al., 2008)

Banquereau Formation is Late Cretacous to early Quaternary in age (Ings et al., 2005). The Missisauga Formation is mainly sandstone with some minor siltstone beds. It is commonly broken into an Upper and Lower unit, with the "Base O-Marker" found within the Upper Missisauga Formation. This O-Marker is a regional stratigraphically correlatable unit, easily identifiable on seismic data and comprises carbonates and shale (CNSOPB, 2008). The Missisauga Formation can broadly be defined as comprising fluvio-deltaic sediments (Jansa et al., 1990). The Logan Canyon Formation has several members with variable amounts of sand or sand and shale, but the main component is a thick shale succession, interpreted as a marine transgression above the Missisauga Formation (Jansa et al., 1990). The Dawson Canyon Formation is mainly shale. The Wyandot Formation is chalk-dominated, highly bioturbated, with minor amounts of marl and shale (Ings et al., 2005). Paleontological evidence indicates there is a hiatus associated with the top of the Wyandot Formation (McIver, 1971) above which lies the Banquereau Formation. As described in Section 1.2 the Banquereau Formation is mudstone dominated with minor amounts of silt and sand in a prograding series of clinoforms (McIver, 1971; Fensome et al., 2008).

Chapter 2: Methods

2.1 Data

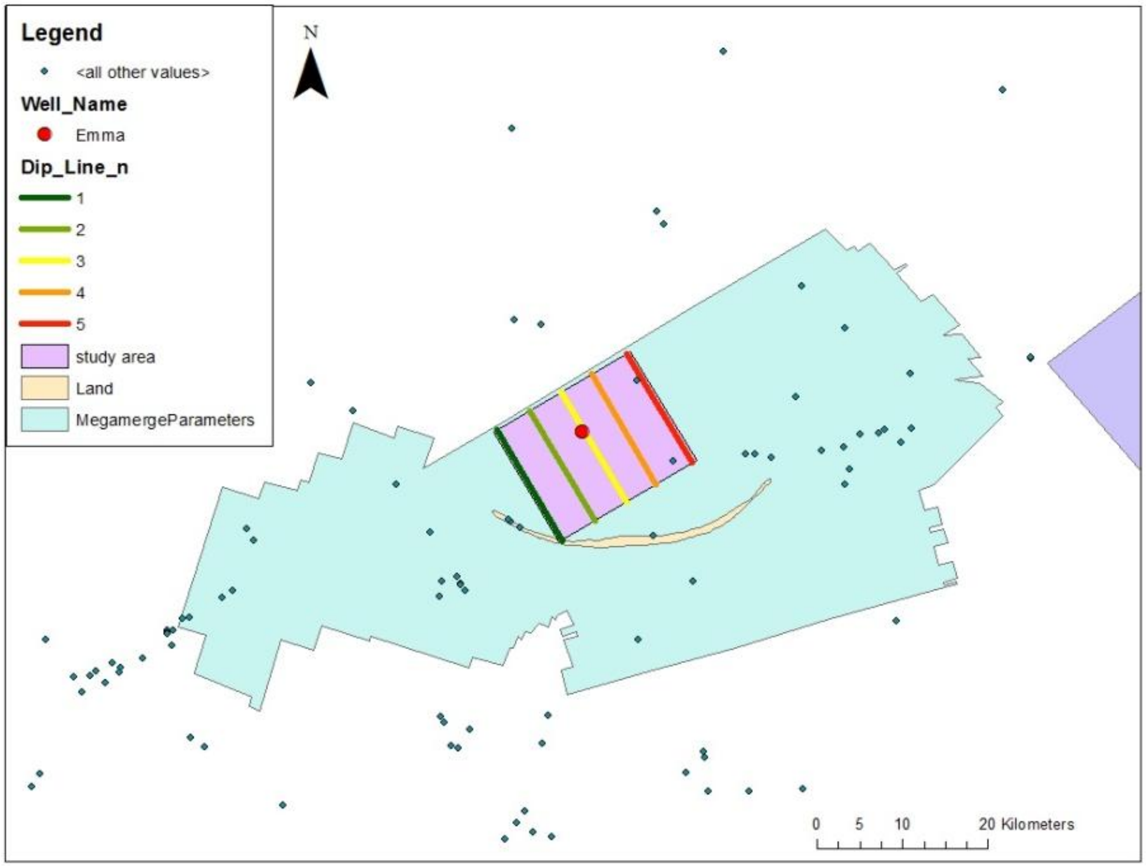


Fig. 2.1 Map showing the location of the five interpreted seismic lines and the one well with digital files available within the study area.

The data used in this thesis are 3D seismic data within the Sable MegaMerge dataset, donated to Dalhousie University by ExxonMobil (2012). The Sable MegaMerge dataset is a large 3D seismic volume that comprises seven seismic volumes which have been reprocessed with proprietary techniques by ExxonMobil so that the data are normalized and merged into one large volume. The study area for this thesis is a subset measuring approximately 18 km by 14 km (from inline 5600 to 6600 and from crossline 1200 to 2000) giving a total surface area of 260 km^2.

A known reflector on the seismic data which represents the top of the Wyandot Chalk Formation was chosen as the depth in two-way travel time as the cut-off for this subset at 1500 ms. There is only one well with available digital data located within the thesis area, and this well has not allowed for a time-to-depth correlation due to there not being sonic logs which are needed to create a synthetic time-to-depth conversion. A preliminary time-to-depth correlation has been calculated from Campbell (2012) by calculating the average rate of change for four individual wells included in Campbell (2012) values of time-to-depth. As these four averages for four different wells were very similar, they were then averaged together to provide a single value which could then be multiplied to the time value of seismic data in this thesis to provide an approximate depth for the purposes of understanding the scale of features seen on seismic data. This provided an approximate thickness of one kilometre of the Banquereau Formation in this sub-volume of which this thesis focuses on the bottom 500 m.

To interpret this seismic volume this study uses seismic interpretation, sequence stratigraphy, Petrel and an open-source software called OpendTect. Five seismic lines (Fig. 2.1) have been chosen as they show the nature of the dipping reflectors in the Banquereau Formation. and are evenly spaced throughout the extents of the seismic volume.

2.2 Seismic Interpretation

Seismic data represent density changes within the subsurface. There are four components to acquiring seismic data and these are a target location, a source, a reflector and a receiver (Short, 1999). The target location defines a specific subsurface depth to be imaged through seismic data. A source creates energy waves in the subsurface which are then reflected from the next important component -- the reflector, a subsurface boundary. A source, in the past, has been explosives both on land and in the water. Today seismic acquisition in water uses a water or air gun. A water gun drives a piston through the water fast enough to create a vacuum bubble releasing a shock wave whereas an air gun holds compressed air and once fired will expel this compressed air into the water, also creating a shock wave that will oscillate and propagate through the subsurface (Desler, 1999). A seismic reflector is a feature of the subsurface (rock layer, water or hydrocarbons) which has a change in density from the surrounding rocks. This density change will reflect the energy

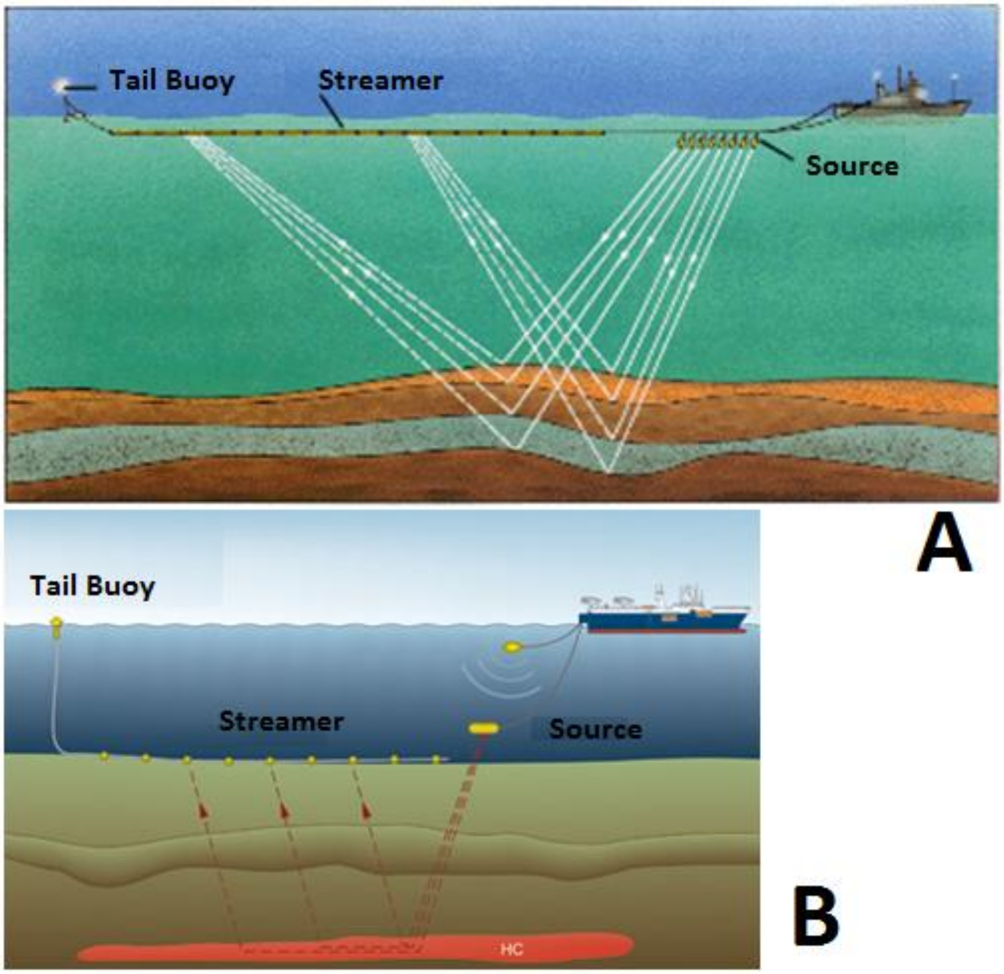


Fig. 2.2 A) Marine seismic survey, showing location of streamer at the top of the water column, rock reflectors and source (Modified from Schlumberger Oilfield glossary).
B) Ocean bottom survey showing location of hydrophones on the bottom of the ocean, source and reflector (Modified from Johnstad et al., 2009).

wave and send it to the waiting receiver. A receiver is a geophone or hydrophone depending on the location of seismic gather, land or water respectively. A geophone turns energy reflected from the changes in density into electrical voltage (Short, 1999). The arrival times of the energy waves are recorded electronically. A hydrophone is similar to a geophone, only designed for water gathers and uses pressure differences to create electric signals which are recorded electronically. Hydrophones are towed behind a ship which carries the source (Fig.2.2), and are towed in long strings also called streamers of 25 to 40 hydrophones, either floating on the top or near surface of the water column in deeper water (Fig.2.2A), or are dropped to the bottom of the ocean in shallow water (Desler, 1999)(Fig. 2.2B). A seismic survey can be either arrayed in 2D or 3D gathers. To

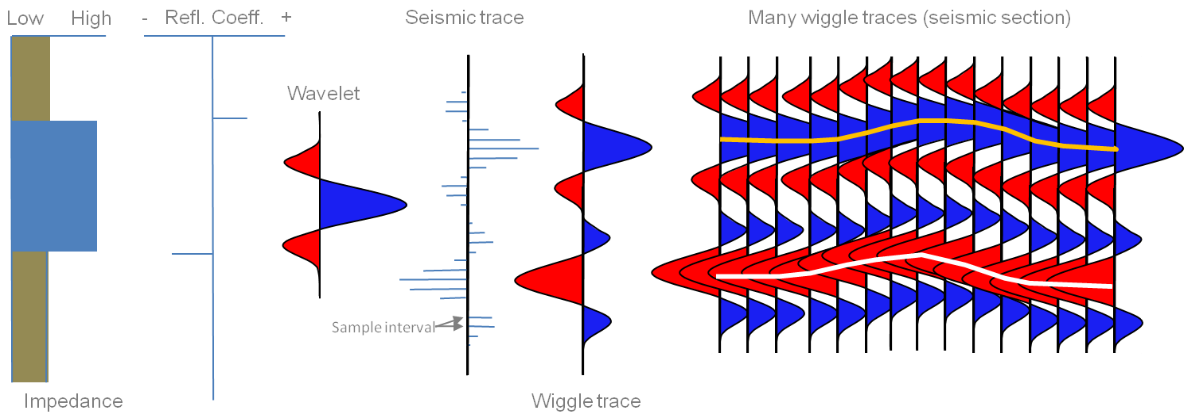
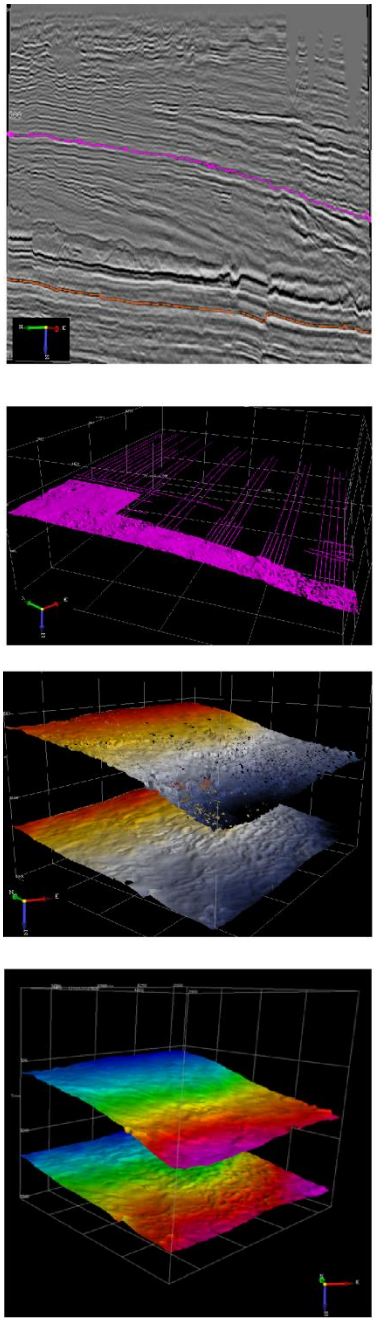


Fig. 2.3 The formation of peaks and troughs on a seismic trace (Agile Geoscience, 2011).

produce 2D seismic data a single line of geophones or hydrophones is used while 3D seismic surveys use a grid of closely spaced receivers and to produce a 3D image of the subsurface.

Seismic reflections are produced due to density differences in the subsurface. Density increases in rock layers with depth, which cause an increase in impedance, will be seen as a peak on seismic data. The reverse is true when transitioning from a dense layer to a less dense layer and will produce a trough (Fig. 2.3) (Reddy, 1999). This is the North American convention; this model is reversed for European seismic reflections (Agile Geoscience, 2011). Many of these peaks and troughs are grouped together (Fig.2.3) which aligns peaks and troughs into rows, and in 3D these become layers representing a change in rock properties in the subsurface. These lines and surfaces are interpreted using geoscience software packages such as Petrel (Schlumberger), and OpendTect which have been used for this thesis.

As mentioned in Section 2.1, a subvolume of the Sable Mega-Merge dataset has been created and this was then uploaded into an interpretation software to map reflections in 2D space (Fig.2.4 A). After mapping reflections for the same reflection throughout the whole 3D package the software can then extrapolate between the 2D horizons to create a 3D surface (Fig.2.4 B). OpendTect software requires two surfaces to be interpreted and mapped in 3D (Fig.2.4 C) and artificially smoothed (Fig. 2.4 D). These bounding surfaces, which constrain the area of interest, allow for analytical processes to be performed on the seismic data, examples are in Figure 2.5. This image was produced by analysing the perceived dip of the seismic data and colouring the image to highlight areas of high dip with red or pink colours and areas of low relative dip with blue and green colours; this information is called “dip steering”. After the dip steering data is created, another process in the interpretation software package creates a horizon cube like that in Figure 2.5 B. This is a dense set of interpreted seismic horizons which identify seismic reflections, even if they are not continuous reflections. By colouring all interpreted seismic lines in this rainbow pattern the colours become coeval. These images will be used in the Results chapter (Chapter 3) to identify periods of sedimentation or sediment bypass.



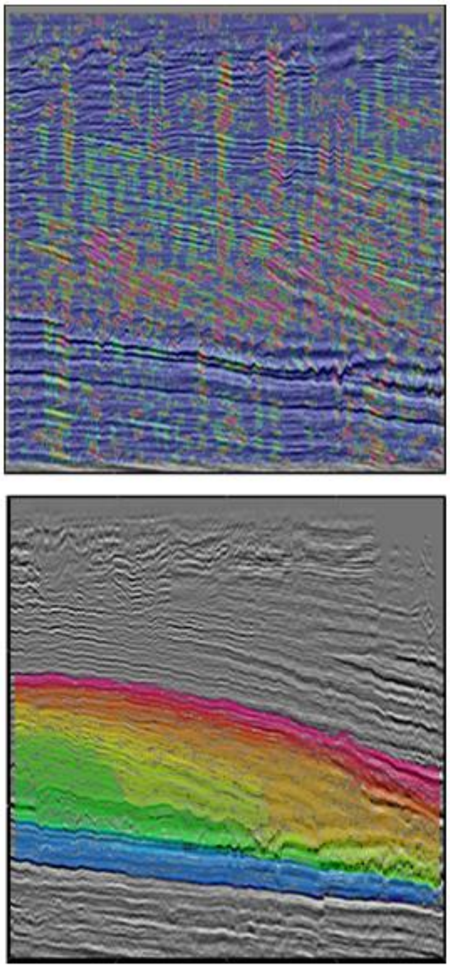
A. An example of 2D mapped seismic horizons as pink and orange lines.

B. Using 2D horizons to create 3D surfaces in a seismic interpretation software.

C. Top and bottom bounding surfaces constraining the area of interest.

D. Top and bottom surfaces after smoothing effects. Blue indicates area of highest elevation, pink lowest elevation

Fig. 2.4 The workflow though which 3D surfaces are created in OpendTect (vertical scale stretched by 20 in all A-D).



A. A dip steering cube with areas of high dip indicated with pink or red colours and areas of low dip indicated with blue or green.

B. A Horizon cube with interpreted surfaces falling between the two bounding surfaces from Figure 2.4.

Fig. 2.5 The effects of seismic processing using interpretation software (vertical scale stretched by 20 in both A&B)

2.3 Seismic and Sequence Stratigraphy

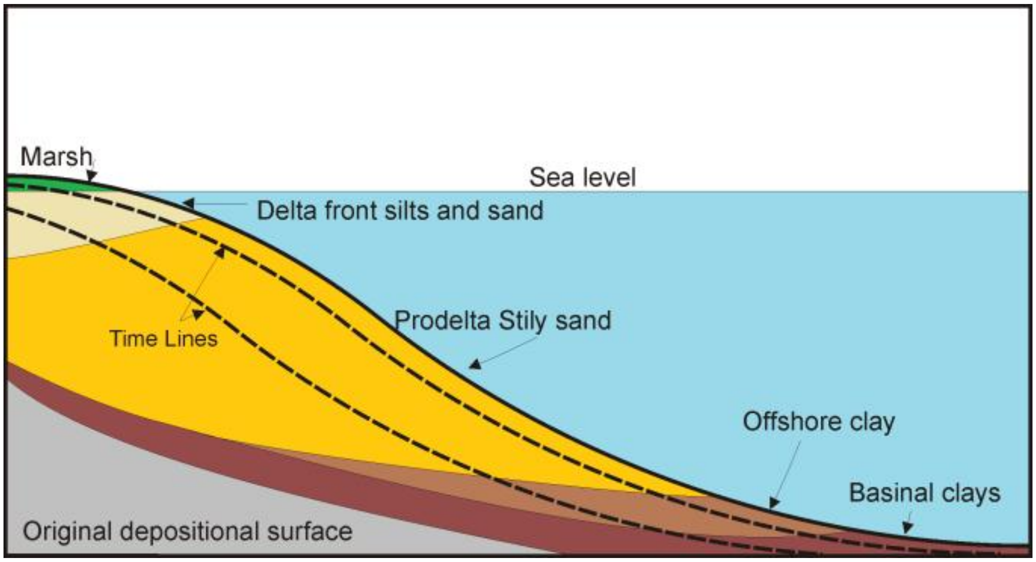


Fig. 2.6 A cross section of a prograding delta. Dashed lines indicate coeval deposition of sediments and clinoform shape.

Sequence stratigraphy is an approach to describing strata within a temporal framework (Catuneau et al., 2009) and has been described as the study of sediments and sedimentary rocks in terms of repetitively arranged facies and associated stratal geometry (Christie-Blick, 1995). For the case of a deltaic succession, this is based on the premise that deposition of sand on the delta front is coeval with silt and clay being deposited in the prodelta area (Fig.2.6). The deposition of sediment along an inclined surface creates a distinctive sigmoidal shape seen in Fig.2.6, called a clinoform, which marks a near-isochronous event across the area but may also record a change in lithology when the layer is traced downdip. Clinoforms can form within prograding delta and shelf margin depositional settings. The main distinction between the two is the relative size difference; <100 m height for deltaic clinoforms and 100-1000 m height for shelf margin clinoforms (Johannessen et al., 2005).

Sequence stratigraphy identifies discontinuities which separate older and younger rocks and allow sediment packages to be divided into time packages, which can indicate depositional characteristics (Christie-Blick, 1995). This leads to the definition of a depositional sequence as "a

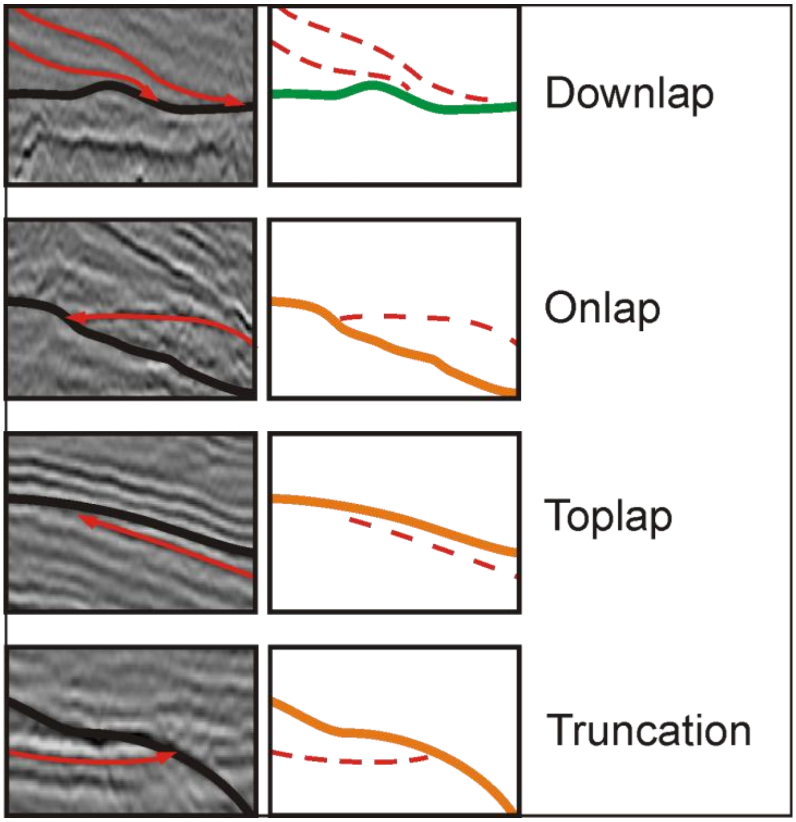


Fig. 2.7 Sequence stratigraphic terminations as seen in seismic data of this thesis. Green lines indicate maximum flooding surfaces and orange lines indicate Sequence Boundaries red lines seismic reflections that terminate in the indicated manor.

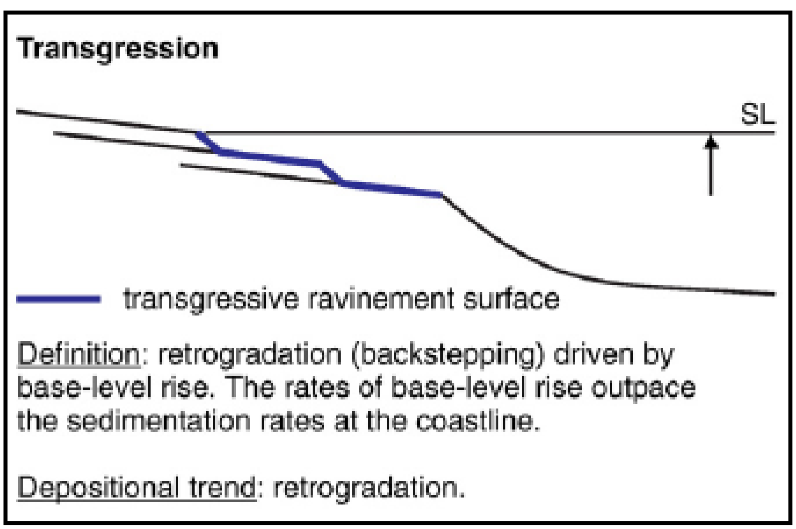


Fig. 2.8 Transgressive surface explained due to relative sea level rise and low sediment input to the basin (modified from Cataneau et al., 2009).

relatively conformable succession of genetically related strata bounded at base and top by unconformities and their correlative conformities" (Mitchum et al., 1977). These sequences are defined in seismic stratigraphy through the identification of reflection terminations.

There are four main types of termination identified within the data of this thesis (Fig.2.7): downlap, onlap, toplap and truncation. Downlap is where "an initially inclined stratum terminates downdip against an initially horizontal surface" (Mitchum et al., 1977). Onlap is defined where "an initially horizontal stratum laps out against an initially inclined surface or in which an initially inclined statum laps out updip against a surface of greater inclination" (Mitchum et al., 1977). Both downlap and onlap are two types of baselap, where there is lapping out at the lower boundary of a depositional sequence (Mitchum et al., 1977). The opposite of baselap is toplap, which is the "lapout at the upper boundary of a depositional sequence" (Mitchum et al., 1977). Finally erosional truncation, which as the name implies is formed through erosion, occurs at the "upper boundary of a depositional sequence; and it may extend over a wide area or be confined to a channel" (Mitchum et al., 1977).

By identifying these terminations (Fig. 2.7) surfaces that help to define sequences are also identified. The major surface between sequences is the sequence boundary, identified by truncation, downlap and toplap (Fig. 2.7) (Abreu et al., 2010). A maximum flooding surface is identified by downlap and is a surface which represents the most "landward extent of the basinal facies" (Abreu et al., 2010). Transgressive surfaces are identified by a landward progression of onlap and downlap surfaces (Fig. 2.8).

2.4 Seismic Systems Tracts

The movement of relative sea level changes the location of sediment deposition through time and creates identifiable seismic terminationsand allow for the classification of systems tracts. There are three systems tracts necessary used for this thesis; the highstand systems, lowstand systems and transgressive systems tracts.

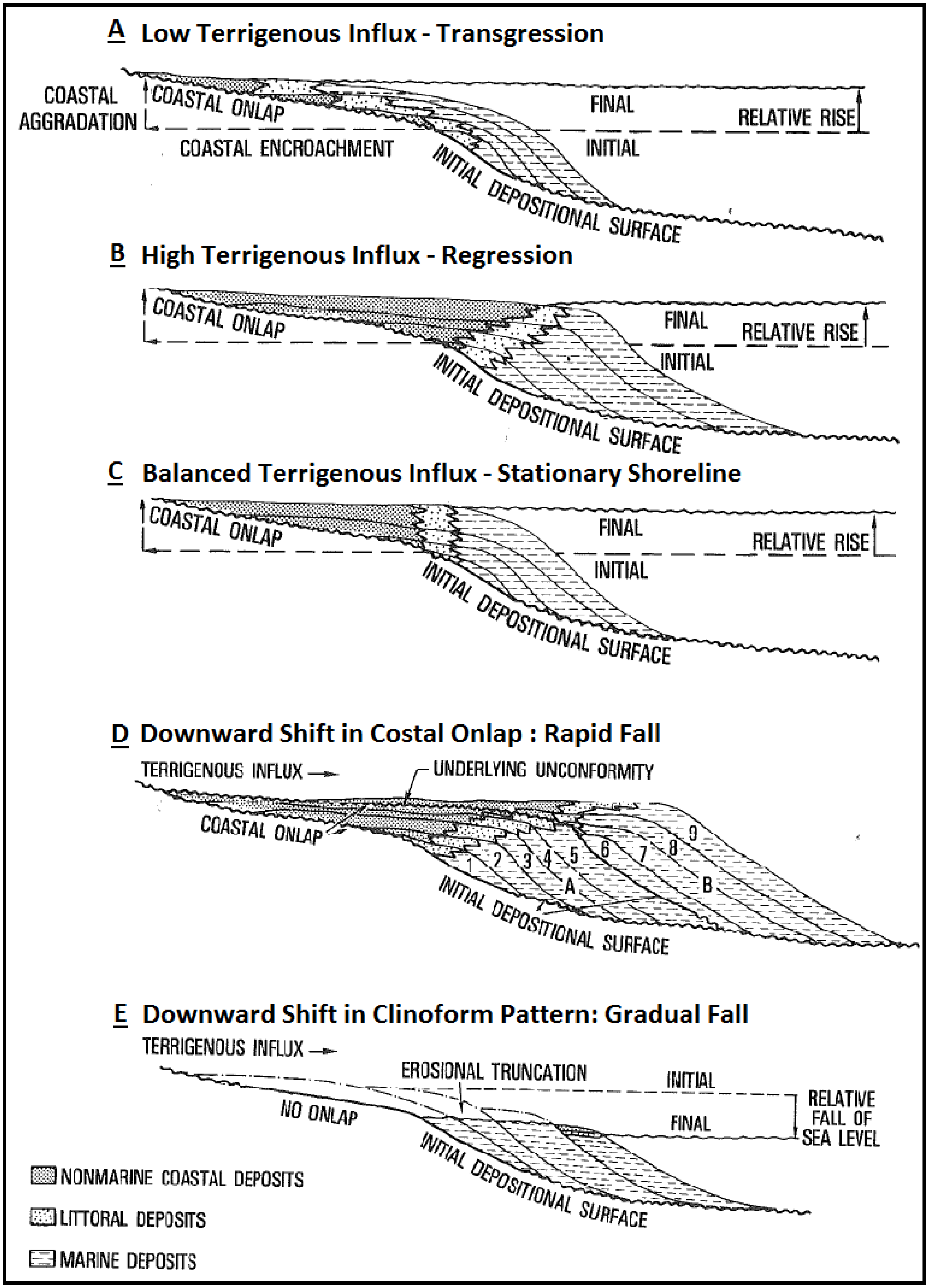
Highstand systems tracts are formed when a relative sea level rise is accompanied by sufficient sedimentation for the coastline to advance. Strata of the systems tract rest on a maximum flooding surface and are capped by a sequence boundary. This is identified on seismic data by onlap in a shoreward direction, or coastal onlap (Vail et al., 1977). There are three different changes in seismic reflection patters from this relative rise in sea level depending on the amount of sediment input to the basin (Fig. 2.9; A, B, & C) resulting in either transgression, regression, or a stationary/aggradational shoreline. Regression and aggradation are indications of highstand systems tracts.

Transgressive systems tracts are the result of rising relative sea level with very low sediment input and are rare within the data of this thesis (Vail et al., 1977). They include strat up to the level of a maximum flooding surface. Lowstand systems tracts occur when there is relative sea level drop and they are topped by a transgressive surface. Lowstand systems tracts can be identified on seismic following a downward or basinward shift in onlap or a downward shift in the clinoform pattern (Vail et al., 1977). There are two different responses to relative sea level fall depending on the rate at which this occurs (Fig. 2.9; D & E). A rapid sea level fall will result in an unconformable surface with costal onlap resuming once sea level begins to rise again (Vail et al., 1977). If the fall in relative sea level is slow the result will be a basinward shift in onlapping patterns (Fig. 2.9; E)(Vail et al., 1977) which is known also as offlap (Catuneau et al., 2009).

Fig. 2.9 A, B & C: Clinoform stacking patterns resulting from rising sea level

D & E: Clinoform stacking patterns resulting from lowering relative sea level

(Modified from Vail et al., 1977)



Chapter 3: Results

3.1 Seismic Features

Anomalous features of the seismic data package were identified before interpreting the seismic data with certainty (Fig. 3.1). Figure 3.1 (image 1) shows a seismic artifact which is interpreted as being due to poor seismic data as the corner of the data area crops out underneath Sable Island. This poor seismic response prevents interpretation near this feature and restricts the interpretation to the lower sections of the seismic data. A second seismic feature (Fig. 3.1, image 2) is an artifact created from the merging of the marine and ocean bottom surveys (Chapter 2).

3.2 Seismic Facies

The first seismic facies is seen in image A (Fig. 3.1), which is relatively parallel dipping seismic reflections, with clear alternating black and white reflections. This is common with alternating lithology between more and less dense materials (Chapter 2). This seismic facies is found in the topsets of

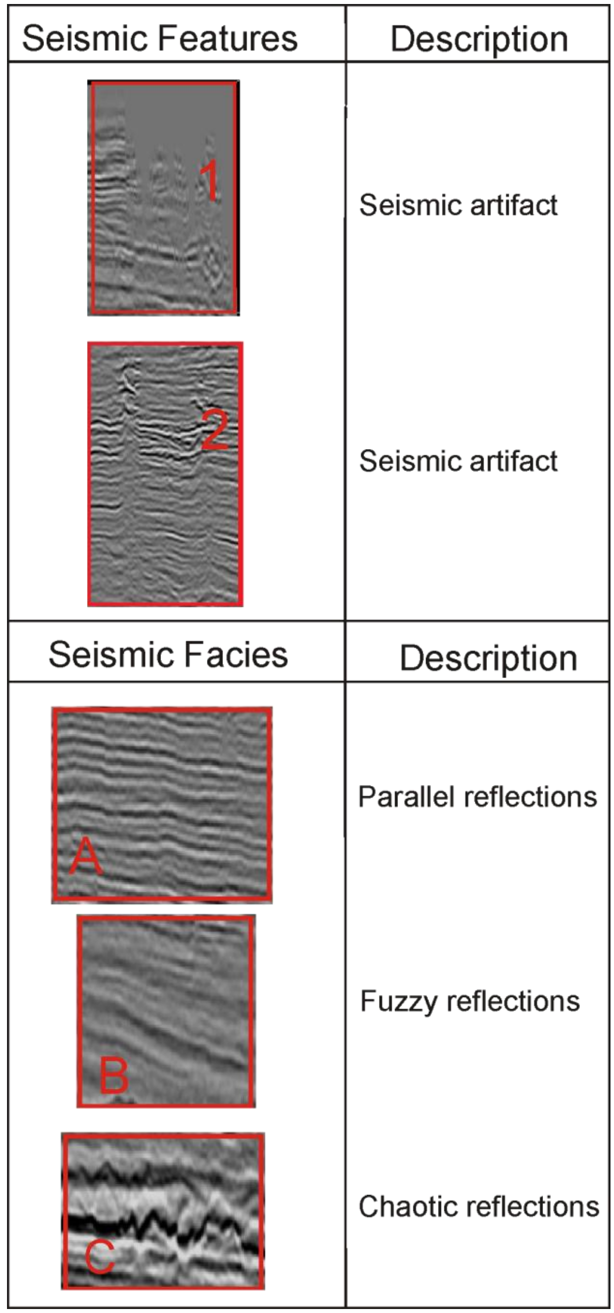


Fig. 3.1 Seismic features and facies associated with the seismic data of this study.

clinoforms within the data, and could represent alternating sand and silt layers, or sand and conglomerate layers. Fensome et al. (2008) described the Banquereau Formation with sandstone in the topsets of clinoforms and this would agree with this assessment.

Image B (Fig. 3.1) shows the second seismic facies. This indistinct seismic facies may represent a nearly homogeneous interval of sediment without defined density differences that normally create clear seismic reflections. These are found within the foresets of clinoforms. They could represent nearly homogenous clay, silt or very fine grained sand. Fensome et al. (2008) described the foresets of clinoforms within the Banquereau Formation as mudstone which could potentially create the seismic facies of image B. Interpretation of this facies becomes difficult in the data region with seismic artifacts of image 2 (Fig. 3.1), and produces lower confidence for interpretation (indicated by dashed lines in later figures).

The third seismic facies found in image C (Fig. 3.1) is typified by chaotic, erratic reflections. This seismic facies is associated with the top of the Wyandot Formation and can be interpreted as a major erosional surface or polygonal faults described by Hansen et al. (2004). This facies and the irregular nature of the contact of the Banquereau Formation with the Wyandot Formation, makes interpretation along this surface difficult. It is artificially smoothed in the following images to focus interpretation on the overlying clinoforms.

3.3 Seismic Interpretation

Five seismic lines have been interpreted in this thesis. These are spaced evenly along the 18 km length of the seismic package with approximately 4.5 km separating each seismic line. They are numbered one through five, from southwest to northeast. Five images (Figs 3.2, 3.5, 3.6, 3.10, 3.12) are illustrated with three different types of interpretation along with an un-interpreted version of the seismic data. The four images for each line are labelled A,B,C and D. The first image is the line with no interpretation (A), the second has sequence boundaries and maximum flooding surfaces identified (B), the third has the systems tracts filled in (C), and the fourth image is a

OpendTect Horizon cube output image (D). Each image in this section has been stretched vertically by a factor of 20 to allow for greater visible expression of the clinoform shapes. The length represented from the left to right edges of each image is approximately 14 km. The location of the seismic trace is indicated in the inset map in the lower right hand corner of the image. The left side of the images are towards the northwest and the right side is to the southeast. Interpretation of these images is focused on the lower portion of the Banquereau Formation as the goal was to interpret many lines over an extensive area rather than a few lines with a thick sequence interpreted. Also, due to seismic artifacts found in the upper portions of the data set (see Section 3.1) interpretation of some high levels would drastically decrease confidence in these portions of the data. Instead greater detail of interpretation was able to be done on the lower sections. Some general interpretations of the upper data have been incorporated with the detailed assessment of the lower part. The slope and shape of the clinoforms of this image indicate that the basin at the time of deposition was to the southeast and the sediment supply was to the northwest, with a paleoflow direction to the southeast.

Seismic line one (Fig. 3.2) is the most southwesterly line. The lower most surface interpreted is the top of the Wyandot Formation and is a major downlap surface, interpreted as a maximum flooding surface. The surface has been smoothed artificially because the actual surface between the Banquereau and Wyandot formations, as mentioned before, is either a major erosional surface and/or generated by polygonal faults, creating the chaotic seismic reflections (chapter 2). The large-scale features of this interpretation are a set of clinoforms with an estimated original height of 400-500m, with smaller features within on a scale of approximately 100-200m. The systems tracts show mainly periods of highstand deposition, inferred from the progradation of clinoforms. In most cases the associated lowstand and transgressive deposits for many of these highstand deposits have either been eroded or were deposited in more distal regions not covered by the data of this thesis. The result is a downward shift in onlap found above the upper

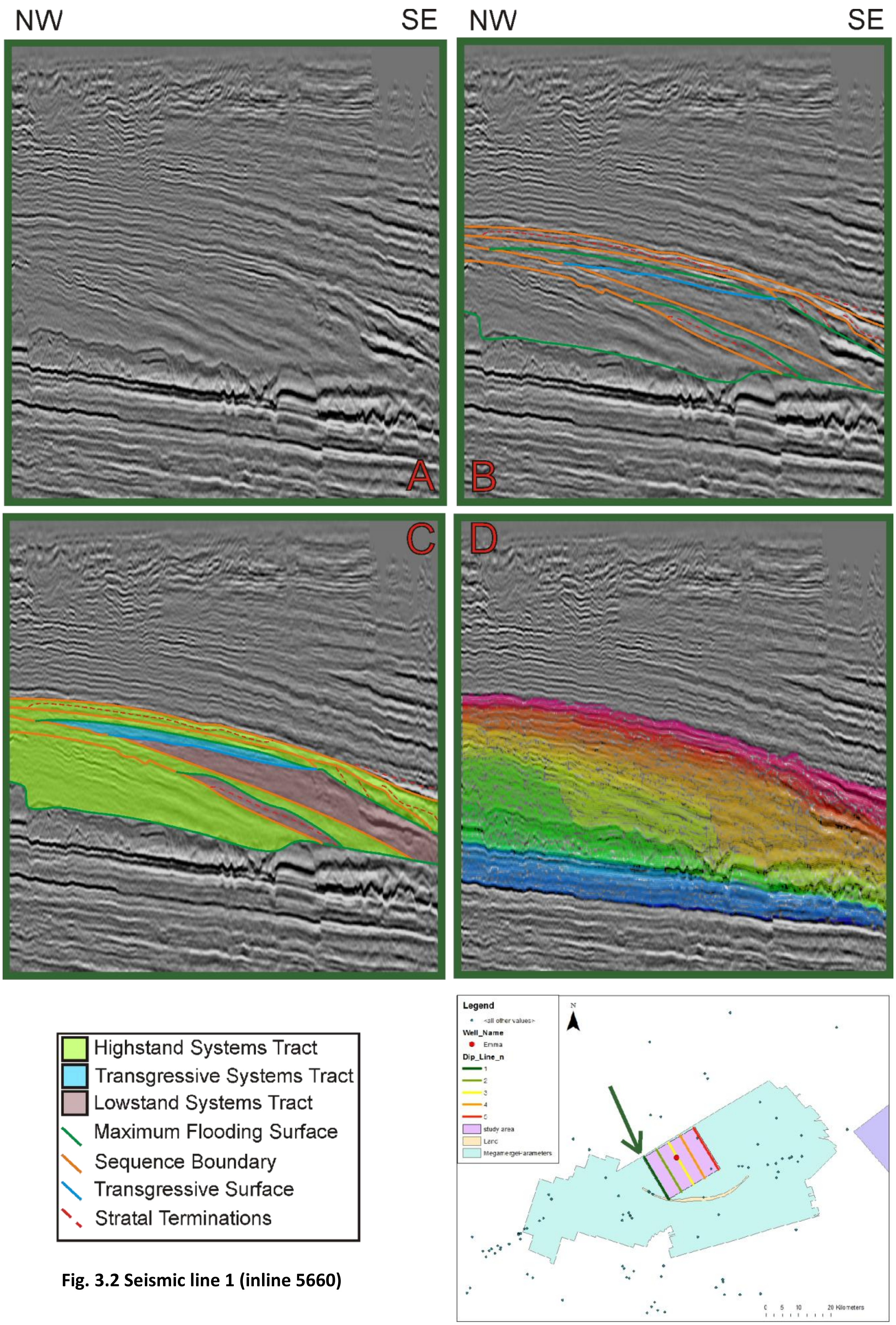


Fig. 3.2 Seismic line 1 (inline 5660)

maximum flooding surface and the sequence boundaries found in this uppermost interpreted section are shifting basinward (see Chapter 2 Fig. 2.9 D)

The rainbow coloured image of block D produced through the OpendTect seismic software shows deposition through time. All the colours represented in Figure 3.2 and those to follow are time-related, indicating that all reflection intervals of the same colour were deposited within a

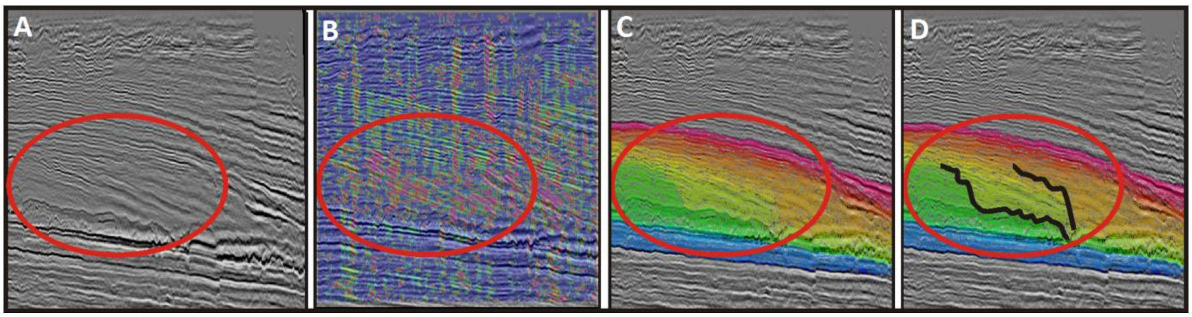


Fig. 3.3 Seismic line 1 with no interpretation, dip steering data, and Horizon Cube data overlain. Right-most image is annotated to highlight the vertical jumps in the data which are an artifact of the interpretation software.

similar, relatively short interval of time; if this is a large package, there was a lot of sediment deposited at this time, and the reverse is also true. The base of the image in royal blue is the Wyandot Formation. There was a relatively large amount of sediment deposited in the region of this seismic line in the times indicated by green- to orange-coloured lines on the image. There was very little sediment deposited during the times of red to pink in this area. This seismic line is a clear example of why it is not always good to rely on automatic interpretation software to create seismic interpretations. Figure 3.3 shows the same seismic line as figure 3.2 but, with the uninterpreted data and the dipsteering data for this line, there is no indication of why there are vertical jumps in the Horizon Cube image (black lines on right pane of Fig. 3.3). Above the topmost interpreted line there are nearly uniformly dipping beds, with some minor stratal terminations visible near the artifact in the upper right hand corner due to the proximity to Sable Island.

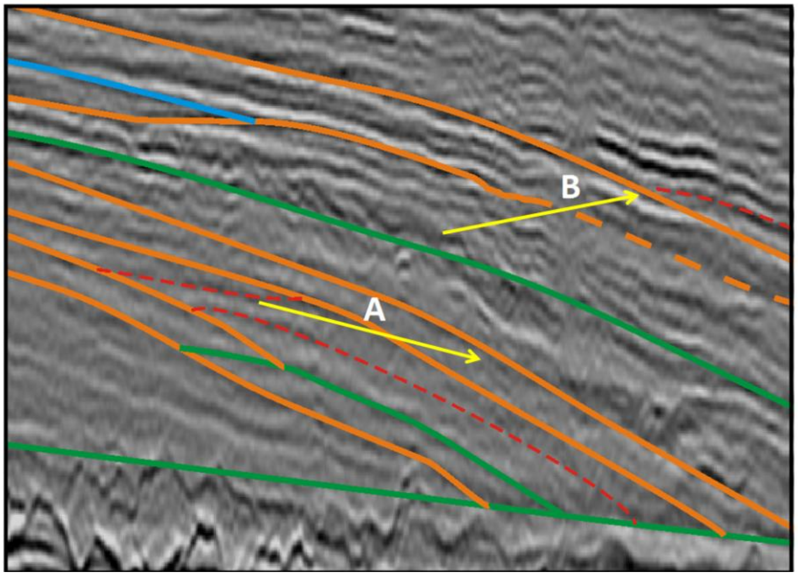
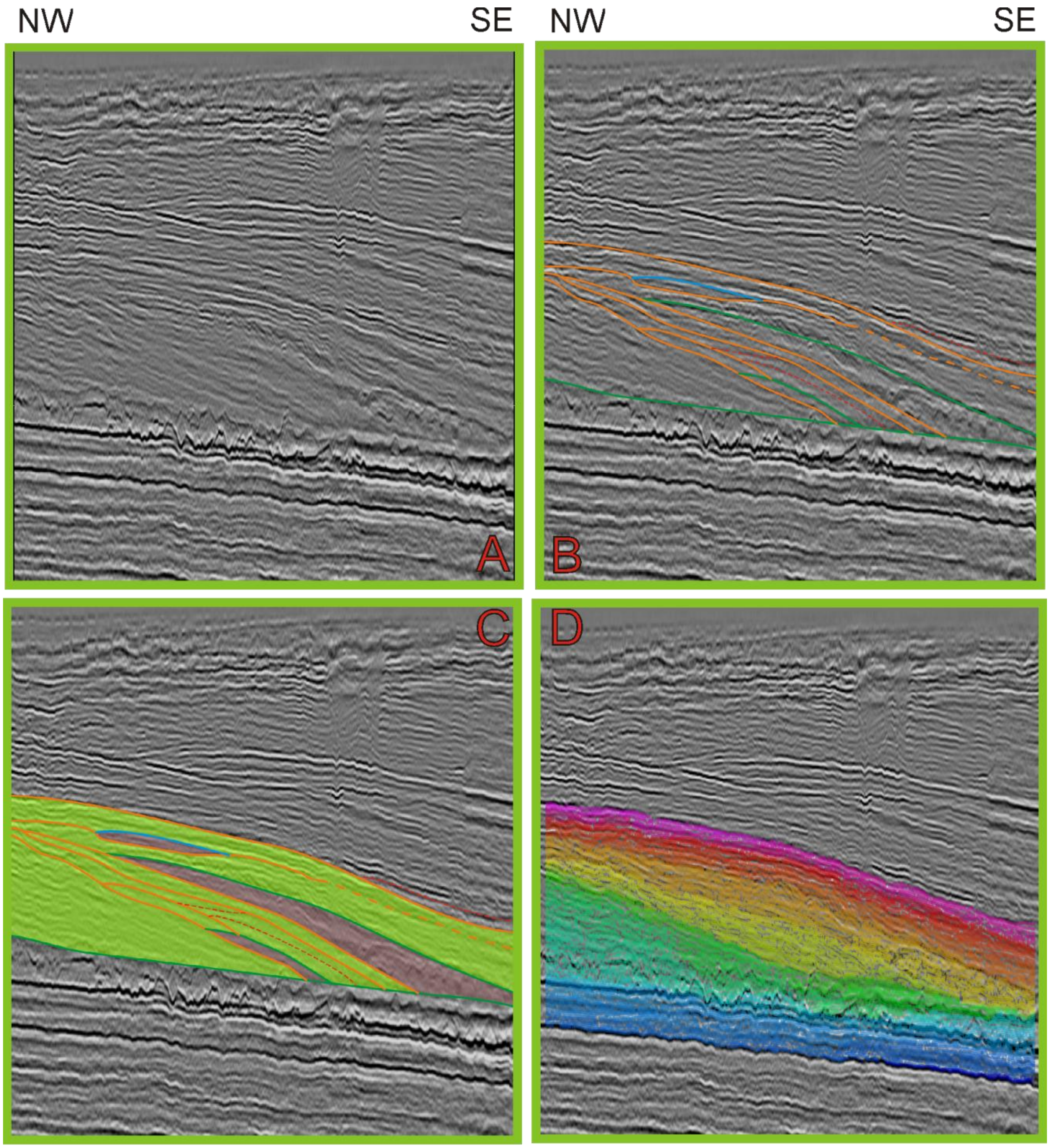
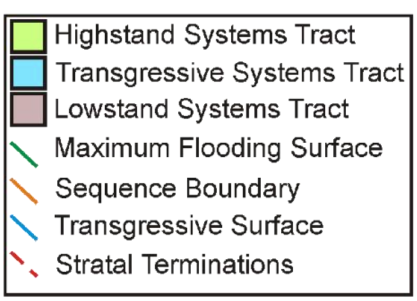


Fig. 3.4 Detail image of Fig. 3.5 showing small scale (100-200 m) features within larger clinoform sets.

Figure 3.5 shows the second of the seismic lines. The lower most surface interpreted is a downlap surface on the Wyandot Formation. Downlapping stratal sets are of similar size to these observed in seismic line one, at the larger scale from 400-500 m in height, while there are smaller scale features of 100-200 m height (Fig. 3.4) within the overall package. The lower portion of this interpreted section (Fig. 3.4 A) shows similar downward shift in onlapping reflections as found in seismic line one. In the top portion of the interpreted section, above the top most maximum flooding surface, there is a general trend of progradation (Fig. 3.4 B) through relative sea level rise coupled with high sedimentation in the area (Fig. 2.9 B). There seem to be fewer strata formed during the lowstand systems tract within this image compared to the first seismic line. There is low confidence in the right hand side of the interpretation due to indistinct seismic reflections and seismic artifacts within the data; indicated on the image as a dashed orange line instead of a solid line. There is a relatively small potential channel feature identified by erosional truncation of reflections on both ends of the feature, indicated by a truncation near the top of the interpreted sequence, which was not seen on the previous seismic line. There is also clear onlapping on the topmost interpreted surface. Above this surface there are stratal terminations with onlapping visible but uninterpreted as this interval was not the focus of this thesis. The Horizon Cube image for this seismic line has royal blue time intervals as well as a teal relative time interval for the Wyandot Formation. There are smaller sequences of green to orange





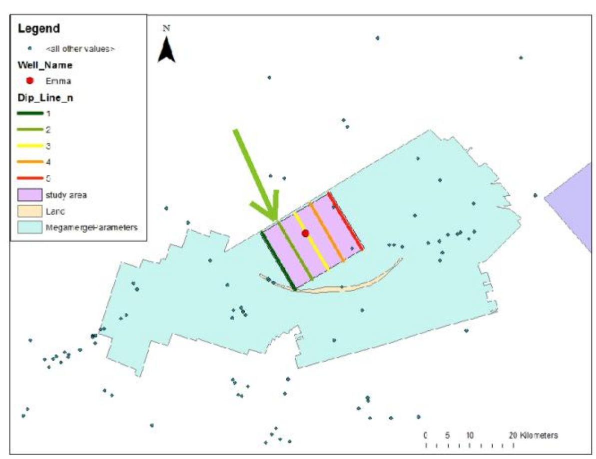
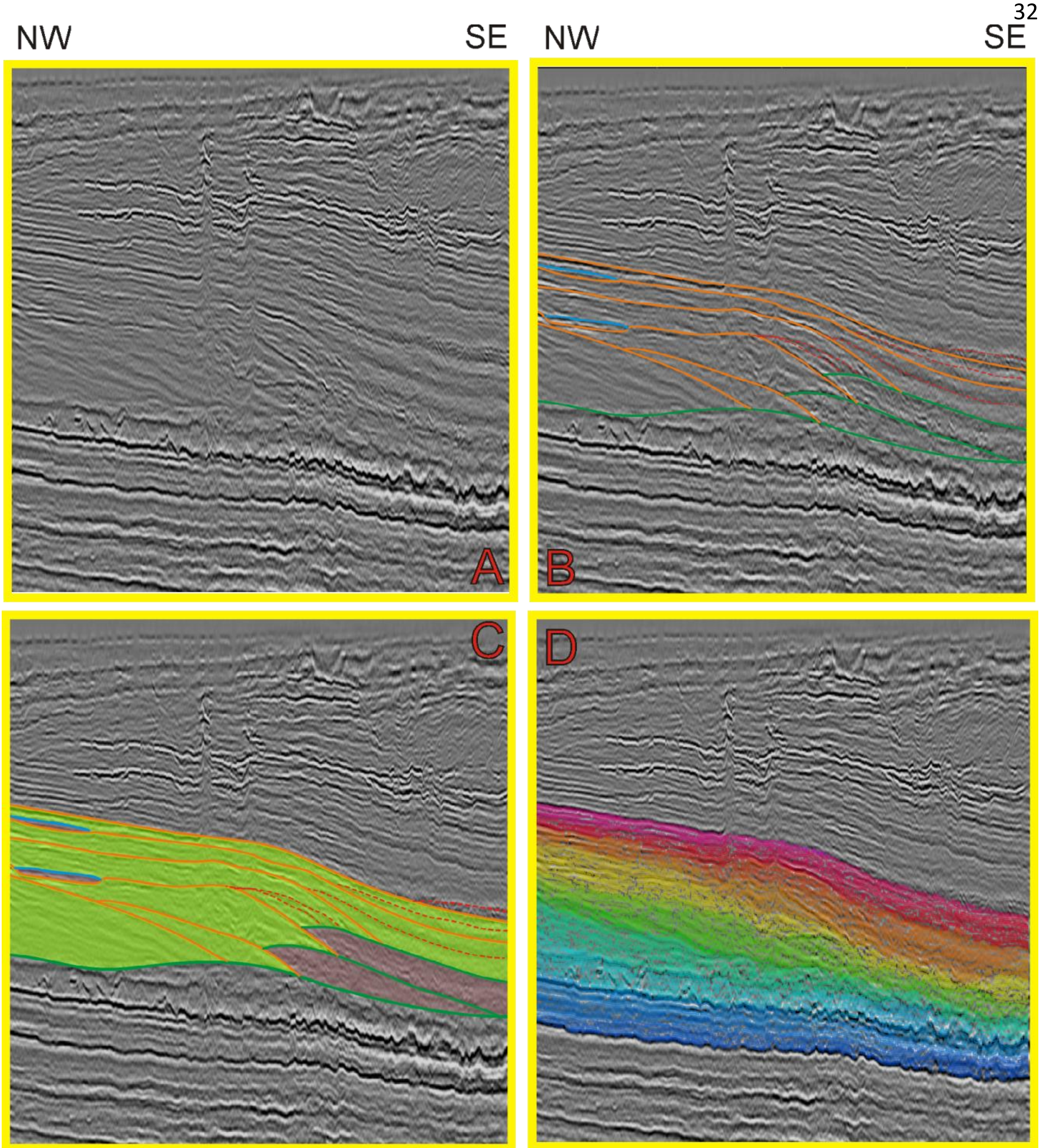


Fig. 3.5 Seismic line 2 (inline 5910)



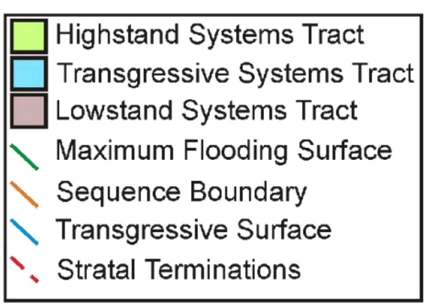
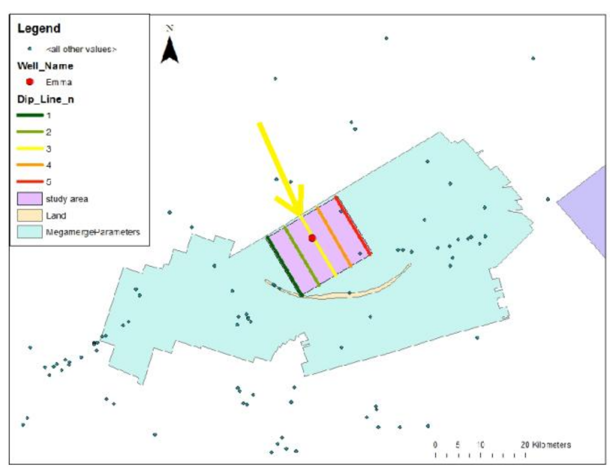


Fig. 3.6 Seismic line 3 (inline 6160)



on this image, compared to seismic line one, and there is a similar amount of red to pink time interval deposition as in the previous seismic line.

Figure 3.6 shows the interpretations of seismic line three. The top of the Wyandot Formation continues to be a downlap surface, and the scale of the features of this seismic line are also similar to the previous two. There are small-scale downlapping units (<100 m thick) within some of the larger sequences (Fig. 3.7 - see red dashed terminations). The lowstand deposits of this seismic line are found in much more distal areas, without the lowstand deposition reaching the proximal areas which were seen in seismic lines one and two. There are also two small channel-like features instead of one in the previous seismic line. This seismic line is the first to show clear progradation (Fig. 3.7 yellow arrow) with additional minor amounts of aggradation, implying that there was relative sea level rise with initially sufficient sediment input to cause costal advance, which was followed by a balancing of these two factors (Fig. 2.9 B & C), (Fig. 3.7). Within this overall progradation there are small reflectors which exhibit offlapping which might indicate cycles of transgression and regression during the overall rise in relative sea level. There are clear onlapping relationships on top of the upper most interpreted surface, as with the previous seismic line. Above this top surface the seismic reflections are mainly dipping uniformly to the southeast with very few stratal terminations determinable. The Horizon Cube image for this seismic line has royal blue and teal time periods representing the Wyandot Formation. The green to orange time period represents less sediment in this area than in the previous two lines, with a steady

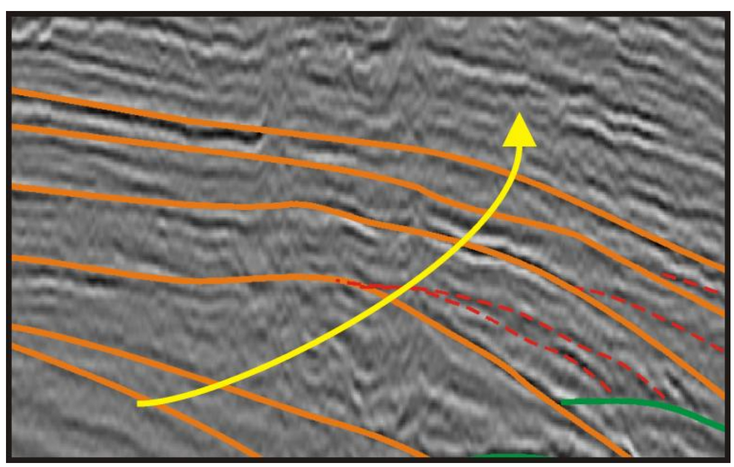


Fig. 3.7 Detail of figure 3.6 showing the visible progradation-aggradation.

decline in its thickness from the first seismic line. The orange time period has increased in thickness, relative to the green and yellow intervals. The red to pink time intervals show a slight increase in the amount of sediment deposition.

Seismic line four (Fig. 3.10) shows similar features to the previous three, including the downlap surface on the top of the Wyandot Formation, and a dominance of highstand deposits with only small amounts of lowstand deposits. There is a definite shift in the location of lowstand sedimentation from the previous seismic lines. This line has lowstand deposits in more proximal areas compared to the previous lines. There is an area of low confidence in the right hand side due to seismic facies B (Section 3.2) and seismic artifacts, similar to seismic line two. There are small-scale downlapping and onlapping features of <100 m height within Figure 3.10 which are shown in detail in Figure 3.8. The two maximum flooding surfaces exhibit a possible transgressive nature (Fig. 3.8 A) suggesting a rise in relative sea level with lower levels of sediment input. The series of sequence boundaries interpreted above these maximum flooding surfaces could be interpreted to show progressive progradation or offlapping (Fig. 3.8 B). The overall downward shift in the sequence boundaries above this small section (Fig. 3.8 C), indicates it is more likely this is an offlapping relationship caused by slow relative sea level fall followed by a more rapid relative sea level fall causing these downward lapping reflections. There is a possible channel feature within the topmost interpreted surface.

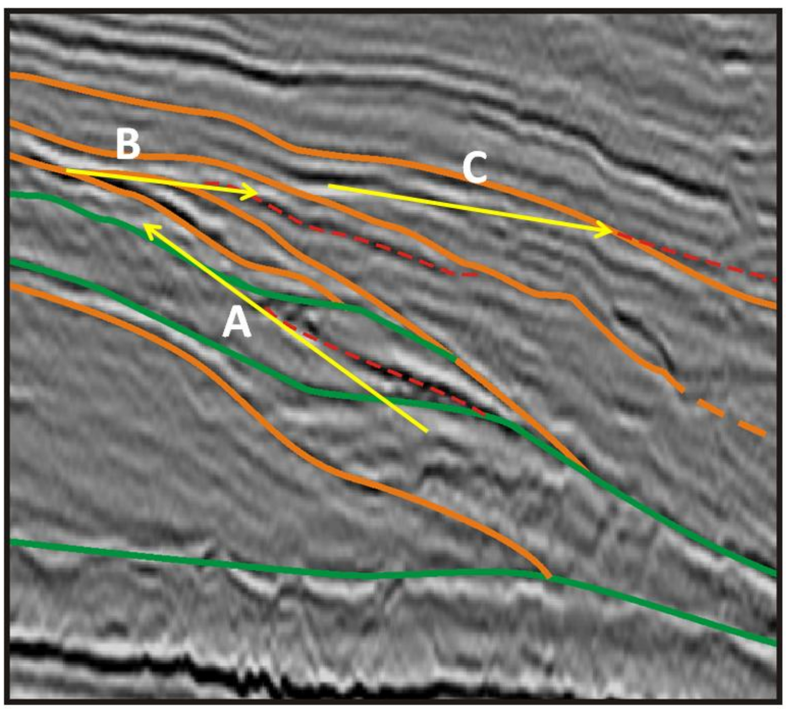


Fig. 3.8 Detail from seismic line 4, showing detail of the small scale features, width of image is approx. 6km wide.

Above the top surface there are some stratal terminations in the upper right uninterpreted area showing an onlap relationship on top of nearly uniform dipping reflections.

There is a clear change from the previous three seismic lines in the Horizon Cube image of Figure 3.10 block D. This seismic line has a large sequence of red to pink relative time deposition, the green to yellow interval is small, and the orange time interval of deposition has stayed relatively the same from the previous seismic line. This seismic line also demonstrates the importance of not relying on an interpretation software without understanding the limitations of the software (Fig.

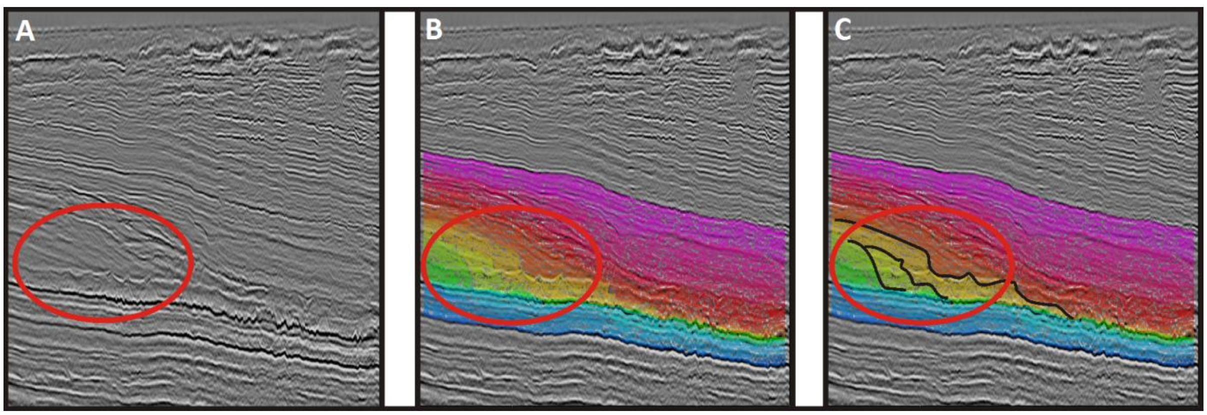
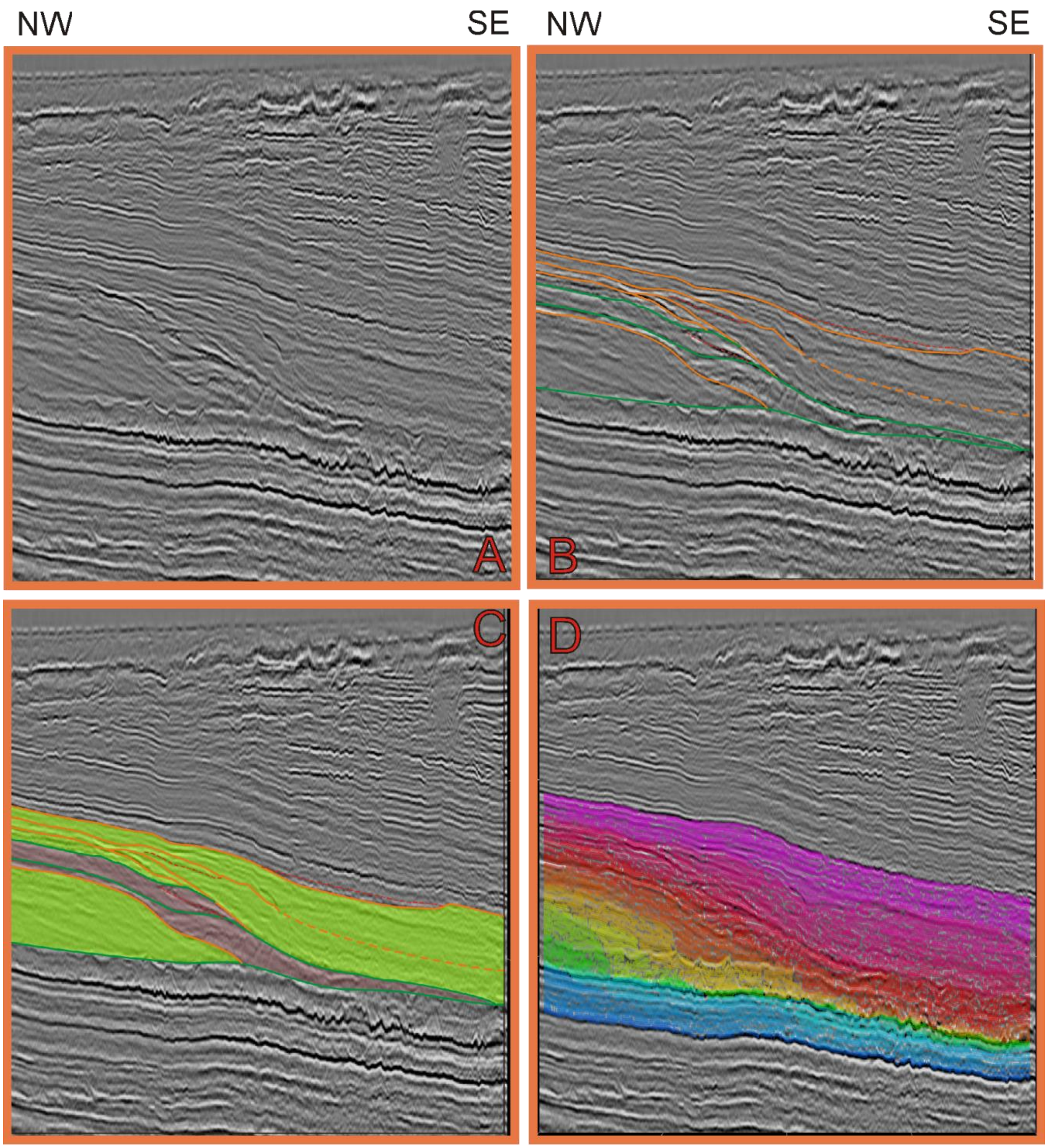
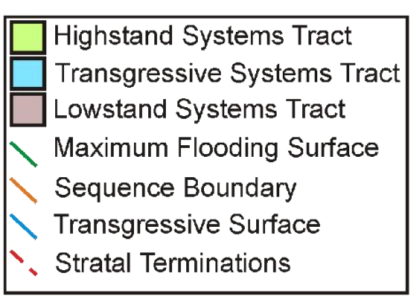


Fig. 3.9 Seismic line four with no interpretation, the Horizon Cube overlay and the Horizon Cube overlay annotated to show the artificial breaks in colour which are created by the software and are not seen in the seismic on the left.

3.9). The black lines in Figure 3.9 image C show the artificial breaks visible in the data (Fig. 3.9 B) created by the Horizon Cube software during interpretation which are not visible on the original seismic data (Fig. 3.9 A)





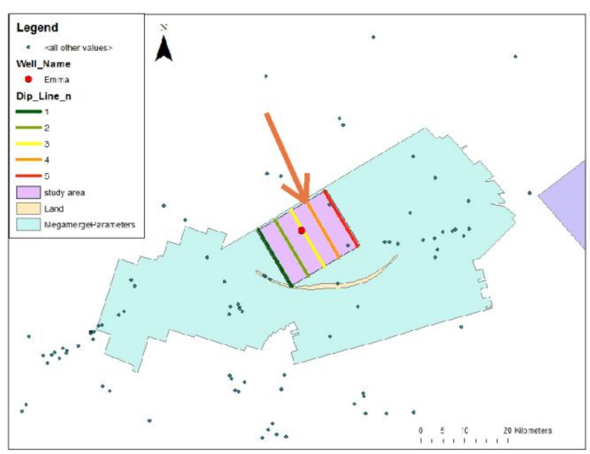


Fig. 3.10 Seismic line 4 (inline 6410)

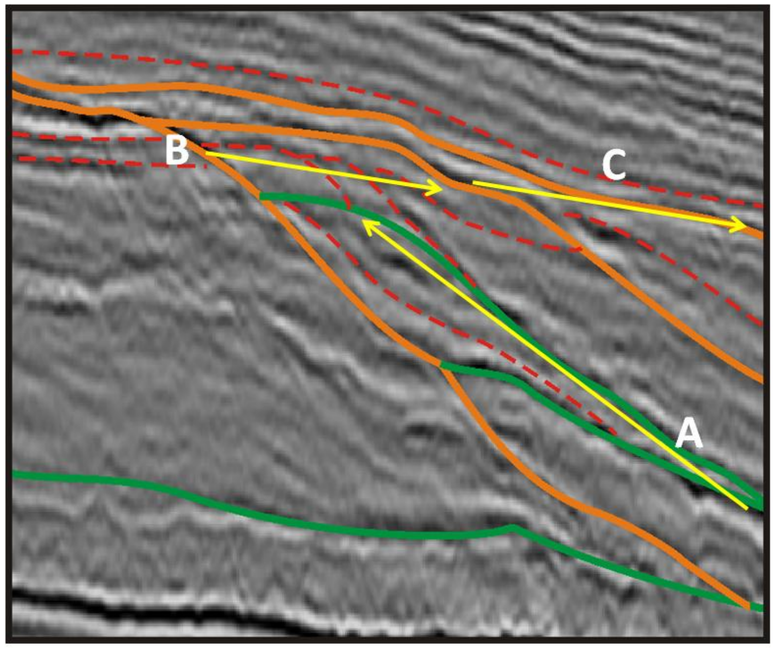
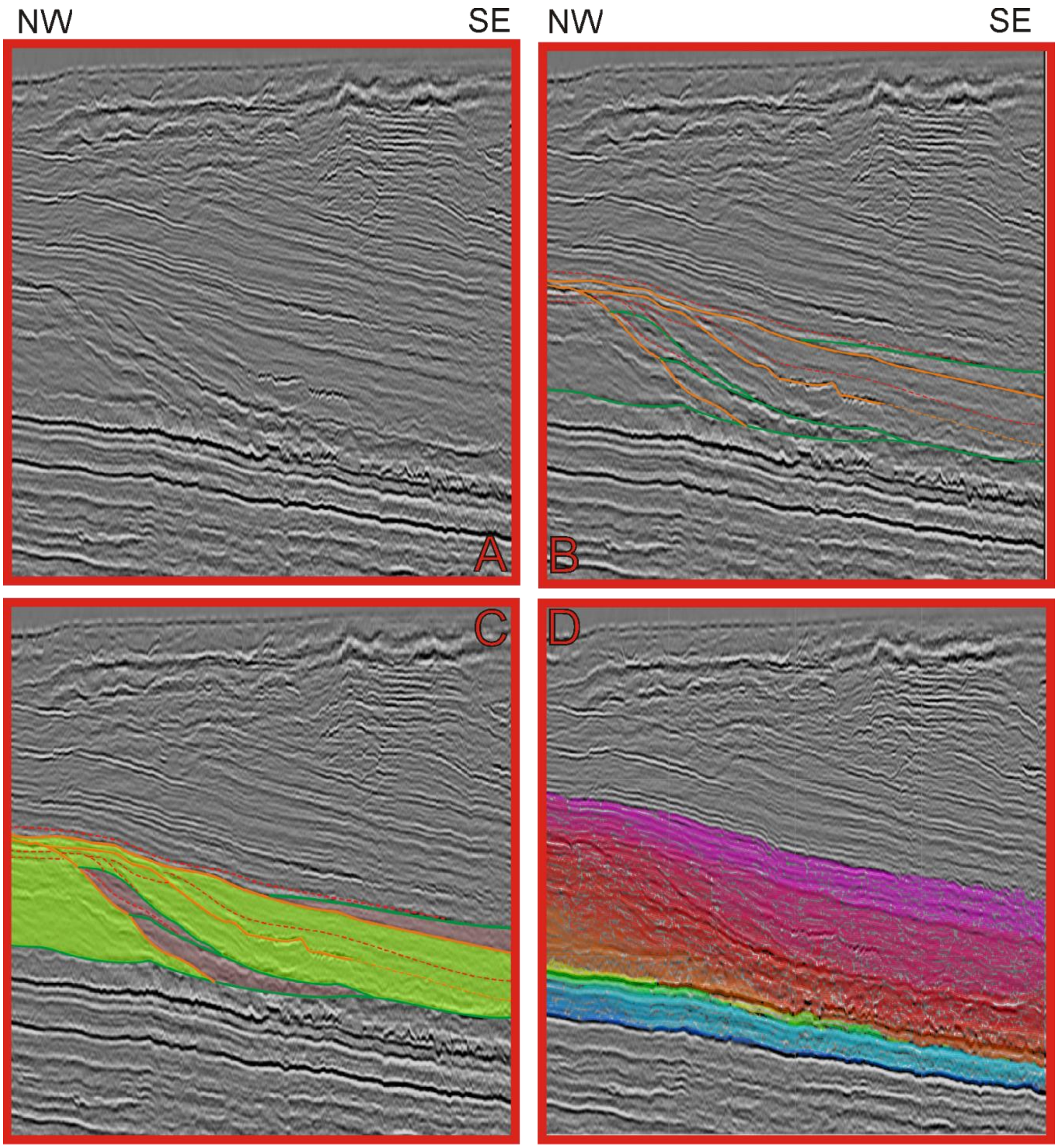
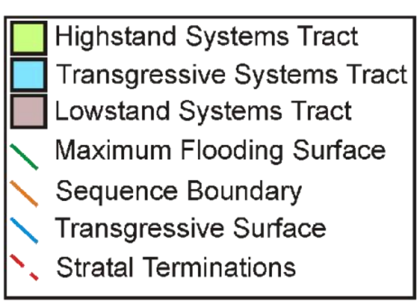


Fig. 3.11 Detail from seismic line 5 showing detail of small scale features, width of image is approx. 5.5km wide.

Figure 3.12 is the fifth seismic line and has many similarities to seismic line four. There are two proximal periods of lowstand deposition, which suggest transgression (Fig. 3.11 A), within a highstand. Similar to seismic line four, there are small-scale features, less than 100m in original height shown in red, that indicate an offlapping relationship (Fig. 3.11 B). The series of sequence boundaries above this section also show a downward shift in onlap, similar to seismic line four and this can be interpreted to have occurred due to similar changing conditions of deposition for the two areas. This seismic line, unlike the previous four lines, has a maximum flooding surface on the top sequence boundary which can indicate the beginning of a shoreward shift in costal onlap as relative sea level began to rise again. Above this topmost interpreted surface there are uniformly dipping reflections without any clear stratal terminations visible. The Horizon Cube image of image D shows the green and yellow time deposits as a single line at the bottom of the sequence of orange to pink time deposits which dominate the rest of the interpreted section. The royal blue Wyandot Formation has been replaced by the teal deposits, but is still identified as the Wyandot Formation. This change in colour from seismic line one to five in the colour of the Wyandot Formation suggests that there were changes in the focal point of deposition during deposition of the Wyandot formation or a possible source of error with using this software for definitive interpretations.





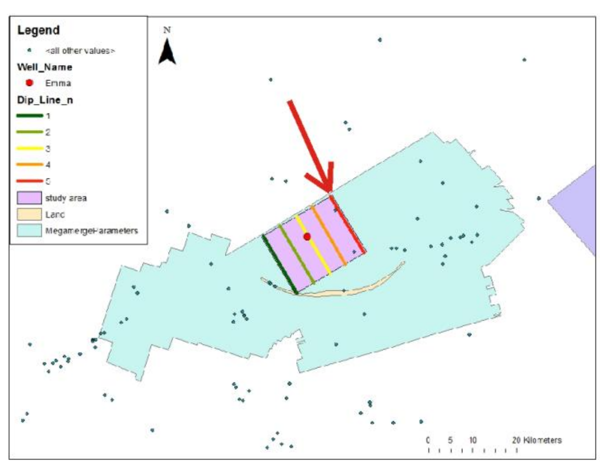


Fig. 3.12 Seismic line 5 (inline 6598)

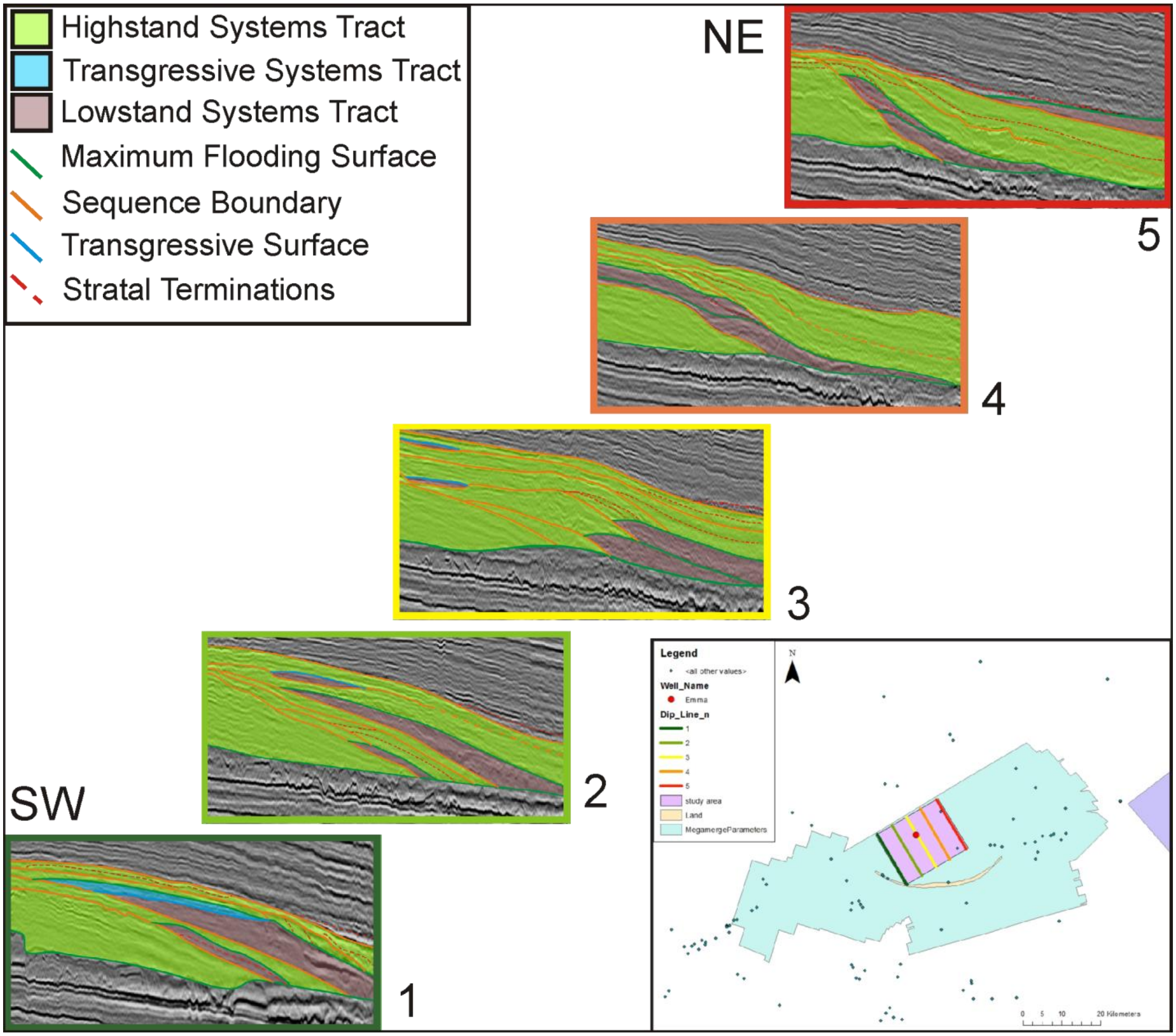


Fig. 3.13 Comparison image showing all five seismic lines displaying the interpreted systems tracts, arranged spatially with the first seismic line from the southwest found in the bottom left corner to the fifth seismic line from the northeast to the top right. Seismic lines are bordered by the same colour as the corresponding seismic line found on the inset map.

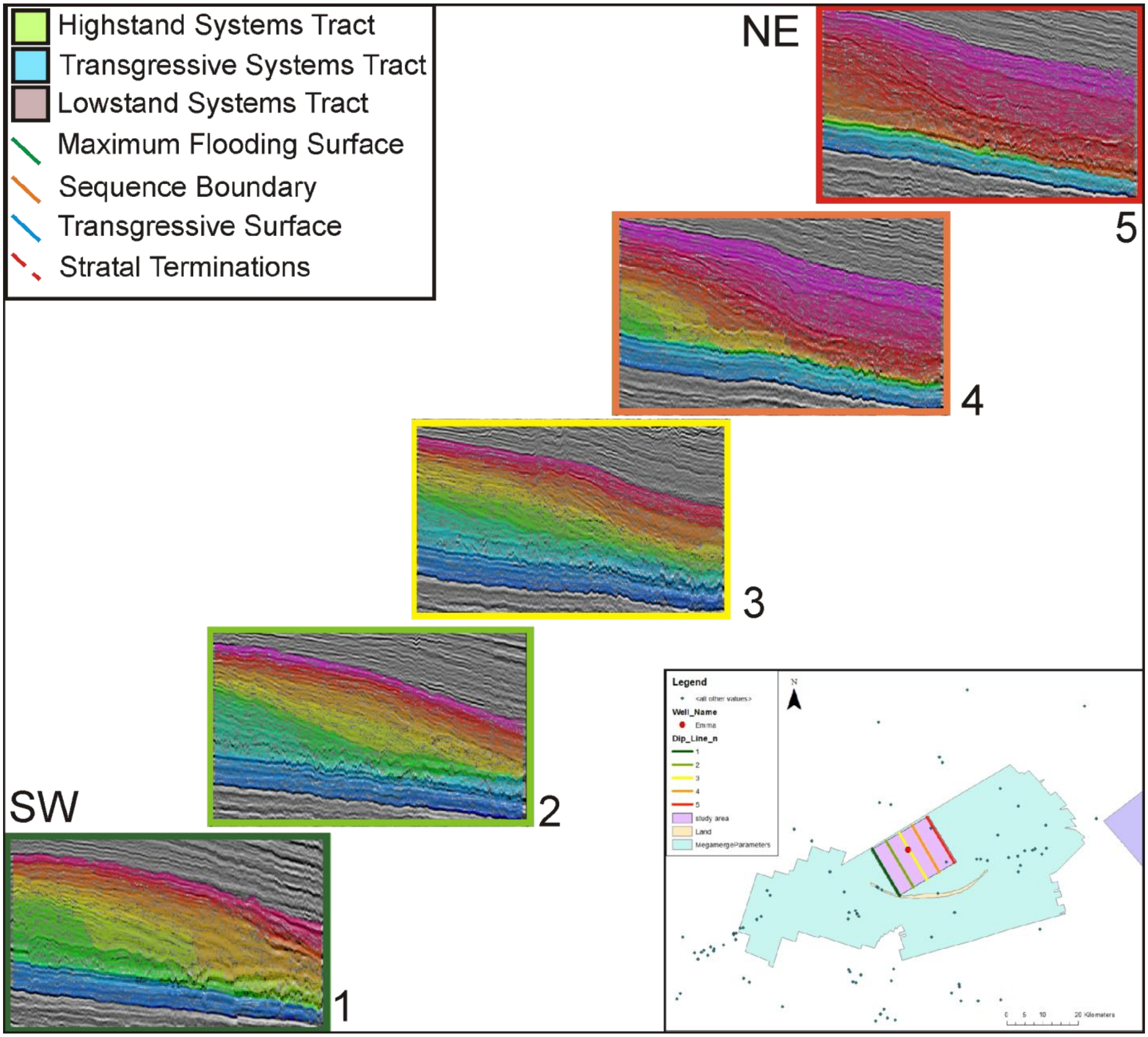
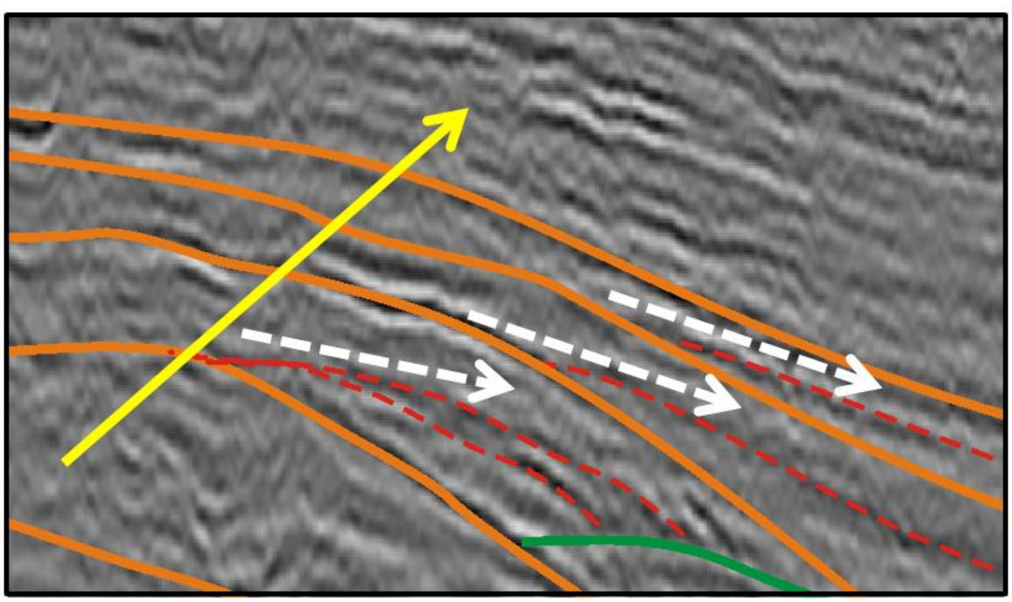


Fig. 3.14 Comparison image showing all five seismic lines displaying the Horizon Cube output images arranged spatially with the first seismic line from the southwest found in the bottom left corner to the fifth seismic line from the northeast to the top right. Seismic lines are bordered by the same colour as the corresponding seismic line found on the inset map.

By arranging the seismic lines one through to five (Figs 3.13 and 3.14) spatial comparisons of the five seismic lines are possible. Figure 3.14 shows the comparison of seismic lines of the Horizon Cube output data and there is a definite change from the image of seismic line one through five. Although the gradual reduction in the green to yellow relative time intervals coupled with the increased red to pink time intervals was explained previously, arranging the five seismic images spatially as they are in this image, there is a distinct gradual change from the southwest to the northeast. This sequence of images shows there is a shift in sedimentation from the southwest to the northeast through time.

This shift in sedimentation is not as apparent with the systems tract images in Figure 3.13 but correlations can be made between each of these images. The changes in systems tracts described previously suggest changes in overall relative sea level. It should be noted that sequence boundaries represent the beginning and end of a full stratigraphic cycle of rise and fall (Cataneanu et al., 2009). The majority of the data represented in this thesis are composite sequence (Abreu et al., 2010) and discussing relative rises or falls in sea level with these composite sequences are

Fig. 3.15 Detail of seismic line 3 showing overall progradation and aggradation with small scale regression between sequence boundaries



describing large scale changes which do not account for individual cycles for each successive sequence. Figure 3.15 shows a detail image from seismic line three with a solid yellow arrow indicating the large scale progradation visible in this seismic line, and the small scale cycles within each sequence is shown by the dashed white arrow.

Changes in relative sea level were discussed for each subsequent image and combined together they provide an understanding of the large scale relative sea level changes for the region (Fig. 3.16). Starting at the bottom of seismic line one through the top of seismic line five there are commonalities which tie these seismic lines together in respect to sea level changes. Seismic line one has an overall downward shift in onlap (Fig. 3.16 Line 1), which indicates a quick fall in sea level. The lower portion seismic line two shows (Fig. 3.16 Line 2, A) a similar trend of sea level fall, and the upper portion shows a progradation caused by sea level rise with high sediment input to the basin (Fig. 3.16 Line 2 B). This change from the lower half of the image to the upper half can be linked to the shift of the yellow time interval from seismic line one to two as well (Fig. 3.14). Seismic line three shows a sea level rise with a high sedimentation rate, similar to that of the second half of seismic line two, and the upper section of the interpreted portion of the image show a reduction in sedimentation causing aggradation rather than progradation (Fig. 3.16 Line 3). This decrease in sedimentation can also be linked to the shift in the yellow and orange colours of Figure 3.14.

Seismic line four shows a possible transgression (Fig. 3.16 Line 4, A) which indicates a sea level rise without sedimentation which would be a continued decrease in sediment input similar to seismic line three. This could be a result of the spatial change from the southwest to northeast. As the sedimentation was focused in the southwestern areas there would be decreased sedimentation to the northeast; coupled with the rise in sea level, this would result in a change from aggradation to transgression from the main zone of sedimentation to the margins of deposition towards the northeast. Following this possible transgression in seismic line four there is a downward shift in onlap indicating a rapid fall in sea level (Fig. 3.16 Line 4 B & C). Seismic line five shows a similar transgression (Fig. 3.16 Line 5 A) followed by a downward shift of onlapping reflections as seismic line four (Fig. 3.16 Line 5 B & C), caused by the same rapid fall in relative sea level. All of this together gives an overall relative sea level curve for the area (Fig. 3.16).

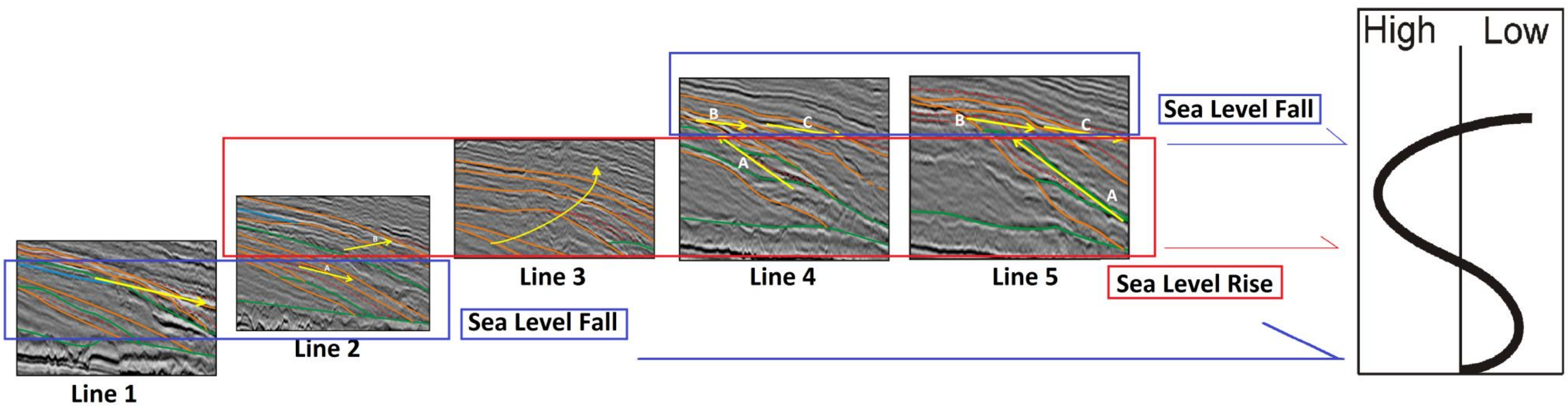


Fig. 3.16 Formation of a relative sea level curve through the correlation of five seismic lines.

Chapter 4: Discussion

4.1 Depositional Environments

The assessment of systems tracts associated with Figures 3.13 and 3.14 have allowed for two theoretical depositional systems to explain the studied interval of the Banquereau Formation. The first hypothesis of deposition for the Banquereau Formation is a switching delta lobe (Fig. 4.1) with two phases. This hypothesis suggests that during the first phase of sedimentation, a delta lobe in the south west the thesis area (Fig. 4.1 A) deposited thick sequences of sediments. As accommodation to the south west was filled the delta lobe switched its focus of sedimentation to the north east (Fig. 4.1 B) where there was available accommodation.

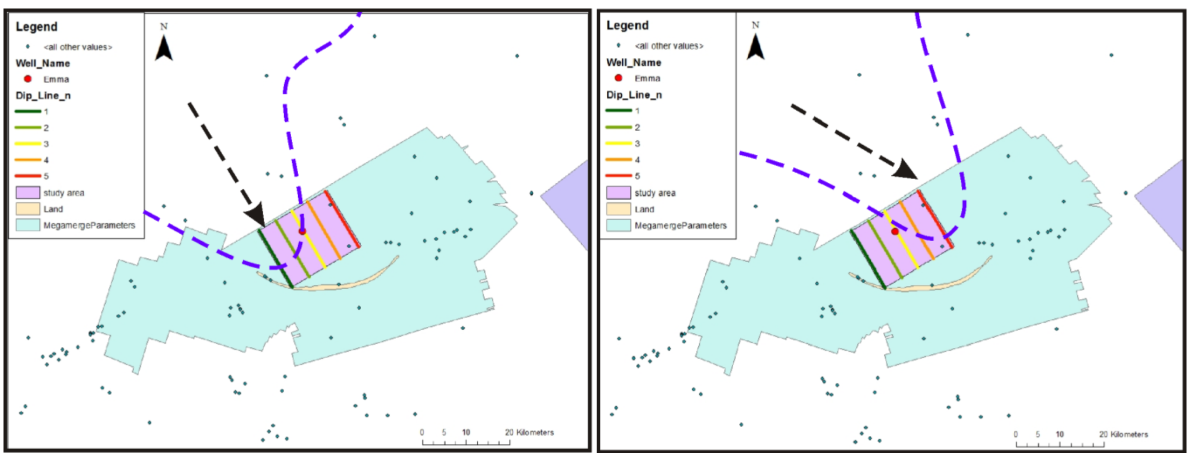


Fig. 4.1 A) Delta lobe switching hypothesis: phase one sediment deposited in the regions of seismic line one and two and lesser amounts in seismic line three.

B) Phase two shows the second position of the delta lobe after undergoing delta lobe switching.

A second hypothesis of deposition for the Banquereau Formation is the progradation of the shelf margin obliquely to the seismic lines of this thesis (Fig. 4.2). As the shelf edge shifted from its initial position (4.2 A) to the second position (4.2 B), the position of sediment deposition would also shift, similar to the switching delta lobe hypothesis. In this prograding shelf front the movement of deposition would be due to the progradation instead of a lack of accommodation which causes the shift in deposition in the delta lobe hypothesis.

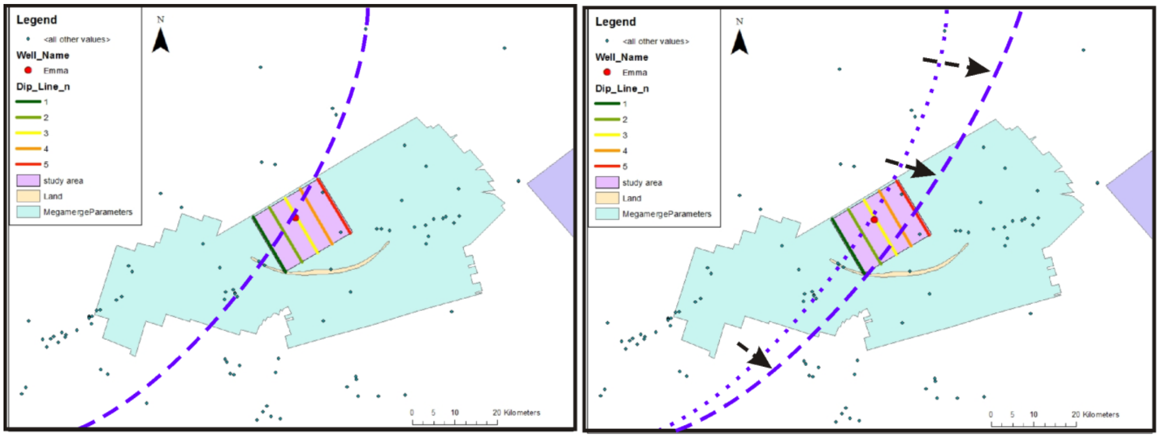


Fig. 4.2 A) Initial position of the shelf margin, depositing sediments in areas of seismic line one and two with lesser amounts in seismic line three.
B) After progradation from the initial position the shelf margin position would have advanced to allow for deposition in more north easterly sections of the study area.

The typical size ranges of clinoforms must be understood in order to better understand which of these two theories better explains the depositional environment of the Banquereau Formation. Johannessen et al. (2005) described shelf-margin clinoforms as having amplitudes of 100-1000's of meters, and deltaic clinoforms generally have amplitudes of less than 100 m since they are formed in shallower water (Fig. 4.3). As described in Chapter 3, there are both small scale (<100 m) and large scale (400-500 m) features found within the clinoforms of the Banquereau Formation in the thesis area. This suggests neither hypothesis described will be able to properly explain the depositional environment of this formation unless the two are combined.

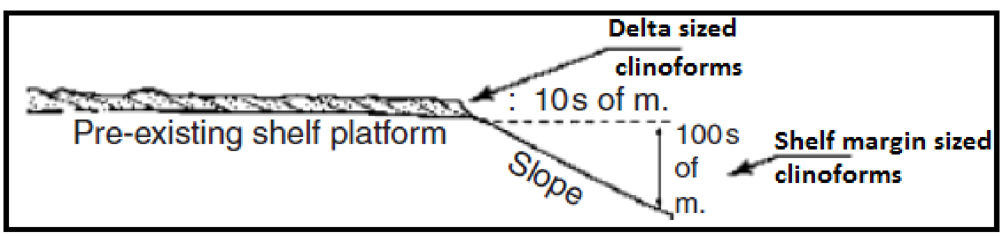


Fig. 4.3 Diagram showing deltaic and shelf margin sized clinoforms (Modified from Johannessen et al.., 2005).

Evidence of a delta combining with a shelf margin is found within seismic data as well as from lithological data of the Banquereau Formation. Deltaic sized clinoforms in seismic line five are topped by larger shelf margin clinoforms (Fig. 4.4). Above the interpreted lower section the clinoforms are nearly uniformly dipping to the southeast and are indicated by dipping yellow lines (Fig. 4.4 A). These dipping reflectors seem to slightly increase in dip angle towards the top of the image indicated by white horizontal lines (Fig. 4.4 B). These large scale dipping reflections do not show signs of stratal terminations associated with small scale deltaic clinoforms as in the lower interpreted section of the image. This change from the lower interpreted section to the upper large scale, more steeply dipping reflectors suggests a change from a shelf margin delta to self margin deposition (Porebski et al., 2003). Similar examples are seen in Kertznus et al. (2009) (Fig. 4.5) where large scale shelf margin deposition is found on top of shelf margin delta sediments. This situation occurs when a fluvial delta (Fig. 4.6 "mid shelf") progrades onto a shelf margin, and eventually combines with the shelf margin completely (Porebski et al., 2003) (Fig. 4.6 "shelf margin delta").

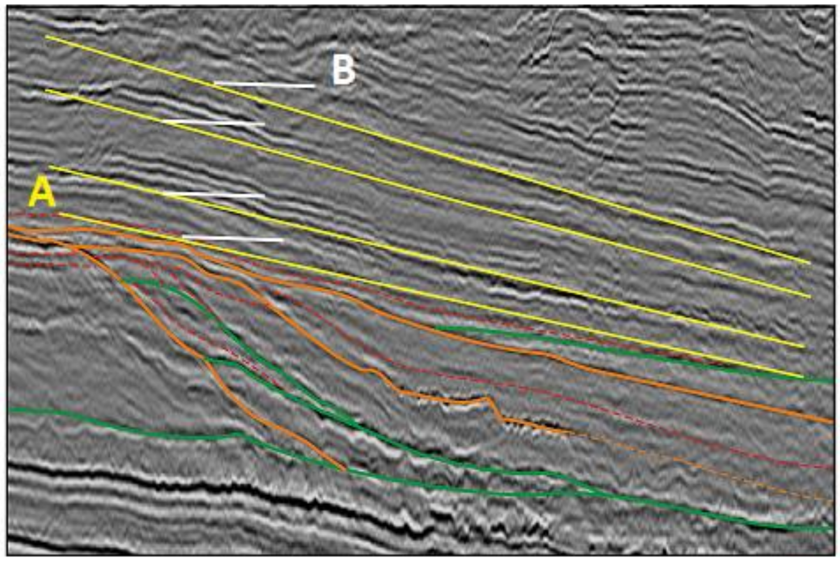


Fig. 4.4 Detail of seismic line 5 showing large scale dipping reflections (yellow lines) above interpreted section, associated with shelf margin

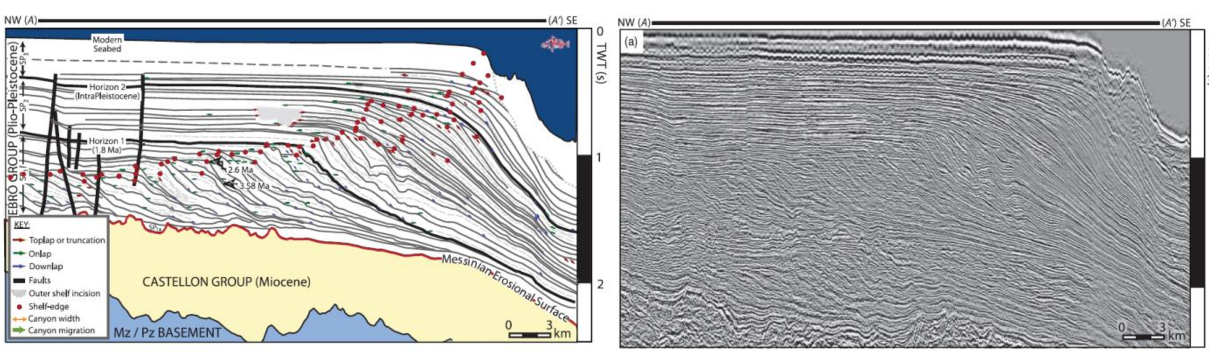


Fig. 4.5 Interpreted and uninterpreted seismic sections from the Modern Ebro Delta showing smaller scale shelf margin deltaic features overlain by shelf margin sediments (Kertznus et al.., 2009).

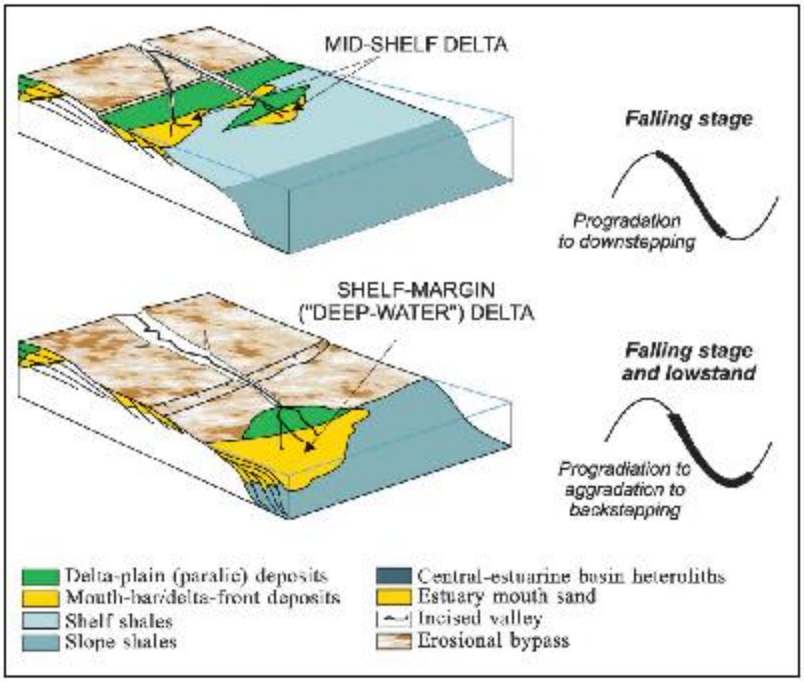


Fig. 4.6 Paleo-geographic reconstruction of a prograding delta into a shelf margin delta (Modified from Porebski et al., 2003)

As discussed by Johannessen et al. (2005) deltas are often the mechanism to bring sediment to a shelf edge and when a delta has regressed to the edge of the slope, the two processes combine. There are two possible outcomes once a deltaic system combines with a shelf margin which depends on sea level in the area (Fig. 4.7). If relative high and low sea level are above the edge of the shelf margin the only sediment grainsize deposited on the fore and bottom sets of the shelf margin clinoforms will be silt and clay (Johannessen et al., 2005) (Fig. 4.7 A). This agrees with the description of mudstone dominated fore- and bottomsets in the Banquereau Formation by Fensome et al. (2008) as described in Chapter 1. The second outcome would be if relative

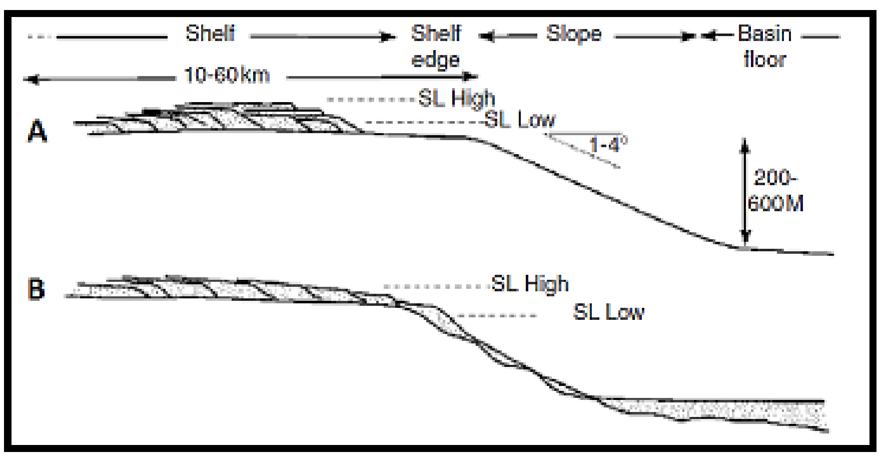


Fig. 4.7 A) Location of sediment deposition with relative sea level above the shelf margin break.

B)Location of sediment deposition with relative sea level at the shelf margin break (Modified from Johannessen et al., 2005).

high and low sea level are at the edge of the shelf margin, a low relative sea level will cause a sand-prone fore and bottom set of the shelf margin clinoform (Johannessen et al., 2005) (Fig. 4.7 B), which does not agree with the description of mudstone dominated fore- and bottomsets in the Banquereau Formation (Fensome et al., 2008).

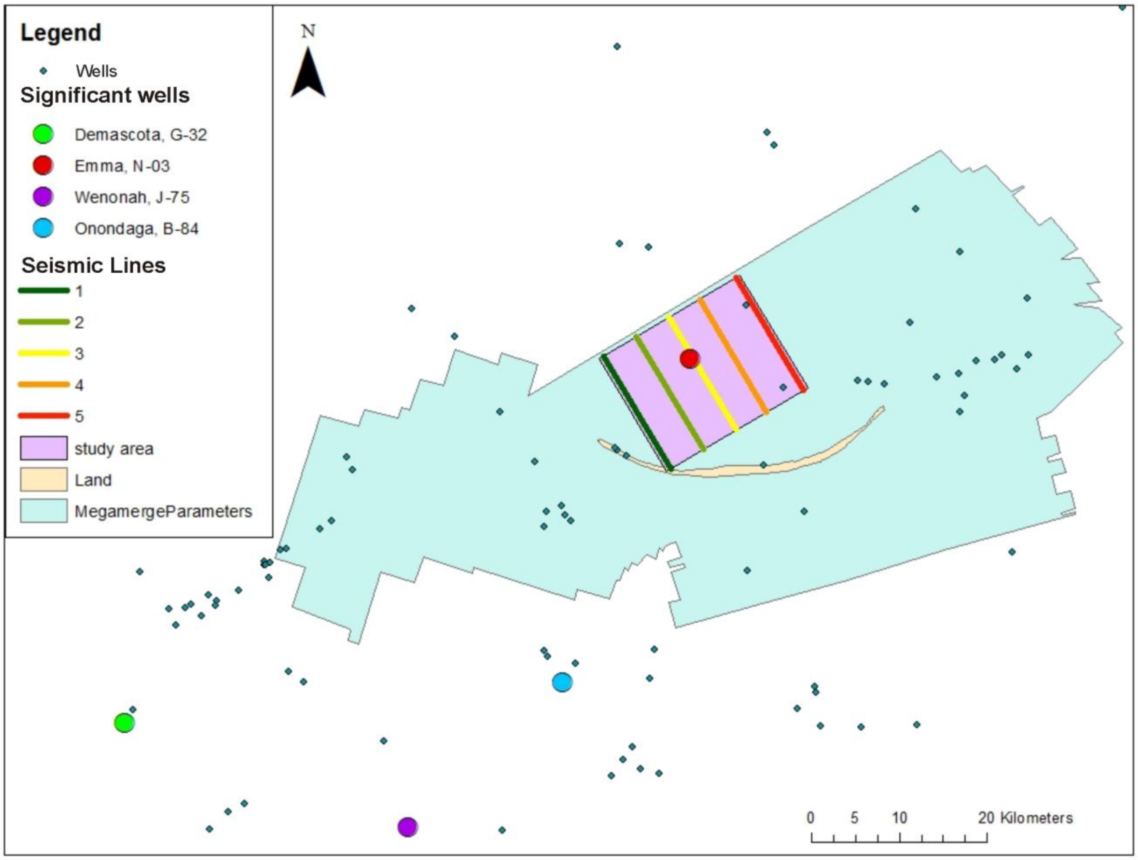
As there is only one well in the study area of this thesis and the focus was of this thesis was seismic stratigraphy, it is necessary to find information about the lithology of the Banquereau Formation from other literature about wells in the area around Sable Island and assume that the lithologies do not change greatly across the region. Figure 4.6 shows the location of three wells (green, purple and blue circles) near to the study area of this thesis. The lithology of the Banquereau Formation, which has been determined by using gamma ray logs and well cuttings for these three wells by Fensome et al. (2008) are predominately shale (SH) and sandstone (SST) with minor amounts of siltstone (SLT ST) and conglomerate (CGL) (Table 1). Although the study by Fensome et al. (2008) includes several other wells, they have been deemed either too distant from the study area for this thesis or there was no information regarding the Banquereau Formation. Introducing the lithological information from Fensome et al. (2008) shows that the Banquereau Formation, at least near the study area, is mostly shale and some sandstone. This information suggests that this prograding delta interacted with the shelf margin and that relative sea level periodically lay near the shelf margin and at times probably at or below the shelf margin break (Fig. 4.4 B).

Table 1 Percentage of lithologies within three wells near to the study area of this thesis. Location is given as direction from study area.

CGL = conglomerate, SST = sandstone, SLT ST = siltstone, SH = shale.

Well name	Location	CGL	SST	SLT ST	SH
Demascota	WSW	-	50%	-	50%
Wenonah	SW	-	30%	5%	65%
Onondaga	SW	5%	34%	1%	60%

Fig. 4.8 Map of three wells from Fensome et al. (2008) with gamma ray and cuttings information along with single well found within thesis study area.



Chapter 5: Conclusions and Future Work

5.1 Future work

In order to further confirm the Banquereau Formation was formed through a delta merging along the shelf edge the scope of the study area should be expanded to include all the Sable Megamerge data. Expanding the study area across the Sable Megamerge dataset would increase the amount of seismic data available for interpretation and would also include more wells with digital information available throughout the dataset to provide log and/or or core/cutting data for the Banquereau Formation to provide information confirming the seismic interpretation of the lithology of the clinoforms.

5.2 Conclusions

The Banquereau Formation is a thick succession of clinoforms dipping to the southeast from the northwest. Deposition of the Banquereau Formation occurred in two different locations at two different times. From the vertical scale of the clinoforms within the Banquereau Formation it can be concluded these were formed in association with a prograding shelf edge. Found within these large scale clinoforms are smaller scale clinoforms interpreted to be formed in association with a delta. This combination of both small and large scale features suggests a prograding shelf delta on a shelf margin edge (Johannessen et al., 2005).

Through systems tract assessment of the seismic data the relative sea level during the deposition of the lower Banquereau Formation can be concluded (Fig. 3.14). Johannessen et al. (2005) demonstrated that elevated amounts of sand in the basin suggest a relative rise and fall of sea level are focused near the edge of the shelf, and conversely, if there is only silt and clay in the basin the position of relative sea level is more proximal. The inclusion of well log studies from Fensome et al. (2008) show the Banquereau Formation is 50% shale 70 km south west of the thesis study area and is 60 to 65% 35 to 60 km south west of the thesis study area. Although this is not directly within the study area it is used to suggest the relative location of the sea level rise and fall in relation to the shelf margin edge during the deposition of the Banquereau Formation. During the time of deposition, sea level in the area is interpreted to be near the shelf edge. Large scale sea level changes are visible through interpretation of condensed sections and an approximate sea level curve has been created. This is a relative sea level curve which does not follow individual sequence scale changes as indicators of sequence scale sea level changes are not visible in the data of this thesis.

After expanding the scope of this project to include the entire Sable Megamerge dataset, a full depositional model for the lower Banquereau Formation on a regional scale for the offshore Nova Scotia area could be created. On the scale of this thesis, it can be concluded the Lower Banquereau Formation was deposited in a progradational delta as it combined with a shelf margin. The regional extent of these features is unknown however the lower portion of the study area is typified by small <100 m height features within larger >100 m height clinoforms which indicates a shelf margin delta which eventually becomes the much larger scale shelf margin as seen in upper portions of the fifth seismic line. This shelf margin is the predecessor to the modern self margin found offshore of Nova Scotia which can be seen today south of Sable Island.

References

Abreu, Vitor; Jack E. Neal, Kevin M. Bohacs, James L. Kalbas (2010) Sequence Stratigraphy of Siliciclastic Systems- The ExxonMobil Methodology *Atlas of Excercises* Society for Sedimentary Geology, Oklahoma USA.

Agile Geoscience, A is for Amplitude (2011) http://www.agilegeoscience.com/journal/2011/1/21/a-is-for-amplitude.html

Campbell, Calvin. (2012) The Late Cretaceous and Cenozoic Geological History of the Outer Continental Margin off Nova Scotia Canada: Insights into Margin Evolution from a Mature Passive Margin. (PhD Thesis, Dalhousie University)

Canada-Nova Scotia Offshore Petroleum Board (CNSOPB), Call for Bids 2007-2008, Regional Geology Overview, http://www.callforbids.cnsopb.ns.ca/2007/01/regional_geology.html

Catuneanu , O.; V. Abreu; J.P. Bhattacharya; M.D. Blum; R.W. Dalrymple; P.G. Eriksson; C.R. Fielding; W.L. Fisher; W.E. Galloway; M.R. Gibling; K.A. Giles; J.M. Holbrook; R. Jordan; C.G.St.C. Kendall; B. Macurda; O.J. Martinsen; A.D. Miall; J.E. Neal; D. Nummedal; L. Pomar; H.W. Posamentier; B.R. Pratt; J.F. Sarg; K.W. Shanley; R.J. Steel; A. Strasser; M.E. Tucker; C. Winker Christie-Blick. (2009) Towards the standardization of sequence stratigraphy. Earth-Science Reviews, 92 pp 1–33.

Colletta, B; F. Monnier; G. Rabary; S. Doublet; P. Letouzey; BeicipFranlab (2011) Offshore Nova Scotia Play Fairway Analysis: 2D Basin Modeling Results. Offshore Technology Conference, Houston Texas, USA.

Cummings, Don I; R. William C. Arnott. (2005) Growth-faulted shelf-margin deltas: a new (but old) play type, offshore Nova Scotia. Bulletin of Canadian Petroleum Geology vol. 53, 3, pp 211-236

Desler, James F. *Marine Seismic Data Acquisition* in "Development Geology Reference Manual" ed Diana Morton-Thompson and Arnold M. Woods. AAPG Methods in Exploration Series, No 10, 1999.

Fensome, Robert A.; Jason A. Crux; I. Gunilla Gard; R. Andrew MacRae; Graham L. Williams; Frank C. Thomas; Flavia Fiorini; Grant Wach. (2008) The last 100 million years on the Scotian Margin, offshore Eastern Canada: an event-stratigraphic scheme emphasizing biostratigraphic data. Atlantic Geology 44, pp 93–126.

Hansen ,Dorthe Møller, John W. Shimeld, Mark A. Williamson, Holger Lykke-Andersen. (2004) Development of a major polygonal fault system in Upper Cretaceous chalk and Cenozoic mudrocks of the Sable Subbasin, Canadian Atlantic margin. Marine and Petroleum Geology 21 1205–1219

References con't

Ings, Steven J. ; R. Andrew MacRae, John W. Shimeld, Georgia Pe-Piper. (2005) Diagenesis and porosity reduction in the Late Cretaceous Wyandot Formation, Offshore Nova Scotia: a comparison with Norwegian North Sea chalks. Bulletin of Canadian Petroleum Geology vol. 53, NO. 3, pp. 237-249

Jansa, Lubomir F.; Victor Hugo Noguera Urrea. (1990) Geology and Diagenetic History of Overpressured Sandstone Reservoirs, Venture Gas Field, Offshore Nova Scotia, Canada. The American Association of Petroleum Geologist Bulletin, V 74, No 10, pp 1640-1658

Johannessen, Erik P., Ron J. Steel; (2005) Shelf-margin clinoforms and prediction of deep water sands. Basin Research, 17 pp521-550.

Johnstad ,S.E.; B.A. Farrelly; and R. Smeda; R. Henman; Per Spärrevik, (2009) New system acquires EM, seismic http://www.epmag.com/Exploration-Geology-Geophysics/New-system-acquires-EM-seismic_33840

Kertznus, Vanessa; Ben Kneller (2009) Clinoform quantification for assessing the effects of external forcing on continental margin development. Basin Research 21 pp 738-758

McIver, N. L., (1971). Cenozoic and Mesozoic Stratigraphy of the Nova Scotia Shelf. Canadian Journal of Earth Sciences, 9, pp 54- 70.

Mitchum, R.M., JR., P.R. Vail, S. Thompson (1977) Seismic Stratigraphy and Global Changes of Sea Level, Part 2: The Depositional Sequence as a Basic Unit for Stratigraphic Analysis. in Seismic Stratigraphy: Applications to Hydrocarbon Exploration (AAPG Memoir 26) Payton, Charles E.(ed) American Association of Petroleum Geologists, Tulsa, Oklahoma USA.

Mukhopadhyay, Prasanta K.; David E. Brown; Arthur G. Kidston; Thomas D. Bowman; Jeff Faber; Paul J. Harvey. (2003) Petroleum Systems of Deepwater Scotian Basin, Eastern Canada: Challenges for Finding Oil versus Gas Provinces. 2003 Offshore Technology Conference held in Houston, Texas, U.S.A., 5–8

National Resources Canada, Stratigraphic overview http://www.nrcan.gc.ca/earth-sciences/energy-mineral/geology/marine-geoscience/geology-of-scotian-margin/7013 last modified: 2010

Porebski, Szczepan J., Ronald J. Steel (2003) Shelf Margin Deltas: their stratigraphic significance and relation to deepwater sands. Earth Science Reviews 62, pp 283-326.

Reddy, Kevin *Displaying Seismic Data* in "Development Geology Reference Manual" ed Diana Morton-Thompson and Arnold M. Woods. AAPG Methods in Exploration Series, No 10, 1999

References con’t

Schlumberger Oilfield Glossary (2013) http://www.glossary.oilfield.slb.com/

Short, Dale M. *Seismic Data Acquisition on Land* in "Development Geology Reference Manual" ed Diana Morton-Thompson and Arnold M. Woods. AAPG Methods in Exploration Series, No 10, 1999.

Vail, P.R.; R.M. Mitchum, JR; S. Thompson (1977) Seismic Stratigraphy and Global Changes of Sea Level, Part 3: Relative Changes of Sea Level from Costal Onlap. in Seismic Stratigraphy: Applications to Hydrocarbon Exploration (AAPG Memoir 26) Payton, Charles E.(ed) American Association of Petroleum Geologists, Tulsa, Oklahoma USA.

Wade, J.A. and MacLean, B.C. (1990) *Chapter 5 - The geology of the southeastern margin of Canada, Part 2: Aspects of the geology of the Scotian Basin from recent seismic and well data .In* Geology of the continental margin of eastern Canada, M. J. Keen and G.L. Williams (Eds.). Geological Survey of Canada, Geology of Canada no.2, p.190-238 (also Geological Society of America,*The Geology of North America,* vol.I-1).