New methods for slicing and dicing seismic volumes

Paul de Groot[1*], Farrukh Qayyum[1], Yuancheng Liu[1], and Nanne Hemstra[1] present techniques whereby geologic information in global seismic interpretation techniques can be unlocked through new methods for dicing and slicing seismic volumes.

Global seismic interpretation techniques aim to arrive at fully interpreted seismic volumes.

'Fully' in this context, however, is misleading as it gives the impression that we are dealing with an end product and that there is no more interpretation to be carried out. This is not the case. The correlated geologic timelines of these volumes open up new ways to analyse seismic data, thereby increasing our understanding of the depositional history and improving our ability to find stratigraphic traps and to build accurate geologic models.

Geologic information in global seismic interpretation techniques can be unlocked through new methods for dicing and slicing seismic volumes. Using HorizonCube, this can be achieved through attributes and a 3D Slider in a workflow that combines 2D and 3D visualization techniques with interactive analysis. Examples of such techniques will be introduced.

The HorizonCube consists of a dense set of horizons that are computed from the seismic dip field. The vertical separation between horizons in a HorizonCube varies spatially. This feature is exploited in a new set of attributes called HorizonCube attributes that capture local and global information. Examples are: HorizonCube density and HorizonCube thickness attributes. Both attributes can be highly effective in the interpretation of unconformities, condensed sections and sedimentation rates.

For slicing and dicing seismic volumes, we use a 3D Slider in a workflow that combines 2D and 3D visualization techniques with interactive analysis. The workflow enables scanning thousands of auto-tracked horizons rapidly with the objective to identify pairs of horizons corresponding to top and base of depositional features of interest. In the next step, isochron thicknesses or attribute responses are computed and geobodies are extracted.

Since computing performance has improved dramatically, global seismic interpretation methods have become more feasible. Global seismic interpretation methods can be defined as automated or semi-automated methods that aim to generate fully interpreted volumes (Stark, 2004; Lomask et al., 2006; de Groot et al., 2010; Hoyes and Cheret, 2011; Dirstein and Fallon, 2012; Labrunye and Jayr, 2013; Stark et al., 2013).

While they may differ in how they correlate time lines and in the way the information is stored, such techniques allow interpreters to stratal slice through volumes of seismic amplitudes 'at will' and derive attributes along geologic timelines, thereby facilitating the recognition of depositional features and potential shallow hazards.

The 'Age Volume' technique, for example, assigns a value representing relative geologic time to each seismic sample position (Stark, 2004). One of Stark's methods to assign age is based on correlating instantaneous phase signals from trace-to-trace. The PaleoScan software from the French company Eliis (Pauget et al., 2009) builds a geologic model on the scale of roughly the seismic sampling by connecting each seismic event (min, max and zero-crossings) to the most probable neighbouring events.

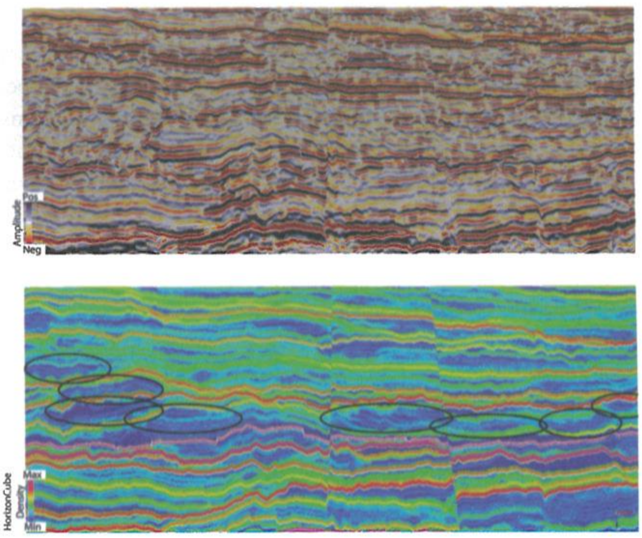

Figure 1 Seismic section (upper image) and equivalent HorizonCube density attribute (lower image) from deep water East-Africa. Hot (red) colours represent high HorizonCube density corresponding to unconformities and condensed sections, Cold (blue) colours represent low HorizonCube density and expanded sections with high depositional rates. The HorizonCube density attribute provides a clear view of the depositional architecture, easily identifying mounded features in a back-stepping configuration (Data courtesy of ION Geophysical).

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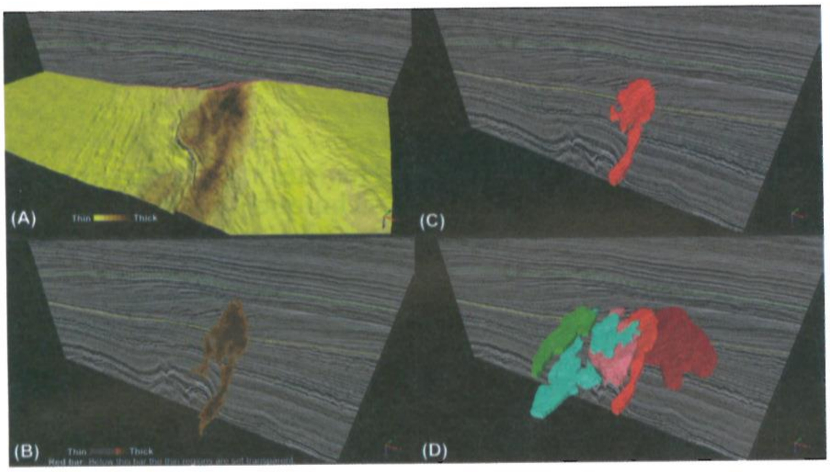

Figure 2 *The interactive workflow to extract 3D bodies from a HorizonCube using a 3D HorizonCube slider. (A) An isochron (thickness) map is computed by specifying the top and the base of a feature of interest in the slider. (B) A thickness cut-off value is set to create a 3D body that is bounded by top and base horizons and the cut-off contour value. To find the optimal cut-off value an interactive slider is moved through the isochron histogram. Values below the threshold value (red bar) are made transparent in the 3D scene. (C) The resultant body is displayed. (D) All forced regressive lobes in the falling stage system tract are extracted in the same way.*

There is also Chevron's 'Volumetric Flattening' (Lomask et al., 2006), a method that is based on inverting the dip-field to flatten the original seismic volume – also known as Wheeler cubes.

In addition, dGB Earth Sciences introduced the HorizonCube (Ligtenberg et al., 2006; de Groot et al., 2006). In this paper the examples are produced using the algorithm, which is described by de Groot et al. (2010). The latest algorithm is based on constrained inversion to flatten dip-fields (Wu and Hale, 2015). A HorizonCube is defined as a dense set of correlated 3D stratigraphic surfaces. Two types of HorizonCube exist: 'continuous' and 'truncated'. In a *continuous* HorizonCube all events exist at every trace location. A *truncated* HorizonCube consists of horizon patches as events are terminated when they get too close together. In either cube, the horizons can never cross each other. Converging horizons tend to do this along unconformities and condensed sections. In these areas, a high density of events in a continuous HorizonCube indicates zero seismic thickness corresponding to erosion, non-deposition, or very low sedimentation rates.

Global seismic interpretation techniques might be perceived as the ultimate end product in seismic interpretation projects. This is absolutely not the case (e.g., Stark, 2006). The output generated by these techniques is the starting point for new applications and workflows to extract more geologic information from seismic data (de Groot, 2013). Hereafter, two methods for slicing and dicing seismic volumes are described to support this statement.

Method 1 – generating HorizonCube attributes

A set of new attributes can be computed from a continuous HorizonCube that helps to unravel the depositional history of a sequence and facilitates identification of stratigraphic features, such as pinch-outs, clinoforms, erosional unconformities and condensed sections (Wolak et al. 2013; McDonough et al., 2013). Attribute examples are: HorizonCube density, which measures the number of events per seismic time (depth) interval and HorizonCube thickness, which measures the thickness between two consecutive events.

A distinguishing feature of these attributes is that they combine local and regional information. Local attribute responses are correlated laterally along the chronostratigraphic framework provided by the cube. Packages of similar age are easily recognizable on these attributes. This helps in interpreting the variations in sedimentary processes in both space and time.

This relation with 'out of plane' information makes these attributes – even when displayed on 2D sections – a great aid in understanding the 3D make-up of depositional events. This is demonstrated using HorizonCube density as an example (Figure 1). This attribute inversely relates to sedimentation/erosion rate. Horizons near the depocentre of a particular depositional feature are spaced widely apart. Moving away from the depocentre, horizons converge until the point that they effectively snap together into a single bundle in areas of non-deposition or erosion.

Method 2 – interactive 3D slider, geobodies and stratal attributes

At the scale of a typical seismic survey, the earth can be considered to be a set of finite geobodies with distinct shapes and certain dimensions. For example, in fluvial-marine environments, an earth model can be constructed from geobodies, such as fan, channel, bar, sheet, drape, levee, etc. Many of these shapes are recognizable on seismic data, especially if we slice through the data along mapped seismic horizons.

Since we have mapped all seismic horizons in a HorizonCube, we have captured sufficient information regarding vertical and lateral extent (or limits) of these depositional patterns in the seismic data. However, we need to realize that a HorizonCube consists of hundreds, even thousands of auto-tracked horizons. That is a lot of data to analyse – meaning that we need new workflows to extract the desired information intrinsically captured in the geometry of these horizons.

Here, the solution is found in a combination of fence views, 3D surfaces and interactive controls that allow an interpreter to rapidly scan the data and to identify top and base horizons corresponding to depositional events. A fence view remains necessary as interpreters (initially) observe, think and interpret on seismic sections. This approach follows the traditional way of interpreting seismic data.

The calculation speed of modern CPUs and GPUs allow us to use interactive 3D sliders. These are HorizonCube based sliders that slice through the seismic data in a geologically meaningful way i.e. by slicing along (relative) geologic timelines. The user controls the 3D sliders to select two horizons of interest: one defines the top of the interval of interest while the other represents the base (Figure 2). Typically top and base are identified on seismic, as explained above, using a slider and HorizonCube attributes such as HorizonCube density.

Now, in the 3D visualization, on-the-fly computations of isochron/attribute maps are performed and the results are visualized on the selected horizons (top and base). Moreover, seismic attributes such as reflection strength, frequency, AVO, coherency, average, maximum, or minimum impedance can be extracted between the stratal limits of the identified depositional event.

Based on cut-off values of isochron thickness or seismic attribute response, depositional events are then converted into geobodies for further assessment, property assignment and exportation to downstream applications, such as reservoir modelling.

Using interactive controls and on-the-fly visualization of isochron and seismic attribute maps, an interpreter thus achieves high productivity. He or she can achieve a detailed mapping and acquire a deep understanding of a large volume of data in a relatively short time.

An example slicing

HorizonCubes are also used in shallow hazard interpretation workflows. Through the Wheeler transformation, the seismic equivalent of the geologic Wheeler diagram (Wheeler, 1958), any attribute of interest can be flattened for further study. Stratigraphic features and anomalies are easier to recognize on Z-slices in the Wheeler domain as these slices are horizons representing relative geologic timelines. For this type of analysis, the horizons do not need to be time-equivalent throughout the entire survey. The main requirement is that they follow the local stratigraphy to an extent that stratigraphic features can be identified and avoided by the drill-bit when needed.

A horizon slicing example targeting a deep-water drilling programme (offshore, East Africa) is demonstrated in Figure 3 (Bouanga et al., 2014). To date, eight exploration well sites have been assessed for shallow hazards using the HorizonCube methodology.

The shallow section in the survey is characterized by cross-cutting channelized and turbiditic deposits. The present seabed shows active canyons. To create a HorizonCube in such complex setting, the shallow section is divided into various packages by mapping the bounding surfaces. These surfaces are mapped using conventional horizons tracking techniques. Each package is then processed with its own set of parameters. This results in a HorizonCube that combines packages with data-driven (dip-steer, auto-tracked) horizons and model-driven (stratal sliced) horizons.

In Figure 3, a sequence of pseudo-stratigraphic amplitude slices is shown from an 8 km by 12 km volume around one of the drill site locations. The slices are extracted from a continuous HorizonCube on a step of every 20. The proposed exploration well location is marked by an orange circle. A starting point for shallow hazard identification is to pan

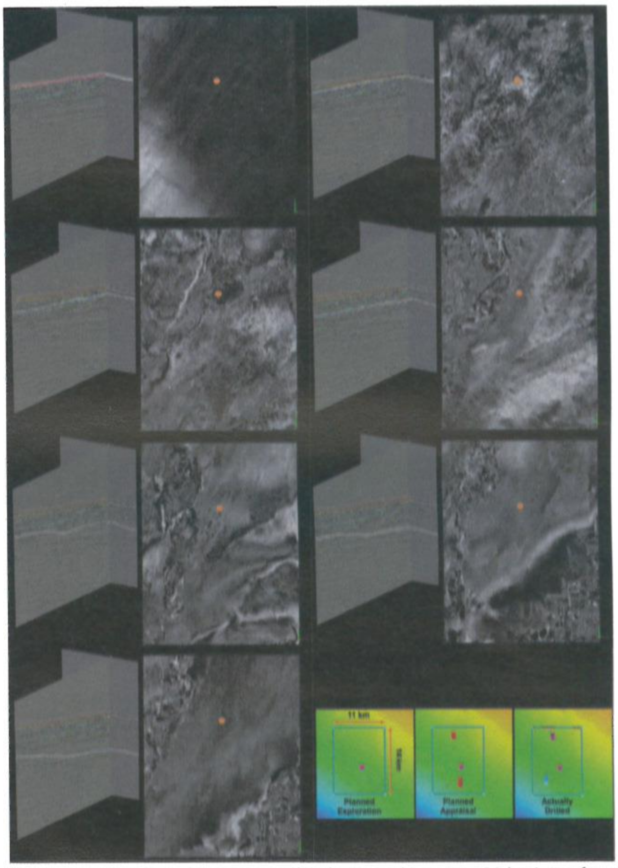

Figure 3 A sequence of horizon amplitude extractions every 20 horizons from a continuous HorizonCube are shown. The 3D seismic display on the left of each horizon slice shows the location within the 3D volume (white line). A possible well location is shown by the orange circular marker. Preliminary scanning of this suite of horizons can be used to identify potential shallow hazards of interest. For example, a channel system (the opaque zone cutting from the lower left to upper right corner in the deeper section) is identified and warrants further investigation with different flattened seismic attributes. Bottom right corner: as a result of these studies, intended well locations have been moved (Data courtesy of BG Group).

through every pseudo-stratigraphic slice. As a result of these studies, intended well sites were moved to safer locations.

An example – dicing

The McMurray Formation onshore Canada represents a fluvial estuarine depositional system, hosting rich bitumen and water-sand reservoirs (Figures 4 and 5). The generalized stratigraphy can be summarized as an overall aggrading system with multiple parasequences of rapidly prograding fluvial systems, followed by erosion and channel incisions during episodes of base level fall (Ranger and Pemberton, 1997).

The unconsolidated sands of the McMurray Formation in the study area are at depths of about 450 m, with a pay thickness of up to 40 m and porosity between 27% and 30% (Tonn, 2010). The sands are inter-bedded to varying degrees with muds. Depending on the depositional environment, the muds can be localized or extended over large regions.

Oil is produced by Steam Assisted Gravity Drainage (SAGD) that uses horizontal well pairs to extract the bitumen. The upper horizontal well is for steam injection and the lower well for oil drainage. SAGD can only be operated efficiently if the subsurface geoscientist team is able to image/model/predict the subsurface with high accuracy. Knowledge of the depositional facies, distribution, geometry of the reservoir (including top and base of the SAGD pay interval and thickness), lateral continuity of potential mud baffles and barriers are critical for a successful SAGD operation. The key for successful placement of the SAGD injector-producer pairs is to understand reservoir heterogeneity.

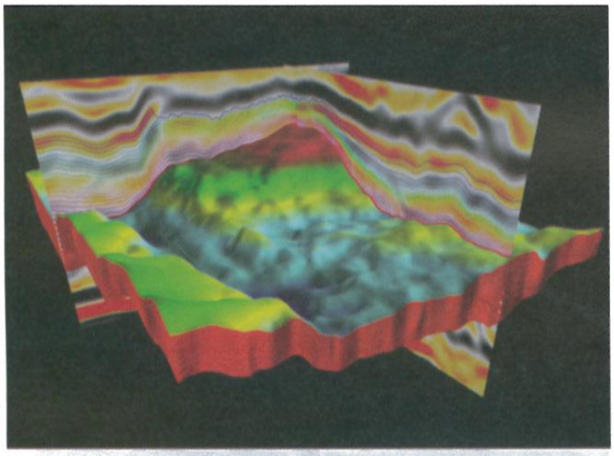

Figure 4 A 3D impression of the HorizonCube covering the McMurray Formation, Canada (Data courtesy of Statoil).

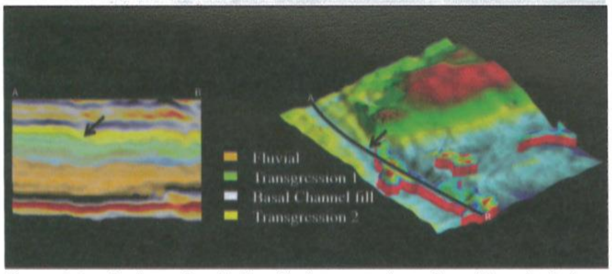

Figure 5 A seismic section (left) with interpreted stratigraphic units (colour-coded) in the McMurray Formation. Channelized bodies (right) are extracted bounded by isochron contour values computed between two selected horizons from the HorizonCube. Top and base horizons were identified on section views. The arrow indicates the knick-point of an incised valley that was subsequently filled by transgressive sands (Data courtesy of Statoil).

Figure 4 is a 3D impression of the HorizonCube covering the McMurray Formation in the study area (Brouwer et al., 2011). The workflow described above that involves the 3D HorizonCube slider was applied in this study to extract channelized sand-prone bodies that could be targeted for SAGD development (Figure 5).

Conclusions

Global seismic interpretation techniques based on mapping seismic chronostratigraphy capture a wealth of geologic information from seismic data. The challenge is to unlock this information by mining the data in an intelligent and efficient way.

One solution to the challenge described above is the computation of HorizonCube attributes – a new set of attributes that capture local and global information in a spatial-temporal framework. This is a valuable property that is not available in conventional seismic attributes.

Another solution to this challenge is to use a 3D Slider tool in a workflow that combines 2D and 3D visualization techniques with interactive analysis. The tool allows the interpreter to rapidly scan thousands of auto-tracked horizons.

Global seismic interpretation techniques represent just the starting point for the application of new and innovative interpretation workflows. The result will have a significant impact on future drilling, well and reservoir management strategies.

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