PS From 2D to 4D Wheeler Diagrams*

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Abstract

Wheeler diagrams provide a useful way to understand the temporal variations in a depositional system. Typically such diagrams are constructed by hand; the interpreter maps top and bottom of the strata on a cross-section and flattens the mapped events. This is laborious process in which information in X and Z (depth) is transformed to X and T (geologic time). In recent years automated Wheeler transforms were introduced in seismic interpretation. In such transforms 2D/3D seismic data is transformed into a 2D/3D Wheeler domains. Basically the Wheeler domain is a flattening of the seismic data along geologic time lines. In general seismic reflectors follow geologic time lines. A fully interpreted seismic volume, which can be achieved by auto-tracking hundreds of seismic horizons, is thus needed as input for the seismic Wheeler transform. In the construction of a conventional 2D Wheeler diagram, as well as in the automated 2D and 3D seismic Wheeler transform, valuable geologic information that is inherently present in the Z direction of the original data, is lost. We propose to put such information back in a 2D or 3D Wheeler diagram using a color overlay. The Z-value seems to be the obvious candidate for the 4th dimension in a Wheeler diagram. However, from an interpretation perspective we propose to use stratal thickness as a color-coded overlay. In the conventional Wheeler diagram stratal thickness can be computed directly from the mapped top and bottom interpretations. In the seismic Wheeler transform hundreds of geologic time lines exist, but there is no direct connection to top and bottom of the strata. Therefore, computing thickness requires an additional interpretation step in which the interval of interest is subdivided in stratal packages, or when possible, into systems tracts. We then compute the isochron thickness for these packages and display this attribute as the missing fourth dimension in the Wheeler diagram. As a result we can interpret how the accommodation space was filled over a relative geologic time period and we get a better insight into 3D depositional shifts. The benefits of this approach will be explained in a case study of the Pliocene interval of the southern North Sea.

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Summary

Wheeler diagrams provide a useful way to understand the temporal variations in a depositional system. Typically, such diagrams are constructed by hand; the interpreter maps top and bottom of the strata on a cross-section and flattens the mapped events. This is a laborious process in which information in X and Z (depth) is transformed to X and T (geologic time). In recent years, automated Wheeler transforms were introduced in seismic interpretation. In such transforms 2D/3D seismic data is transformed into a 2D/3D Wheeler domains. The Wheeler domain is a flattening of the seismic data along geologic time lines. In general, seismic reflectors follow geologic time lines. A fully interpreted seismic volume, which can be achieved by auto-tracking hundreds of seismic horizons, is thus needed as input for the seismic Wheeler transform. In the construction of a conventional 2D Wheeler diagram, as well as in the automated 2D and 3D seismic Wheeler transform, valuable geologic information that is inherently present in the Z direction of the original data, is lost. We propose to put such information back in a 2D or 3D Wheeler diagram using a colour overlay. The Z-value seems to be the obvious candidate for the fourth dimension in a Wheeler diagram. However, from an interpretation perspective we propose to use stratal thickness as a colour-coded overlay. In the conventional Wheeler diagram, stratal thickness can be computed directly from the mapped top and bottom interpretations. In the seismic Wheeler transform, hundreds of geologic time lines exist, but there is no direct connection to top and bottom of the strata. Therefore, computing thickness requires an additional interpretation step in which the interval of interest is sub-divided in stratal packages, or when possible, into systems tracts. We then compute the isochron thickness for these packages and display this attribute as the missing fourth dimension in the Wheeler diagram. As a result, we can interpret how the accommodation space was filled over a relative geologic time period and we get a better insight into 3D depositional shifts. The benefits of this approach will be explained in a case study of the Pliocene interval of the southern North Sea.

Introduction

The development of the concepts of stratigraphy and time dates back to the 1950's. To our knowledge Wheeler and Beesley (1948) were the first to critically review the classification of rocks into lithostratigraphic units and to start a discussion on the 4D nature of stratigraphic units. Wheeler (1958) successfully illustrated a time-space relationship in a 2D diagram that is now-a-days known as the Wheeler diagram. In a Wheeler diagram rock units are plotted in a 2D chart of geologic time (y-axis) versus space (x-axis). The diagrams caught further attention when the Exxon group (Payton, 1977) published seismically driven 2D Wheeler diagrams. Until the introduction of computer aided methods (Stark, 2003; Ligtenberg et al., 2006) seismic Wheeler diagrams could only be generated via a labour intensive manual process. Recent advances in computer technology enabled the extension of the Wheeler diagram from 2D to 3D (Qayyum et al., 2012).

Mapping rock units from the structural domain to the Wheeler domain transforms the vertical depth axis into a geologic time axis (Figure 1). In this transformation important geologic information pertaining to the depth dimension is lost. The method introduced in this paper puts the most relevant depth-related information back in the Wheeler scene by way of colour overlay. The approach enables interpretation in 4 dimensions: X, Y, Geologic Time and Z. Although Z (depth) can be used directly as colour overlay, it is more interesting to display thickness computed per interpreted package, e.g., per systems tract.

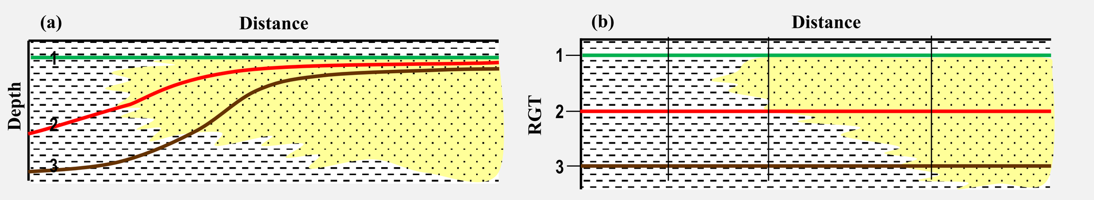


Figure 1 A 2D illustration of constructing Wheeler diagrams: (a) structural and (b) Wheeler diagram. Each horizon has its own assigned relative geologic time (RGT). Note that in the Wheeler diagram (b) – each horizon is flattened – the horizons are evenly spaced on the RGT scale. Thickness information is not present in the Wheeler diagram.. Only inferred facies trends are present in both domains.

Methodology

The method described in this paper utilizes 3D seismic data. The seismic data is densely mapped using the HorizonCube (de Groot et al., 2010). The mapping is done within the interval of interest. Once the HorizonCube is prepared, the data is automatically transformed into Wheeler domain (Ligtenberg et al., 2006). An example of automated 2D Wheeler diagram is presented in Figure 2. Note that this transformation is based on the law of superposition; i.e., older event is placed at the base and the younger on the top. The scale is formed by counting the number of events from top to bottom. In this manner, this arbitrary scale of the HorizonCube (i.e., number of events) become geologically meaningful in an undisturbed stratified succession, and if the scale is calibrated with the relative geologic time scale obtained from the biostratigraphic data, it could become more significant in stratigraphic interpretation.

The interpretation of both domains (i.e., structural as well as Wheeler) is done by simultaneous inspection of HorizonCube events in 3D and integration of the observations with the well data. The sequence stratigraphic units (sequences, systems tracts and parasequences) are interpreted by picking the HorizonCube events that form sequence stratigraphic surfaces.

The above method delivers a 3D Wheeler diagram, whereas to create a 4D Wheeler diagram, one needs to do one additional step; i.e., compute and display systems tracts thickness in the Wheeler domain.

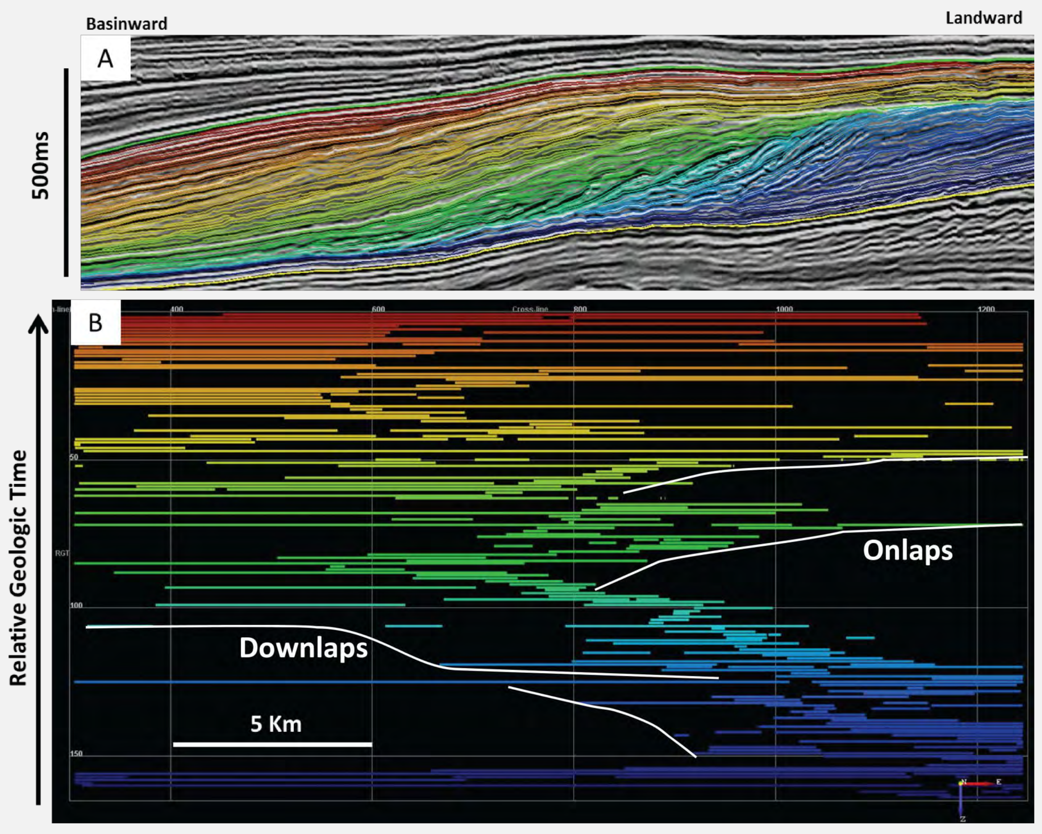


Figure 2 The densely mapped seismic interval of interest (A) is automatically transformed into Wheeler domain (B). The coloured lines represent the HorizonCube.

Systems Tract Thickness

This is defined as the isochore thickness between two isochronous HorizonCube events that define top & bottom of an interpreted package (Figure 3).

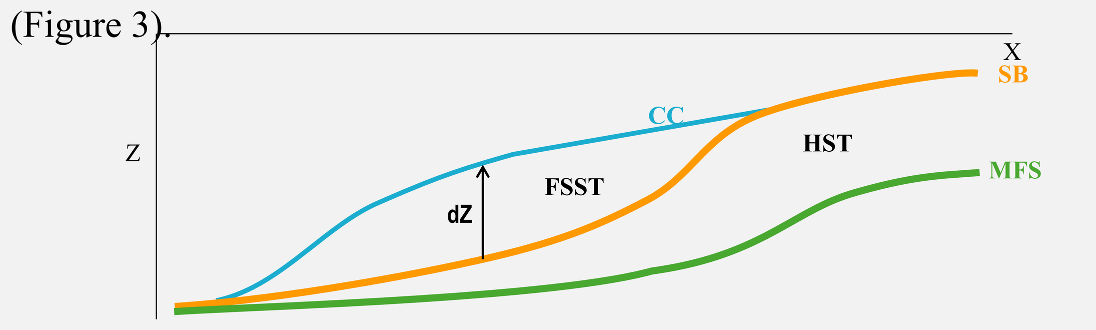


Figure 3 The thickness dZ is the TWT difference (isochore), or depth difference (isopach) between two sequence stratigraphic surfaces interpreted with the HorizonCube. SB – Sequence boundary, CC – Correlative conformity, MFS – Maximum flooding surface, HST – Highstand systems tract, FSST – Falling stage systems tract, dZ – delta Z (systems tract thickness).

Example: Siliciclastic Delta

An example is presented from the seismic data of the Dutch Sector (F3 Block, The Netherlands). The Pliocene interval of the 3D seismic data was auto-tracked with the HorizonCube's dense horizon tracker and transformed into the Wheeler domain (Figure 2). Using the HorizonCube method, three sequences are identified and correlated with the well data (Figure 4a). The lowermost sequence-1 is comprised of TST, HST and FSST. The intermediate sequence-2 is mainly a normal regressive sequence that consists of LST, HST, and FSST. Sequence-3 mainly contains a LST, TST, and HST. The TST of the sequence-3 has mainly formed a healing phase wedge with a distinct region of transgressive lag.

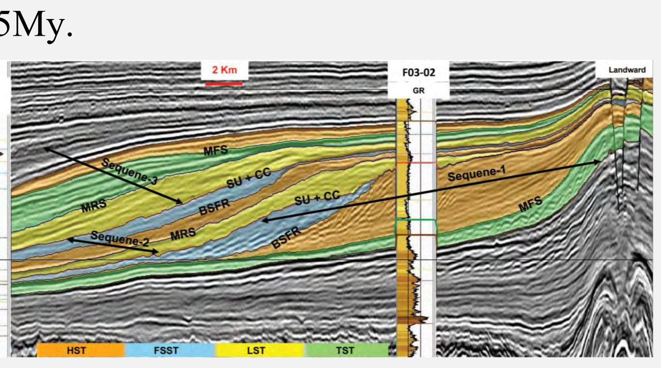
The automated Wheeler diagram (Figure 4b) shows the distinct depositional trends; i.e., aggradational, progradational, and retro-gradational. The 2D diagram represents one single inline of the volume. It clearly shows erosional hiatuses; e.g., during the falling stage (FSST) of sequence-1. This gap is interpreted as subaerial unconformity (SU), and its correlative conformity (CC) is placed as the top of FSST based on the Depositional Model IV (Catuneanu, 2011). The corresponding sequence boundary is a composite surface (SU + CC).

To add more information to the 2D Wheeler diagram (Figure 4b), the thickness of the systems tracts is overlain and colour-coded over the flattened HorizonCube events. In this manner, it is possible to interpret how net accommodation space was filled in conjunction with depositional trends observed in the Wheeler diagram.

Figure 5 shows a fence view of a 3D Wheeler diagram with two vertical sections and a horizon slice. The vertical sections are colour-coded with the systems tracts' thickness while the horizontal slice shows colour-blended Spectral Decomposition attributes. The display shows spatial-temporal depositional shifts from normal regressive units to forced regressive units. In the same image, thickness variations and seismic geomorphology of the lower most MFS of the delta are exposed.

Bio-stratigraphic information (LPP reports) reveals that the study area of about 380 Km^2 was covered with deposits of variable thicknesses in approx. 3.5My.

Figure 4a An arbitrary seismic transect (connecting the wells) is overlain by three interpreted sequences of the Pliocene deltaic depositional system of the Southern North Sea (The Netherlands). The interpretation is made in 3D using the HorizonCube (Figure 2).



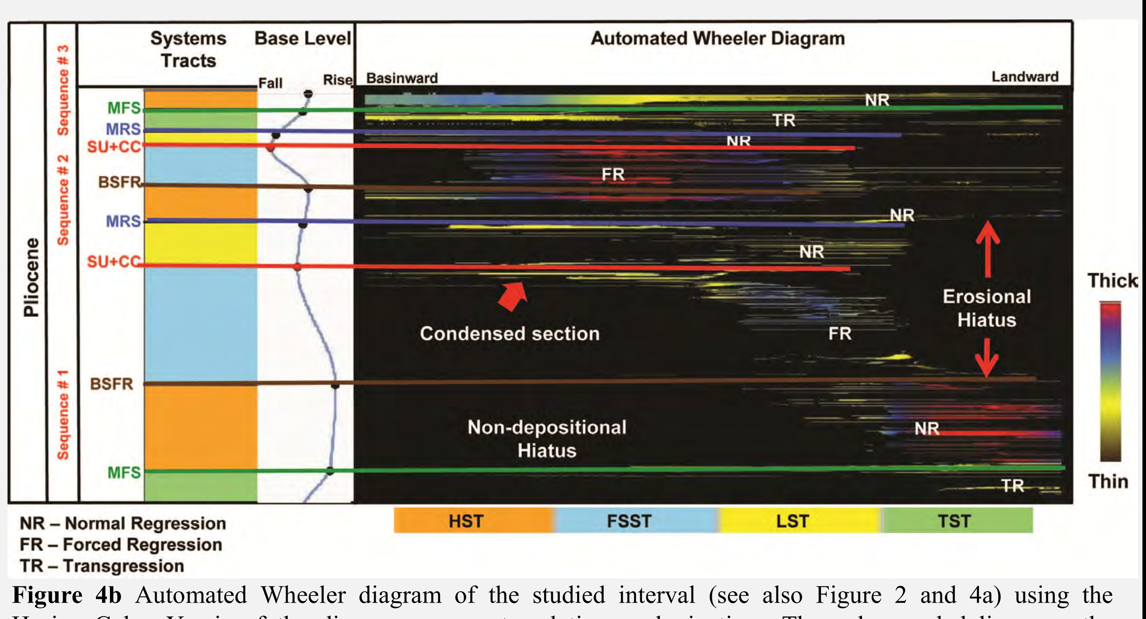


Figure 4b Automated Wheeler diagram of the studied interval (see also Figure 2 and 4a) using the HorizonCube. Y-axis of the diagram represents relative geologic time. The colour-coded lines are the flattened HorizonCube events, while the colours represent the thickness per systems tract as interpreted in Figure 4a. Note that sequence-1 shows low rate of sedimentation in the basinward direction (note the non-depositional Hiatus) compared to sequence-2 and sequence-3.

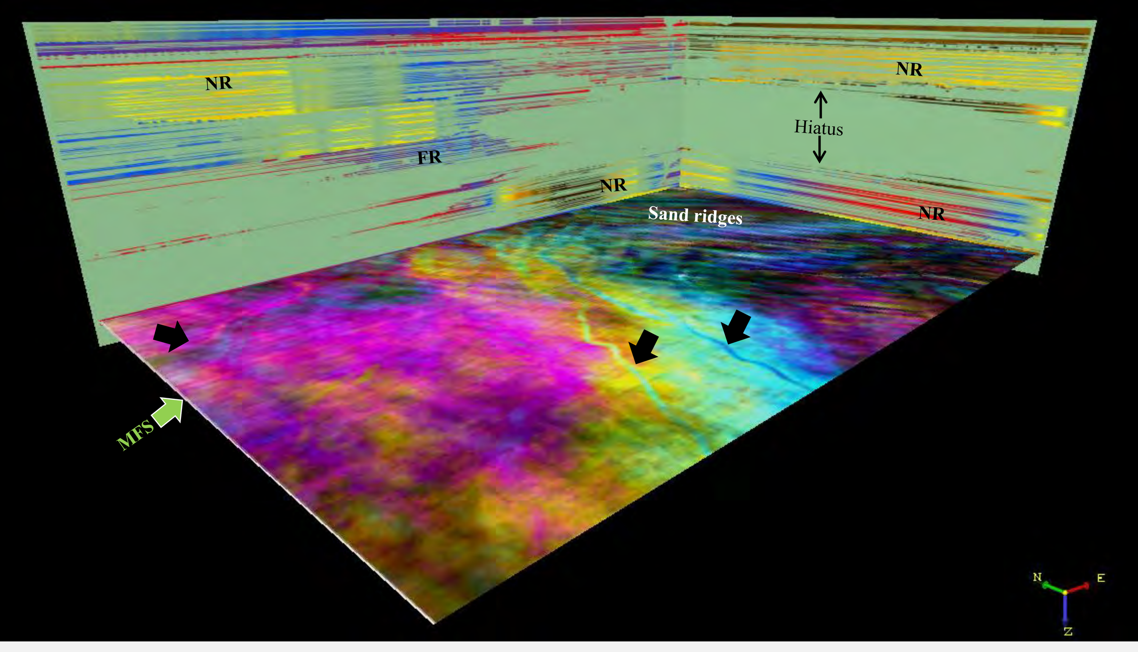


Figure 5 A 3D Wheeler diagram for the Pliocene interval (Figure 4) of the southern North Sea (Dutch sector). Vertical slices show flattened HorizonCube events with systems tracts thickness colour overlay. The bottom slice is a colour-blended spectral decomposition attribute slice at a maximum flooding surface (MFS). Several geomorphological features can be recognized: NE-SW flowing deep water channels (black arrows); NW-SE oriented elongated features are interpreted as sand ridges. These are analogous to present-day North Sea sand ridges (Walgreen et al., 2002).

NR – normal regression, FR – forced regression

Discussions

Advances in seismic technology enabled Wheeler diagrams to be constructed in three dimensions, thus allowing depositional systems to be studied in two-dimensional space and geologic time. Co-rendering thickness in the Wheeler scene adds a fourth dimension to what the authors propose to call the 4D Wheeler diagram. Thickness from seismic data can be computed in different ways for different interpretation objectives.

An automated way is to compute spectral decomposition attributes in a sliding window that slides relative to the HorizonCube (chronostratigraphic) event. For example in a Fourier Transform spectral decomposition, three selected frequencies can be RGB colour-blended in the Wheeler scene (Figure 5, horizontal slice). Spectral decomposition picks up thickness variations of features below seismic resolution as frequency responses are affected by tuning thicknesses. This kind of thickness attribute is useful for highlighting geomorphological features that can then be interpreted in the spatial-temporal context provided by the Wheeler diagram.

A semi-automated thickness that can be used as colour overlay in the Wheeler diagram is the systems tracts thickness. This requires up-front interpretation of systems tracts or other packages of interest. Systems tracts thickness overlays in the Wheeler scene enable studying depocenters and sedimentation rates in space and time.

Conclusions

3D seismic Wheeler diagrams can be extended to 4D Wheeler diagrams when stratigraphic thickness is displayed as a colour overlay over flattened events. The latter type of display allows studying accommodation cycles and preserved thicknesses within a time-space framework.

Acknowledgements

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