Using 3D Wheeler diagrams in seismic interpretation – the HorizonCube method

Farrukh Qayyum,[1] Paul de Groot[1] and Nanne Hemstra[2] **show that their HorizonCube-based transformation of seismic data provides a picture equivalent to the Wheeler diagram. Case studies from The Netherlands and Canada make the case.**

The method is unique because it gives a 3D insight into sequence stratigraphic interpretation. To explain this, two case studies are presented in this paper. The first case study is carried out in a Pliocene interval of the southern North Sea. Here, the HorizonCube based 3D Wheeler domain interpretation helped to integrate the well information with the seismic data and sub-divide the interval into 3rd order sequences. In the second case study, the mid–late Jurassic Abenaki sequence of Scotian Shelf is interpreted based on the same method. Four depositional cycles are interpreted with the correlation of a well. Both case studies demonstrate the benefit of the HorizonCube based Wheeler domain interpretation that helps generate more value from the seismic data in order to establish a good sequence stratigraphic framework.

The Wheeler Diagram and Its Impact on Seismic Interpretation

The Wheeler diagram, developed in 1958 by Harry E. Wheeler, has been used by geologists for a number of decades as a means of understanding the relation of units of rock in 2D space and time (Wheeler, 1958). It generates a time-space relationship which visualizes the geological changes occurring at a particular locality as a function of time. In this way, Wheeler diagrams can help predict reservoir age, systems tracts, and areas of prospectivity.

It was in the 1970s that the Wheeler diagram became closely linked to seismic and became one of the key seismic interpretation methodologies for petroleum geologists, when seismic interpreters from Exxon developed the concept of seismic sequence stratigraphy (Payton, 1977). The aim of seismic sequence stratigraphy is to describe and sub-divide stratigraphic units into sedimentary packages by studying seismic reflection patterns in structural domains (Mitchum et al., 1977).

Today, a significant number of seismic sequence stratigraphers routinely make Wheeler diagrams from manually picked seismic reflection patterns. Although a cumbersome and time-consuming process, it is argued that only in the transformed domain is the relationship between space and time and between the deposits fully revealed.

Furthermore, the arrival of new computing techniques have taken this process a step further with it now feasible to apply Wheeler transforms – the equivalent of the Wheeler diagram – onto seismic data sets (De Bruin et al., 2007). The result is that today all seismic interpreters can access and benefit from the advantages of Wheeler diagrams within their seismic interpretation activities.

Wheeler transforms, for example, are today a key element of dGB's own sequence stratigraphic interpretation

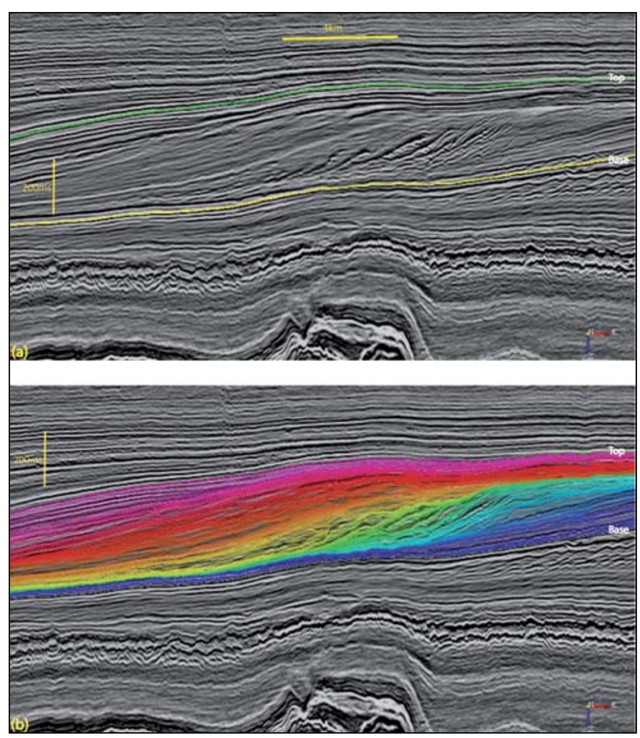

Figure 1 *A vertical seismic section from the Dutch sector (North Sea). The upper section (a) shows the Pliocene interval bounded by top and base horizons. The bottom section shows the 3D HorizonCube (coloured lines) that is used to build the sequence stratigraphic framework and Wheeler diagrams of the Pliocene interval.*

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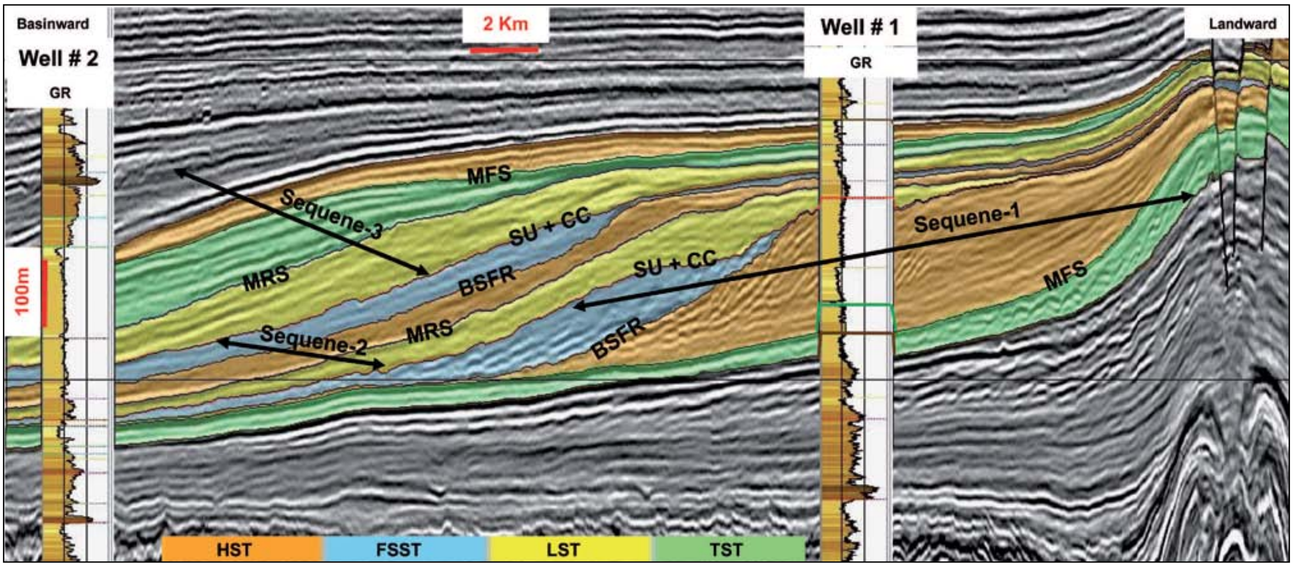

***Figure 2** HorizonCube based systems tracts sud-division of the Pliocene interval (Dutch Sector, North Sea).Well # 1 is projected (3.4Km) at the section. The bold horizontal lines on the Well # 1 track are the correlations between seismic and Well # 1 location.Well # 2 is located at the section.*

system (SSIS) which aims to increase geologist insight into the depositional history of sedimentary packages, improve seismic facies and lithofacies predictions, and provide accurate targeting of reservoir, source rock, and seal potential. Through SSIS, seismic interpreters should be able to flatten 2D and 3D seismic data through moving data from the structural seismic domain to the Wheeler domain, thereby increasing their understanding of the spatial distribution and timing of sediment deposition.

Furthermore, seismic interpretation using Wheeler transforms today apply both to 2D and 3D surveys. With no equivalent 3D Wheeler diagram, there is every chance that we may learn even more about sequence stratigraphy.

The rest of this article will look at some examples as to how, 54 years on, the work of Wheeler (1958) remains at the forefront of seismic interpretation, helping to illuminate the subsurface and generate detailed seismic knowledge of subtle petroleum reservoirs.

HorizonCube based Wheeler transforms

As previously mentioned, the Wheeler transform is the seismic equivalent of the Wheeler diagram. In a Wheeler diagram, rock units are plotted in a 2D chart of geologic time (y-axis) versus space (x-axis), with the diagram showing the temporal-spatial relationship between rock units. On the other hand, in a Wheeler transform, the seismic interpreter flattens the seismic data (or derived attributes) along flattened chronostratigraphic horizons. The vertical axis in the Wheeler transformed domain is relative geologic time as opposed to absolute geologic time.

3D automated Wheeler transforms are part of dGB's HorizonCube interpretation solution (De Groot et al., 2010). HorizonCube is a dense set of auto-tracked correlated 3D stratigraphic surfaces, created by an auto-tracker, with each horizon in the HorizonCube representing a (relative) geologic time line. It is this dense set of horizons which enable Wheeler transformations and systems tracts interpretation to operate at their full potential.

The HorizonCube method of integrated seismic volumes, well data and the dense set of auto-tracked seismic events can be simultaneously analyzed in the relative geologic time (Wheeler) domain and in the structural domain. HorizonCube derived attributes (e.g., systems tracts thickness volume in this text) can then be extracted to help analyze relative changes in sedimentation rate, base level variations, depositional trends, and geomorphologic patterns. Furthermore, by displaying flattened seismic data through Wheeler transforms, seismic interpreters will see all kinds of stratigraphic detail to help increase their understanding of the depositional environment.

North Sea example

Introduction

The first case study of automated Wheeler transformation is carried out in a Pliocene interval (Dutch Sector, North Sea) of fluvio-deltaic 3rd order sequences (Figure 1a). The sequences show clinoform geometries that are prograding basinward. The sequences are developed due to the enlargement of a large scale fluvio-deltaic drainage system (Eridanos delta) that has dominated the northwestern Europe during the late Cenozoic Period (Overeem et al., 2001).The drainage system started during the Oligocene period (Rohrman et al., 1995) while the Scandinavian shield was being uplifted. The uplift rate increased during the late Miocene (Sales, 1992) and again in early Pliocene (Ghazi, 1992; Jordt et al., 1995). As a result of late uplift, high sediment influx filled the northern offshore regions of the Dutch sector (see Figure 1 in Overeem et al.,2001). The increasing sediment load has resulted in a differential load throughout the region. Consequently, the buried Permian Zechstein salt (Qayyum, 2008) started moving in the region and several localized unconformities were formed within the Pliocene interval that are underlain by salt domes (Figure 1a). Several of these unconformities are identified in this case study after HorizonCube preparation and subsequent Wheeler transformation.

The automated HorizonCube (Figure 1b) is used to transform the 3D seismic data into the Wheeler domain. The interpretations are done after simultaneous inspection of stacking patterns in the structural domain and the Wheeler (chronostratigraphic) transformed domain and by calibrating against available well information (De Bruin et al., 2006). After that, the Depositional Model IV (Hunt and Tucker, 1992; Catuneanu, 2002) is selected to sub-divide the interval into systems tracts and label corresponding sequence stratigraphic surfaces. Furthermore, the relative base level curve is automatically generated from the interpreted systems tracts.

Interpretation

Three 3rd order sequences are identified in the studied interval. Figure 2 illustrates the corresponding sequence stratigraphic interpretation. The coloured packages represent systems tracts. The comparisons between the structural domain (Figure 2) and Wheeler transformed domain (Figure 3) are now there for all to see. Figure 3 shows an automated Wheeler diagram highlighting the sequence stratigraphic framework constructed by integrating seismic and well data.

To provide yet another insight into the Wheeler domain (Figure 3), temporal thickness volume is computed as a HorizonCube attribute. It is an isochron between two HorizonCube events that are interpreted as sequence stratigraphic surfaces separating one systems tract from another. Such an attribute is a measure of (preserved) depositional thickness and can also be used as an indicator of relative sedimentation rate per systems tract. Note that the absolute sedimentation rate requires calibration of the HorizonCube to an absolute geologic time using biostratigraphic information. This thickness attribute is being displayed in the Wheeler domain (Figure 3) as an add-on to sequence stratigraphic interpretation (Figure 2) to consider sedimentation rate while interpreting a sequence.

The lower sequence # 1 marks an initial deltaic phase with a high sedimentation rate during the late normal regression (Highstand systems tract - HST). The uplift in the landward direction caused a large scale landward erosion and subsequent fall in base level at the shoreface. This phase has developed a distinct forced regressive wedge that is interpreted as a falling stage systems tract (FSST). As a consequence, a highly diachronous composite surface is developed that correlates up-dip to a sub-aerial unconformity (SU) and downdip with a relative conformable correlative (correlative conformity - CC) surface capping the forced regressive deposits. The composite surface is interpreted as the first sequence boundary (SB)

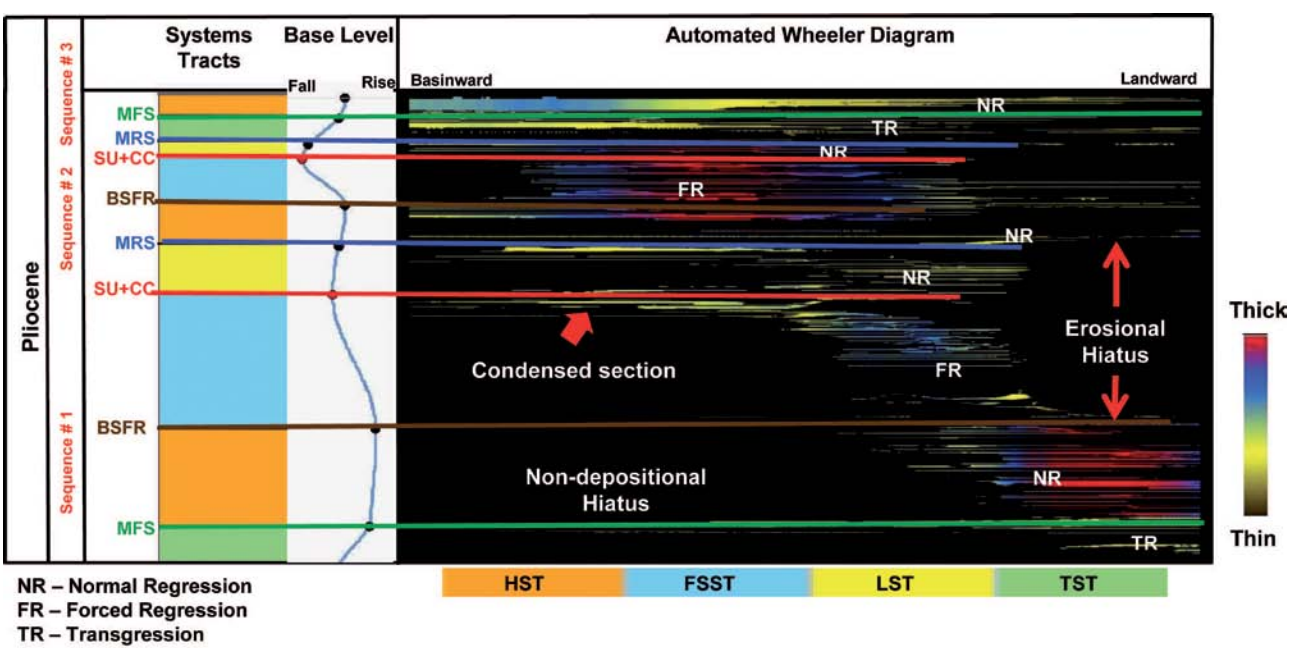

***Figure 3** An automated Wheeler transformed display (right) with interpreted systems tracts sub-division (left) and the automated base level curve (middle). The colours in the Wheeler display represent the thickness per systems tracts in TWT (seconds) units.*

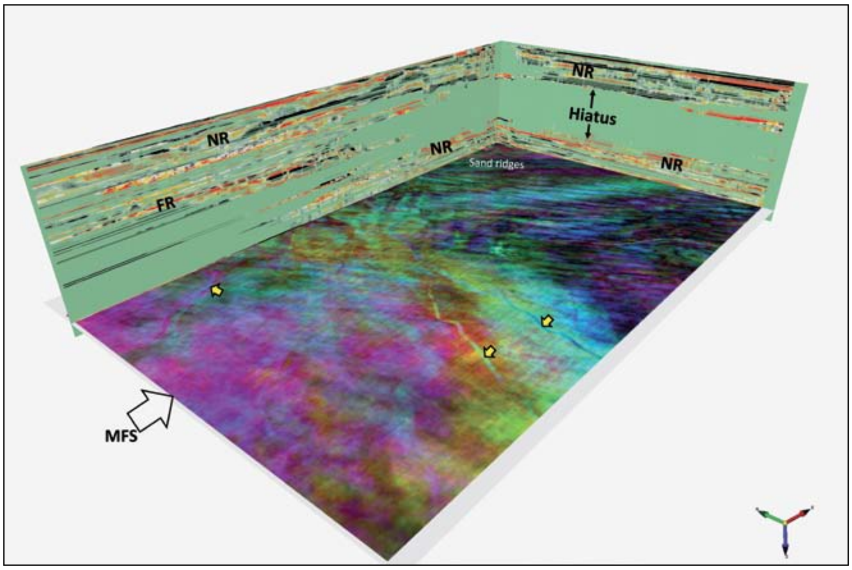

***Figure 4** A 3D perspective of Wheeler diagram for the Pliocene interval (Figure 3) of the southern North Sea (Dutch sector). The 3D Wheeler domain shows a nice time-space relationship that is better than a 2D Wheeler diagram. The bottom slice is a colour-blended spectral decomposition attribute slice for a particular HorizonCube event (MFS – maximum flooding surface). Yellow arrow marks subtle deep marine channels. (NR – Normal regression, FR – Forced regression).*

separating the lower sequence # 1 from the upper sequence # 2. Deposition of sequence # 2 started while the base level was slowly rising with a relatively slow sedimentation rate compared to sequence # 1. During the initial stage, normal regressive deposits filled the available accommodation space. The normal regressive deposits developed during this stage are further subdivided into two systems tracts: lowstand systems tract (LST) and highstand systems tract (HST). These systems tracts are separated by a distinct maximum regressive surface (MRS). During the deposition of sequence # 2, the Permian salt was still moving slowly which caused further uplift at the proximal vicinities. Differential sediment load and subsequent salt movement caused the base level to fall at the shoreface where another FSST was deposited. The top of the FSST systems tract is interpreted as the second SB marking the end of sequence # 2. The sequence # 3 is interpreted as a wave-tide dominated deltaic phase. The initial stage of this sequence is a basinward restricted unit (LST). Above this, a transgressive unit dominates that is developed during a rapid rise in base level. Therapid transgression caused large scale wave (and tidal) erosion at the shoreface. Parts of the LST deposits were reworked at the shelf-slope settings. This stage is called the healing-phase of the sequence and the corresponding unit is interpreted as a transgressive systems tract (TST). The end of

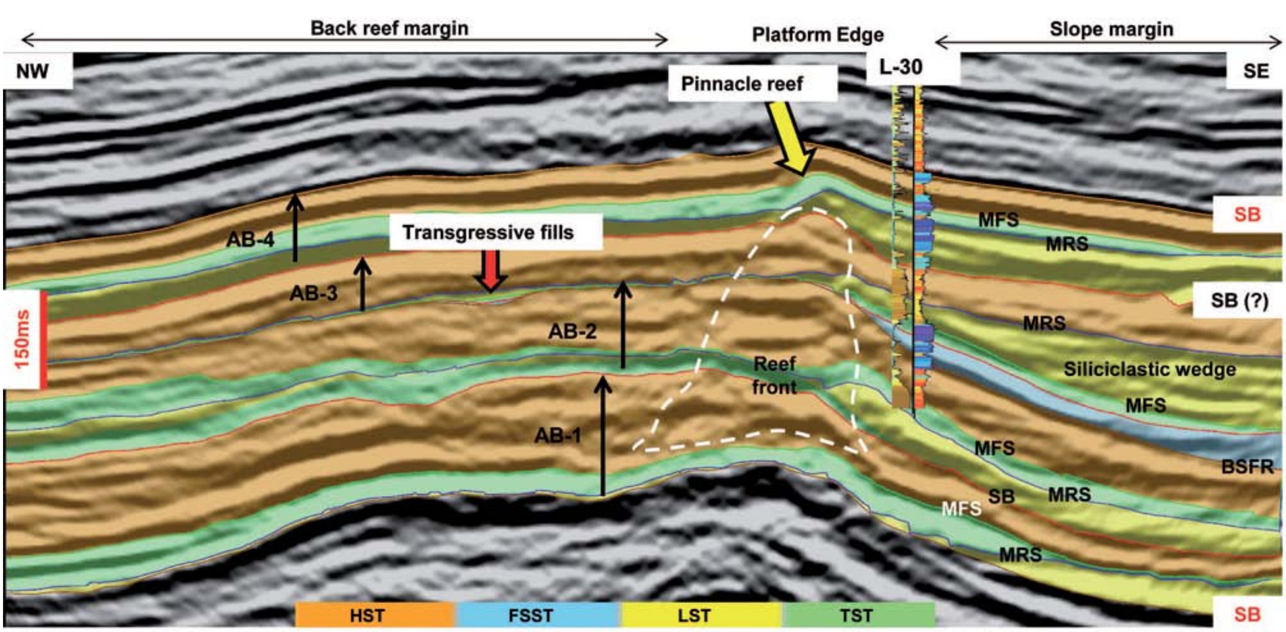

***Figure 5** A structural view of a dip oriented seismic section. The interpretation is done in the mid to late Jurassic intervals of Abenaki carbonate Bank (Nova Scotia, Sable Island, Canada). The colour- coded semi-transparent overlay represents interpreted systems tracts.*

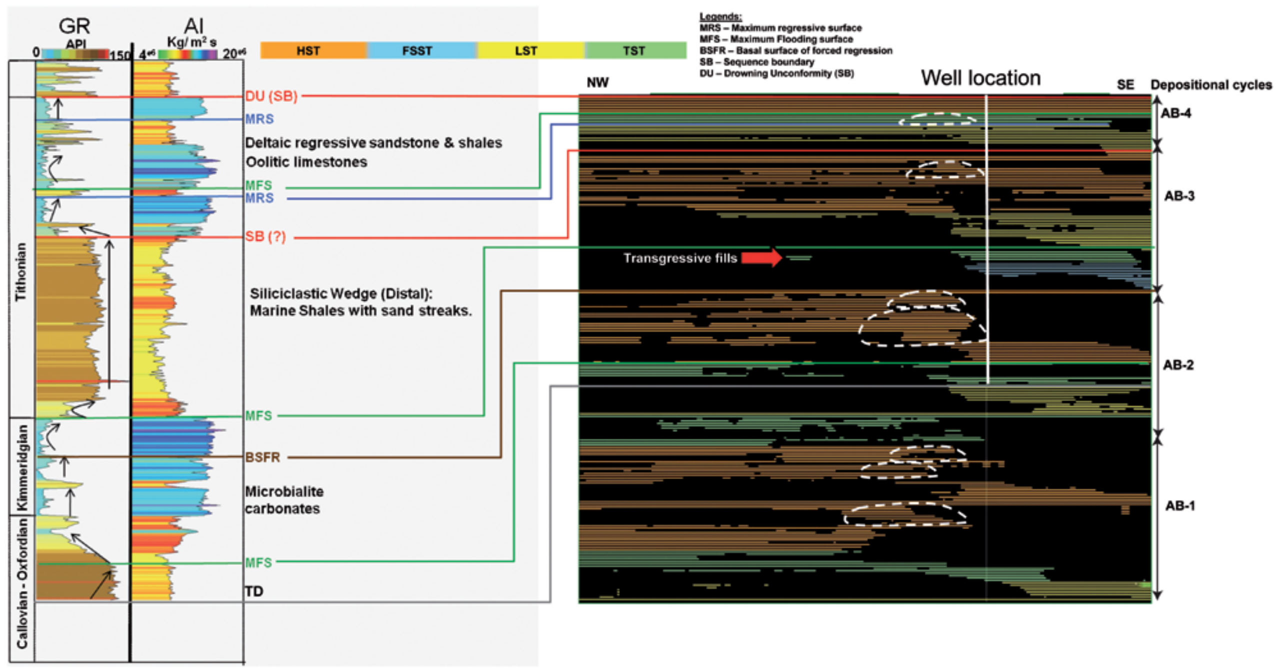

Figure 6 *Wheeler transformed seismic section (Figure 5) and the interpreted systems tracts. The well display presented on the left hand is located at a white line location on the Wheeler domain. The dashed white lines on the wheeler display mark the reefs front location (Figure 5).*

this phase is defined by a maximum flooding surface (MFS). Above this surface, normal regressive deposits are observed with a relatively low sedimentation rate. This final package is interpreted as HST.

The three-dimensional Wheeler transform is a possible game-changer for systems tracts interpretation, which is essentially based on 2D observations. Using a 2D Wheeler diagram a particular interval can either be interpreted as regressive - or transgressive systems tract. In three dimensions, due to local variations in sediment supply, wave energy and tectonics, we have to consider contemporaneous development of regressive and transgressive system tracts. This is beyond current interpretation standards. Figure 4 is a three dimensional view of the Pliocene interval. In this view, one may easily pinpoint the erosional vs. non-depositional gaps in the 3D Wheeler domain. The depositional trends, shoreline shifts, and accommodation history of the interval are also evident.

Scotian Shelf (Canada) Example

Introduction

The Scotian shelf (eastern Canada) contains a large scale carbonate bank that was developed during the Jurassic period while the northern Atlantic Ocean was spreading (Jansa, 1981; Eliuk, 1978; Weissenberger et al., 2006). The interval is well investigated in the Deep Panuke field (Weissenberger et al., 2006). However, there is an opportunity to study the development of a carbonate bank that was formed while the Sable delta (Eliuk, 2010) was prograding to the basin. The basin contains enough hydrocarbon potentials that are equivalent to Morocco offshore discoveries (Luheshi et al., 2012). They also proposed the rifting model that explains the end of Triassic tectonic settings (see Figure 12 in Luheshi et al., 2012).

In the Nova Scotia regions, the Jurassic carbonate sequences started developing over the Triassic continental margin (Jansa, 1981) while the shallow marine environment was established. The carbonates in most of the Scotian shelf are shallow water on ramps and deep water in the shelf-slope margins (Eliuk, 1978; Weissenberger, 2006) with basinal siliciclastic deposit. In this case study, the automated Wheeler transformed seismic section at a well location is used to interpret the carbonate development during the mid to late Jurassic periods. The interpretations are done by calibrating seismic observations with available wireline logs, cuttings and core data information. Moreover, the Wheeler domain is also used to do stratal (proportional) slicing of a model based HorizonCube between the interpreted major stratigraphic surfaces. The study reveals more information from the seismic data and thus helps to better understand the carbonate bank growth in the area.

The approaches of interpreting HorizonCube and Wheeler diagrams are the same as explained in the previous example.

Interpretation

The mid-late Jurassic Abenaki (AB) sequence at Sable Island (Nova Scotia, Canada) is an example of a mixed siliciclastic-carbonate depositional system (Figure 5). The lower sequence is dominated by carbonate build-ups on the initial ramp setting (Kidston et al., 2005). The upper sequence

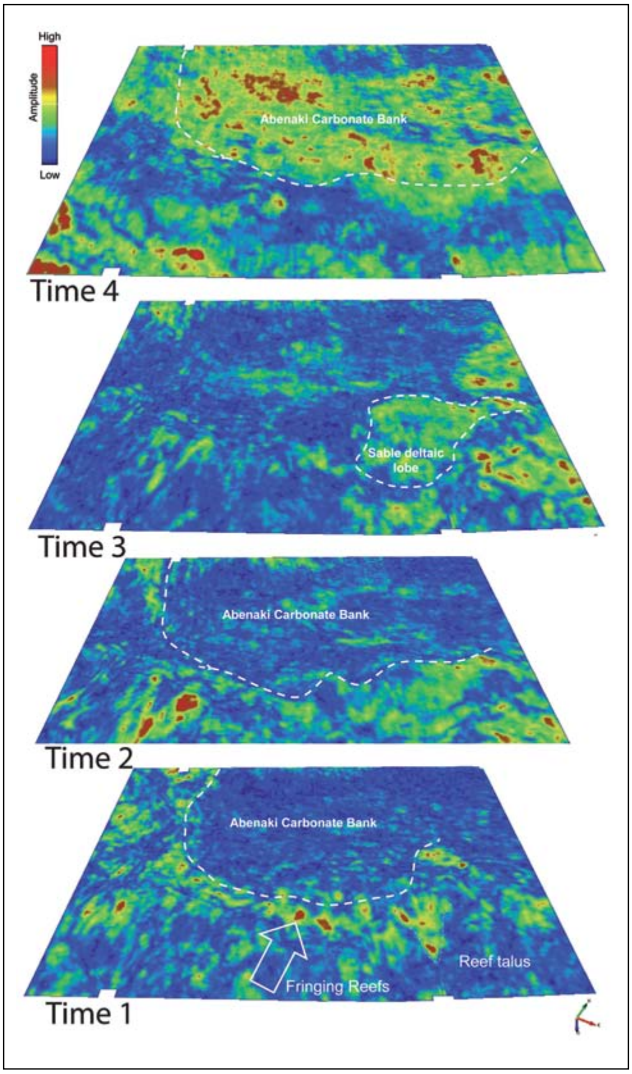

***Figure 7** Perspective views of HorizonCube events in Wheeler domain. The colours represent volumetric seismic amplitude. The slices represent the Abenaki carbonate bank development over time.*

contains contemporaneous shoaling upward carbonate and siliciclastic deltaic deposits (Figure 6).

Four depositional cycles (AB-1 to AB-4) are interpreted in the Abenaki sequence.The seismic section in the structural domain is overlain by interpreted systems tracts and associated sequence stratigraphic surfaces. The well (L-30) has been drilled at the platform edge-slope environment. Note that not all systems tracts are fully observed at the presented seismic level. The back reef margin mainly contains patchy reefs with NW prograding patterns interpreted as highstand systems tracts (HSTs). The dashed outline of reef front (at the platform edge) has also been interpreted on the Wheeler domain to understand the relative preservation and development of the reefs over a geologic time. The slope margin is being filled with Sable deltaic sedimentations which have formed several lowstand systems tracts (LSTs).

The AB-1 cycle of Callovian stage – the late stage of mid Jurassic period – is a time transgressive unit (Figure 5 and 6) that marks the onset of a base level rise during the opening of Atlantic margin. The unit contains lowstand systems tract (LST) in the slope-basin margin that is later overlain by a thin back-stepping transgressive systems tract (TST).

The end of this cycle is an aggrading to NW-prograding highstand systems tract (HST). The AB-2 cycle of the Oxfordian stage – the earliest age of the late Jurassic period – is interpreted as a catch-up to keep-up cycle. The base of this cycle is a LST deposited in the slope margin environment. The cycle is further divided into TST and HST systems tracts marking the further rise in base level during that time.

At the end of the AB-2 cycle, the base level started falling and the platform was partially exposed in the northern direction. This fall in base level has developed a thin falling stage systems tract (FSST) in the basinward direction (SE).

Following this stage, the base level started rising and the further siliciclastic sedimentation filled the slope margin and developed a shallow marine environment at the back reef margin. This marine transgression has filled the karstified/channelized shape features with transgressive fills.

Due to the shallow marine environment at the platform, carbonate production resumed again and a thick aggrading to prograding HST was developed. This cycle is marked as AB-3 sequence of the early Tithonian stage. The late Tithonian stage of Abenaki sequence is marked as sand shoals cycle AB-4 with prograding siliciclastic delta. The Wheeler domain shows basal prograding LST overlain by thin transgressive and aggrading units. Carbonate production, however, was forced to cease during and at the end of the Tithonian stage, caused by deltaic progradation and marked by a drowning unconformity (DU) at the top of the platform.

To further understand the 3D picture of the Abenaki carbonate bank, HorizonCube events are sliced in a Wheeler domain using the proportional slicing method (Zeng et al., 1998). Volumetric seismic amplitude shows several bright amplitudes with circular morphologies that are reefs. During the AB-I cycle the reefs mainly developed at the edge of the bank. With time the reefs often prograded basinward and the Sable delta started prograding to the bank (Time 3 in Figure 7). The later stage (Time 4) of the bank shows a shallow water environment in the back reef margins with dominant patchy reefs development.

This infers the benefit of working in the Wheeler domain in the case of mixed siliciclastic-carbonate settings. The HorizonCube method has not only helped to subdivide the Abenaki sequence into various 2nd order cycles but it is also used to establish a 3D depositional model of contemporaneous sedimentation of siliciclastic Sable delta and carbonate growth. The examples presented in this case study will help to predict and characterize the carbonate as well as siliciclastic reservoirs present in the area.

Conclusions

To build an accurate subsurface sequence stratigraphic framework, an interpreter ideally needs to correlate all seismic events with available well data and to map events simultaneously in the relative geologic time domain and in the structural domain. What this article has demonstrated is the crucial role the Wheeler diagram and Wheeler transforms are now playing in building detailed sequence stratigraphic frameworks and interpreting seismic data today.

Wheeler transforms and the HorizonCube workflow, which integrates seismic data and well data, allow this to be achieved.

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