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Developments and Future Trends in Wheeler Diagrams

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SUMMARY

Wheeler diagrams are mainly constructed within the context of sequence stratigraphy with the diagrams initially proposed by Harry E. Wheeler to help establish a depositional framework of a time stratigraphic unit. Seismic data has shown another perspective of interpreting such diagrams by allowing large regions of a depositional setting to be observed in 3D within a defined spatiotemporal framework. Nevertheless, seismic data mostly contains limited vertical resolution and requires integration with well data. This paper reviews the advantages and pitfalls of seismically driven interpretations and argues that 4D Wheeler diagrams, with the introduction of a fourth dimension of stratigraphic thickness, are likely to become an important future trend in subsurface sequence stratigraphic interpretation.

Introduction

Early concepts of stratigraphy were primarily concerned with the physical characteristics of a rock unit. The developments in time stratigraphic concepts are briefly described in Table 1. The base level concept was introduced by Joseph Barrell in 1917 and was later embraced by Harry E. Wheeler. Wheeler pioneered the idea of a time stratigraphic unit and constructed a diagram (Wheeler, 1958) that is now commonly known as the Wheeler diagram. The fundamental concept of the Wheeler diagram was to represent the unit within an arbitrary relative geologic time (RGT) scale by flattening the interpreted surfaces.

Sloss (1963) practically represented a similar chart when he subdivided the sedimentary cover of the North American craton into megasequences. He correlated the megasequences based on a concept that sequences are unconformity bounded stratigraphic units.

Later on, Wheeler (1964) extended the concepts of base level and lithospheric variations, laying down the foundation for modern sequence stratigraphic interpretations.

Further implications of Sloss' and Wheeler's ideas were developed by the Exxon Research Group who studied the subsurface with the aid of seismic and well data (Payton, 1977). The Exxon Research Group proposed the idea that a seismic reflector could be treated as a geologic time line that may represent periods of erosion or non-deposition. The Exxon methodology incorporated the manual construction of chronostratigraphic charts using the seismic data, which represented the depositional shifts between the basin edge and the depocenters. Their Wheeler diagrams become increasingly popular, and people routinely constructed such diagrams with an arbitrary RGT scale.

Pioneering Periods	Major Development
1910s – 1950s	Conceptual developments in stratigraphy: base level (Barrell, 1917), sequence (Sloss et al., 1949).
1950s – 1964	First 2D Wheeler diagram and the development of the stratigraphic sequence concept. (Sloss, 1963) subdivided the sedimentary cover of the North American craton into six sequences. Wheeler (1964) explained the concept of lithospheric variations.
1964 – 1977	Subsurface sequence stratigraphy and seismically driven 2D Wheeler diagrams.
1977 – 2006	A progression from manual 2D Wheeler diagrams to automated 3D Wheeler diagrams.
2006 – 2012	Integration of the automated Wheeler diagrams with well data and stratigraphic attributes development (such as convergence and divergence patterns, etc.).
2012 – Future	4D Wheeler diagrams.

Table 1: *Major developments in the construction of Wheeler diagrams*

This paper starts from the existing concepts of Wheeler diagrams and explains the advantages of seismically driven diagrams, recommending the integration of seismic data with well-log, core and outcrop data sets, whenever possible, for the mutual calibration of data and the reliable construction of Wheeler diagrams. The paper continues by explaining the advantages of illustrating the ever-missing fourth dimension in the diagrams(Qayyum et al., 2012b).

Basic Concepts of Wheeler Diagrams and Pitfalls

Wheeler diagrams rely heavily on three fundamental concepts: (a) that the spatial dimension of a stratigraphic unit remains the same; (b) that an interpreted marker or surface is a geologic time line; and (c) that two flat (or horizontal) surfaces defining the top and bottom of a stratigraphic unit distort the spatial scale. These concepts and their pitfalls are explained in the following sub-sections.

Spatial Dimensions: A stratigraphic unit is spatially as well as temporally limited and has four dimensions: dX, dY, dZ and RGT (Relative Geologic Time). The four dimensions are rarely fully captured by an outcrop and well data, with only the vertical dimension typically measured. It is only the seismic domain that enables the visualization of the three spatial dimensions of a stratigraphic unit but with the major drawback of vertical resolution. Furthermore, the quantitative measurement of the spatial dimensions (dX and dY) can lead to limitations where the stratigraphic units are subjected to post-depositional deformation (e.g., compression or extension).

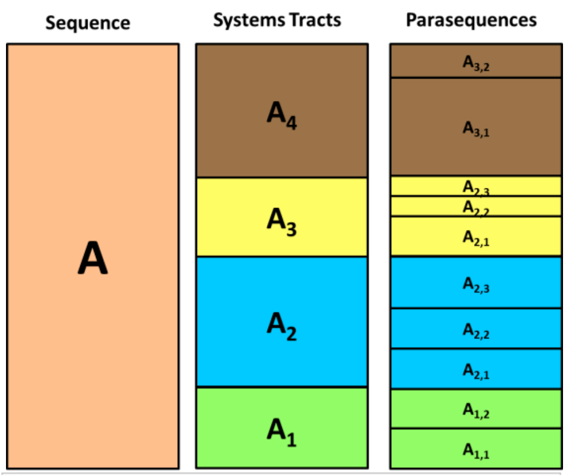

Figure 1. A conceptual sketch of hierarchal sequence stratigraphic framework that may be developed by integrating multi-datasets to circumvent the resolution limitations of seismic data. A is a sequence that is subdivided into systems tracts (A_1, $A_{2,...,}$ A_4) and parasequences ($A_{1,1}$, $A_{1,2}$,… $A_{2,1}$,…).

RGT Lines Concept: The RGT lines concept was originally introduced by Wheeler and Sloss in the definition of their time stratigraphy. Subsequently, Vail and others (Payton, 1977) used a similar concept but on another datasets: well-log and seismic. The question of how to deal with multi-resolution datasets to construct a sequence stratigraphic model was tackled by Miall (2010) (also see Figure 1). Here, seismic data provides good spatial resolution but lacks the vertical resolution. Yet, on the other hand, well data contains enough vertical information but lacks lateral resolution. In the case of outcrops, one may collect information at the centimetre scale but the spatial dimension is always limited. This suggests that if a stratigraphic unit is defined on the seismic data, one could further subdivide it into sub units (e.g., systems tracts, parasequences) by integrating it with well and outcrop datasets.

A Flat RGT Surface: Figure 2 illustrates the construction of a Wheeler diagram from the structural domain interpretation. Interpretation is made in such a way that each horizon has an assigned arbitrary RGT value. The same units are represented in the Wheeler domain (Figure 2b) by flattening them relative to their associated top and base surfaces. By doing this, the stratal dimensions (dX, dY and dZ) are distorted. This means that in the Wheeler domain, strata are not restored but simply flattened along time lines. This principle remains the same for creating such diagrams in all cases (outcrop, well correlation and seismic data).

Emerging Trends: The construction of Wheeler diagrams started traditionally from the 2D seismic domain, and required a time consuming, manual interpretation approach.

Many people (Keskes, 2002; Lacaze et al., 2011; Ligtenberg et al., 2006; Lomask and Guitton, 2007; Stark, 2004) therefore proposed automated methods to construct Wheeler diagrams from seismic data. Such automated algorithms may be applied to both 2D and 3D seismic data with the 3D transformation bringing a new trend of subsurface sequence stratigraphic interpretation if integrated with well data (Qayyum et al., 2012b). Table 2 provides a brief overview of the two types of Wheeler diagrams. Note that the 3D Wheeler diagrams (Figure 3) could not be created from the outcrop data

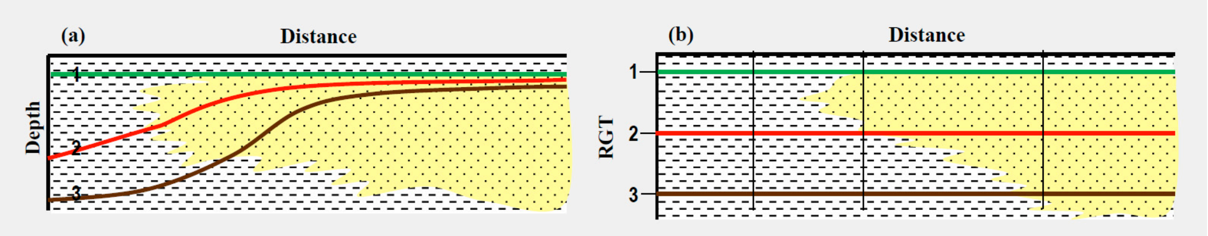

Figure 2. *The construction of a conventional 2D Wheeler diagram. (a) Structural domain with interpreted surfaces as indicative of relative geologic time (RGT). The same surfaces are flattened to create a Wheeler diagram. Modified from Qayyum et al. (2012a).*

but could be integrated with the outcrop/high resolution diagrams to add subordinated cycles.

Types	Supporting data	Limitations	General Applications
2D Wheeler diagrams	Outcrops Well cross-section Seismic	Spatially limited Lateral resolution Vertical resolution	Understand depositional shifts along basin dip / strike. It generally lacks 3rd dimension.
3D Wheeler diagrams	Seismic	Vertical resolution	As above, also provides third dimension to understand a stratigraphic unit within a spatiotemporal framework. It also provides seismic geomorphological information that one cannot visualize in 3D using outcrop or well data.

Table 2: *Wheeler diagrams types, supporting data, their primary limitation and generalized applications*

Future Trends – 4D Wheeler Diagrams

Recently 4D Wheeler diagrams (Qayyum et al., 2012a) were introduced that take the conventionally created (Table 1) diagrams to the next step with one additional dimension - the thickness of an interpreted stratigraphic unit. Such an attribute overlay in the 3D Wheeler domain allows for the study of the four dimensions of the stratigraphic unit, enabling the full illustration of a stratigraphic unit on 2D as well as 3D Wheeler diagrams. Along the time lines, one can now represent the change in thicknesses per stratigraphic unit that allows interpreters to explain not only the depositional changes but also the post-depositional processes.

The 4D Wheeler diagrams (Figure 4 shows a 4D diagram from the dataset in Figure 3) forms an important future trend in sequence stratigraphic interpretation and may become a common practice where interpreters construct 2D or 3D Wheeler (or chronostratigraphic) charts for a part of a basin or a region that would represent full stratal dimensions. It is easy to adopt such an approach as one can also display the thickness variations (of a sequence stratigraphic unit) along the time lines case of outcrops or well correlations.

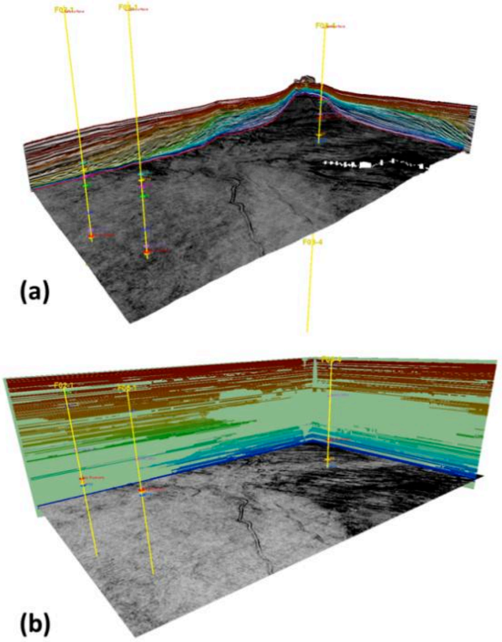

Figure 3 *Using dGB's HorizonCube mapped in the structural domain (a) the seismic data can be transformed into a 3D Wheeler domain (b). This example is from the F3 Block of The Netherlands. Yellow coloured vertical lines are the well locations. The horizontal densed horizons are the colour coded HorizonCube events.*

Another task one needs to do is to calibrate a full 4D Wheeler diagram with absolute geologic times. Such a study has not yet been publically presented, due to two principal limitations: (1) limited chronostratigraphic datasets in the subsurface; (2) the fact that a time surface can only be diachronous on a real scale but remains isochronous (flat) on an RGT scale.

Conclusions

While Wheeler diagrams are perhaps not the optimum technique for quantifying the actual area of deposition and volume of sedimentation, due to scale distortion, the diagrams are nevertheless an excellent means of describing the spatiotemporal relationship of stratigraphic units qualitatively. The addition of the missing dimension (i.e. stratal thickness) in the Wheeler diagrams can also be extended for the outcrop datasets. At present, only the seismic data allows construction of 4D Wheeler diagrams as a tool for subsurface sequence stratigraphy.

In conclusion, the authors believe that 4D Wheeler diagrams will become increasingly influential in bringing the vital fourth dimension – the thickness of an interpreted stratigraphic unit – into sequence stratigraphy and will be an important future tool in unconventional hydrocarbon exploration and production.

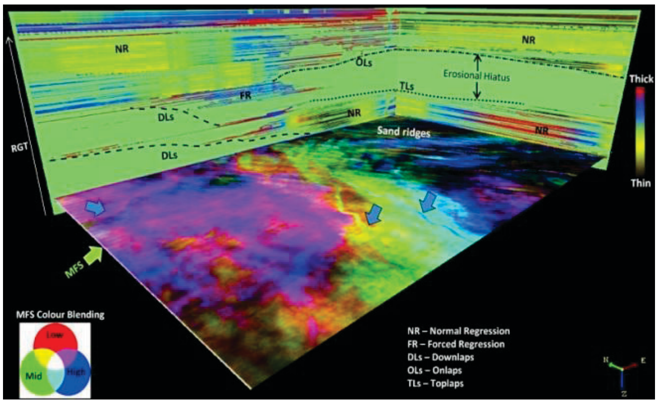

Figure 4 *An automated 4D Wheeler diagram (extended from Figure 3 dataset) with the vertical sections showing the systems tracts isochron. The horizontal slice is a MFS surface that is colour blended amplitude responses at three discrete frequencies (red = 20Hz, green = 40Hz and blue= 60Hz). On the horizontal slice, the blended response indicates the relative thickness variations such that the bluish regions are thinner compared to the reddish regions.*

References

Barrell, J., 1917. Rhythms and the measurements of geological time. Geological Society of America Bulletin, 28: 745–904.

Keskes, N., 2002. GEOTIME TM: A New Tool for Seismic Stratigraphy Analysis., VailFest; Sequence Stratigraphic Symposium, A Tribute to Peter R. Vail.

Lacaze, S., Pauget, F., Lopez, M. and Gay, A., 2011. Seismic Stratigraphic Interpretation from a Geological Model – A North Sea Case Study, 81st International Annual Meeting. Society of Exploration Geophysics (SEG), San Antonio.

Ligtenberg, H., de Bruin, G. and Hemstra, N., 2006. Sequence Stratigraphic Interpretation in the Wheeler Transformed (Flattened) Seismic Domain, 68th EAGE Conference & Exhibition, Vienna.

Lomask, J. and Guitton, A., 2007. Volumetric flattening: an interpretation tool. The Leading Edge, 26(7): 888-897.

Miall, A.D., 2010. The geology of stratigraphic sequences. Springer Verlag, Heidelberg ; New York, pp. xvii, 522 p.

Payton, C.E., 1977. Seismic Stratigraphy: Applications to Hydrocarbon Exploration. Memoir 26. American Association of Petroleum Geologists, Tulsa, Oklahoma, 523 pp.

Qayyum, F., de Groot, P.F.M. and Hemstra, N., 2012a. From 2D to 4D Wheeler diagrams, Strata and Time - Probing the gaps in our understanding (William Smith Meeting). The Geological Society, London, United Kingdom.

Qayyum, F., de Groot, P.F.M., Yasin, J. and Akhter, G., 2012b. Building a Sequence Stratigraphic Framework from HorizonCube and Well Data, 74th EAGE Conference & Exhibition incorporating SPE EUROPEC 2012. European Association of Geoscientists and Engineers (EAGE). Copenhagen, Denmark.

Sloss, L.L., 1963. Sequences in the Cratonic Interior of North America. Geological Society of America Bulletin, 74(2): 93-114.

Sloss, L.L., Krumbein, W.C. and Dapples, E.C., 1949. Integrated facies analysis. In: C.R. Longwell (Editor), Sedimentary Facies in Geologic History, Memoir 39. Geologic Society of America.

Stark, T.J., 2004. Relative geologic time (age) volumes—Relating every seismic sample to a geologically reasonable horizon. The Leading Edge, 23(9): 928-932.

Wheeler, H.E., 1958. Time-stratigraphy. Amercian Association of Petroleum Geologists Bulletin, 42(5): 1047-1063.

Wheeler, H.E., 1964. Baselevel, Lithosphere Surface, and Time-Stratigraphy. Geological Society of America Bulletin, 75(7): 599-610.