New Methods for Slicing and Dicing Seismic Volumes – Part 1

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Summary

Global seismic interpretation techniques aim to arrive at fully interpreted seismic volumes. "Fully" in this context is misleading as it gives the impression that we are dealing with an end-product and there is no more interpretation to be done. This is not the case. The correlated geologic time lines of these volumes open up new ways to analyze seismic data, thereby increasing our understanding of the depositional history and improving our ability to find stratigraphic traps and build highly accurate geologic models.

In this poster first the link between seismic reflections and geologic time and how this link is used in Wheeler transformations (seismic flattening) is described. Next the HorizonCube algorithm is presented. A HorizonCube consists of a dense set of horizons that are generated by a dip-steered auto-tracker. The vertical separation between horizons in a HorizonCube varies spatially. This feature is exploited in a new set of attributes called HorizonCube attributes. Special about these attributes is that they reveal local information in the context of a globally consistent spatial-temporal framework. Examples are HorizonCube density and HorizonCube thickness attributes which are both useful in in the interpretation of unconformities, condense sections and sedimentation rates.

Furthermore, in this poster an interactive work flow is described that utilizes the geometric shapes of the horizons to extract 3D bodies from the HorizonCube.

Examples of slicing and dicing through a HorizonCube are given in this poster.

Geologic Time

The algorithms behind Global Seismic Interpretation techniques have in common that they aim to correlate seismic positions along geologic time lines to arrive at fully interpreted seismic volumes. Correlating along geologic time lines is doable because seismic reflectors are first order approximations of geologic time lines (Vail et al., 1977). In other words, mapping horizons that follow seismic reflectors is basically equivalent to mapping geologic time.

It should be realized however, that not all seismic reflectors are true iso-geologic time lines. Figure 1 (A) shows a seismic line with a number of stratigraphic surfaces that were mapped using conventional amplitude and similarity trackers. The display in the middle (B) shows geologic time. It was generated by auto-tracking hundreds of horizons by following the pre-calculated dip (see later for details). The bottom display (C) shows the Wheeler transformed seismic data. This display is the seismic equivalent of the geologic Wheeler diagram that maps Stratigraphy versus Absolute Geologic Time. The seismic Wheeler display is constructed by flattening the seismic response along HorizonCube horizons and ordering the flattened response vertically from old to young. The vertical axis thus represents Relative Geologic Time. The gaps represent hiatuses caused by erosion, or non-deposition and condensed sections. The latter are not present in the geologic Wheeler diagram. In the seismic display they occur when auto-tracked horizons follow the same path and jointly get below the seismic resolution.

Note in the Wheeler display how the depocenters continuously shift over geologic time from the land side (left) to the basin side (right) and backwards. Such cyclic depositional patterns are more easily recognized in the Wheeler scene than in the structural domain (A), which makes the Wheeler scene an important instrument for interpreting systems tracts.

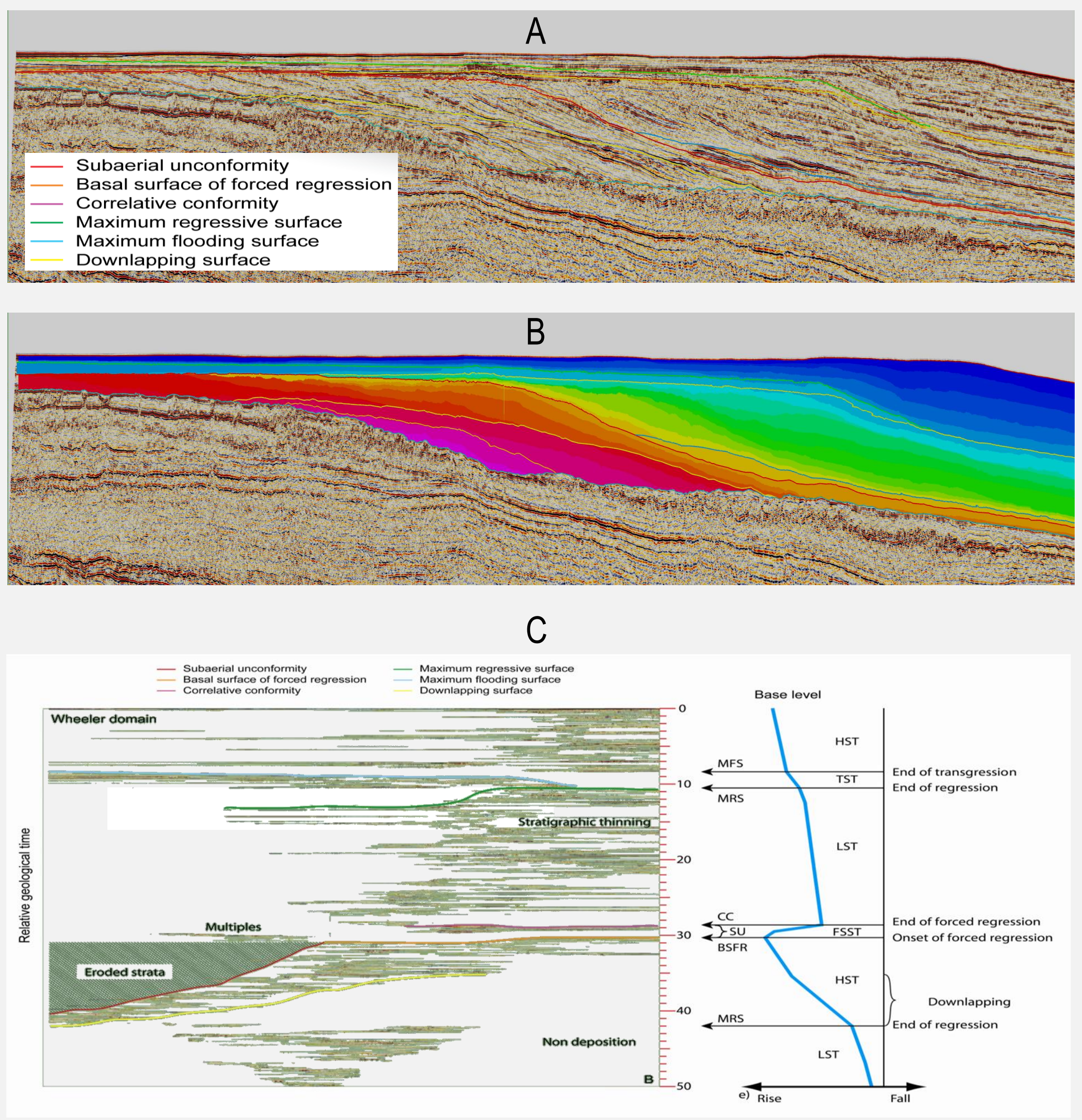

Figure 1 (A) Prograding deltaic sequences with mapped stratigraphic surfaces from the Barents Sea. **(B)** HorizonCube variable density display. Colors represent Relative Geologic Time. **(C)** Wheeler Transformed domain. The interpreted systems tracts (HST=Highstand; TST=Transgressive; LST=Lowstand) were used to reconstruct the relative base level curve (in blue). Note that the subaerial unconformity (red) and the downlapping surface (yellow) are not isochronous lines. All other stratigraphic surfaces are nearly horizontal, meaning they approximate isochronous lines. Data courtesy Statoil.

HorizonCube Processing

The HorizonCube workflow in dGB's OpendTect software is used as starting point. A HorizonCube is defined as a dense set of correlated 3D stratigraphic surfaces. The primary input required to create a HorizonCube is a dip field. The dip field is available in the SteeringCube, a volume with dip/azimuth information at seismic resolution. Previously mapped horizons can be used as boundary constraints. By providing a fault framework as input, any significant faulting will be accounted for in the tracking of the HorizonCube.

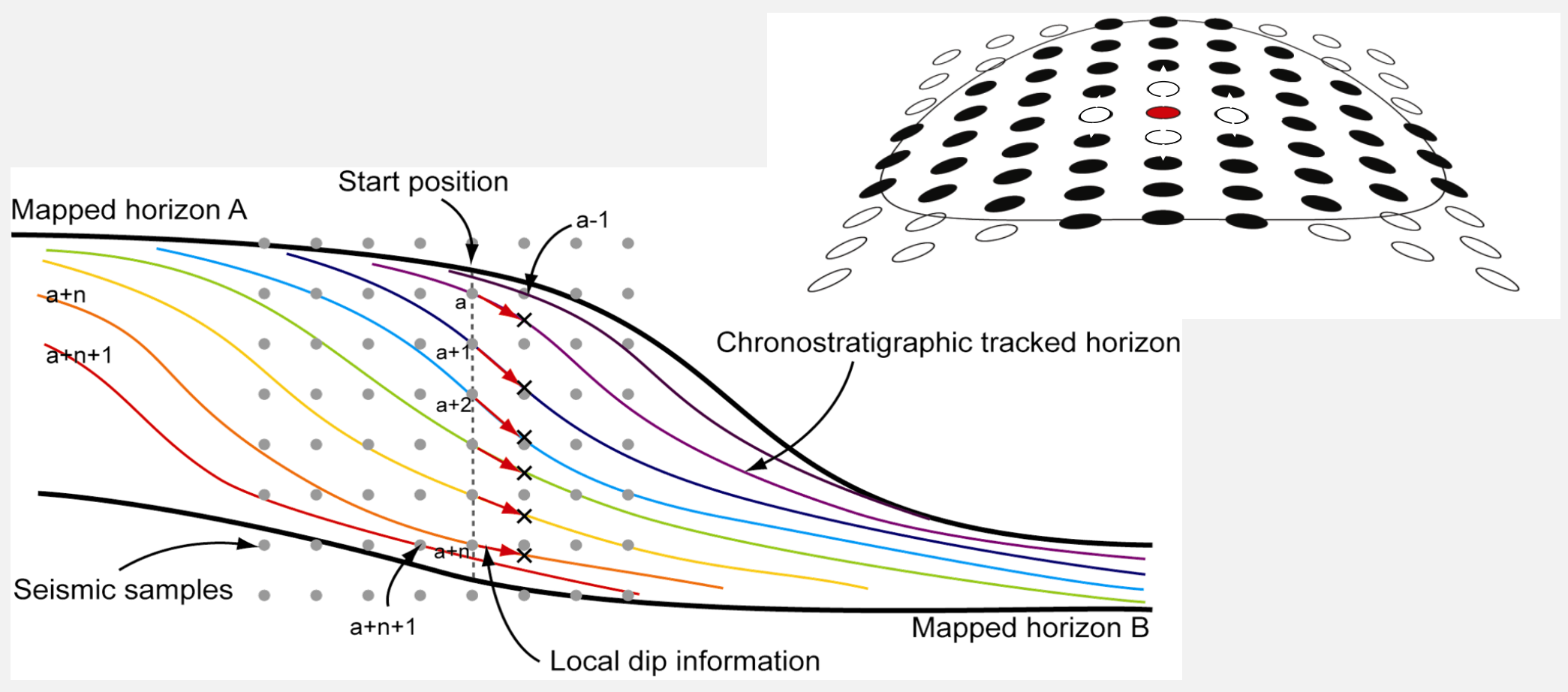

Figure 2 The HorizonCube's dip-steered auto-tracker starts at a user-defined position to simultaneously track a dense set of horizons. The vertical spacing at the starting position is a user-defined parameter. At each starting position the local dip is followed to the next trace (in three dimensions). At the intersection the local dip is updated to proceed to the next trace and so on. If horizons diverge holes are created that are filled in subsequent runs. If horizons come too close together either one horizon stops, leading to a truncated HorizonCube, or both continue along the same path resulting in a continuous HorizonCube.

The dip-steered auto-tracker follows the pre-calculated dip field in the SteeringCube from a seed position to generate hundreds of horizons, each representing a relative geologic timeline (Figure 2; 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 because dip-fields are more continuous. In addition, the effect of noise can be significantly reduced by smoothing the dip field.

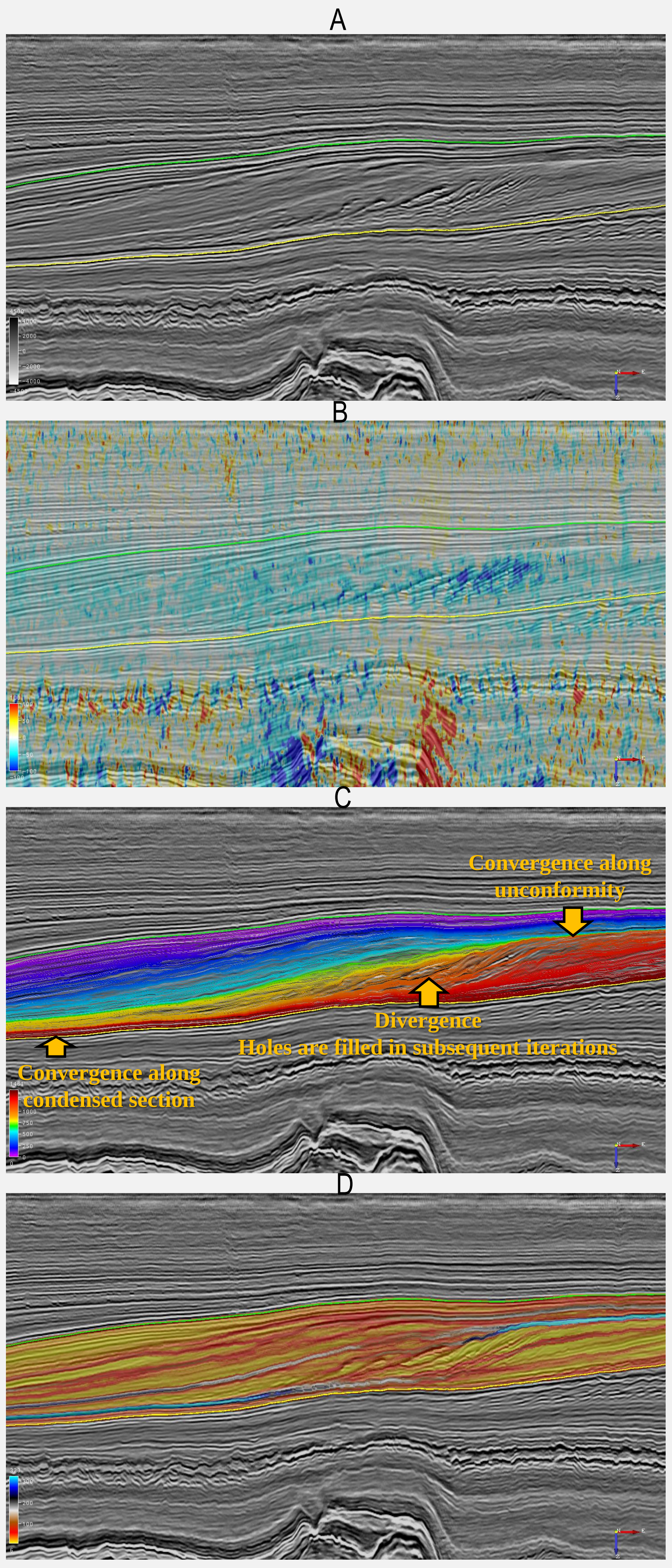

Figure 3 HorizonCube processing workflow. **(A)** Top and Base Horizons are mapped to mark the target interval. Optionally intermediate horizons and major faults are mapped. **(B)** A SteeringCube (with dip-azimuth information at every seismic sample) is computed. **(C)** The HorizonCube auto-tracker is run. In this case it generated a continuous HorizonCube. Holes are filled in by running the algorithm again. **(D)** Optionally, HorizonCube attributes are computed. The HorizonCube density shown here highlights unconformities and condensed sections.

If horizons are extended infinitely a "continuous" HorizonCube is created (Figure 3). Alternatively, horizons can be terminated when they get too close to horizons tracked earlier in the process, creating a "truncated" HorizonCube. In a continuous HorizonCube horizons can diverge, or converge but they can never cross each other. Horizons that diverge will create holes in the HorizonCube that are filled in by iterating the tracking process a few times. Horizons that converge tend to do this along unconformities and condensed sections. In these areas high HorizonCube density indicates zero seismic thickness corresponding to erosion, non-deposition, or very low sedimentation rates (Figure 3D).

A new starting point

Global seismic interpretation techniques, such as the HorizonCube, might be perceived as the ultimate end-product in seismic interpretation projects. This is absolutely not the case. In fact the HorizonCube is an enabling technique and a starting point for new applications and workflows to extract more geologic information from seismic data (de Groot, 2013). Hereafter, two methods are described to support this statement.

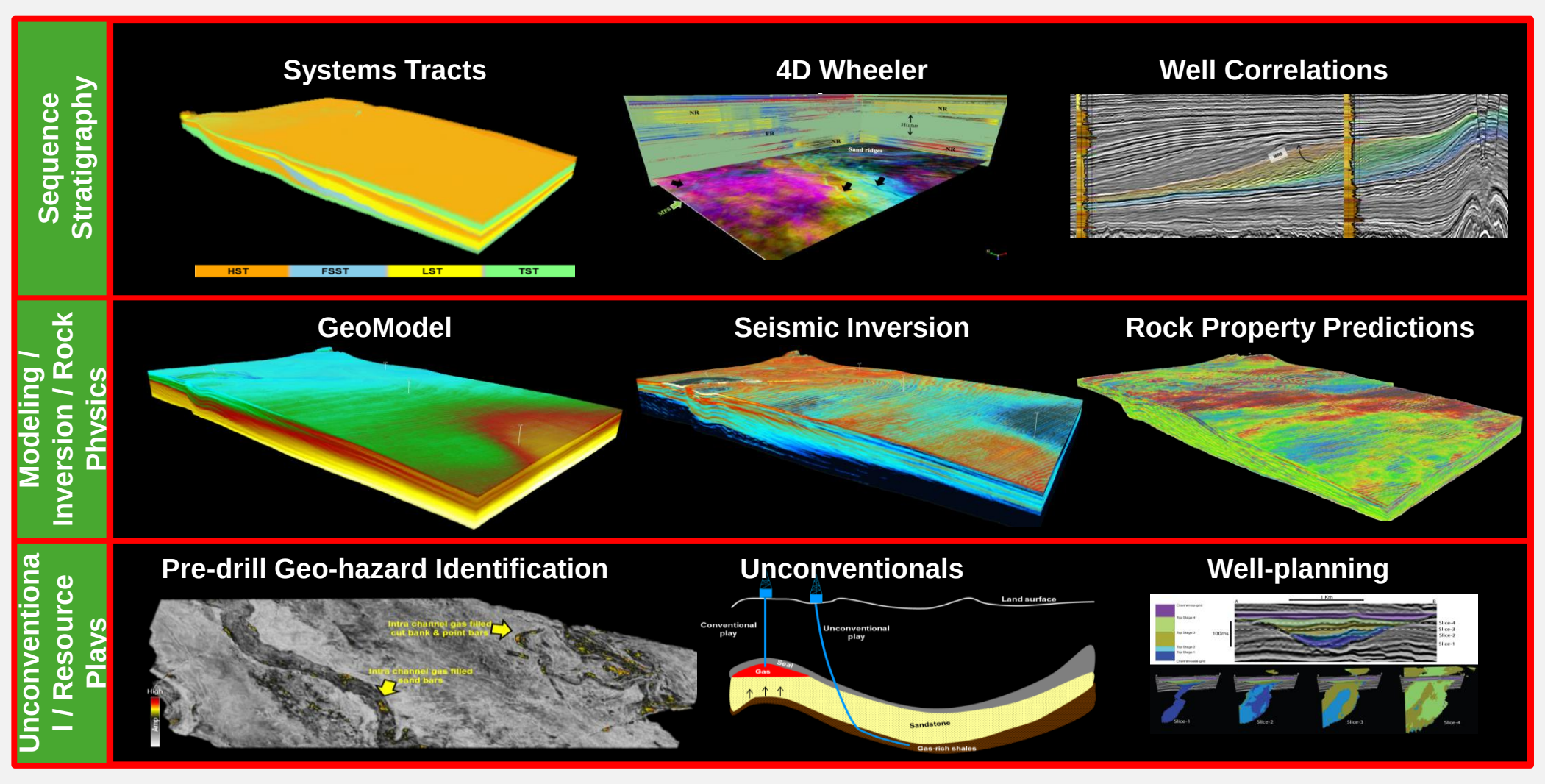

Figure 4 "Fully" Interpreted Volumes are not the end point of a seismic interpretation. Instead these volumes mark a new starting point from which more geologic information can be extracted from seismic data. To fully exploit the wealth of information captured by the geologic time lines new workflows are needed.

A new workflow to extract 3D bodies

At the scale of a typical seismic survey, earth can be considered a set of finite geo-bodies, with distinct shapes and certain dimensions. For example in fluvial-marine environments, a significant petroleum play, an earth model can be constructed from bodies, 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 a wealth of information regarding vertical and lateral extent (or limits) of these depositional patterns in the seismic data at our hands. However, we need to realize that a HorizonCube consists of hundreds, even thousands of auto-tracked horizons. That is a lot of data to analyze, which means that we need new workflows to extract the desired information that is intrinsically captured in the geometry of these horizons.

Here the solution is found in a combination of 2D seismic views, 3D surfaces and interactive controls that allow the user to rapidly scan the data and to identify top and base horizons corresponding to depositional events (Figure 5). A grid of 2D sections remains necessary as interpreters (initially) observe, think and interpret seismic data in 2D. This approach follows the natural way human interpreters work. Moreover, it has the added advantage that, after making a 3D interpretation, the 2D sections serve as quality control.

The calculation speed of modern cpu's and gpu's 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 geologic time lines. The user controls two 3D sliders to select the horizons of interest: one slider selects the top of the interval of interest while the other represents the base (Figure 6). Typically top and base were identified on 2D seismic grids, as explained above, using a 2D slider and HorizonCube attributes such as HorizonCube density (Figures 3 and 5). Now, in the 3D slider module, on-the-fly computation of isopach maps is performed and the results are visualized on one, or on both of the selected horizons. 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 in isopach thickness, or seismic attribute response, depositional events are then converted into bodies for further assessment, property assignment and export to downstream applications, such as reservoir models.

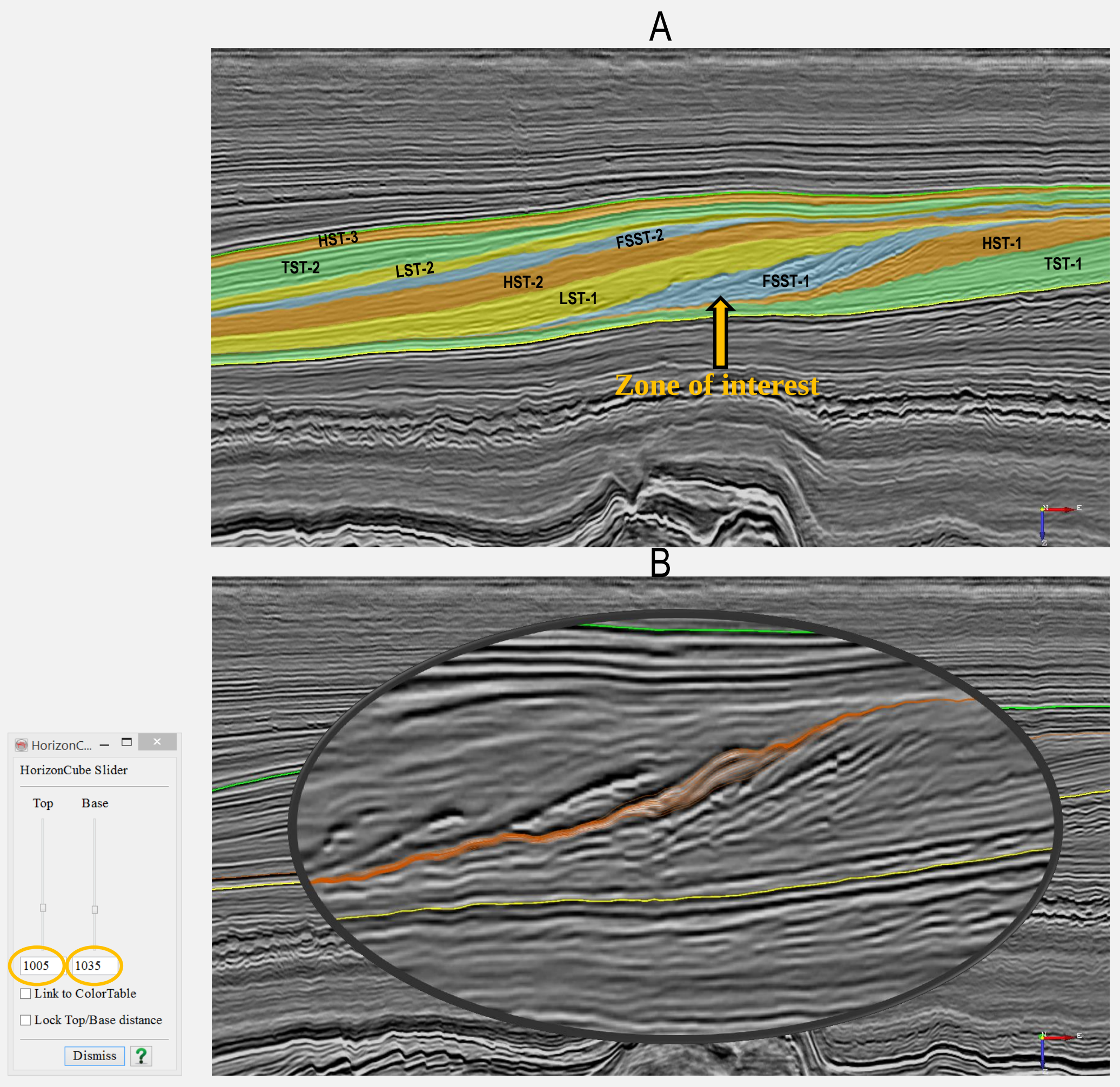

Figure 5 First part of the interactive workflow to extract 3D bodies from a HorizonCube. The 2D HorizonCube slider. **(A)** The user identifies a zone of interest. In this case a Falling Stage Systems Tract (FSST) with slightly elevated seismic amplitudes indicating possibly gas-filled forced regressive sediment lobes. **(B)** An interactive slider is used to identify which horizons mark top and base of one of the forced regressive lobes.

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New Methods for Slicing and Dicing Seismic Volumes – Part 2

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A new workflow to extract 3D bodies (Cont.)

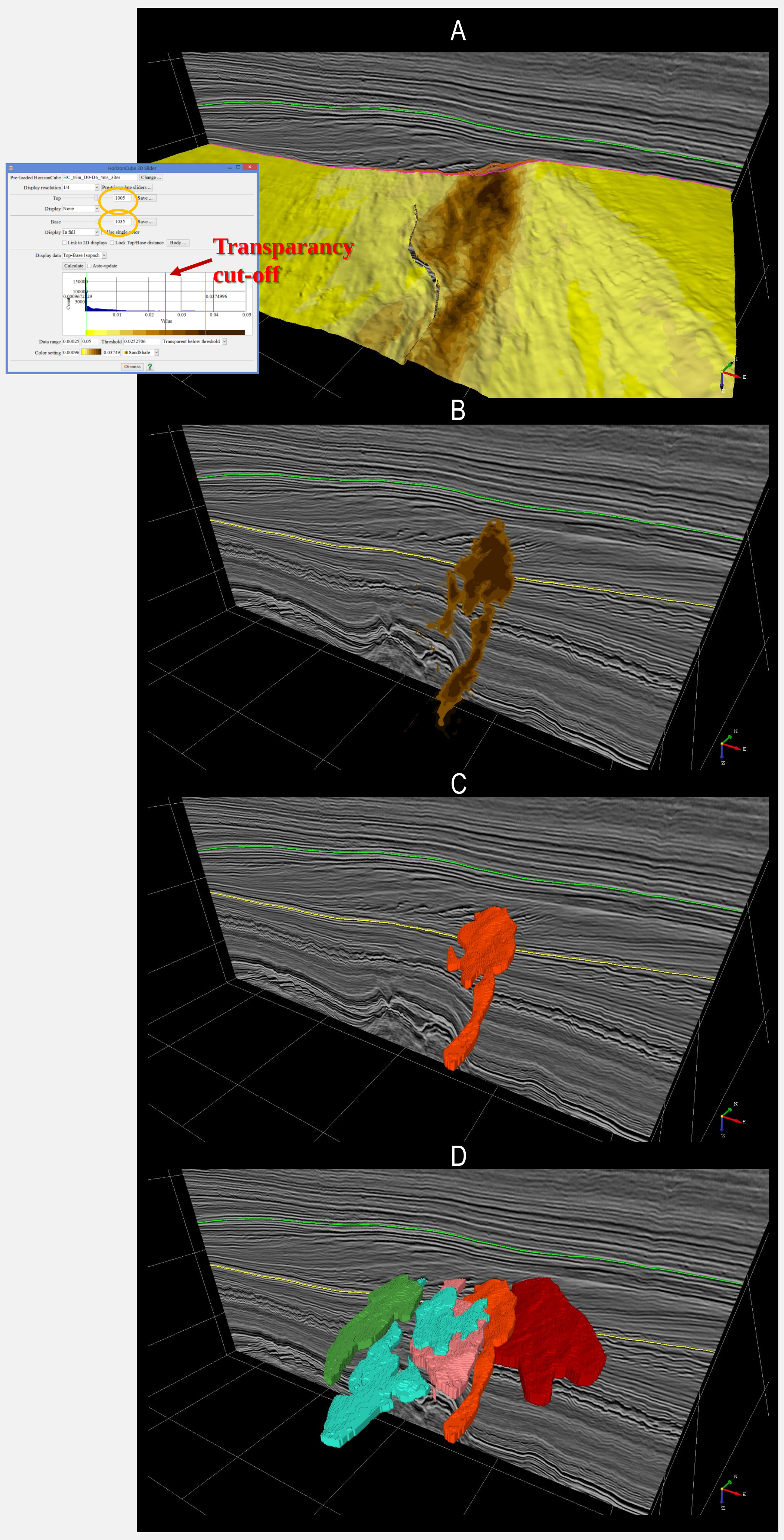

Figure 6 Part 2 of the interactive workflow to extract 3D bodies from a HorizonCube: the 3D HorizonCube slider. **(A)** Two sliders are positioned at the identified top and base of the feature of interest. Between these two events the isopach thickness (or alternatively a seismic attribute) is computed and displayed in the 3D scene. **(B)** A thickness (attribute) cut-off value is needed to create a 3D body that is bounded by top and base horizon and the cut-off contour value. To find the optimal cut-off contour value an interactive slider is moved through the isopach histogram. Values below the threshold value (red bar) are made transparent in the 3D scene. **(C)** The body is created. **(D)** All forced regressive lobes in the falling stage system tract are extracted in the same way.

Example – HorizonCube Attributes

HorizonCube density inversely relates to sedimentation rate. Horizons near the depocenter of a particular depositional feature are spaced widely apart. Moving away from the depocenter horizons converge until the point that they effectively snap together into a single bundle in areas of non-deposition or erosion. Figure 7 shows a seismic line from East Africa. The interval of interest is oil-bearing in the landward direction to the left. The HorizonCube density attribute gives a clear overview of the depositional architecture. High density (slow deposition rate or erosion) is shown in warm (red) colors while low density (high deposition rate) shows up in cold (blue) colors. The marked areas in the middle of the section are interpreted as back-stepping deep water fan deposits.

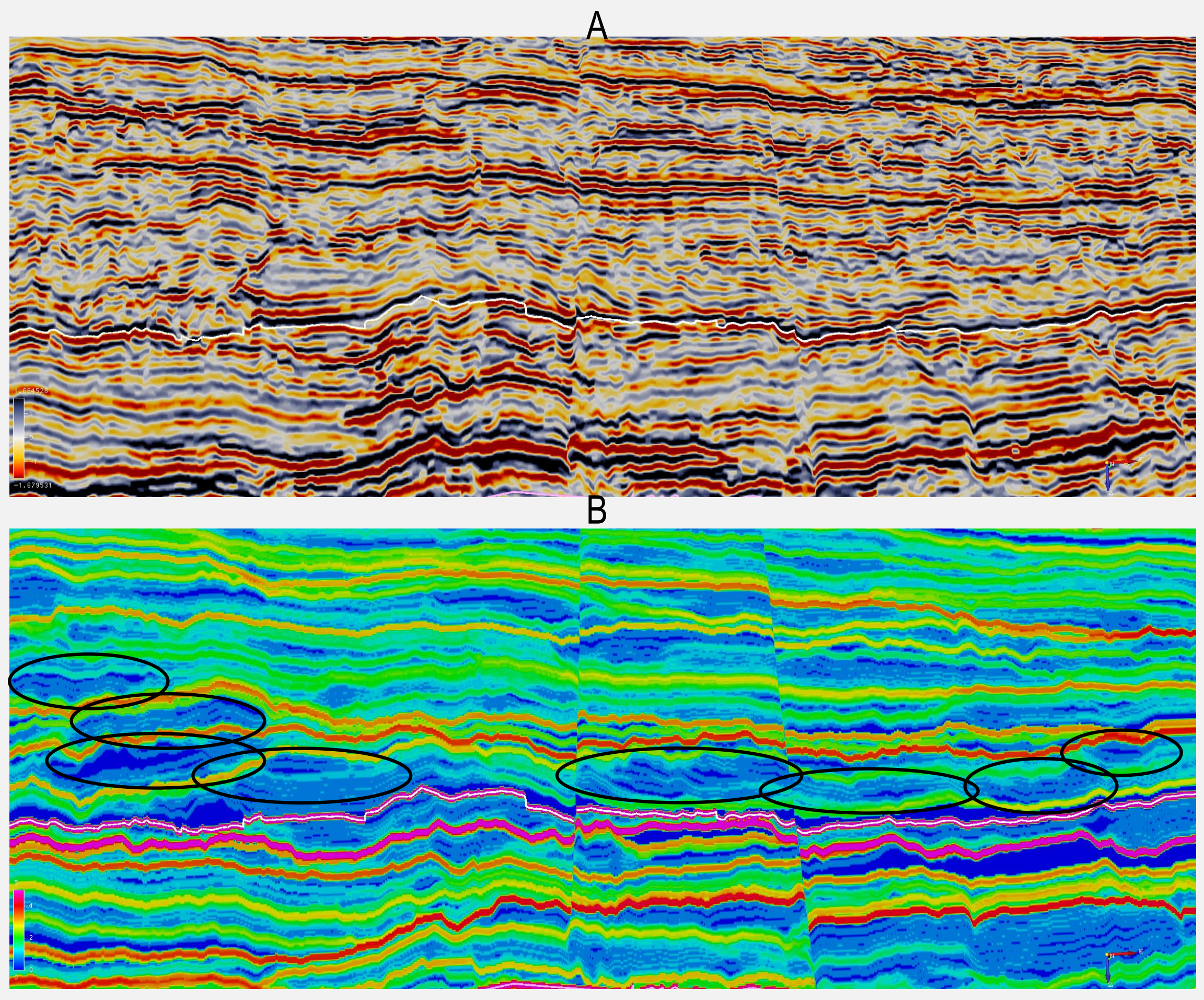

Figure 7 (A) Seismic section and equivalent HorizonCube density attribute **(B)** from deep water East-Africa. Hot colors represent high HorizonCube density and condensed sections, blue colors represent low HorizonCube density and expanded sections with high depositional rates. The HorizonCube density attribute provides a clear view of the depositional architecture, easily identifying several mounded features in a back-stepping configuration. Data courtesy: ION Geophysical.

Example - Slicing

The power of geo-slicing is demonstrated with a deep-water geo-hazard interpretation project offshore East Africa (Bouanga et al., 2014). To date eight exploration well site locations have been assessed for shallow hazards using the HorizonCube methodology. The main motivation for using the HorizonCube in this example was to accurately map the complex shallow section around the proposed well locations.

The present seabed is characterised by active canyons and this depositional environment is reflected in the cross-cutting channelized and turbiditic deposits evident in the shallow seismic. Interpretation of the appropriate hazard level associated with high amplitude features within the shallow section is significantly enhanced by the ability to slice through volumes along horizon slices. Potential connection between sand–prone channels and deep-seated faults that could provide a gas migration pathway can also be studied. These can be further risked based on potential pinchout, isolation of sand bodies within encasing shales and/or conformance of sand bodies to structure. Looking for anomalies in the Wheeler domain increases the interpreter's understanding of the spatial distribution and timing of sediment deposition. Attributes can be flattened to assess shallow hazards, such as: gas-filled shallow channels, fluid and lithology variation relating to seismic amplitude, pockmarks, bottom simulating reflectors, and faulting or truncations based on similarities. Windowed amplitude extractions are recommended to take account of any imperfections in the HorizonCube.

Wheeler transformed attribute volumes create less interpretation ambiguity compared to time (or depth) slices, or parallel to seabed slices (Figure 8).

This is because the HorizonCube follows gross dip in a truly 3D sense. By using the Wheeler domain it becomes possible to see many stratigraphic details which can help increase understanding of the depositional environment and better analyse shallow hazards.

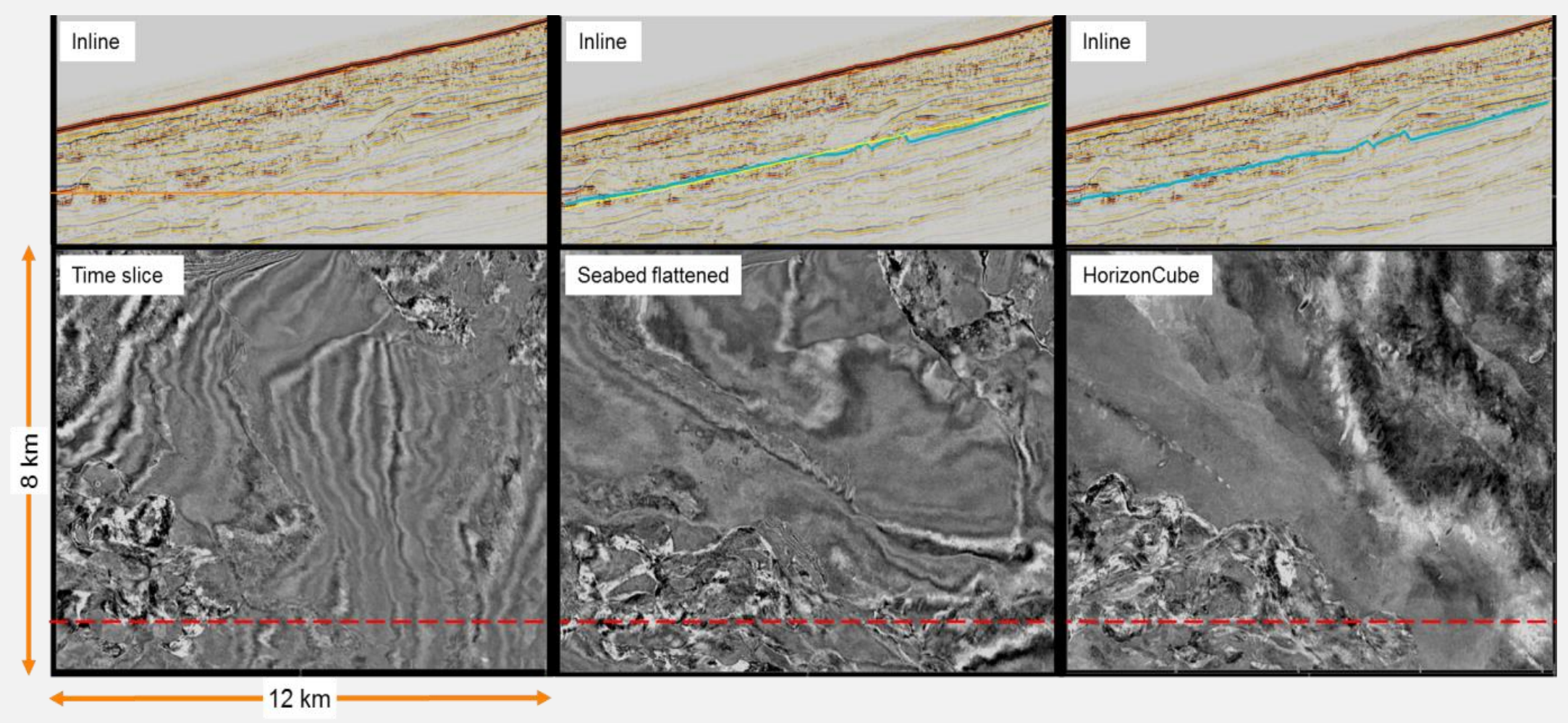

Figure 8 A comparison between time slice, seabed flattened and HorizonCube amplitude extractions. The location of the inline is shown by the red dashed line. Indicated on the inline section (top left) bright amplitudes are seen, but understanding their geometries is not straightforward on a time slice (bottom left). A seabed parallel extraction (middle bottom) shows that these amplitudes are associated with a complex channel system. The HorizonCube slice clearly shows this complex channel system. Data courtesy BG Group.

In Figure 9 a sequence of pseudo-stratigraphic amplitude slices are shown from an 8 km by 12 km volume for one of the drill site locations. The slices are extracted from the 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 through every pseudo-stratigraphic slice. As a result of these studies intended well sites have moved to safer locations.

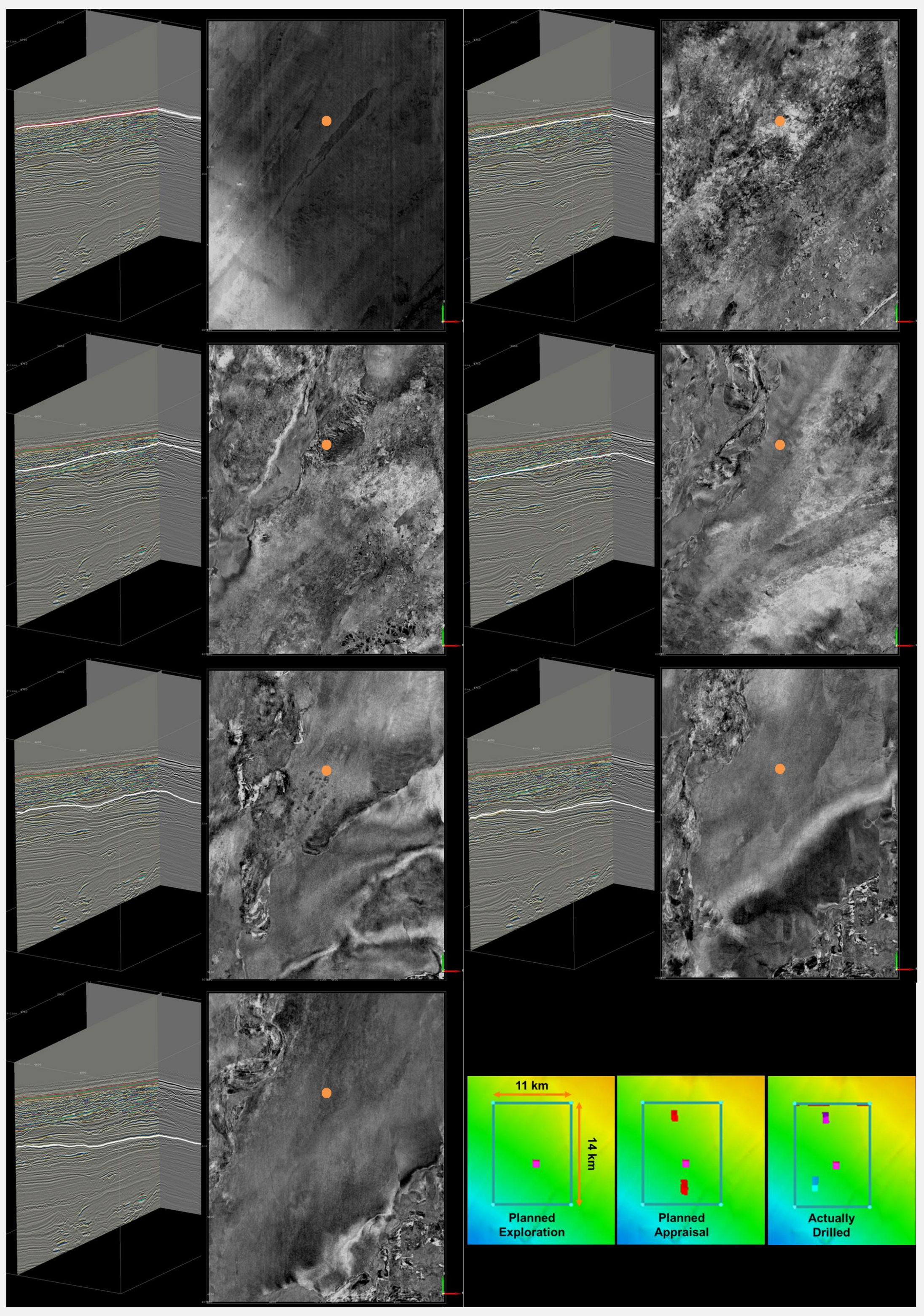

Figure 9 A sequence of horizon amplitude extractions every 20 horizons from a continuous HorizonCube are shown. The 3D seismic display on the left of each horizon slice shows the location within the 3D volume. A possible well location is shown by the orange circular marker. Preliminary scanning of this suite of horizons can be used to identify potential shallow hazards of interest. For example, a meandering channel system 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 BG Group.

Example - Dicing

The McMurray Formation represents a fluvial estuarine depositional system, hosting rich bitumen and water-sand reservoirs. 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 % to 30 % (Tonn, 2010). The sands are inter-bedded to varying degrees with muds. Depending on the depositional environment, the muds can be localised or extended over large regions.

Oil is produced by Steam Assisted Gravity Drainage (SAGD), which 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, geometry of the reservoir (including top and base of the SAGD pay interval and thickness), distribution and 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 understanding reservoir heterogeneity.

Figure 10 is a 3D impression of the HorizonCube covering the Murray Formation (Brouwer et al., 2011). The work flow described above that involves 2D and 3D HorizonCube sliders was applied in this study to extract channelized sand-prone bodies that could be targeted for SAGD development (Figures 11-12).

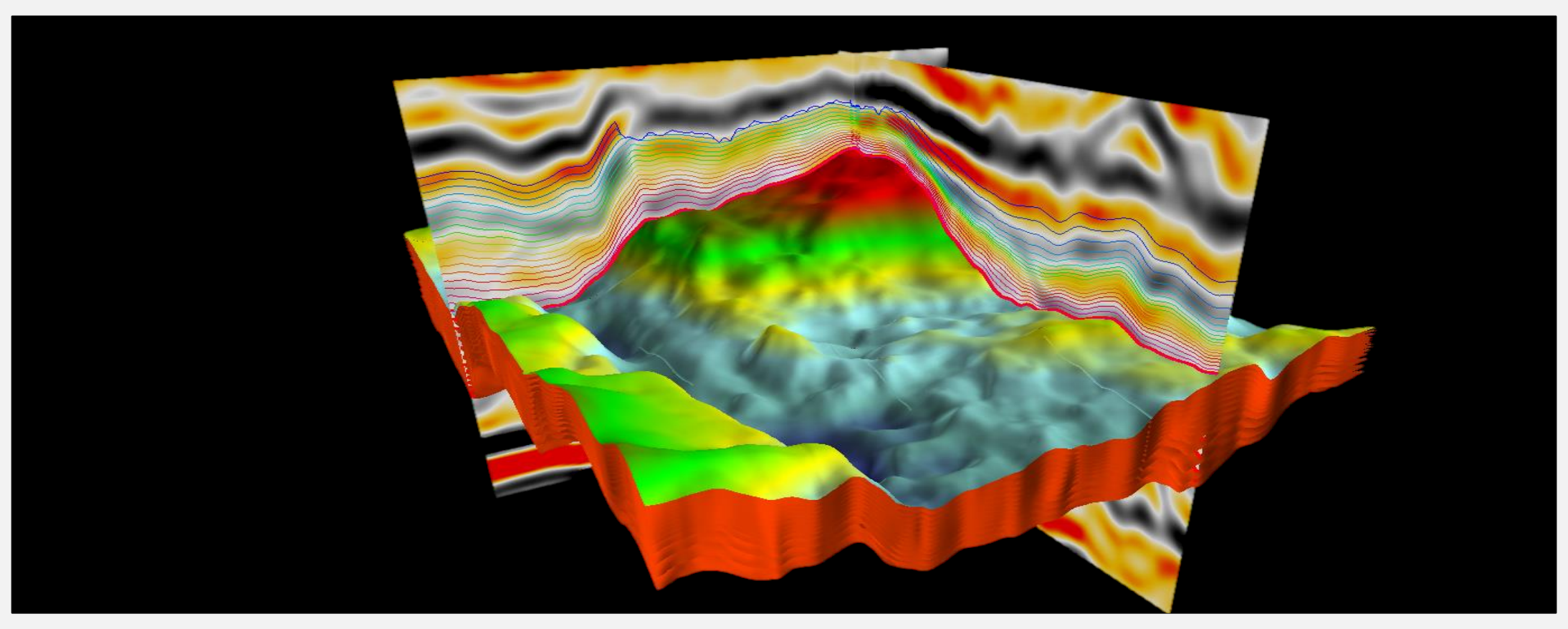

Figure 11 A 3D impression of the HorizonCube covering the Murray Formation. Data courtesy Statoil.

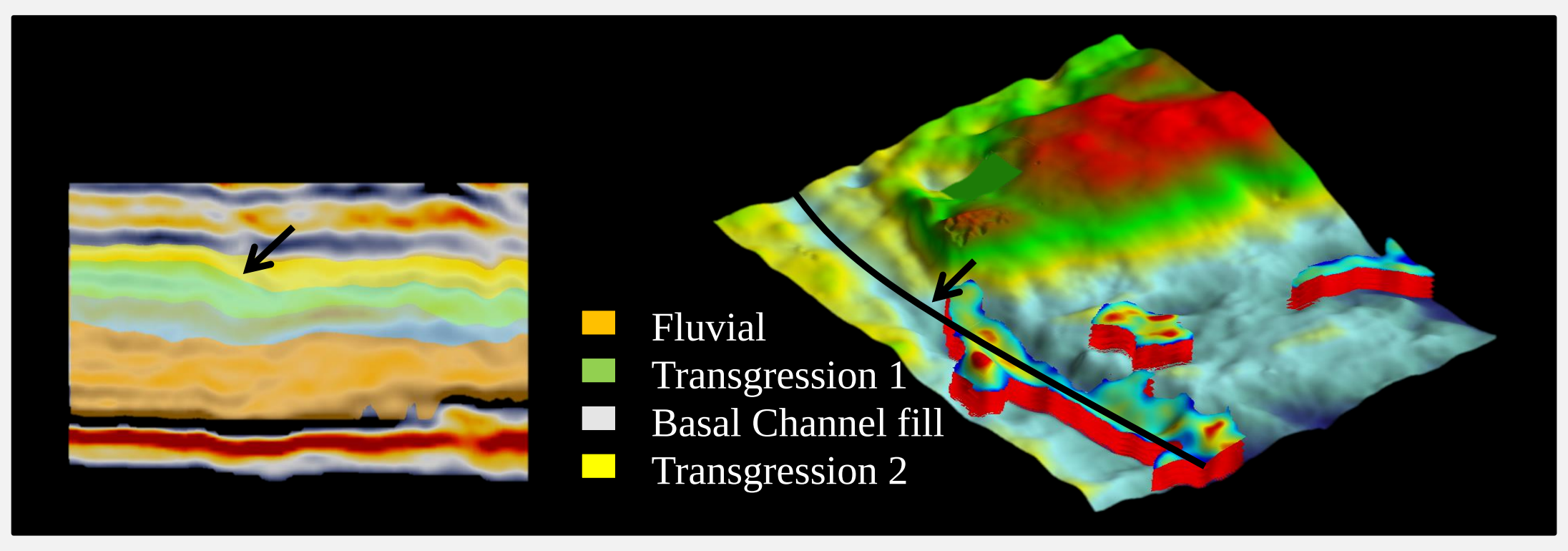

Figure 12 Extracted channelized bodies bounded by isopach thickness contour values computed between two selected horizons from the HorizonCube. Top and base horizons were identified on section views. The arrow indicates the knick-point of an incised valley that was subsequently filled by transgressive sands. Data courtesy Statoil.

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