# Reconstruction of depocenter evolution through time using relative stratigraphic thickness

JEANNETTE WOLAK, Tennessee Technological University
NANNE HEMSTRA, dGB Earth Sciences
JESUS OCHOA and MICHAEL PELISSIER, Marathon Oil Company

In this article, we describe a new approach to seismic stratigraphic interpretation. We build on the concept of the relative geologic time attribute introduced by Stark (2004) to define a relative stratigraphic thickness attribute, which can then be interpreted to reconstruct depocenter migration from seismic data.

## Introduction

The principles of seismic stratigraphy were established in the classic *AAPG Memoir 26*. At this time (1977), manual interpretation of 2D seismic was still typical in the E&P industry. Simple truncation geometries such as onlap, downlap, and toplap were used to characterize sequence boundaries and flooding surfaces. Recent work continues to emphasize these 2D concepts, for example, using them in introductory sequence stratigraphic exercises. The routine use of 3D seismic emerged in the 1980s and, with it, computer-assisted interpretation. The main focus of the industry was on large structural traps. Highly effective 3D structural interpretation workflows developed in the 1980s still form the core of current interpretation workflows. Given the time-consuming nature of seismic interpretation, most geoscientists are forced to limit their mapping to major unconformities and flooding surfaces. These correspond to first- and second-order sequences boundaries and occupy only a small fraction of the typical seismic volume. It was common then, and now, to infer stratigraphy by averaging attributes such as seismic amplitudes between structural picks.

A general observation applicable to most good-quality seismic data is that nearly all of the reflection events are localized and cannot be followed far; these events represent higher-order stratigraphic boundaries. Although such events are exceedingly difficult to interpret using traditional methods, and may often be mistaken for noise, they are in fact remarkably well organized geologically, often characterized by high signal-to-noise ratios. In recent years, a new discipline of geophysics has emerged to exploit this localized seismic energy. This involves the use of computational methods to derive correlated stratigraphic surfaces in a 3D seismic volume, and the subsequent interpretation of the geologic information embedded in the interrelations between these surfaces. We might call this discipline computational seismic stratigraphy.

As noted by Hoyes et al. (2011), the global methods which track a set of horizons simultaneously in a seismic volume can be subdivided into several categories: dip-driven, horizon patches, and global optimization. These methods share a common goal and result in a dense set of horizons closely spaced in two-way time; their order can be thought of as representing geologic time. In this study, horizons are tracked or extracted from a continuous dip field. When compared to similar workflows, e.g., Lacaze et al. (2011), this method does not require construction or refinement of a global geologic model.

If we extend all horizons across a seismic volume, honoring structural breaks and the relative geologic time concept, we will find that most of the associated isochrons are of zero thickness except locally. Consider the following two examples: (1) a series of prograding clinoforms and (2) a deep-water channel complex. In the former, a stack of horizons representing the clinoforms would be characterized by an isochron thickness of zero except where phases of clinoform growth occur (Figures 1 and 2). The relative geologic time may be on the order of hundreds to thousands of years to millions of years, and the relative stratigraphic thickness may measure several hundred meters thick.

The latter example of a deep-water channel complex would have a thickness of zero except where the complex exists. The relative geologic time spanned by the complex thus corresponds to a three-dimensional relative geologic time distribution, which can be thought of as a small-scale architectural element or geobody. In this case, the relative geologic time may be on the order of hundreds to thousands of years; the relative stratigraphic thickness, a few kilometers wide by less than a hundred meters thick.

These examples illustrate the scale-independent nature of computational seismic stratigraphy. The recognition of a relative geologic time attribute (Stark, 2004) and the relative stratigraphic thickness attribute presented here are novel approaches to mapping depocenter evolution. No longer limited to first and second-order sequence boundaries, we use the term “depocenter” to denote the area of thickest deposition in any given geometry. We emphasize that these concepts can be applied to any geologic feature or used to subdivide a feature; thus, they have applications across the entire E&P spectrum, from regional exploration to geologic modeling.

## The HorizonCube

A HorizonCube is defined as a dense set of correlated 3D stratigraphic surfaces. The calculation of this HorizonCube is a crucial step in the seismic stratigraphic interpretation workflow described in this article. The single input required to create a HorizonCube is a continuous dip field. Mapped horizons can be used as boundary constraints and can be acquired by traditional horizon trackers or extraction from the continuous dip field. The dip field is available in the SteeringCube, a volume with local dip/azimuth information at seismic resolution.

A special autotracker tracks the dip field to generate hundreds of horizons, each representing a relative geologic timeline (de Groot et al., 2006; de Groot et al., 2010). Using the dip field to track horizons has an advantage above using the amplitude field as it is much more continuous. In addition, the effect of noise can be significantly reduced by smoothing the dip field. Alternatively, the HorizonCube can be created using a model-driven approach (stratal slicing or parallel to the upper/lower boundary).

## Relative stratigraphic thickness: The 3D chronostratigraphic slider

A typical HorizonCube may comprise dozens or even thousands of layers; thus, a tool is necessary to investigate the relative geologic thickness attribute between any two horizons. The 3D chronostratigraphic slider is a method for computing the isochron for an arbitrary stack of horizons in real time, using a slider bar to specify the range of horizons to be investigated. In this way, the interpreter can immediately see the 3D thickness expression of a feature observed in a given cross section (Figure 1c).

Functionality of the 3D chronostratigraphic slider includes the ability to either: (1) move the top or bottom horizons up or down in the HorizonCube; or (2) "lock" the distance between the top and bottom horizons prior to moving them up and down within the HorizonCube. Changes in isochron thickness may be displayed automatically, and operations using this tool take seconds to complete (Figure 2).

The 3D chronostratigraphic slider can be used to investigate relative stratigraphic thicknesses at any scale. Two end-member applications are presented as case studies here. In the first, the 3D slider is used to map depocenter evolution in clinoforms of the North Sea. A much smaller-scale application is also described, confined channel complexes on the Scotian Shelf. This tool has also been used in a number of other geologic

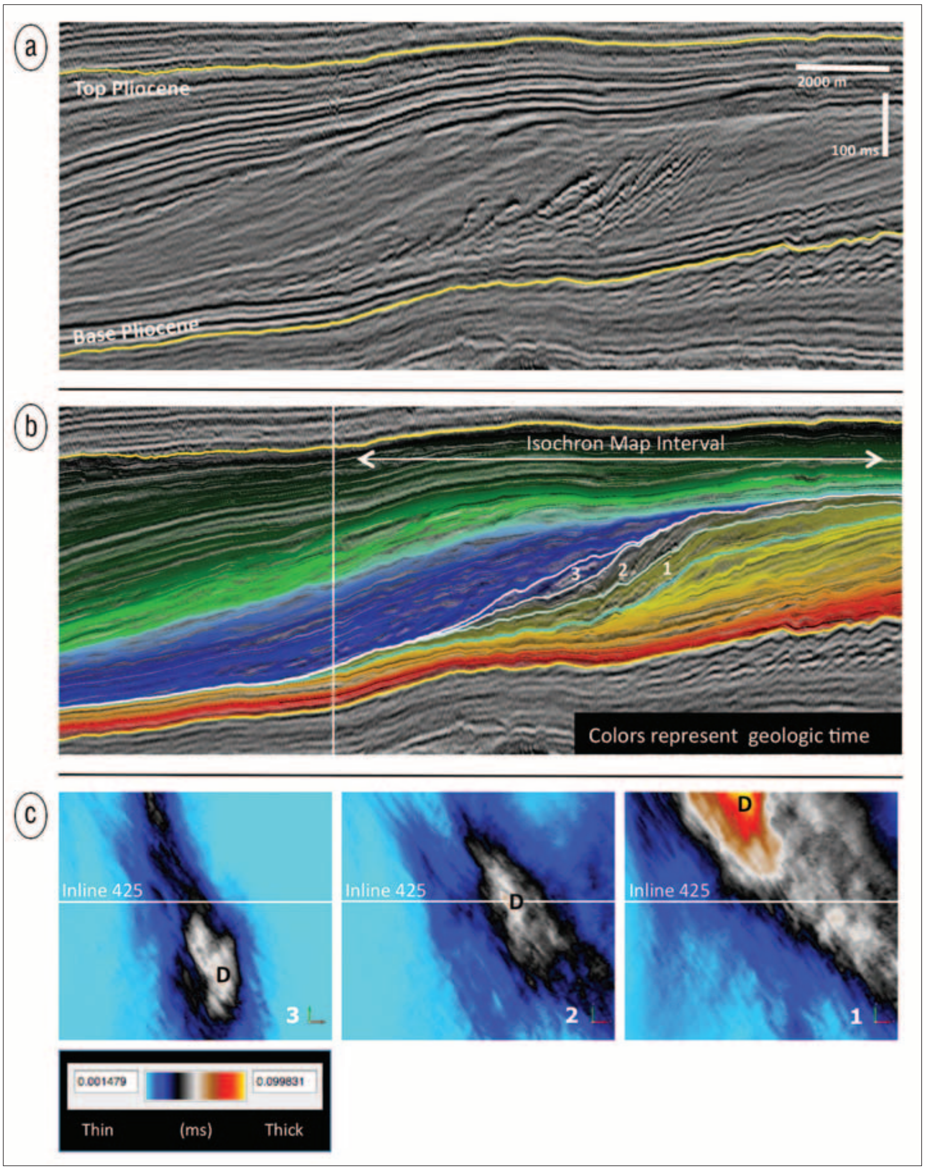

*Figure 1.* An example of depocenter evolution and clinoform progradation from the Dutch sector in the North Sea. Inline 425 is shown in (a), and the top and base Pliocene reflectors are labeled. (b) a dip-driven HorizonCube comprising more than 600 horizons that characterize clinoform packages, labeled 1, 2, and 3. Maps shown in (c) correspond to the isochron map interval on the right side of (b). Each map illustrates the 3D migration of deposition. Depocenters are labeled D.

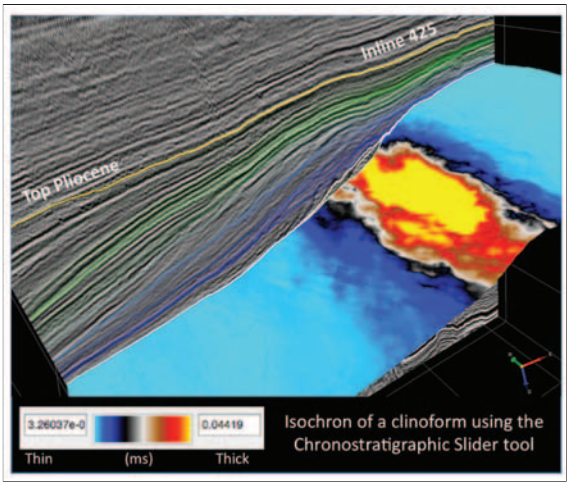

*Figure 2.* Illustration of an isochron generated using the 3D chronostratigraphic slider tool. In this case, the thickness of a single clinoform is calculated and displayed on the basal horizon of the clinoform.

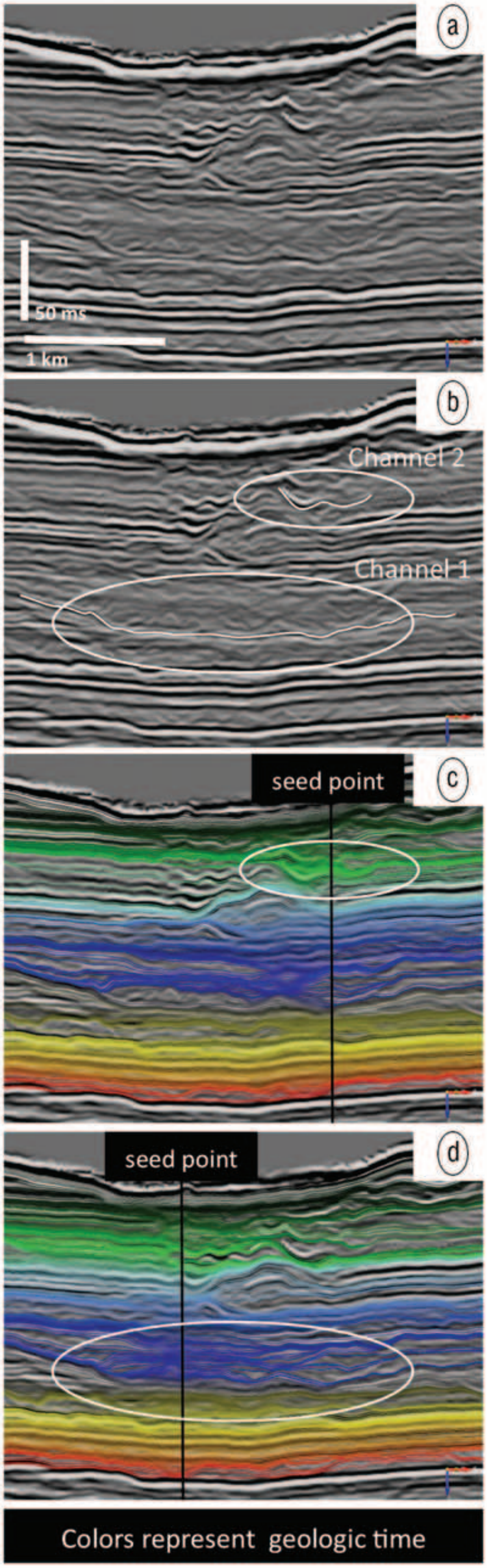

*Figure 3. Stacked, amalgamated channelform elements in a shallow seismic cross section from the Scotian Shelf. (a) Channels are characterized by scallop-shaped bases, and two channelforms within the larger complex are identified in (b). In (c) and (d), seed points placed directly over channels 2 and 1, respectively, capture complex internal heterogeneity.*

settings, including: (1) regional submarine fan lobe switching; (2) localized fan lobe stacking patterns; (3) channel complexes migrating in a slope setting; and (4) subsalt successions including channel and lobe complexes and composite bodies.

## Case study 1: Clinoform progradation in the North Sea

To illustrate depocenter evolution in a sequence stratigraphic framework, we first present data from the Dutch sector of the North Sea. As noted by other workers, the Eridanos delta, a large-scale fluvio-deltaic system, controlled deposition during the Late Cenozoic (Overeem et al., 2001; de Groot et al., 2010; Qayyum et al., 2012). Delta progradation during the Pliocene, illustrated in Figure 1, was mostly because of sediment influx as a result of regional uplift. A cross section trending east-west illustrates classic clinoform development, characterized by sigmoidal shapes that stack to the west. For more information, de Groot et al. (2010) and Qayyum et al. (2012) present details on HorizonCube construction in the North Sea and a chronostratigraphic framework.

Within the HorizonCube, it is possible to investigate a relative stratigraphic thickness between any two horizons using the 3D chronostratigraphic slider. For example, a HorizonCube constructed for the Pliocene interval in the North Sea is composed of more than 600 horizons (Figure 1b). To demonstrate depocenter evolution, four horizons were selected that constrain three phases of clinoform growth to the west, labeled 1, 2 and 3. In Figure 1c, isochron maps generated using the 3D slider show that depocenter evolution is in a clockwise motion, moving from north to south and east to west.

Maximum relative stratigraphic thicknesses (i.e., depocenters) for clinoforms 1 and 3 are north and south of the cross section, respectively. This type of lateral sedimentation has previously provided a key challenge to seismic interpretation in both 2D and 3D data sets (Johannessen and Steel, 2005). For example, Karner and Driscoll (1997) described the assumption that most depositional models used bidimensional sections perpendicular to the shelf-edge trajectory to explain sediment transport from shelfal to deepwater areas. This type of approach continues to be used and may overlook the importance of sediment transport processes that operate oblique or parallel to the shelf edge (e.g., alongshore drift in shallow marine settings, bottom currents in deep-water settings, etc.). In the clinoform example, the HorizonCube and 3D chronostratigraphic slider capture local physiographic controls and underlying structures as well as changes in deposition along dip and strike sections.

Could these clinoforms be mapped manually using the seismic? It would be a time-consuming endeavor with multiple iterations of horizon mapping and isochron construction. The HorizonCube and 3D chronostratigraphic slider technology provide a data-driven, interactive tool for quick visualization of depocenter evolution (Figure 2).

## Case study 2: Backfilling of a channel complex on the Scotian Shelf

Shallow seismic from offshore Nova Scotia is used to illustrate depocenter evolution within a confined channel complex. High-quality seismic data, combined with filtering algorithms based on the continuous dip field, are used to create a clear image of near-surface features. Channelform elements are at the edge of Scotian Shelf in

Late Cenozoic clastic sediments (Figure 3). In cross section, channelforms are characterized by sharp seismic reflections and scallop-shaped bases.

Two types of channelforms are identified on the Scotian Shelf and shown in Figure 3. Channel 1 is an older, broad-based channelform feature that measures > 1 km wide; this is interpreted to represent a channel complex with multiple filling events. Internal architecture is evident in the 3D seismic but poorly defined. The second channelform feature, channel 2, is a younger, narrower channel that measures < 0.5 km wide and appears to be confined within a steep-sided erosional container. In both cases, manual horizon mapping within the channels would be nearly impossible given the seismic image.

HorizonCubes constructed for the interval shown in Figure 3 use seed points to define channel margins and capture internal heterogeneity within a much larger, amalgamated channel complex. In Figure 3c and Figure 3d, seed points that fall outside the targeted channels do a good job of defining channelform bases and margins; however, they may not reflect internal channel architecture. Seed points that bisect each channel are used to capture high-resolution internal heterogeneity. An alternative to this method is to use a single HorizonCube with multiple iterations to fill gaps within each channelform.

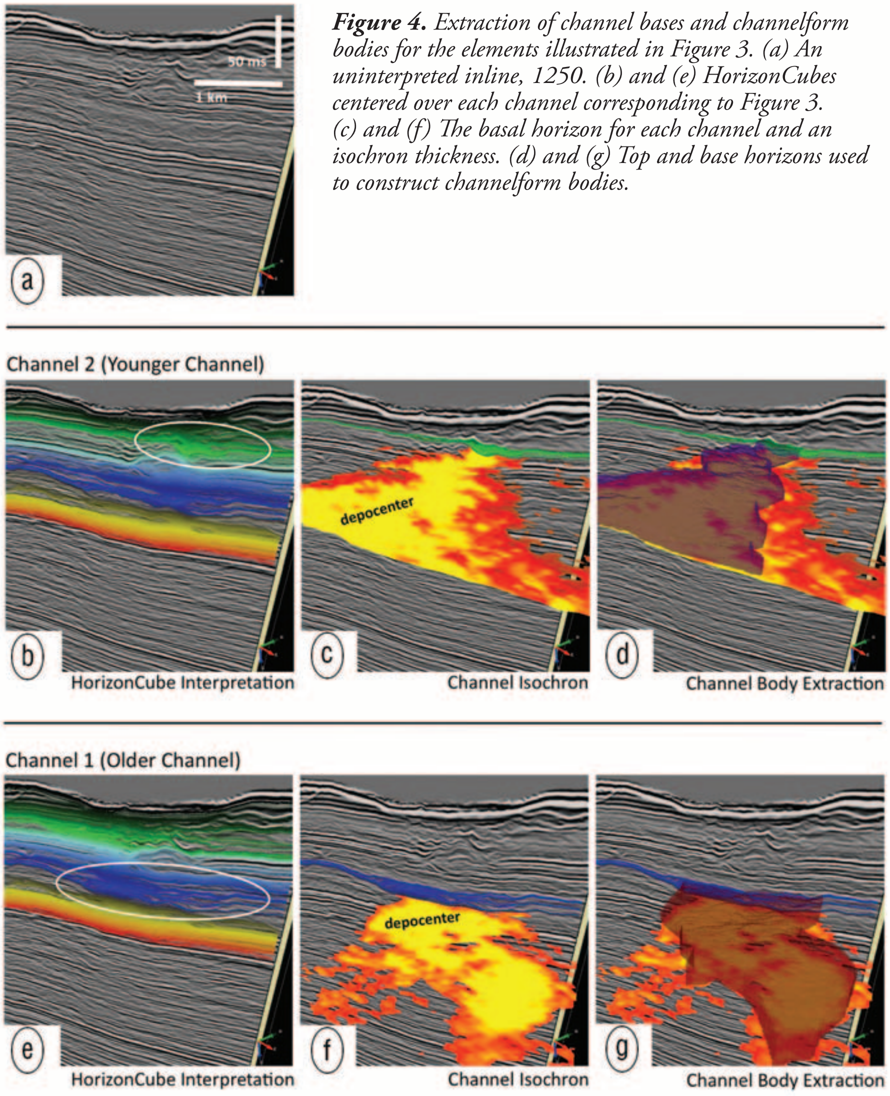

***Figure 4.*** *Extraction of channel bases and channelform bodies for the elements illustrated in Figure 3. (a) An uninterpreted inline, 1250. (b) and (e) HorizonCubes centered over each channel corresponding to Figure 3. (c) and (f) The basal horizon for each channel and an isochron thickness. (d) and (g) Top and base horizons used to construct channelform bodies.*

More than 400 horizons are available for each HorizonCube shown in Figure 3; horizon spacing at the seed point is 2 ms. Thus, horizons can be selected that capture channel bases, margins, and phases of channel fill. It is important to note that this heterogeneity is visible within both channelforms; there is no size or scale limit to the HorizonCube tool.

Depocenters and relative stratigraphic thicknesses of each channelform can then be interrogated using the 3D chronostratigraphic slider. Isochrons in Figure 4 illustrate filling of the younger, narrow channelform with little deposition outside the channel. In other words, the isochron thickness is zero except where the channel exists. In contrast, the older channelform has a depocenter that measures > 1 km wide and appears to accommodate deposition within the channel thalweg as well as along channel margins. Thus, the younger channel is erosionally confined, whereas the older channel is partly confined.

Using information from the 3D slider and horizons extracted from the HorizonCube, it is also possible to generate three-dimensional channelform bodies (Figure 4). In this case, channelform bodies are constructed using top and base horizons identified via the 3D chronostratigraphic slider tool. Channel margins are manually selected using a polygon tool by evaluating the areas of maximum thickness and their relationship with seismically resolvable sedimentary bodies. Multiple channelform bodies can be used to characterize regional channel stacking patterns. In the example shown, there is a clear stratigraphic change from older, partly confined channelforms to younger, erosionally confined channelform features.

In addition to channel migration, relative stratigraphic thicknesses within a channel can be used to characterize backfilling patterns. While these patterns may be poorly defined in seismic, dip-driven HorizonCube data can be used to interpret them in 3D. For example, internal architecture within the older, broad-based channel is shown in Figure 5 and characterized by multiple phases of filling (labeled 1–6). The channel is oriented north-northeast by south-southwest, and the 3D chronostratigraphic slider is used to interactively visualize depocenter evolution within the feature (Figure 6). In this example, the earliest phases of channel fill, phases 1 and

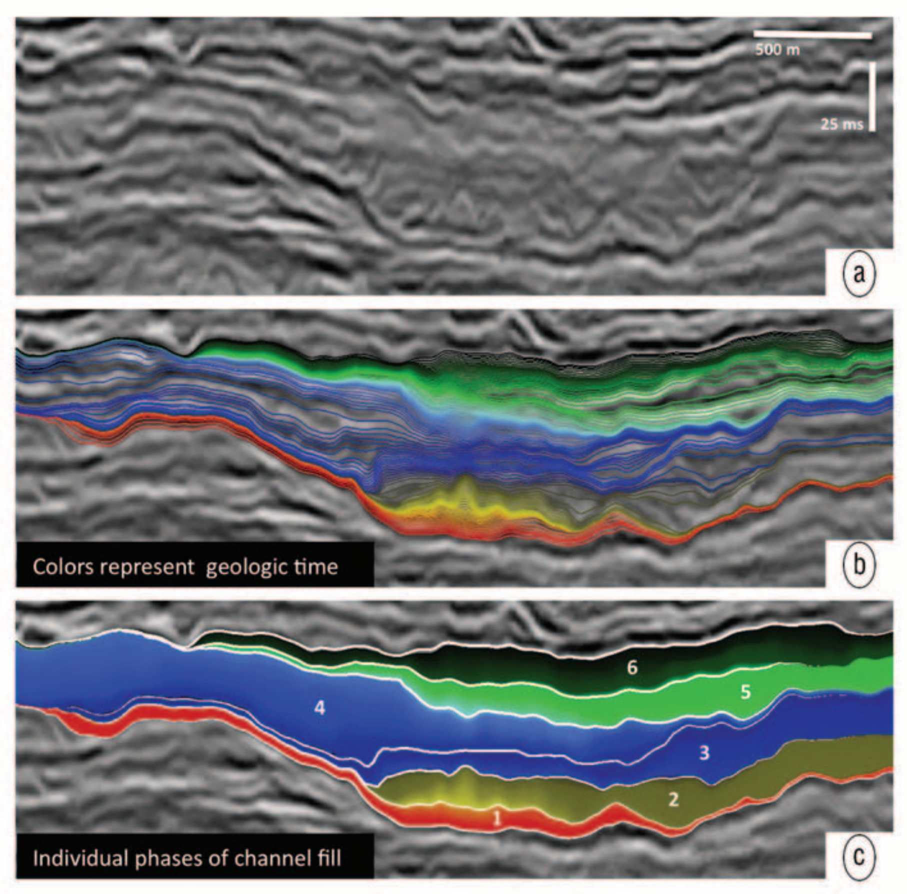

*Figure 5.* *Relative geologic age of fill within a partly confined channelform element, offshore Nova Scotia. The channelform is characterized by a sharp, erosional base; however, internal architecture is difficult to resolve in filtered seismic (a). The dip-driven horizon cube shown in (b) maps channel-fill elements, labeled 1–6 (c). See Figure 6 for corresponding isochron maps of channel fill stages.*

2, are characterized by thin depocenters located along the channel thalweg. Phases 3 and 4, however, are characterized by bypass within the thalweg and deposition along the channel margins. The youngest deposits, phases 5 and 6, capture backfilling of the channel, characterized by depocenter evolution updip, from the south in phase 5 to the north in phase 6.

Let's assume that the top and base of the channelform feature were mapped using traditional manual methods. A bulk isochron generated for the channel would have the following limitations: (1) architecture and heterogeneity within the channel would not be captured; (2) internal features such as thalweg and marginal deposits would be merged into a single isochron package; and (3) proportional slicing within the channelform would cross lithologic changes within the channel. In Figure 6, a cumulative isochron for the channelform feature does not reflect any of the internal heterogeneity and, in fact, masks the channel thalweg completely.

## Conclusions

The HorizonCube and 3D chronostratigraphic slider are innovative tools that can be used to map relative stratigraphic thicknesses and depocenter evolution

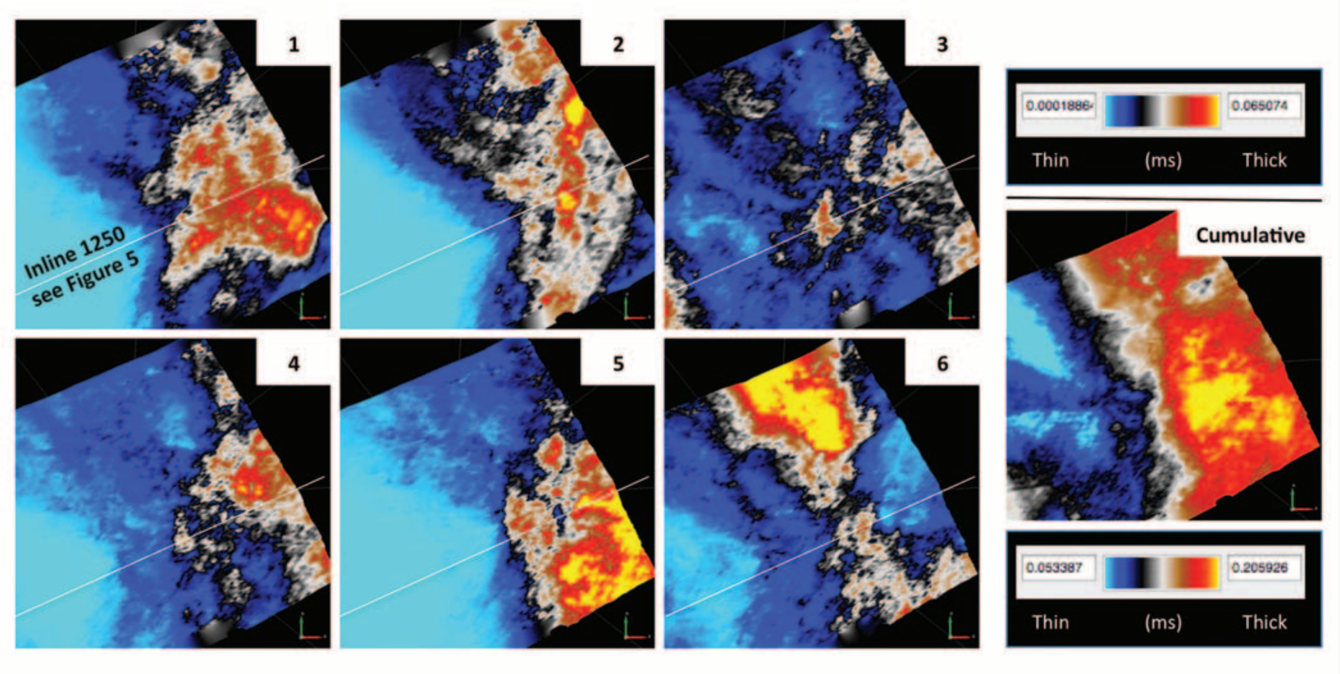

*Figure 6.* *Isochron maps corresponding to channel fill stages shown in Figure 5. From oldest (1) to youngest (6), the isochrons illustrate deposition in a NS-trending channelform on the Scotian Shelf. A cumulative isochron is also shown, which captures a general NS trend but no internal heterogeneity.*

at a range of geologic scales. The two examples presented here demonstrate usefulness in a regional sequence stratigraphic study (North Sea) as well as in architectural element analysis (Scotian Shelf). In both cases, manual mapping of seismic and construction of isochrons would be challenging; however, computational seismic stratigraphy and dip-driven techniques provide an alternative approach. TLE

---

*Editor's note: Author Michael Pelissier is currently with Roc Oil Company.*

## References

de Groot, P., G. de Bruin, and N. Hemstra, 2006, How to create and use 3D Wheeler transformed seismic volumes: 76th Annual International Meeting, SEG, Expanded Abstracts, 1038–1042, http://dx.doi.org/10.1190/1.2369690.

de Groot, P., A. Huck, G. de Bruin and N. Hemstra, 2010, The horizon cube: A step change in seismic interpretation!: The Leading Edge, **29**, no. 9, 1048–1055, http://dx.doi.org/10.1190/1.3485765.

Hoyes, J. and T. Cheret, 2011, A review of "global" interpretation methods for automated 3D horizon picking: The Leading Edge, **30**, no. 1, 38–47, http://dx.doi.org/10.1190/1.3535431.

Johannessen, E. P. and R. J. Steel, 2005, Shelf-margin clinoforms and prediction of deep-water sands: Basin Research, **17**, no. 4, 521–550, http://dx.doi.org/10.1111/j.1365-2117.2005.00278.x.

Karner, G. D. and N. W. Driscoll, 1997, Three-dimensional interplay of advective and diffusive processes in the generation of sequence boundaries: Journal of the Geological Society, **154**, no. 3, 443–449, http://dx.doi.org/10.1144/gsjgs.154.3.0443.

Lacaze, S., F. Pauget, M. Lopez, A. Gay, and M. Mangue, 2011, Seismic stratigraphic interpretation from a geologic model—A North Sea case study: 81st Annual International Meeting, SEG, Expanded Abstracts, 1134–1139, http://dx.doi.org/10.1190/1.3627403.

Overeem, I., G. J. Weltje, C. Bishop-Kay, and S. B. Kroonenberg, 2001, The Late Cenozoic Eridanos delta system in the Southern North Sea Basin: A climate signal in sediment supply?: Basin Research, **13**, no. 3, 293–312, http://dx.doi.org/10.1046/j.1365-2117.2001.00151.x.

Payton, C. E., ed., 1977, Seismic stratigraphy applications to hydrocarbon exploration: AAPG Memoir 26.

Qayyum, F., P. de Groot, and N. Hemstra, 2012, Using 3D Wheeler diagrams in seismic interpretation—the HorizonCube method: First Break, **30**, no. 3, 103–109.

Stark, T. J., 2004, Relative geologic time (age) volumes—Relating every seismic sample to a geologically reasonable horizon: The Leading Edge, **23**, no. 9, 928–932, http://dx.doi.org/10.1190/1.1803505.

*Acknowledgments: The examples shown in this article are generated in OpendTect, an open-source seismic interpretation system, using the DipSteering and HorizonCube plugins. The data sets used in the examples are available without charge via bit-torrent technology from the Open Seismic Repository (http://www.opendtect.org/osr). The authors gratefully acknowledge ongoing collaborative efforts among dGB Earth Sciences, the Quantitative Geology Research Group at Marathon Oil Company, and Tennessee Technological University. The following individuals are also recognized for their contributions in early stages of this research: Friso Brouwer and Donald Caldwell.*

*Corresponding author: jwolak@tntech.edu*