Unravelling a carbonate system: technical advances in seismic sequence stratigraphy

Geert de Bruin,[1]* Kirstin McBeath,[2] and Nanne Hemstra[1] show how recently introduced software could be the key to greater use of seismic sequence stratigraphy

Introduction

In essence, sequence stratigraphy is used to provide a chronostratigraphic framework for correlation and mapping and for stratigraphic prediction (Emery and Myers, 1996). Although, sequence stratigraphy has proven to be a powerful instrument, and despite major advances in concepts since its introduction in the 1970s, sequence stratigraphy has not lived up to its potential because of the lack of supporting software tools. Recently a new software system, OpendTect SSIS, came to the market with the aim of filling this gap.

Concept

The basic concept of OpendTect SSIS is that all stratigraphic events (horizons) are auto detected by the system and placed into stratigraphic order (Ligtenberg et al., 2006; de Bruin et al., 2006; and de Groot et al., 2006a, 2006b). These chronostratigraphic surfaces are generated at sub-seismic resolution and tracked throughout the seismic volume within the limits of conventionally mapped bounding surfaces. They are assigned relative geological time indices, or 'geotimes'. Numerous horizons are thus placed in stratigraphic order, which has a number of distinct advantages:

- It enables visualization of the depositional history of inlines and crosslines by displaying the chronostratigraphic events (hereinafter chronostratigraphy) as intersecting coloured lines, or as continuous colour overlays.
- It enables true horizon slicing through 3D seismic volumes, without distortion by structural interference (as is the case with time-slicing and horizon-slicing in a non-parallel layered earth).
- It enables automated construction of chronostratigraphic diagrams a.k.a. Wheeler diagrams. Previously, Wheeler diagrams were constructed by hand, making them time-consuming, which is why this operation was often skipped in a production environment. This is unfortunate because the Wheeler diagram or Wheeler transform, as its seismic counterpart is called, is a very valuable tool for gaining insight and for extracting additional information. For example, non-depositional or erosional hiatuses are visible, the lateral extend of stratigraphic units can be determined at a glance, and a clear understanding of the lateral shift in deposition over time can be established. The Wheeler transform is constructed by simply flattening each chronostratigraphic event, thus enabling the user to study seismic data and its derivatives (attributes or neural network outputs) in the Wheeler domain in three dimensions.
- It enables a systems tract interpretation to be performed. Such interpretations can be displayed as overlays on the seismic data in both the depositional (structural) and the Wheeler transformed (chronostratigraphic) domain.
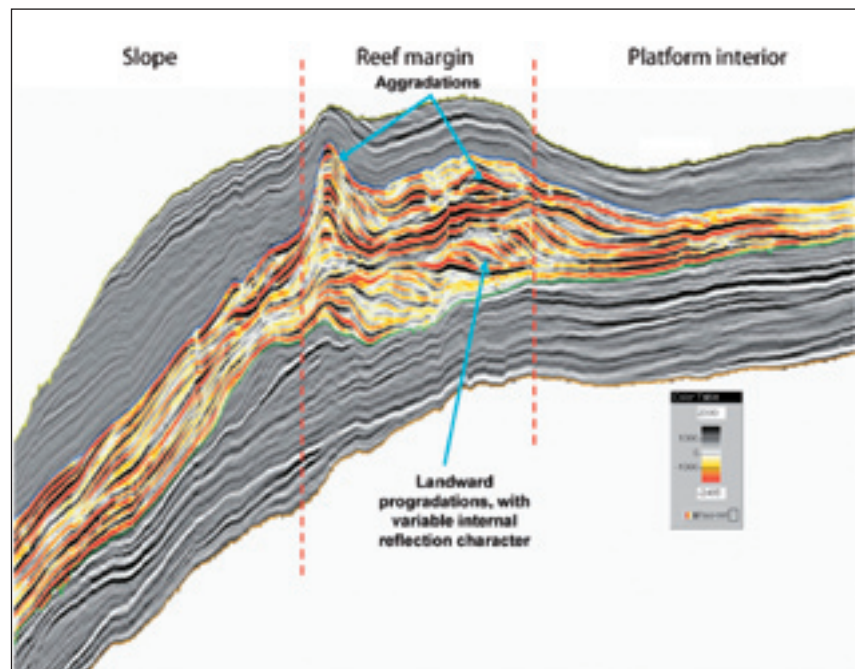- The combination of the chronostratigraphy, Wheeler transform,

Figure 1 *Seismic dataset with facies belts.*

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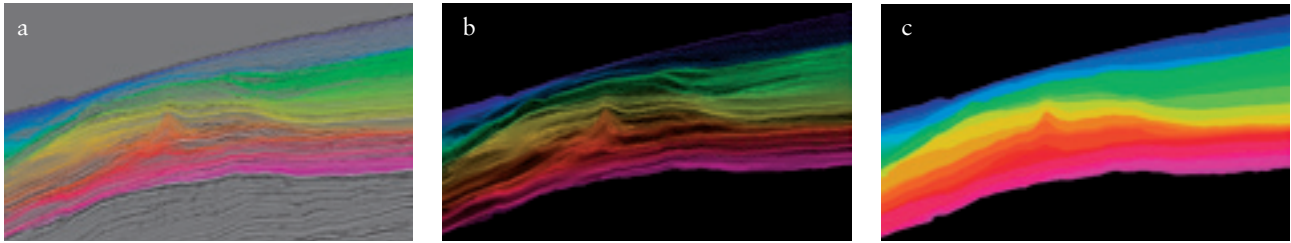
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Figure 2 *Various displays of the chronostratigraphy on inlines/crosslines*

and systems tracts interpretation increases the insight in the depositional history, and improves seismic facies and lithofacies predictions, thus helps in identifying potential stratigraphic traps.

Study objectives

All previous publications incorporating this technology involved clastic systems. This is the first paper that describes the application on a green field carbonate exploration play. The aim of the study was to assess and understand the spatial and temporal significance of potential reservoir facies within a complex carbonate system in both the depositional and Wheeler transformed 'flattened seismic' domain. Systems tracts interpretation allowed for the prediction of potential reservoir facies distribution prior to drilling a deepwater well offshore West Africa. The analysis was performed on a three dimensional pre-stack time migrated seismic volume of good quality. At the time of the study, no well was drilled inside the seismic survey area.

Dataset

A seismic cross-section through our dataset (Figure 1) reveals a large aggrading/prograding carbonate complex, showing an overall transgressive trend. It features distinct landward progra-

dation, highlighting the backstepping nature of the system. It is interpreted as an early Palaeocene aggrading/prograding carbonate platform (Williams, 2002) based on information from the closest available well. The carbonate platform is characteristic of the T-factory (e.g. tropical carbonate platforms - Schlager, 2005). Three main facies belts can be identified, i.e. slope, reef margin, and platform interior. Within the slope facies belt, the lobe-like geometries are interpreted as slumps (or gravity placed sediments) of redeposited reef margin sediments due to reef margin collapse. Such carbonate deposits are a result of over-steepened platform margins. The build-up geometries of the reef margin facies belt represent the development of elevated, wave-resistant structures either by organic frame-building or by cementation of sands on the sea floor, or during brief exposures (Schlager, 2005). The reef margin evolves to a rimmed platform that protects a subdued, low-energy, potentially lagoonal environment of the platform interior. These 'defended' platform margins are probably the most important features in the sequence anatomy of tropical carbonate accumulations (Schlager, 1999 and 2005).

Draping over the entire carbonate structure are late Eocene predominantly outer shelf clastics (siltstones, shales).

Deposition was probably rapid, marking the demise and drowning of the carbonate platform. The convex reflectors over the aggradational geometries of the carbonate interval suggest the topography was preserved during the deposition of this late Eocene interval, showing subsequent differential compaction resulting in compressed seismic reflection events and thinning over the topographic highs.

Results

Chronostratigraphy

The first step in the analysis is the calculation of the chronostratigraphy. Basically, the chronostratigraphy is a set of horizons that are auto-tracked simultaneously, placed in stratigraphic order, and assigned a relative geological time. The chronostratigraphy can be displayed as an overlay on inlines and crosslines, but also the individual horizons can be displayed. Each line depicted in Figure 2a & b is a chronostratigraphic event. The colour indicates the relative geological age, with purple colours representing the oldest deposits and the blue the youngest. In Figure 2c, a constant fill is performed in between the chronostratigraphic events.

Furthermore, the individual chronostratigraphic events can be viewed and used as horizons (Figure 3a), e.g., for attribute analyses (Figure 3b) or neural network waveform segmentation.

Wheeler transform

The Wheeler transform is constructed by flattening each chronostratigraphic event. There are several distinct differences between a (geological) Wheeler diagram and a (seismic) Wheeler transform:
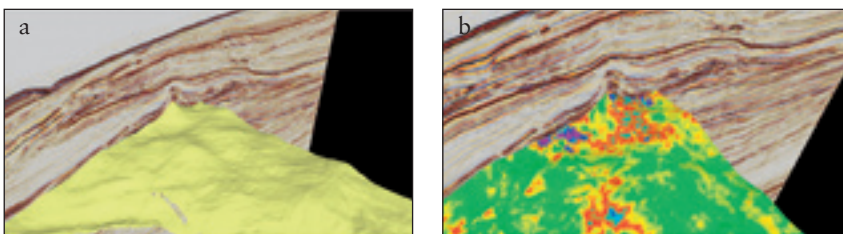

Figure 3 *Individual chronostratigraphic horizon. b) Attribute analysis on chronostratigraphic horizon.*

- The Wheeler transform is constructed automatically while the Wheeler diagram is typically constructed manually.
- The Wheeler transform is three dimensional or, when applied to a single line, two dimensional while the Wheeler diagram is always two dimensional.
- Chronostratigraphy, seismic data, and its derivatives (attributes, neural network outputs) can all be Wheeler transformed while the Wheeler diagram only displays chronostratigraphy itself.
- In the current version of the software one other difference is that the vertical axis of the Wheeler transformed data is *relative* geological time while the vertical axis of the Wheeler diagram represents *absolute* geologic time.

Data is best studied simultaneously in the Wheeler and normal or depositional domain. In the depositional domain structural features are visible, but other features stay hidden. Several of these features are exposed in the Wheeler domain, but this domain lacks the structural aspect. One of the most apparent features in the Wheeler transform is that hiatuses are visible. Both non-depositional events and erosional truncations can be distinguished (Figure 4c). Stratigraphic thinning or condensed sections can also be identified in the Wheeler transform. During deposition of condensed sections sedimentation rates are very low causing stratigraphic events to merge below seismic resolution such that they cannot be auto-tracked. So, although stratigraphic thinning or condensed sections might not be true hiatuses, they do show up in the Wheeler transform (and the original Wheeler diagram) as such (Figure 4c).

Furthermore, the lateral extent of stratigraphic units or individual chronostratigraphic events can be determined with ease in the Wheeler transform. This can be a daunting task in the depositional domain, especially when no chronostratigraphy (Figure 2) is available. The Wheeler domain is thus ideal

for studying the development of deposition over time, i.e. how does deposition shift (laterally) over time? andwhat is the lateral and temporal distribution of a certain packages?

Systems tracts
Within the sequence stratigraphic community several different sequence models are currently used, each with its own set of terminologies for systems tracts and stratigraphic surfaces and with its own position of the sequence boundary (Catuneanu, 2002). The software is not bound to any one of these models, since systems tracts terminology and the position of a sequence boundary are user-defined variables.

A systems tracts interpretation is made based on user-defined geo-time intervals. A systems tract is thus bounded by two chronostratigraphic events selected by the user. All intermediate chronostratigraphic events are assigned a particular systems tract. Similar to the chronostratigraphy, an overlay can

be made on inlines and crosslines (Figure 4b, d, & f).

This flexibility also allows sequences to be subdivided into depositional packages, giving an individual colour and name to each package, when systems tracts interpretation is impossible or difficult.

In this study we subdivide a full sequence into four systems tracts: Falling stage systems tract (FSST), Lowstand systems tract (LST), Transgressive systems tract (TST), and Highstand systems tracts (HST). The interpretation is based on the following basic principles:

- A transgression is a landward shift of facies and shoreline, while a regression is a seaward shift of facies and shoreline. (Catuneanu 2002).
- A transgression or transgressive systems tract is characterized by a retrogradation and aggradation. This occurs when base-level is rising and more accommodation space is created than is consumed by sedimentation.
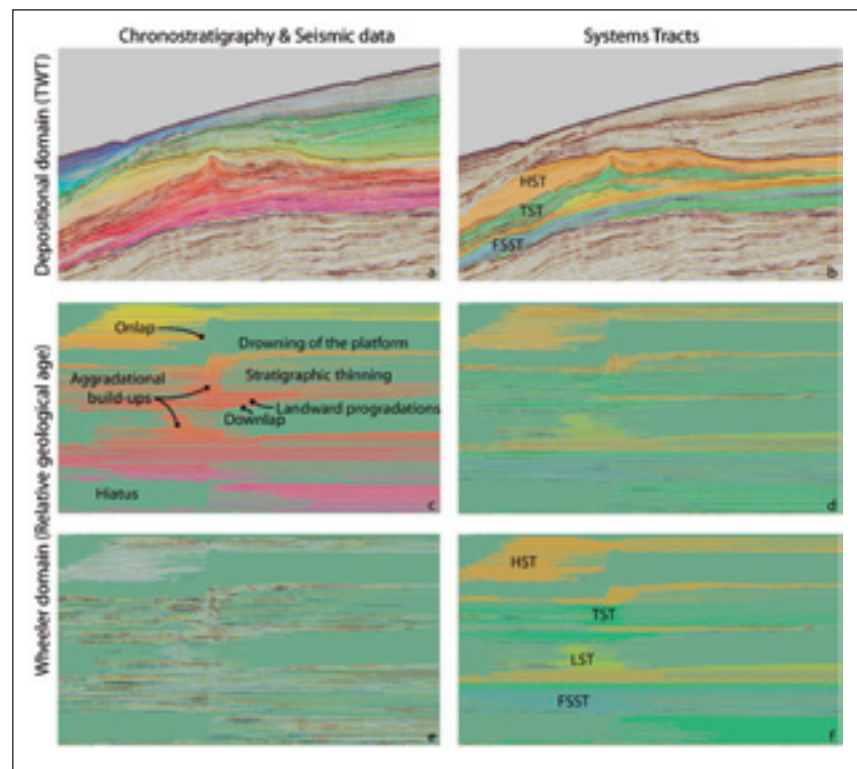

Figure 4 *Depositional domain a) Chronostratigraphy, b) Systems tracts interpretation. Wheeler transforms, c) Chronostratigraphy, d) Semi transparent systems tracts display overlain the seismic data, e) Seismic data in, and f) Systems tracts interpretation.*

- Regressions can be subdivided into normal and forced regression:
  a. During forced regression base level is dropping, forcing the system to prograde. Forced regression is characterized by progradation and incision (erosion).
  b. During normal regression base level is rising but the consumption of accommodation space by sedimentation exceeds the creation of accommodation space by the base level rise. Normal regression occurs during the first and last stages of base level rise and is characterized by progradation

and aggradation. The lowstand systems tracts and highstand systems tracts are both normal regression deposits.

Figure 5 depicts a cartoon of the depositional history, each picture showing a particular systems tract. The deposits in the first image of the cartoon (Time step 1) show a clear retrograding stacking pattern and are therefore interpreted as transgressive systems tracts that are deposited during Campanian (upper Cretaceous). The sediments depicted in the second image (Time step 2) show pure progradation, indicating a dropping base-level, hence they are interpreted as falling stage systems tracts.

The transgressive and highstand systems tracts (Time steps 3 and 4) are deposited during Maastrichtian, when base level was rising. A distinct change in deposition pattern is visible after Time step 4. Sedimentation is more localized and shows a mounded structure (from Time step 4 to 5). This first mounded structure is characterized by aggradation and progradation, therefore they are interpreted as normal regressive deposits (LST). On top of these initial mounded deposits, the first landward progradations occur (Time step 6). The landward progradations indicate a landward shift of facies, characteristic of a transgression (TST), and are a sign that the carbonate platform has difficulties keeping up with the base level rise.

Next, the carbonate platform is purely aggrading (Time step 6), keeping pace with the sea level rise. This indicates that the consumption of accommodation space by sedimentation is almost equal to the creation of accommodation space by base level rise. Next a second phase of landward progradation occurs (Time step 8). Backstepping occurs when carbonate platforms are faced with a base level rise that slightly exceeds their growth potential (Schlager 2005). There are several reasons why backstepping may be advantageous for the carbonate platform: the energy of waves is less; carbonates reach higher ground when differential subsidence (increase of subsidence basinward) occurs; and backstepping shifts sedimentation to areas with lower subsidence rates (Schlager 2005). Since a very distinct mounded aggradation occurs at the same time as the landward progradation, differential subsidence and wave energy seem to be less likely. During the Thanetian (Time step 9) the mounded structures continue to aggrade (HST) and, as the slopes steepen, slope failure occurs. Landward, two smaller aggradational mound structures colonized the flat top of the underlying section.

In early Eocene times (Ypresian) a rapid rise in sea level (represented by Time step 10) drowned the entire
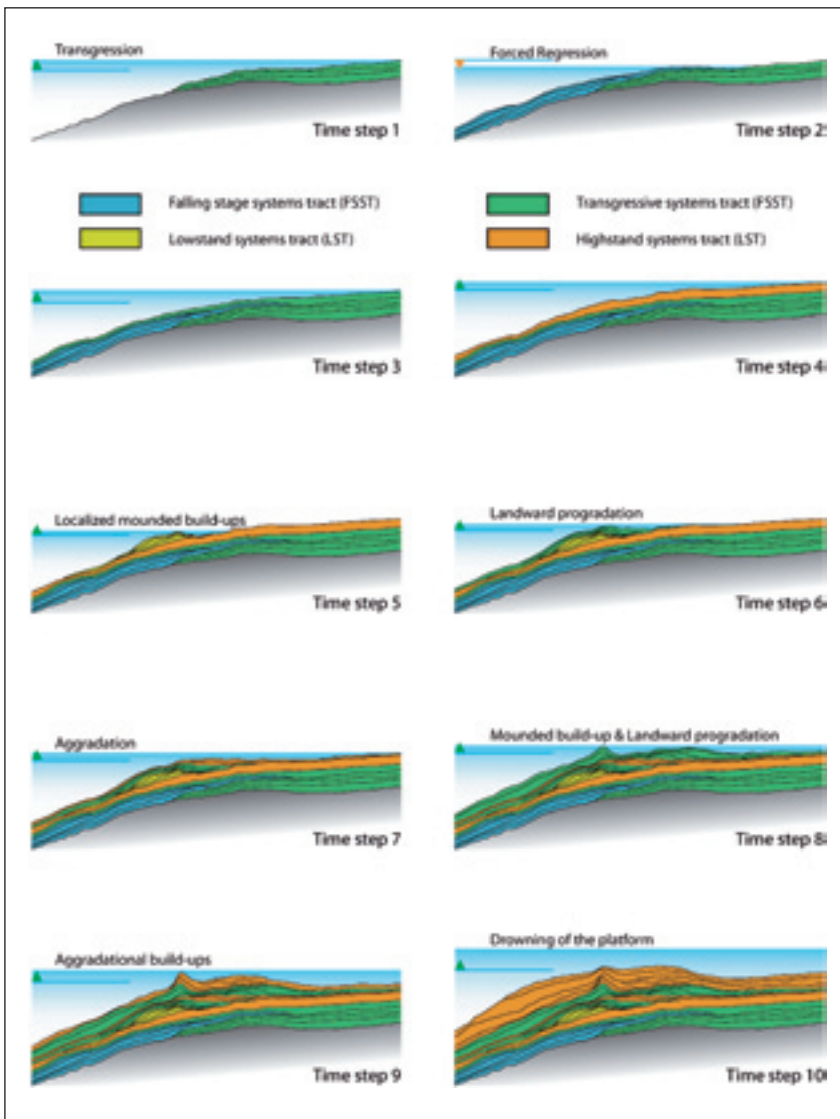

Figure 5 *Cartoon of depositional history.*

carbonate structure. This represents the demise of the carbonate platform, resulting in the entire structure being immersed within a deepwater environment. Tremblay (2005) proposed that the demise of the carbonate platform coincides with the Palaeocene-Eocene Thermal Maximum climatic event (PETM); a sudden global climatic change that represents one of the most rapid and extreme global warming events recorded in geologic history. The PETM is characterized by a massive injection of at least 1000 Gt of isotopically light carbon into the ocean or atmosphere (Dickens, 2000).

Discussion

The automated tracking of chronostratigraphic events clearly has many benefits: chronostratigraphic displays, Wheeler transforms, systems tracts interpretations, etc.. The usefulness of the method depends on the quality of the chronostratigraphic horizons (de Groot et al., 2006a). In the current system all seismic events are auto-tracked. Multiples, incoherent noise, migration artifacts, etc, should be removed prior to auto-tracking (de Groot et al., 2006a).

The quality of the data in this case study is in general very good, but also in this survey some major seismic disturbances are present that caused artifacts in the chronostratigraphy. There-fore, the chronostratigraphy was also calculated as two dimensional sections on a grid of inlines and crosslines. The quality of the two dimensional chronostratigraphy grid was considered superior to the three dimensional chronostratigraphy calculated and was therefore used for the systems tracts interpretation. These issues are currently addressed in the industry sponsored SSIS II project. Other planned improvements and extensions of SSIS include calibration of the chronostratigraphy to absolute geologic time, and manual sequence stratigraphic interpretation capabilities.

Acknowledgements

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