Sequence stratigraphy of a mixed siliciclastic-carbonate setting, Scotian Shelf, Canada

Farrukh Qayyum[1], Octavian Catuneanu[2], and Crépin Eric Bouanga[3]

Abstract

During the Jurassic Period, a large-scale carbonate bank (Abenaki Formation) and a siliciclastic (Sable) delta coexisted in North America. Conventionally, carbonate systems (in situ) are separated from siliciclastic systems (transported) because of their contrasting origin. However, we developed a case study to show that the basic principles of sequence stratigraphy remain applicable. We integrated the results obtained from a regional 2D study and a detailed follow-up study using 3D seismic data of the Scotian Shelf, Canada. The results were integrated with the prepared Wheeler diagrams, and a unified sequence stratigraphic framework was proposed. We determined that two second-order sequences were developed on a larger scale during the Jurassic Period. The first sequence developed during the transition from a ramp to rimmed margin. The second sequence developed during the evolution from a rimmed to ramp margin. These sequences formed a distinct stratigraphic style throughout the Scotian Shelf. The siliciclastic supply varied from the northeast to the southwest depending on the studied site; however, the regions close to the siliciclastic supply contained well-defined clinoform patterns. The topsets of such clinoforms were mostly eroded. Their directions were also found to be different than the carbonate-related clinoform geometries. Most of the carbonates were developed; as such, they kept up and prograded toward a backreef margin during the rimming stages. The second-order sequences were further subdivided into four third-order sequences. These were studied using the 3D seismic data and were found to contain several barrier reefs that could have stratigraphic exploration potential in the Penobscot area.

Introduction

The Scotian Shelf is a part of the North American continental margin where a megascale carbonate bank existed, trending north–south during the Middle Jurassic to the beginning of Cretaceous time (Eliuk, 1978, 2009; Jansa, 1981; Welsink et al., 1989; Keen and Potter, 1995). The bank contains a variety of carbonate facies ranging from backreef moats, patchy reefs, barrier reefs/islands, fringing reefs, and slope-to-basinal detrital carbonates. These carbonate lithologies are known as the *Abenaki Formation*. Following the Triassic rifting, North America was uplifted, while the seafloor spreading continued until the Early-Middle Jurassic. This has formed several subbasins and initiated a large siliciclastic influx (Sable Delta) that filled parts of the Abenaki carbonate bank and subbasins. The coexistent system is hereafter referred to as the *Abenaki-Sable sequence*.

In this paper, we focus on the development of the Abenaki-Sable sequence in the study area (Figure 1a) by performing an integrated sequence stratigraphic interpretation. The 2D seismic data were regionally mapped to identify a trend of the Abenaki carbonate bank and study the lateral facies change in the study area. We found that the geometric patterns differ depending on the dominant system (i.e., carbonates or siliciclastics). To highlight such changes, several Wheeler diagrams are presented ranging from the distal to proximal vicinities. They show the relationship between the stratal stacking patterns and their development within a defined relative geologic time scale. The 3D seismic data were further investigated to examine the detailed patterns of the Penobscot area. The latter was found to be an isolated carbonate bank margin evolved from a ramp to a rim stage during the Middle to Late Jurassic. Subsequent deposition resulted into a stable ramp stage during the end of the Jurassic Period. Further study found several barrier reefs that developed during the evolution of the Jurassic bank in the Penobscot area. These reefs are proposed as possible stratigraphic traps that may have commercial significance. They may contain reservoir properties analogous to the nearest known fields of the Abenaki Formation (Deep Panuke).

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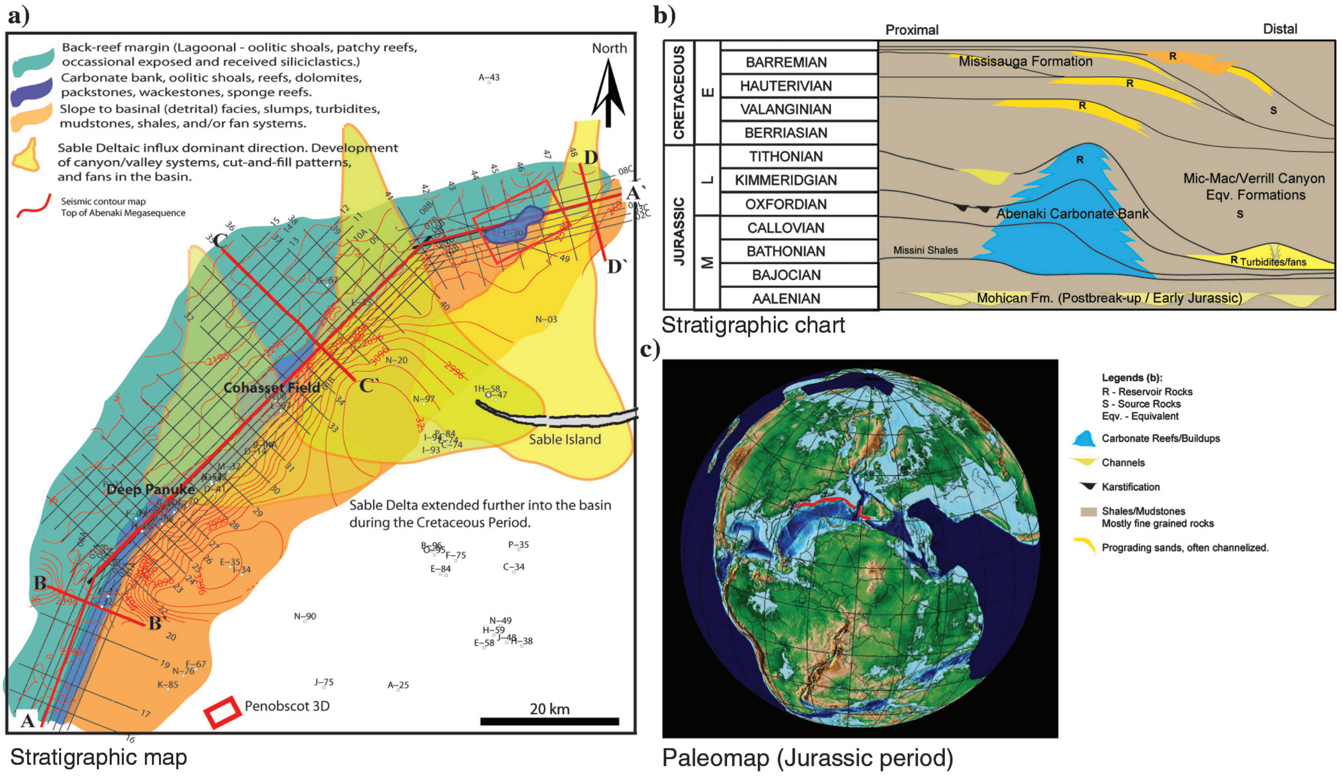
General geology

The Scotian Shelf is a part of the eastern North American margin that developed over the fractured continental edge of the North American plate. The entire shelf broadens toward the north; e.g., Newfoundland (see Figure 1 in Jansa 1981). Late Triassic to Early Jurassic rifting developed several subbasins that were also further influenced by the Argo Salt (Early Jurassic) movement (Welsink et al., 1989; Keen and Potter, 1995; Deptuck, 2010; Piper et al., 2013). This rifting formed several highs, lows, and depocenters, separated by oceanic fracture zones that may extend landward on to the continental crust (Welsink et al., 1989). A passive margin started forming, which resulted in a postrift stratigraphic succession. The Scotian Shelf was dominated by shallow marine environments that allowed the development of a large-scale carbonate bank during the Middle to Late Jurassic periods (Eliuk, 1978; Jansa, 1981; Weissenberger et al., 2006). The interval is well investigated in the Deep Panuke field (Weissenberger et al., 2006). The time-equivalent carbonates also developed even in the Lusitanian Basin, Portugal (Leinfelder, 1993; see also Figure 1c in this paper). In both regions, a mixed setting prevailed. Specifically, the Sable Delta advanced toward the shoreface of the Scotian Shelf and often partially terminated the carbonate factory at several sites (see also Figure 2). In some cases such as the H-52 site, the carbonate factory is reestablished on the existing siliciclastic dominated shoreface/mouth bar. However, both depositional systems continued to aggrade throughout the Jurassic Period until the younger delta, also known as the Mississauga Delta, permanently drowned the underlying carbonate platform (Figure 1b).

The lithostratigraphy of the Jurassic succession is subdivided into several formations, namely, the Argo Salt, Iroquois, Mohican, Mohawk, Mic Mac, and Abenaki Formations, respectively. The Argo Salt is present near/at the base of the Jurassic section. The Iroquois Formation contains transgressive shallow marine to tidally influenced dolomites with anhydrites and siliciclastics. They were broadly deposited in restricted marine conditions. Following this, fluviomarine conditions prevailed on the Scotian Shelf and Mohican Formation were deposited. The formation extended into the basin, where it was dominantly containing muds or shales that blanketed the newly formed oceanic crust. This formation is overlain by shallow marine deposits known as the Abenaki Formation, which is dominated by limestones, dolomites, reefs, and mudstones. During the same time, the Sable Delta also developed and several time-equivalent stratigraphic units were formed (the Mohawk and Mic Mac Formations). These are dominated by siliciclastics, but with intercalations of carbonates (Figure 1b).



Stratigraphic map

Stratigraphic chart

Paleomap (Jurassic period)

Figure 1. An integrated location map of the study area, Scotian Shelf, Sable Island, Eastern Coast Canada. (a) A regional stratigraphic map of the Abenaki Formation and the siliciclastic deltaic development during Jurassic time. The contour map is prepared using the studied 2D seismic data. (b) Generalized stratigraphic chart of the Jurassic and Cretaceous systems of the Scotian Shelf. (c) Paleomap of the Jurassic Period outlining the location (in red) of the large-scale carbonate bank development during this time (image courtesy of C. R. Scotese).

The Middle to Late-Jurassic carbonates and the siliciclastic rocks contain enough economic potential, according to the Canadian-Nova Scotia Offshore Petroleum Board (CNSOPB), to warrant possible future exploration opportunities. The Deep Panuke (Figure 1a) gas field contains the proven potential among the Abenaki carbonates. However, a similar potential may also be present along the interpreted Abenaki trend (Figure 1a). Other authors have also predicted further potential in the Abenaki carbonate bank (Eliuk, 2009; Luheshi, 2012). The commonly known traps in the vicinities consist of the combination of reefs/buildups, which are often dolomitized and karstified; turbiditic deposits; roll-over anticlines, which are often fault bounded; growth faults; drape structures; and salt diapirs. Most of the proven reservoirs can be seen to exhibit sediment compaction and growth faulting. The deep marine-organic-rich shales of the Mic Mac and Mississauga Formations (Cretaceous) are considered as the source rocks.

Data set

This study is accomplished using a set of 2D and 3D seismic surveys (see the location map in Figure 1). These surveys were released by the CNSOPB into the public domain to open up research opportunities along the eastern coast of Canada.

The 2D seismic data were acquired in the early 1980s. The purpose of this survey was to evaluate the geologic trends and identify hydrocarbon accumulation along the Scotia Shelf. The data helped in the identification of several prospects; one of them is the proven gas field, Deep Panuke. The 3D seismic survey (60 fold) was acquired in 1991 to evaluate the Penobscot area, which was drilled by two wells: B-41 (a dry well, reaching the Cretaceous succession) and L-31 (a dry well with oil and gas shows; penetrated into the Jurassic succession). The 3D seismic data were further reprocessed to optimize visualization of the structural and stratigraphic trends in the Jurassic and Cretaceous systems.

The seismic data polarity is SEG normal — The increase in the acoustic-impedance boundary is reflected as a peak or positive amplitude.

The background information was collected from more than 100 wells and nearest fields (e.g., Panuke and Cohasset).

The 2D seismic survey was used to study the regional depositional trends of the Abenaki-Sable sequence. The 3D seismic data were studied to perform detailed sequence stratigraphic interpretation of the Penobscot area.

Methodology

The workflow applied in this study comprises three parts: data preparation, dense mapping, and integrated interpretation (Figure 3).

Data preparation

Initial stratigraphic framework

The workflow starts with conventional mapping of a set of horizons and faults, which is referred as a *framework*. The framework was prepared using sequence stratigraphic principles (Payton, 1977; Emery and Myers, 1996; Catuneanu, 2003, 2006). It forms a regional constraint to produce detailed results and perform further interpretation. The horizons were interpreted on 2D/3D seismic data sets. The 2D interpretation was performed primarily to understand the regional stratal stacking patterns. The detailed interpretation was performed on the 3D seismic data.

Improving resolution

Vertical seismic resolution was enhanced by performing the seismic spectral blueing (SSB) technique

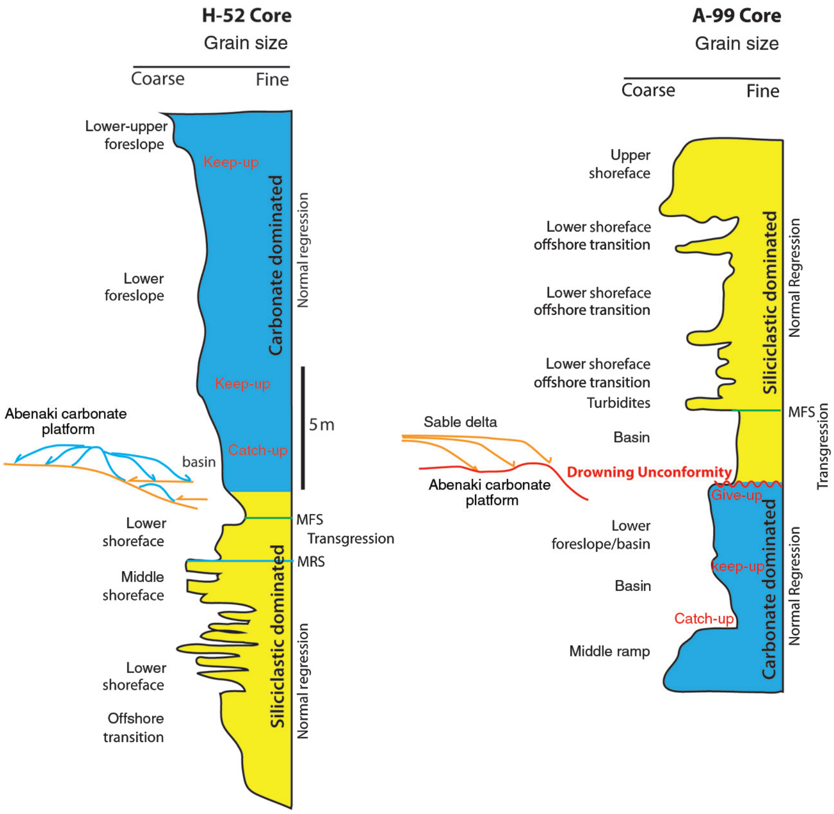


Figure 2. Core data show the development of two depositional systems (carbonate and siliciclastics) at two well locations. For a given site, these two depositional systems do not dominate simultaneously. However, it is either a carbonate-dominated interval or a siliciclastic-dominated interval. The H-52 core log suggests a transition from a shallow marine siliciclastic-dominated setting to a carbonate-dominated setting, which is marked by an MFS. The A-99 core log suggest a transition from a shallow marine carbonate setting to a siliciclastic-dominated setting, which is marked by a DU (MRS, maximum regressive surface; MFS, maximum flooding surface; and DU, drowning unconformity). Modified from Weissenberger et al. (2006).

(Blache-Fraser and Neep, 2004). It is similar to colored inversion; however, it differs in the sense that it is applied on reflectivity data rather than acoustic-impedance data. For the Abenaki megasequence, the bandwidth of the desired blueing operator was set to 10–35 Hz (Figure 4a and 4b).

This spectrally blued volume was used as an input to compute the dip field and proceed for dense horizon mapping.

Dip steering and filtering

Dip steering is an approach to calculate the dip and azimuth from seismic data. There are various ways to extract the seismic dips: phase based, event based, or frequency-amplitude based (Tingdahl and de Groot, 2003; Chopra and Marfurt, 2007). The phase-based or event-based methods are not preferable because the seismic phase is a noise-sensitive attribute. The frequency-amplitude-based method (also known as *fast Fourier transformation*) is preferred because it incorporates the amplitude and frequency changes with depth and produces superior results. The resultant volume is referred to as a "steering cube." The spectrally blued data are used to compute detailed dip-azimuth information.

The spectrally blued data were smoothed by performing a dip-steered filter (Figure 4c). It is a statistical filter applied on the seismic data, such that it follows the dips instead of a horizontal window. Vertically, the filtering time gate was set to zero suggesting no temporal changes were expected. However, the filter runs spatially (5–10 traces on average) by filtering out the outliers along the dips. It produced smoothed seismic data. The latter was used to recompute a final detailed steering cube for dense horizon mapping.

Dip-steered gridding

In this paper, we did not use conventional gridding algorithms, such as triangulation and inverse distance gridding. Instead, the 3D seismic data were utilized by using the steering cube to follow the geologic trends. In mixed settings, small patchy reefs can be very phase inconsistent, meaning they can neither be autotracked precisely nor can the conventional gridding techniques help in the identification of such reefs. The adopted approach of dip-steered gridding helps not only in mapping but also in the identification of geomorphologic features, such as patch reefs, buildups, karsts, and channels. All framework horizons were produced using dip-steered gridding with a preprocessed dip field. More details on the algorithm can be found in the following section.

Seismic inversion

Deterministic seismic inversion was not considered feasible due to limited well data within the 3D survey. Therefore, seismic colored inversion was considered as an optimum choice (Lancaster and Whitcombe, 2000). The objective of performing colored inversion is to aid in interpretation such that one can qualitatively differentiate between the siliciclastic and carbonate intervals.

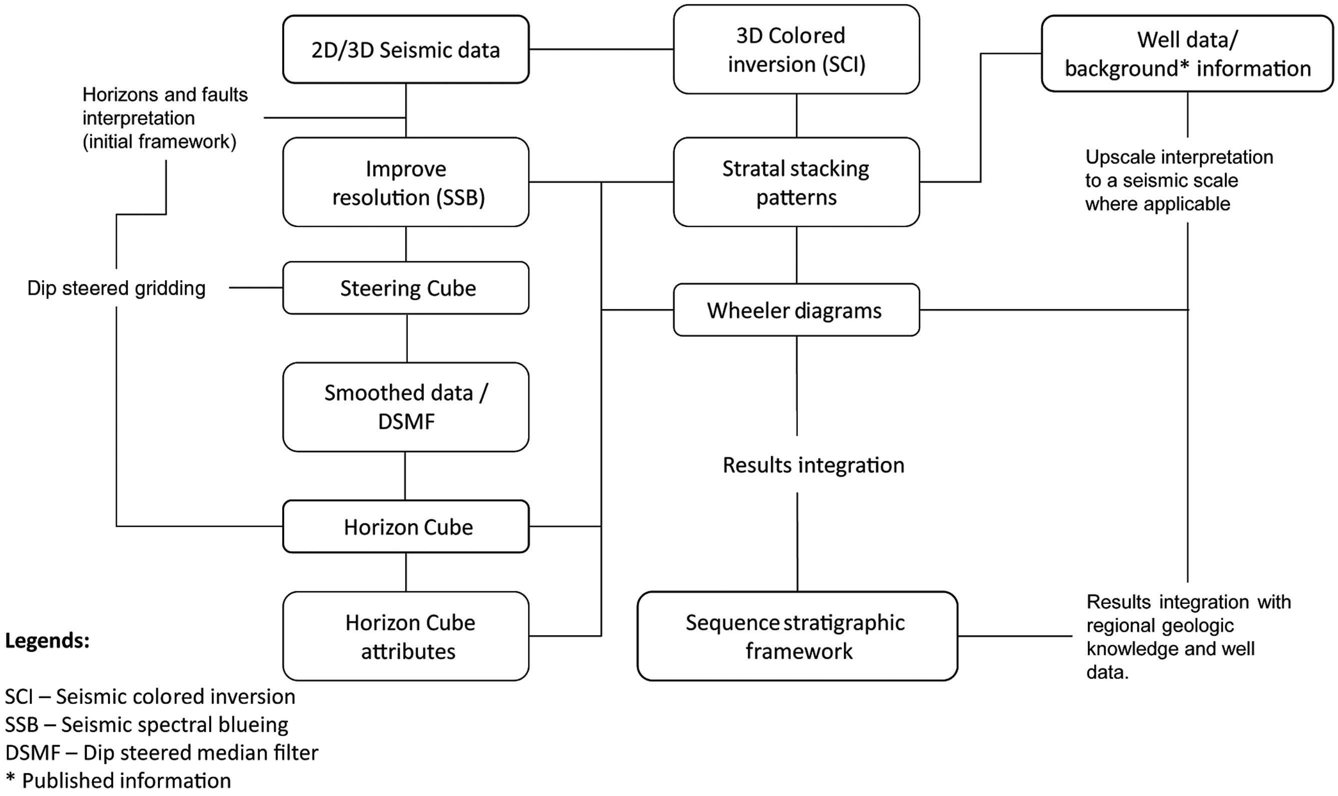


Figure 3. An illustration of the applied workflow to accomplish this case study.

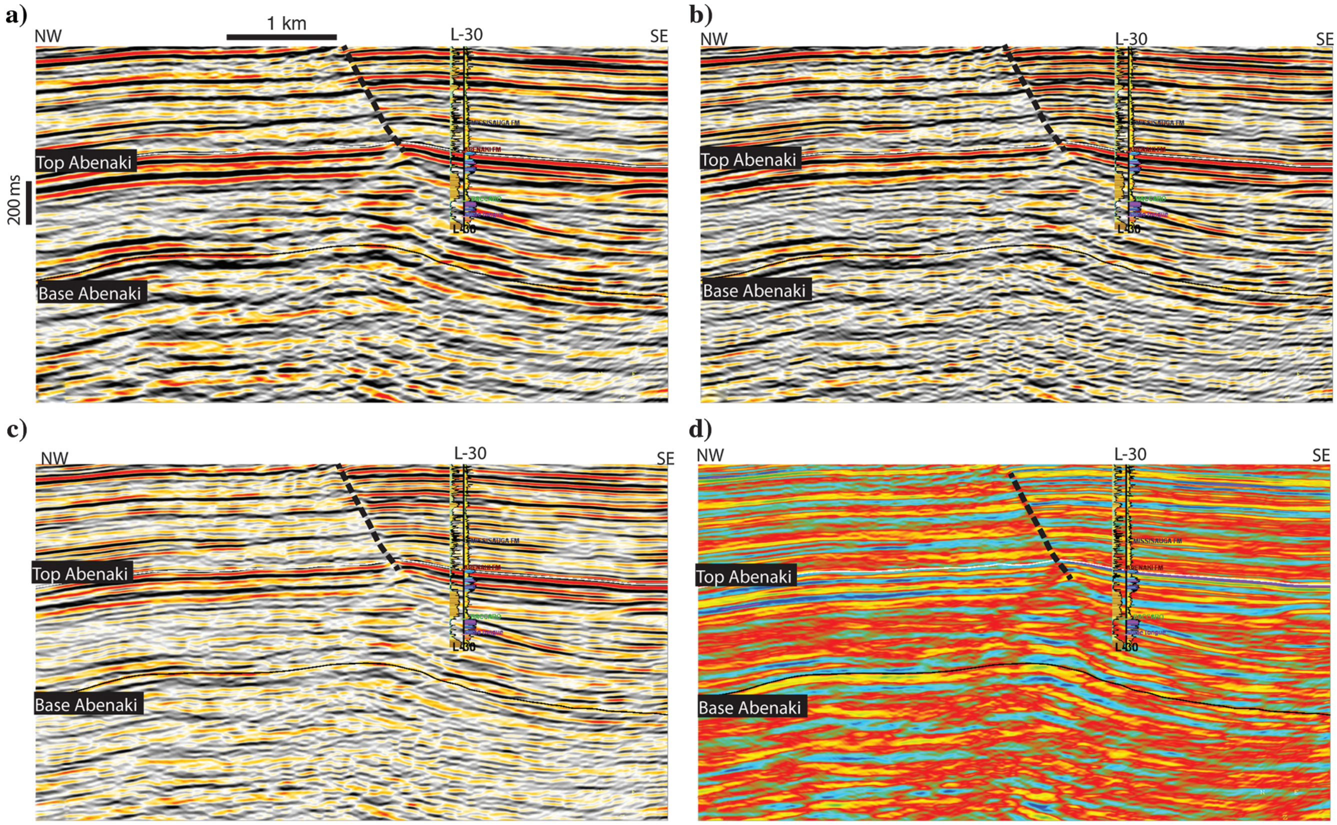
In this process, a global inversion operator was designed using the available well. Specifically, this was done by matching the amplitude spectra of the seismic and well data. The desired bandwidth for this matching was set at 10–35 Hz. The operator was then convolved with the seismic data to produce a 3D seismic volume showing relative acoustic impedance values (Figure 4d). This volume was not used for the dip estimation. It was used for the qualitative interpretations.

HorizonCube — Dense horizons mapping

The mapping of all seismic events within an interval of interest using an automated algorithm is referred to as *dense mapping*. It is an essential step to establish a detailed sequence stratigraphic framework because it helps in integrating 3D seismic data with the well data (de Groot et al., 2010; Qayyum et al., 2012b). It also assists in creating 3D or even 4D Wheeler diagrams (Stark, 2005; Qayyum et al., 2013c, 2014a). There are several algorithms available in the oil industry that help in producing densely mapped seismic data (Hoyes and Cheret, 2011; de Groot, 2013; Stark et al., 2013). The approach used in this paper is called the *HorizonCube method* (Ligtenberg et al., 2006; de Groot et al., 2010; Qayyum et al., 2013b). After computing a dip data, an autotracker tracks seismic horizons bounded by an initial framework. It may generate hundreds of seismic horizons. The horizons are stratigraphically sorted, arbitrarily numbered, and stored as grids. The HorizonCube can be data driven (using a steering cube) or model driven. If the data have already been interpreted in detail, the model-driven approach can be used to slice through the 3D seismic data and identify geologic features.

There are two types of HorizonCube: continuous and truncated (Qayyum et al., 2013b). The *continuous HorizonCube* contains events that may converge together but never cross each other. This allows the identification of unconformities, stratigraphic pinchouts, condensed sections, or erosional features. The *truncated HorizonCube* contains seismic events that terminate against each other when the thickness between the events reaches a given threshold.

Data-driven methods are always sensitive to seismic noise (such as multiples, side swipes, bad data zones, and poor energy penetration) and data resolution. Careful interpretation and good data integration can help in establishing a good stratigraphic framework at the seismic scale. For this, covisualization and integration lead to success as explained in the subsequent section.



L-30: The left log is a gamma ray log display, which increases its value toward the right. The log colors such as brown represent shales, whereas the blue color represents limestones or sandstones. The right log is an acoustic impedance log display, which increases its value toward the right. High impedances are represented in blue to dark-blue colors

Figure 4. A seismic crossline through the 3D seismic data that lies at the well location (see Figure 1 for location). Various steps were performed in data preparation: (a) Input seismic data, (b) frequency enhancement through SSB, (c) after the frequency enhancements, the data are smoothed using a dip-steered median filter, and (d) colored inverted seismic data "a".

Integrated interpretation

The HorizonCube assists only to map the seismic data. It always requires detailed investigation and interpretation to discriminate between true geologic trends versus seismic noise. To ascertain a good model, an interpreter has to observe the autotracked events in 3D by studying the data in a structural domain as well as in the Wheeler domain. The latter is prepared by flattening a truncated HorizonCube. The y-axis of this domain is formed using the time series obtained from the HorizonCube. This time series can be treated as a relative geologic time scale. Therefore, the seismically driven Wheeler domains can be treated as Wheeler equivalent diagrams. These Wheeler scenes have several advantages, but pitfalls are also known (Ligtenberg et al., 2006; Qayyum et al., 2012a, 2013b, 2014b).

The model-driven HorizonCube can be parallel to either an upper horizon or a lower horizon, or it can be proportionally created. The third approach was used to perform strata slicing (Zeng et al., 1998) in the Penobscot area. It revealed several promising features that further helped to understand the interpreted sequences.

Furthermore, the subaerial unconformities (SUs) and the condensed sections can also be identified using the HorizonCube density attribute (Qayyum et al., 2013a, 2013b). This attribute counts the number of autotracked seismic horizons in a given time gate. It is a valuable attribute when applied on a data-driven HorizonCube. Such an attribute contains converging and diverging horizons. Intervals with higher convergence will naturally contain more horizons when compared with the intervals of higher divergence. Therefore, higher density values reflect a region with higher convergence and can directly help in interpreting the geometric configuration of associated reflections. The converging reflection patterns are common characteristics of condensed sections, unconformities, and reef top; therefore, this attribute plays a vital role for 3D interpretation. For such cases, the diverging patterns can be ignored or considered as transparent features.

Intepretation: Abenaki-Sable sequence

The Abenaki-Sable sequence is studied using the transgressive-regressive (T-R) sequence model (Johnson and Murphy, 1984). The end of transgression is defined as a *maximum flooding surface* (MFS). The underlying stratigraphic unit is called a *transgressive systems tract* (TST or TR). The end of regression can be marked by a maximum regressive surface. The corresponding underlying unit is called a *normal regressive systems tract* (NR). The SU is placed if the platform is exposed or the topsets of the clinoforms are incised or eroded. It is extended to the basin with a conceptual surface called *correlative conformity* (CC) (here defining the time-equivalent slope to the basin margins).

Second-order T-R sequences (2D)

Introduction

To understand the regional depositional architecture, stratal stacking patterns, and the internal geometric configurations, the 2D seismic data were thoroughly studied. This helped in defining the second-order sequences developed during the growth of the Abenaki-Sable sequence.

The seismic mapping showed a regional extent of the carbonate bank during the Jurassic Period (Figure 1a) that even extends to the north (Penobscot area). The mapping also showed that the carbonate banks could be laterally isolated, which are a result of carbonate growth, bathymetry, and siliciclastic influx. The Penobscot area, specifically, seems to be an isolated bank compared with the vicinities of the Cohasset and Deep Panuke fields (for approximate locations, refer to Figure 1a).

Although this is a mixed setting, stratal stacking patterns were observed that were similar to those established in the 1970s (Payton, 1977; Catuneanu, 2006; Catuneanu et al., 2011). Similar examples of “reciprocal” stratigraphic patterns have also been documented in fully siliciclastic settings between different subbasins of the same sedimentary basin (Catuneanu et al., 1999, 2002). The two key core data sets taken from A-99 and H-52 wells clearly demonstrate the dominance of two depositional systems at these specific sites (see Figure 2). The results obtained from the core data show that if a siliciclastic system dominates at a given site, e.g., the H-52 (lower part) well, the carbonate factory is not established and the reverse is also true. So, despite the fact the mixed lithologies are present, a depositional system has developed based on a dominance character and remains site specific. Due to this, the sequence stratigraphic interpretation was performed by considering the dominant nature of a depositional system at the given local site.

Regional stacking patterns

The entire Abenaki-Sable sequence can be considered as a large-scale “megasequence” developed during the Jurassic Period. This megasequence contains a wide variety of stratal stacking patterns and morphologies.

The regional composite line demonstrates the geometric architecture of this megasequence (Figure 5). The megasequence clearly shows a seismic-scale carbonate bank that was onlapped by younger sediments. These are interpreted as infills dominated by shallow marine carbonates and mudstones. Several downlapping patterns are also observable (Figure 5b). They often have siliciclastic sediments derived through channelization and associated processes. The lateral strata also exhibit clinoform geometries approaching the isolated bank (Figure 5c). Note that small-scale carbonate shedding away from the bank is also evident. This could have been developed during the same time as when the siliciclastic delta approached these areas. It clearly demonstrates that the two systems coexist, but they remain on specific sites. In this case, the siliciclastic delta only dominates when the carbonate bank is drowned, that is, the youngest stage lying above the top of the Abenaki megasequence. This is also referred as the *drowning stage of the carbonate banks*. West to southwest of the Penobscot area, a large-scale channel system was observed and interpreted as a valley/canyon system (Figure 5d). This system shows the dominance of the Sable Delta at this site. The delta approached the Abenaki carbonate bank and cut through the platform margins. It could possibly have developed deepwater fan systems onto the basin floor. The parallel to subparallel reflections above these valley/canyon systems could be related to the deposition of shales/mudstones.

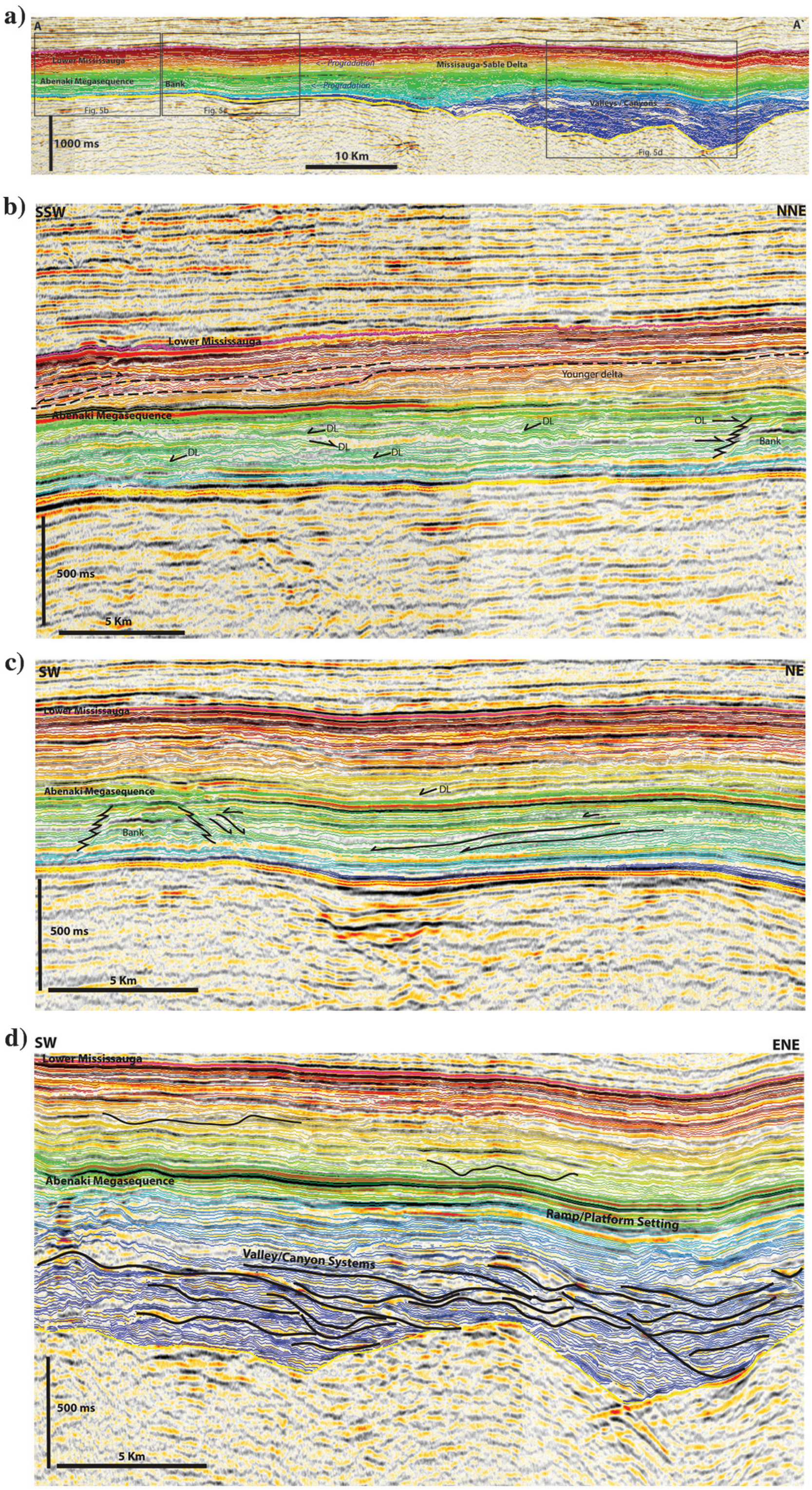


Figure 5. (a) A regional seismic section (AA′; see Figure 1 for the location) showing the broad carbonate platform and associated deltaic patterns. Three detailed views of this section are presented to demonstrate the stratal patterns and morphologies of the study interval: (b) The western segment of section AA′. The Abenaki megasequence shows several downlapping patterns that are mostly away from the interpreted bank. The seismic data show onlapping patterns to this bank. The younger delta contains several sigmoidal reflection patterns related to the Mississauga Delta. (c) The middle part of section AA′ shows the complete extent of the inferred bank, local shingled reflections (toward the northeast) away from the bank, and associated downlaps in the opposite direction (northeast–southwest). (d) The eastern part of the seismic section AA′ shows a broad valley/canyon system above which the parallel reflections are inferred to be associated with a stable ramp setting. The Lower Mississauga Delta contains mostly continuous reflection patterns that are occasionally channelized. DL, downlaps; and OL, onlaps.

In contrast, the Mississauga-Sable Delta, a younger interval, contains a completely different geometric configuration. The clinoforms in this specific interval are larger in scale, and the aggradational topsets are also visible. The channelization patterns are also smaller in scale (Figure 5).

Sequence stratigraphy

The Abenaki megasequence is subdivided into two second-order T-R sequences (with suffixes of 1 and 2):

1) The lower Abenaki-Sable sequence 1 interval is dominated by reefs/buildups, isolated banks, backreef progradation (often clear, and sometimes being shingled reflections on the seismic data), and aggradational patterns.
2) The upper Abenaki-Sable sequence 2 contains a thicker progradational to aggradational platform margin with occasional reefal growths close to the platform edge. Away from the platform margin, the same system contains large-scale clinoform geometries that are often incised.

The lower Abenaki-Sable sequence 1 started to form soon after the marine transgression (note the backstepping reefs and onlapping geometries in Figure 6). This established an initial catch-up stage to develop shallow marine carbonates on the shelf. The end of the transgression is marked by a maximum flooding surface (MFS-1). The underlying interval is defined as TR-1. Above this unit, the carbonates build upward and prograde toward the backreef margin/lagoon, evident on the Wheeler diagrams. This develops a regional keep-up stage. The distal/basinal parts remained relatively starved and condensed. The carbonate factory was terminated when the shelf was partially exposed — see the hiatus above the SU-1 in Figures 6–8. The slope-to-basinward extension of this surface could be traced by a composite surface (i.e., onlap/escarpment surface) plus a correlative conformity, which may underlie the younger turbidites, fans, or shales. Proximally, the progradational clinoforms are clearly evident and show that several high-resolution cycles may have formed within this sequence (Figure 8). For instance, note the high-resolution shingled clinoforms prograding toward the backreef margin. These could also be treated as laterally meandering channels. To validate this interpretation, 3D coverage is required. As such, a region is close to the siliciclastic influx; therefore, the overlying clinoform patterns are inferred to be sourced by the siliciclastic delta, defined as a *normal regression* (NR-1). The SU-1 and its correlative parts are obvious on the Wheeler diagrams, which are onlapped by a younger TR-2. Local brightness within the clinoforms could be a result of in situ carbonate growth or detrital carbonates.

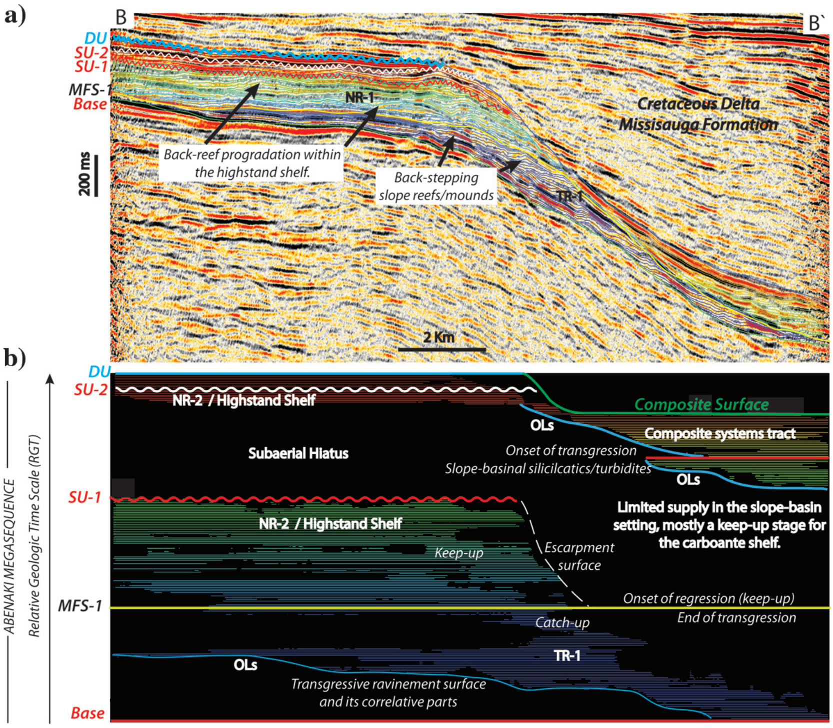
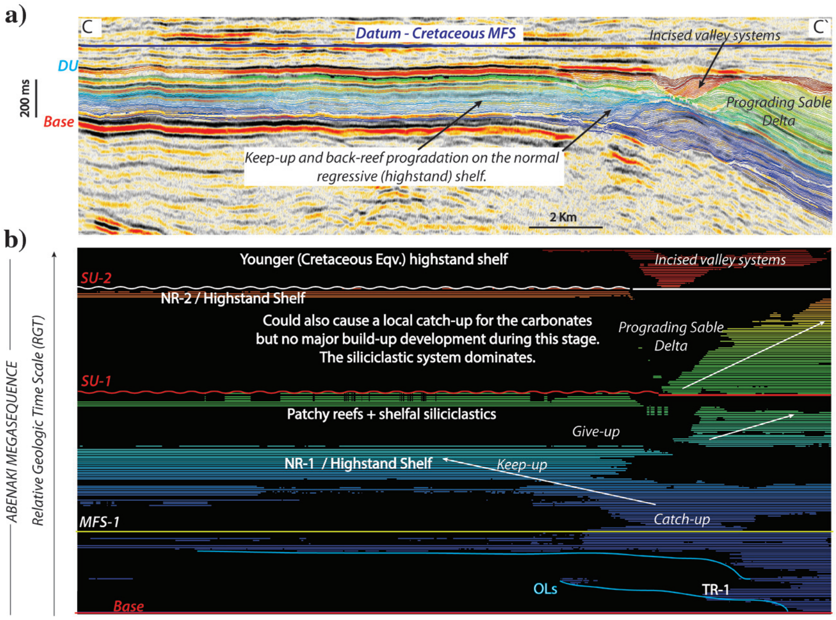


Figure 6. A seismic section (BB′; see Figure 1 for the location) showing the morphology of the Abenaki-Sable sequence. (a) Seismic data in the structural domain with an overlay of the HorizonCube and (b) the HorizonCube display in a Wheeler domain. The section illustrates two interpreted sequences based on the stratal stacking patterns. The transgressive onlaps and backstepping reefs are evident. The normal regressive (highstand) shelf mostly contains backreef progradation and aggradational patterns. DU, drowning unconformity; SU, subaerial unconformity; MFS, maximum flooding surface; OLs, onlaps; NR, normal regression; TR, transgression; and Composite systems tract, transgressive plus regressive nature cannot be separated out due to seismic resolution and data coverage.

The upper Abenaki-Sable sequence 2 is relatively thin on the platform but thicker toward the basin. This sequence is dominated by the siliciclastic system in the basin, whereas on the platform, it is difficult to infer much because the seismic resolution does not allow for geometric interpretation. However, from the knowledge of well data, the platform contains patchy reefs. The 3D seismic data clarify platform morphologies during this stage (see the following section of this paper). Toward the southwest, the basinal part of this sequence is dominated by onlapping stratal configurations that have a largely concave upward morphology (see Figure 6). The downslope wedge is a difficult part and is not subdivided on 2D seismic data. Neither the seismic data nor the Wheeler diagram suggests whether this should be considered as a transgressive or a lowstand systems tract. This is because of data resolution and the limited scale. For simplification purposes, it is considered as a composite systems tract interval. Another line (Figure 7) shows the sigmoidal character of the younger deltaic progradation (see also the Wheeler diagram). The topsets of the clinoforms are mostly eroded in this area. This interval is interpreted as an NR-2 highstand shelf. Some parts of these clinoforms are also incised especially close to the underlying reef. The maximum incision level could be approximated to the underlying reef top. In proximal locations such as Figure 8, the TR-2 and the last highstand (NR-2) shelf are definable. The seismic section DD′ is also interesting because it defines both sequences clearly (Figure 8). The only contrasting element is that the NR-1 (highstand shelf) progrades toward the basin instead of the backreef margin. This section lies close to the siliciclastic influx brought by the Sable Delta; hence, a distinct stratal stacking pattern is observed. The lower most part of this section contains shingled seismic geometries (Figures 8 and 9). Here, two interpretations are possible. These shingled reflections described the backreef progradation. However, with a flat datum, the slope margin is evident, giving some uncertainties on this interpretation. Contrarily, these reflections can also be considered as laterally



Abbreviations: DU - Drowning Unconformity; SU - Subaerial Unconformity; MFS - Maximum Flooding Surface; OLs - Onlaps; NR - Normal Regression; TR - Transgression. Eqv. - Equivalent.

Figure 7. A seismic section (CC′; see Figure 1 for the location) showing the morphology and stratal stacking patterns of the Abenaki-Sable sequence. (a) Structural domain with a HorizonCube overlay, and (b) the same HorizonCube is displayed in a Wheeler domain. This section lies close to the siliciclastic influx, and hence the associated geometries, such as incision patterns and clinoforms prograding toward the basin (C′ or southeast) are observable. However, the carbonate factory mostly keeps up and builds out toward the backreef margin. The shelf remains in a highstand setting. The overlying clinoforms with weaker seismic amplitudes are dominated by siliciclastics and their topsets are mostly eroded. The incised valley systems are interpreted as a much younger phenomenon. DU, drowning unconformity; SU, subaerial unconformity; MFS, maximum flooding surface; OLs, onlaps; NR, normal regression; TR, transgression; and Eqv, equivalent.

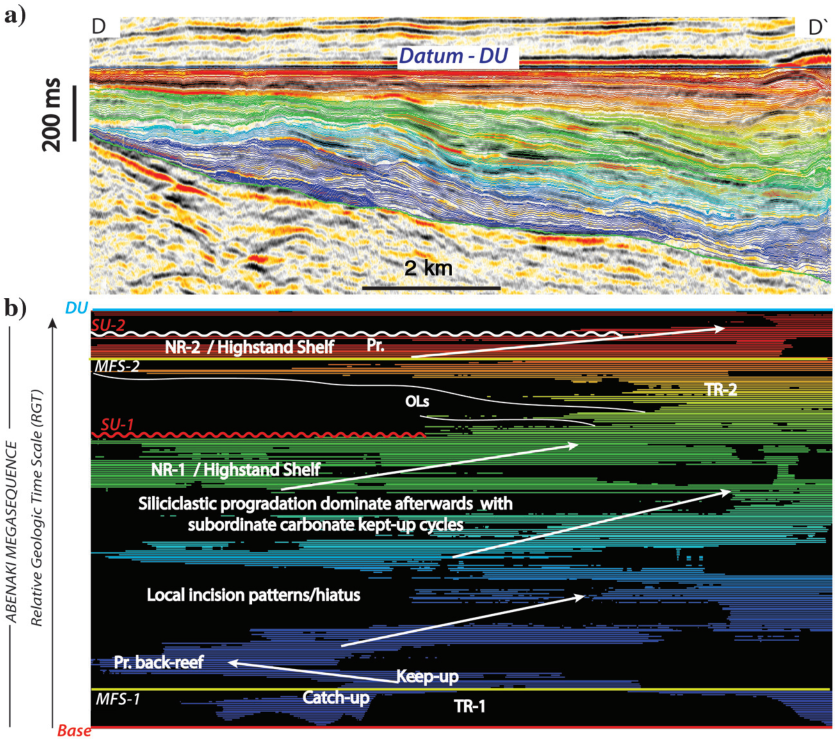


Figure 8. This seismic section (DD′; see Figure 1 for the location) is demonstrating several clinoform patterns that were not evident in the previous figures (Figures 5–7). (a) Structural domain with a HorizonCube overlay, and (b) the same HorizonCube is displayed in a Wheeler domain. Further note that this line lies close to the inferred siliciclastic influx. The lower sequence contains several aggradational to progradational patterns interpreted as a normal regressive/highstand shelf (NR-1) setting. These clinoforms have higher slope compared with the upper normal regressive shelf (NR-2). DU, drowning unconformity; SU, subaerial unconformity; MFS, maximum flooding surface; OLs, onlaps; NR, normal regression; TR, transgression; and Pr, progradation.

migrating channel systems that move updip with time. For this specific interval, further data are required, such as well data, which were not available while accomplishing this study. The upper interval is clearly definable as a prograding unit that terminates when the first onlap (OL in Figure 9) is observed.

Third-order T-R sequences (3D)

Abenaki margin in the Penobscot area

Regional mapping showed that the Penobscot area evolved as a barrier island during the Jurassic Period (Figure 1a). The 3D seismic data acquired in this area further clarify the morphology of this region and suggest that the entire Abenaki succession was developed on a preexisting high (a domal structure) that resulted in a local bank or an isolated ramped margin (Figure 10). The development of the Abenaki ramp margin progressed by accretionary growth of reefs along the margins and the ramp stage progressively evolving into a rimmed stage (equivalent to the second-order sequence 1 as defined in this paper). The distal parts of the margin became progressively steeper and were filled by younger detrital sediment, such as siliciclastics and carbonates. The entire bank began drowning when the margin reappeared as a stable ramp (equivalent to the second-order sequence 2) above which the siliciclastic delta was prograding (Figure 10). The variations in carbonate platforms such as ramp-rim-ramp stages are well known in carbonate settings (Read, 1985; Tucker et al., 1990; Pomar, 2001; Schlager, 2007). In this case, the distally steepened ramp margin lies close to the continental shelf adjacent to the North Atlantic Ocean and is characterized as a high-energy ramped margin. It is also filled by younger sediments transported during the enlargement of the Sable Delta.

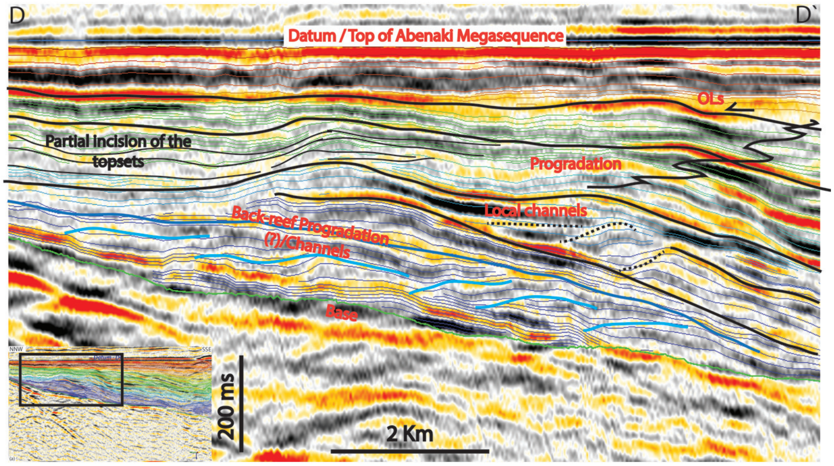


Figure 9. A detailed view of seismic section DD′ (see also Figure 8). The lower part contains shingled reflection patterns that could either be backreef progradation or channelization. Further data (such as well/3D) are required to make a unified interpretation for this interval. This is overlain by clear prograding clinoforms that are subsequently onlapped by younger transgression (TR-2; see Figure 8). Often, the topsets/foresets of the clinoforms are being incised suggesting channelization due to terrestrial influx.

The 3D morphology of the platform was defined by performing stratal slicing through the volume using a proportional HorizonCube (Figure 11). Seismic amplitudes were extracted and displayed along selected horizon slices. The higher amplitude values observed mostly reflect the carbonates or condensed sections depending on their location with reference to the bank margins. The horizon slices suggest that the Abenaki bank maintained an arcuate shape throughout its development. Evidence of deltaic lobes near the bank was also found (Figure 11d and 11e) suggesting the relative time, entry point, and advancement of the siliciclastic delta beyond the bank margin.

Sequence stratigraphy

The 3D seismic data assisted in subdividing the second-order sequences further into four third-order sequences.

Sequence I is formed with an onlapping transgressive system establishing shallow marine environment on the Penobscot bank. This is marked by a transgressive systems tract labeled as TR-I and is terminated at the defined MFS-I (Figures 12 and 13). Following this, a downlapping unit is formed and overlies it. This unit is interpreted as an NR-I. Due to limited extent of the 3D survey, it is not possible to define the origin of these clinoform geometries — siliciclastic or carbonate. Above this unit, the hiatus is visible on the Wheeler diagrams (Figures 12 and 13). The end of the regression is marked by a subaerial exposure marked as SU-I and its extension to the basin with a CC-I. This sequence is not reached by the L-30 well (Figure 14).

For sequence II, the NR-I unit of sequence I is overlain by a distinct transgressive system (TR-II in Figures 12 and 13). Note the backstepping buildups in Figure 12. During this stage, the top of the underlying NR-I unit could have been partly eroded/reworked through the transgressive ravinement process. The TR-II unit is overlain by a small progradational unit. The bank edge is well defined on the seismic data. This unit is interpretable on the high-resolution data, such as the well log of L-30 (Figure 14). The basal MFS-II is obvious, which is overlain by a shoaling upward cycle (NR-II). These are microbial carbonates developed on the slope margin (L-30 core). The top of NR-II is defined as a second SU-II; note the incision equivalent pattern in Figure 12 (annotated as "K/E"). The end of this sequence forms a distinct rimmed carbonate platform, whereas the accommodation space increases beyond the platform edge, creating a space where the siliciclastics could develop.

On the log scale, two fourth-order sequences are interpretable.

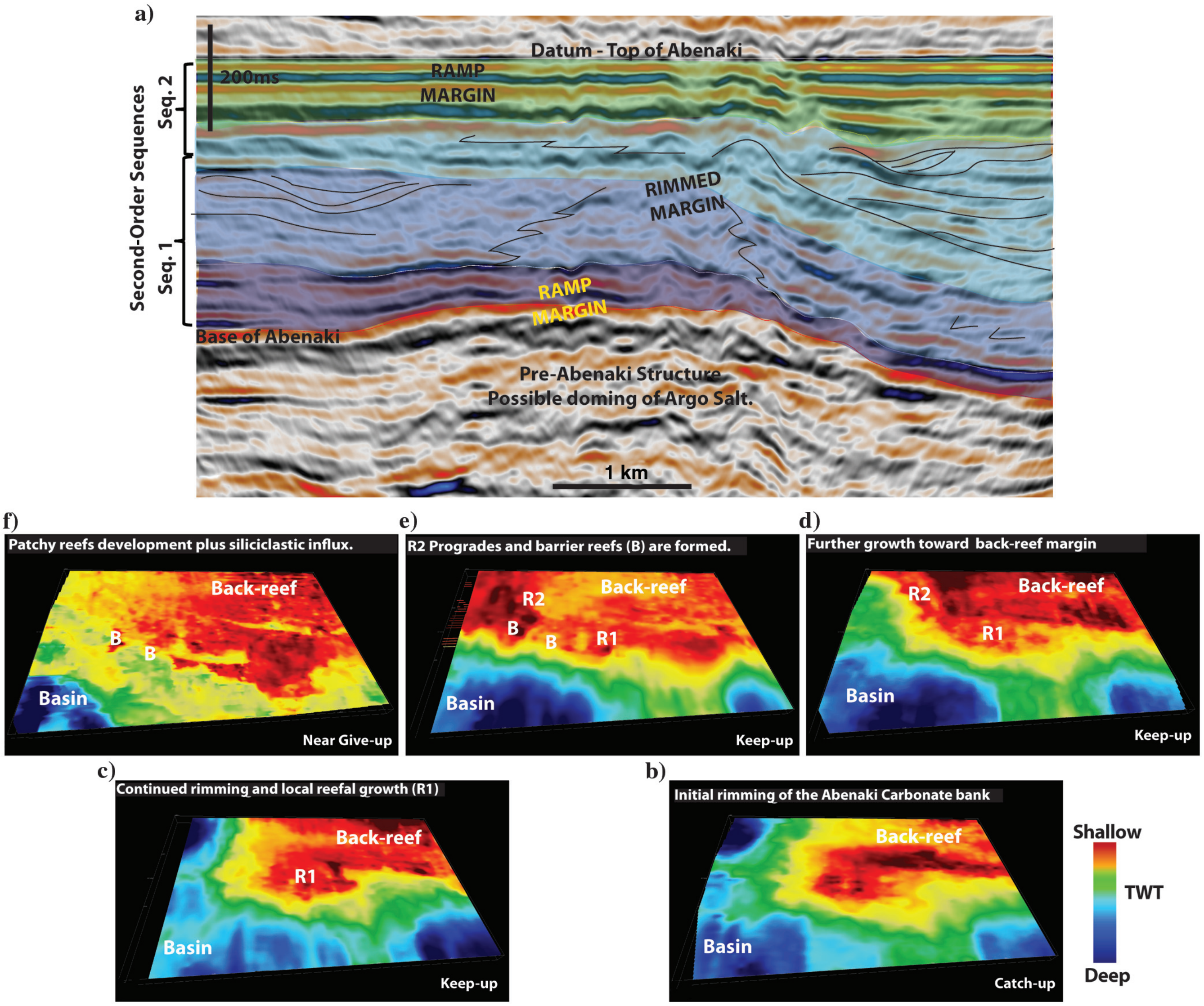


Figure 10. The growth of the Abenaki carbonate bank in the Penobscot area (a crossline from the 3D seismic data). The section and corresponding TWT maps are presented using a datum on the top of the Abenaki megasequence. This datum was preferred to remove the structural folding that occurred after the deposition of this sequence. (a) The bank evolved as ramped margin that progressively became rimmed (Seq. 1). The subsequent filling of the accommodation space formed another ramped margin (Seq. 2). (b-f) The TWT maps illustrate the approximate growth of the platform during the Jurassic Period. The maps define several reefal colonies; barrier reefs with associated backreef and forereef margins Seq., sequence; B, barrier reefs; R, reefs; and TWT, two-way traveltime.

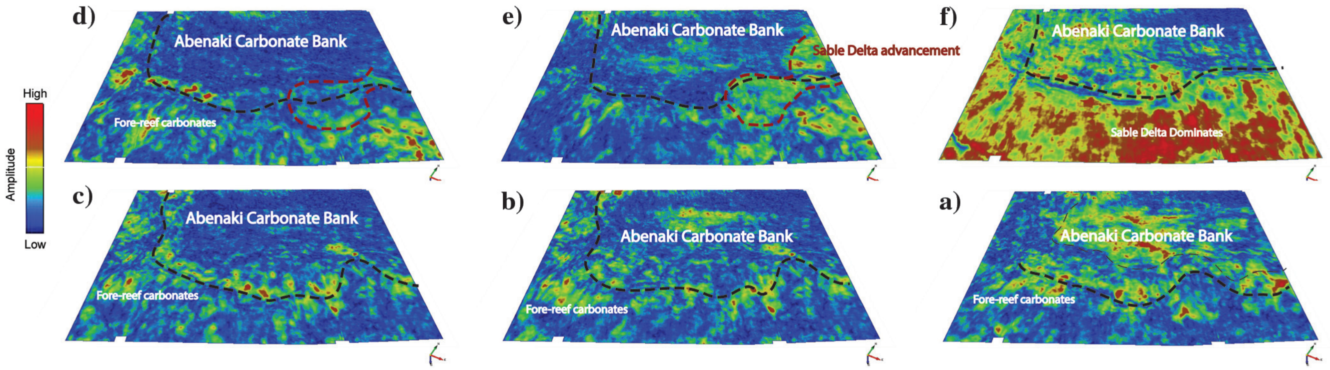


Figure 11. Stratal slicing through the Abenaki carbonate bank in 3D. The seismic amplitude is extracted around each horizon slice and displayed in colors. The bank started evolving from panel (a) to panel (f). The stages shown in the panel (d) or (f) map are the approximate timings of which the Sable Delta reached the Penobscot area. Panel (f) marks the near-drowning stage with some patchy-reef development on the bank and some progradation in the forereef margin.

Sequence III is distally thick and proximally thin (Figures 12 and 13). The lower unit clearly onlaps onto the rimmed platform margin and is interpreted as a TR-III. This transgression reestablishes a shallow-marine carbonate environment and is distally filled by thicker marine shales. The lower part of the TR-III unit is dominated by carbonates, which are deposited in the slope setting; possibly of detrital origin. The upper part of the TR-III unit is dominated by transgressive shales — note the fining upward trend of the GR log (Figure 14). The infills of the incised/karstified regions could be of transgressive nature (Figures 13 and 14). TR-III is followed by a highstand shelf, where the carbonates aggrade and prograde toward the back-reef margin (Figure 13). This stage largely fills the slope-to-basin margin around the Penobscot area and establishes another ramp stage for the carbonate factory to catch up (sequence IV).

Figure 12. Sequence stratigraphic interpretation on the 3D seismic data of the Penobscot area. (a) Structural domain with a HorizonCube overlay and (b) the same HorizonCube is displayed in a Wheeler domain. Four T-R sequences are interpreted. The section shows that the first three sequences (I to III) are developed on a ramped to rimmed shelf. TR-III fills the basinal accommodation space with marine shales. The fourth sequence (above SU-III), with very low gradient clinoforms, is developed on a gently dipping ramp margin NR/TR — These annotations define the system tracts of the third-order sequences, which are not equivalent to the ones defined in the 2D interpretation (which are second-order sequences). T-R, (transgressive-regressive; DU, drowning unconformity; MFS, maximum flooding surface; NR, normal regression; TR, transgression; SU, subaerial unconformity; CC, correlative conformity; OLs, onlaps; K/E, transgressive fills (karstification/erosion); and B1, B2, backstepping buildups.

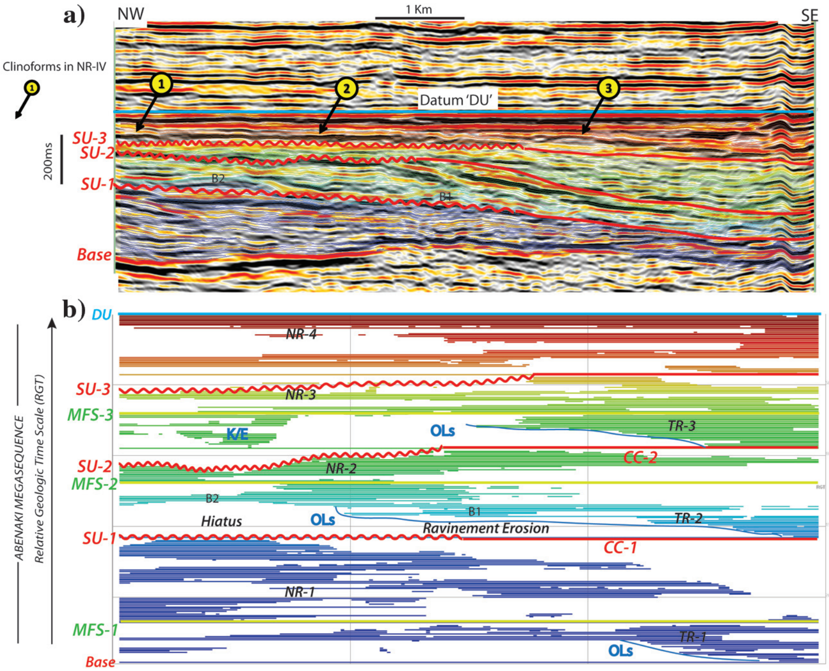
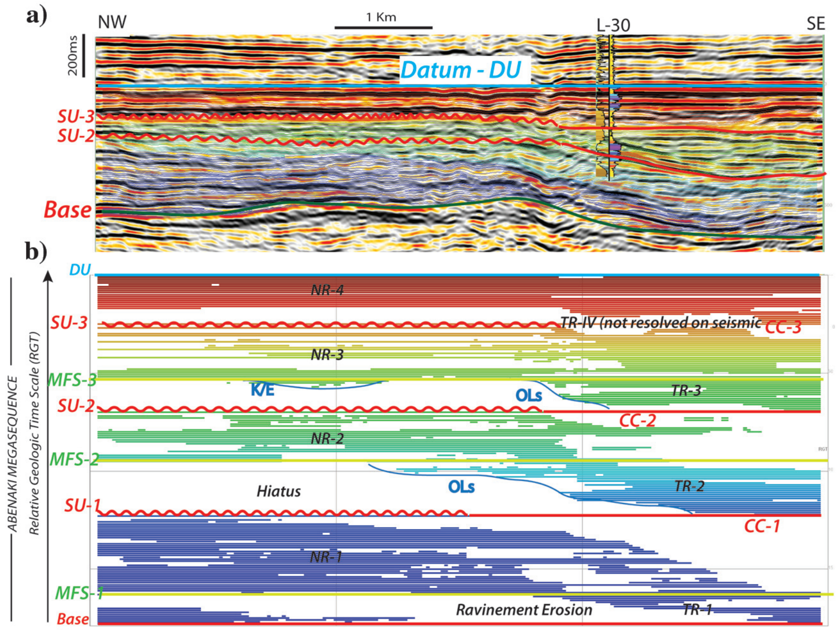


Figure 13. A seismic crossline through the L-30 well. (a) Structural domain with a HorizonCube overlay and (b) the same HorizonCube is displayed in a Wheeler domain. Two logs are displayed for the L-30 well (see also Figure 4 for the log display). This section also demonstrates the same four sequences as interpreted in Figure 12. However, it further shows the relationship of these sequences with the well data. NR/TR — These annotations define the system tracts of the third-order sequences, which are not equivalent to the ones defined in the 2D interpretation (which are second-order sequences). NR, normal regression; TR, transgression; SU, subaerial unconformity; CC, correlative conformity; OLs, onlaps; and K/E, transgressive fills (karstification/erosion).



(b) NR/TR - Here these annotation are defining the systems tracts of the third order sequences which are not equivalent to the ones defined in 2D interpretation (which are second order sequences) .

NR - Normal Regression; TR - Transgression, SU - Sub-aerial unconformity; CC - Correlative Conformity; OLs - Onlaps; K/E - Transgressive fills (Karstification / erosion).

On the log scale, this sequence can further be divided into three fourth-order sequences (Figure 14).

Sequence IV is an overlying unit. The transgression is only evident on the logs, whereas the regression is well defined on logs as well as on the seismic (Figures 12–14). On the seismic data, clinoforms are visible (especially in Figure 12). These clinoforms have high acoustic impedances (AIs) (Figures 4 and 14 — the AI log of the L-30 well) in the Penobscot area. This stage ends with a distinct drowning unconformity above which the Mississauga Delta develops.

This sequence contain up to six possible fourth-order sequences on the log scale (Figure 14).

Penobscot stratigraphic play(s) — Abenaki reefs

The Penobscot area is a carbonate bank separated from the regional Abenaki carbonate trend with a canyon/valley system (Figure 1). It is proposed that the Penobscot area could have two stratigraphic plays (Figure 15):

1) a carbonate play — high-grade, accretionary reefal system
2) a siliciclastic play — low-grade, deltaic lobes that may be sand prone and were developed on the bank.

Well L-30 did not encounter these plays because it missed the target. It was based on old 2D seismic data and clearly misses the proposed accretionary reefal system.

Spectral decomposition was applied around the SU-III horizon using the continuous wavelet transformation. The map was color blended with three output frequencies: 14, 24, and 30 Hz. When all frequency responses are equal, the resultant color is white. Similarly, the low-frequency-dominated (thicker) areas will appear as red and the high-frequency-dominated (thinner) areas will

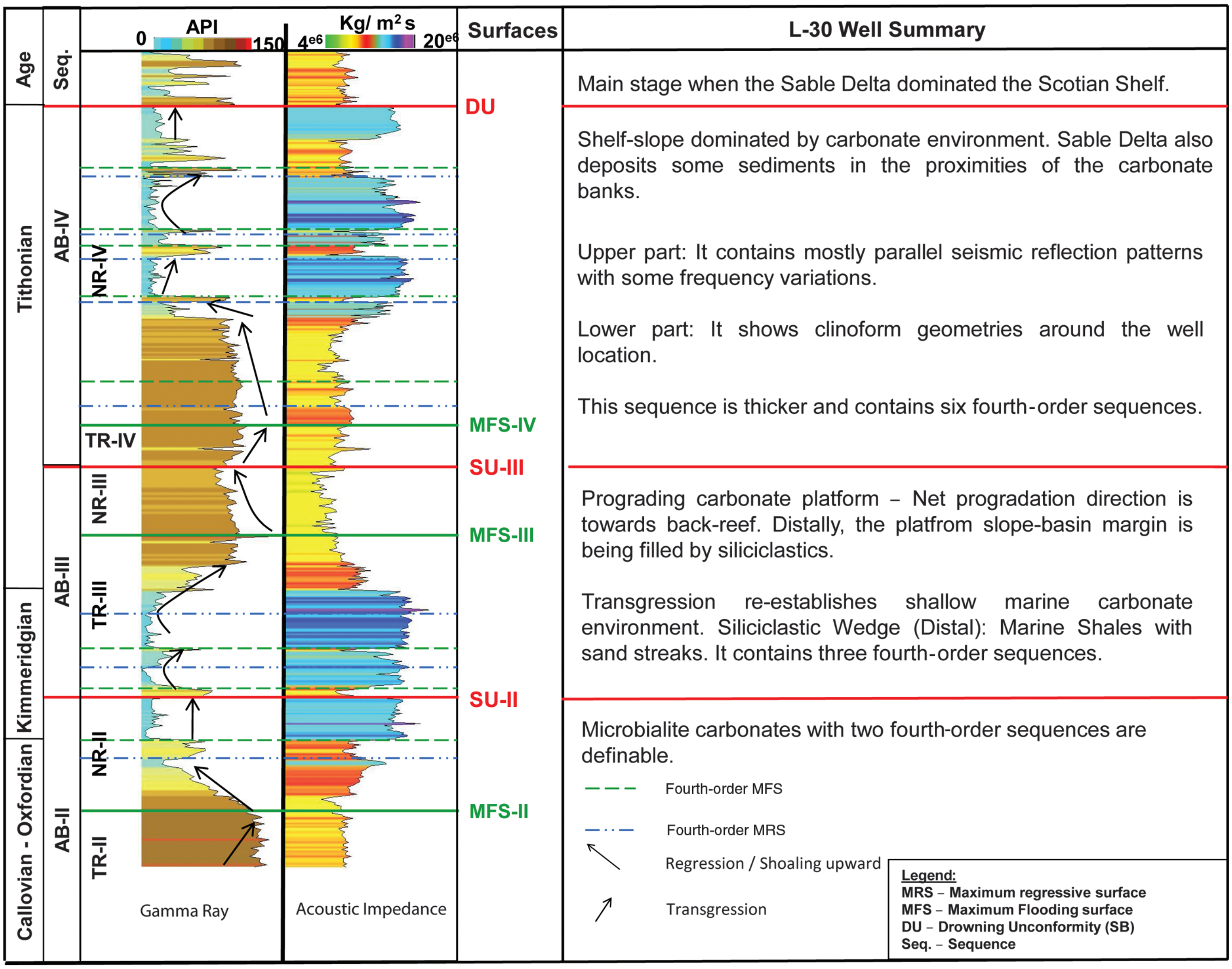


Figure 14. A detailed interpretation of the well data (L-30). The lower sequence I was not reached by the well. However, all other sequences were found. Each sequence can be further subdivided into fourth-order sequences using the gamma-ray (GR) log; however, they may approximate the lithostratigraphy. The arrows point to the coarsening (shoaling) upward and the fining upward trends.

appear as blue. The map highlights the presence of two depositional systems around SU-III and marks the two stratigraphic plays (Figure 15).

The reefal play area was further interpreted using a HorizonCube density attribute (Figure 16). It was prepared after creating a data-driven (continuous) HorizonCube around the carbonate play area only. Only the higher density areas representing the stratal convergence were visualized. This showed the development of isolated reefs around SU-III — possible stratigraphic traps. The stratigraphic hiatus between SU-II and SU-III was also obvious in this visualization. It also shows that L-30 missed these reefal features that could have future potential, and hence the Penobscot area still requires further hydrocarbon exploration for stratigraphic traps.

Discussion

When a carbonate depositional system is mixed with lithologies of contrasting origin, the stratigraphic interpretation can become difficult. However, if both systems developed in response to the same phase of the base level, the resultant stratal stacking patterns can easily be interpreted using conventional sequence stratigraphic principles. Also, note that a siliciclastic system may shut off the carbonate factory (although the contrary is not possible). The rimmed shelves may not only create the accommodation space for the siliciclastic system to develop, but they also can often create a relief of tens of meters. Such a relief is often drowned once the adjoining accommodation space is filled or the relative sea level rises. Based on this basic criterion, it is recommended to treat the depositional systems as isolated while considering them laterally equivalent.

The seismic amplitude (very high) and geometries remain as the defining criteria to discriminate a carbonate-dominated setting from a siliciclastic-dominated setting.

The onset of carbonate production is defined by a regional event, i.e., marine transgression over the ramp/platform settings during Middle to Late Jurassic times. During this time, no signs of stratal assemblages associated with the Sable Delta are observed.

Postmarine transgression, the platform locally aggrades and progrades, unless it is influenced by the Sable Delta. The latter is dominated by the siliciclastic source, i.e., toward the northeast. The carbonates mostly show progradational patterns toward the shallow marine environment, such as backreef progradation maintaining the carbonate factory, which grows toward the lagoon/backreef margins. Highstand shedding toward the basin was not observed.

When the siliciclastic system dominated, it developed large-scale clinoform patterns (e.g., Figures 7 and 9). These clinoforms are mostly of higher water depth and show progradation toward the basin, that is, toward the south–southeast. The distal parts of the basin remained relatively starved receiving less detrital (carbonate and siliciclastic) sediments in comparison with the areas south of the Deep Panuke (Figures 1 or 6).

The large-scale incision patterns postdate the first NR and hence incise through younger clinoforms that are dominated by siliciclastic systems (Figure 7). These incision patterns are also sourced by the siliciclastic

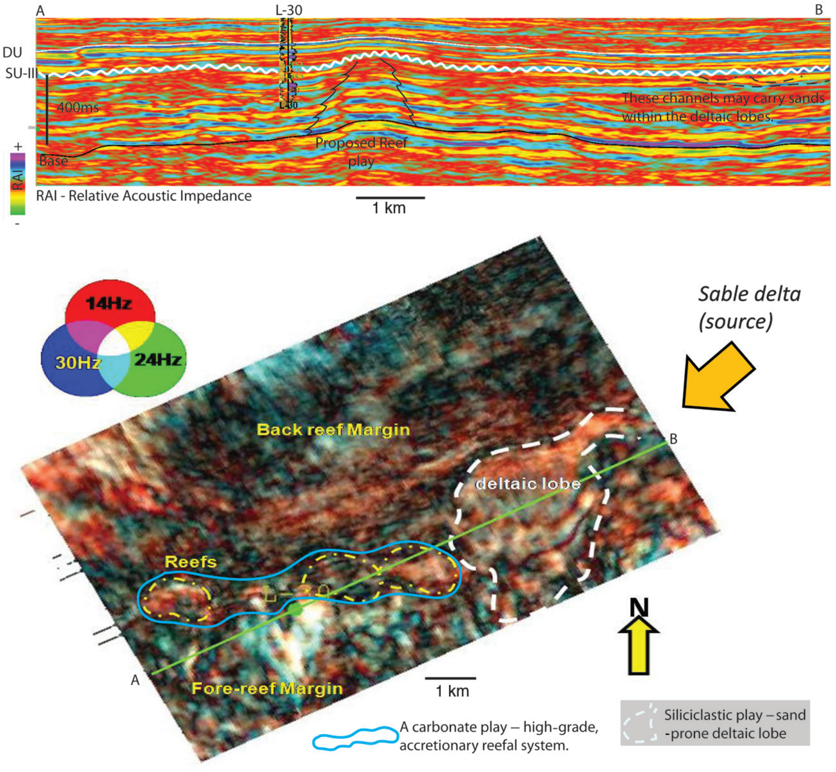


Figure 15. The Penobscot area may contain two stratigraphic plays: carbonate reefs or deltaic sands as illustrated in this figure. The strike section AB shows the vertical nature of the observed morphologies on the lower map. The lower map is prepared by color blending the three spectral decomposition maps generated at 14, 30, and 24 Hz around this horizon (SU-III).

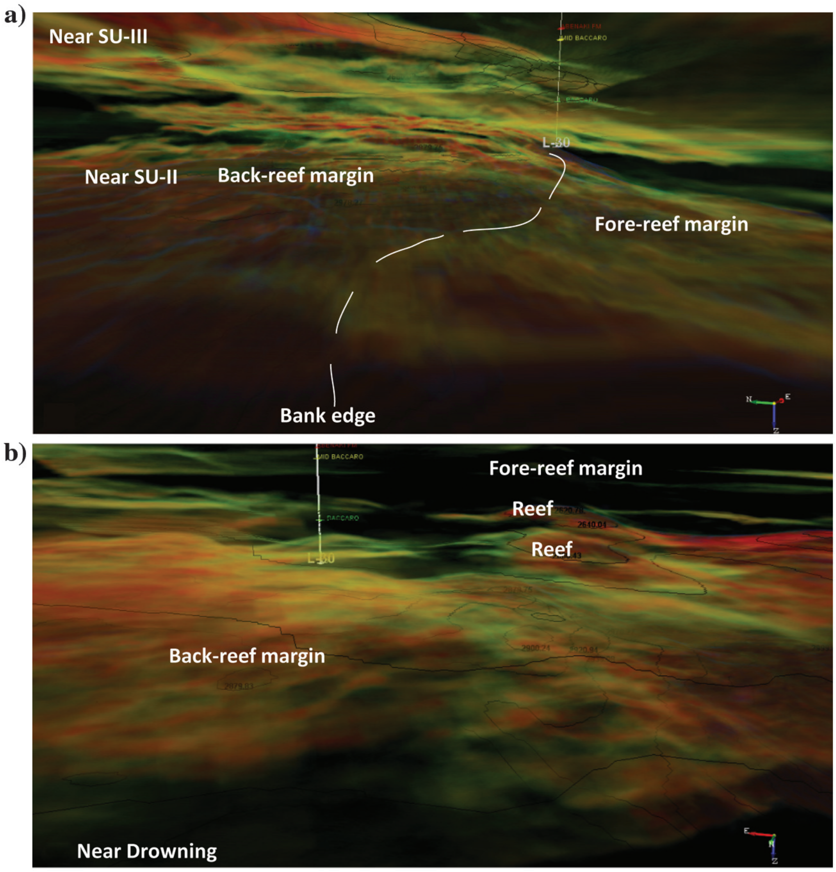


Figure 16. Three-dimensional perspective views of the HorizonCube density attribute around the L-30 well or proposed carbonate-stratigraphic play (Figure 15). Only the higher density intervals (red/yellow colors) are visualized. The lower density intervals are transparent in these views. The dense areas are mostly related to the highstand shelves (SU in this case; (patchy and barrier) reefs, and slope-basin margins. The upper image clearly presents the two unconformities and their surfaces in 3D. The lower image demonstrates the development of barrier reefs near the bank edge. Well L-30 clearly misses the play, and it did not encounter the reservoir.

delta and hence are referred to as *siliciclastic-dominated regions*.

The Wheeler diagrams clearly show the differences between regression versus transgressions and form a key tool to study such complex settings. These may have limitations in defining and extending the condensed sections as stated earlier.

Basinal settings in which the strata show onlapping patterns could be complex. In such settings, composite systems tracts may exist. Stratigraphic onlaps do not necessarily mean that the corresponding strata are of transgressive origin. These could have been developed during axial transport. Their morphologies are mostly concave-upward, suggesting a rise in the base level in the deepwater setting. More data are required to further investigate these patterns. These systems are provisionally defined as composite systems tracts in the study area.

Conclusions

This study has shown that the Abenaki Sable system is geometrically complex, but it contains several encouraging patterns that allowed for the establishment of a sequence stratigraphic framework. On a regional scale, the entire system contains two second-order sequences, which are a result of climatic, relative sea-level, and tectonic changes throughout the Jurassic Period. The Argo Salt movement could have had a minor influence on the geometry of the interpreted sequences. However, it is inferred that the major domal structure was formed prior to the first catch up of the sequence 1.

The semiautomated Wheeler diagrams provided an important tool in assisting the interpretation of the stratal stacking patterns. It is quite common that backreef progradation is present on the carbonate platform; however, the patterns may also resemble backstepping patterns. Hence, covisualization of the structural and Wheeler domains was deemed necessary.

The detailed study revealed four third-order sequences that developed as the platform margin grew from a ramped to a rimmed margin. Further transgression during sequence III not only filled the accommodation space in the forereef setting but also reestablished a shallow marine setting to help carbonates to catch up and subsequently to keep up.

The detailed study helped in defining two possible stratigraphic plays. The carbonate play is considered to be of a higher grade compared with the siliciclastic play. The former may contain accretionary/stacked reefal reservoirs being charged by gas originating from the deep-marine black shales developed in the near slope-basinal setting.

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