Seismic Stratigraphy Gets a New Perspective

Farrukh Qayyum[1], Jan Stellingwerff[1], Victoria Romanova[1], Brad Macurda[2] and David Smith[3]
dGB Earth Sciences[1], The Energists[2], StrataData[3]

Introduction

From denser sampling in space and time through to better algorithms to remove unwanted noise and image data, and the introduction of sophisticated attributes and visualization technologies, the last few years have seen significant advances in seismic acquisition, processing and interpretation technologies.

One of the most significant developments in seismic interpretation today, however, has been in providing a new perspective to stratigraphic interpretation using 3D seismic data.

The ability for interpreters to utilize 3D seismic data sets and examine the three dimensional nature of a stratigraphic unit has provided an increased knowledge of the subsurface. This has also been supported by modern sophisticated algorithms that have helped interpreters slice through the seismic data in a stratigraphic fashion(Stark et al., 2013; Qayyum et al., 2013; de Groot, 2013). The result is that the interpreter is able to look through time and space simultaneously, providing crucial input to the identifying of stratigraphic traps.

In this paper, we summarize several methods that have emerged around seismic stratigraphy and are today routinely used interpretation methods for seismic interpreters.

Advanced Interpretation Methods

Since the advances in 3D seismic technologies, four main interpretation methods have evolved. These are:

1. **Dip-Steering** which influences the majority of modern seismic interpretation techniques such as post-stack filtering, seismic attributes, gridding and horizons tracking etc. The Horizon Cube, for example, consists of a dense set of horizons that are generated by a dip-steered auto-tracker.
2. **Semi-Automated Stratigraphic Interpretation** that supports both geological and geophysical modeling in seismic interpretation from sequence stratigraphy to Wheeler transformations and stratigraphic attributes.
3. **Trend Logs**, that can identify hidden trends in wireline logs, can easily be integrated with the semi-automated stratigraphic interpretation results. Trend Logs are a valuable tool for performing integrated sequence stratigraphy on seismic datasets.
4. The final interpretation technique involves Geobodies based on Connected Voxels. This acts as an addition to volume interpretation in connecting geobodies of common responses within a sequence stratigraphic unit.

This article will examine these four advanced interpretation methods, starting with dip-steering.

Dip-Steering and its Applications

Dip-Steering is a technique that extracts dip and azimuth information from seismic data and is an old method that began with structural interpretation and post-stack filtering (Tingdahl and de Groot, 2003; Chopra and Marfurt, 2007). It progressively evolved into stratigraphic interpretation and today forms the basis of a host of new applications, such as post-stack filtering, dip-steered seismic attributes, dip-steered gridding, and horizons tracking.

Post-Stack Filtering

In the post-stack domain, reflectors' continuities and discontinuities can be enhanced through dip-steered filtering (Brouwer and Huck, 2011). Conventionally, this is carried out in two steps. The first step aims to extract regional dip-azimuth information from the seismic data with the dips stored in a volume (SteeringCube) containing dip-azimuth.

The second step involves a set of seismic attributes and their evaluation to achieve two objectives: smoothing of seismic reflectors and fault enhancements. Reflectors are smoothened by applying a median (statistical) filter on seismic amplitudes along a Steering Cube. Replacing low data quality values with neighboring values of better data then enhances the faults. This is also performed along a Steering Cube. Figure 1 illustrates the results of post-stack filtering on original seismic.

Dip-steered Seismic Attributes

Conventional seismic attributes are calculated in a window without any geological information. Dip-steered seismic attributes overcome such issues by calculating seismic attributes along the dips. As a result, one starts observing geological oriented patterns rather than artefacts. Most of the multi-trace seismic attributes can be made dip-steered while computing statistics in a given sub-volume. Common examples of dip-steered attributes are similarity,

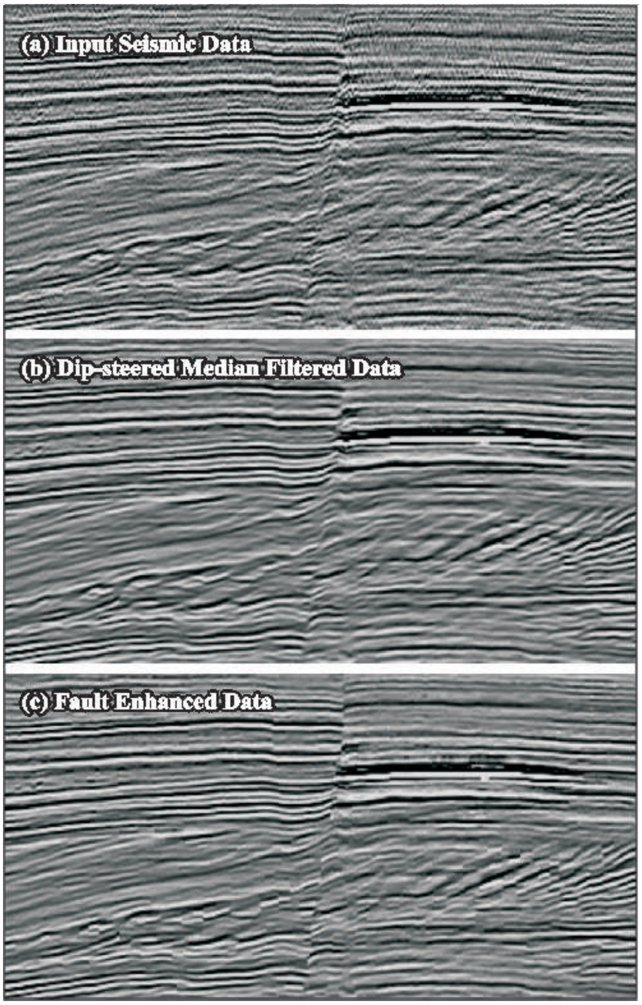

Fig. 1: An example seismic section is showing the results of post-stack filtering: (a) original, (b) dip-steered median filtered data (c) and fault enhanced datasets.

texture, statistics perpendicular to dip etc. An example of dip-steered vs. conventional similarity is shown in Figure 2.

Dip-steered Gridding

In 3D seismic data sets, especially for larger 3D surveys (>1000 Km^2), seismic horizons are mapped in a grid e.g. a grid spacing of 5 or even 10.

If the data allows, the interpretations are auto-tracked and are gridded using conventional gridding algorithms such as inverse distance, triangulations, convergent gridding, etc. This mostly produces unreliable results and reliable seismic attribute analysis can not be performed.

Dip-steered gridding on the other hand helps in accelerating seismic interpretation for such datasets and produces superior data-driven gridding results. The algorithm behind such gridding uses inputs such as horizon interpretation performed in a loose grid (e.g. 50 or even 100 steps), fault planes, and a pre-computed SteeringCube to produce a horizon grid in 3D.

Figure 3 illustrates one example taken from North Sea (Base Tertiary). The interval was loosely interpreted at a grid spacing of 1 Km (40 inline steps). The horizon is then dip-steered gridded, thereby preserving the details in three dimensions and generating superior results when compared to a section view.

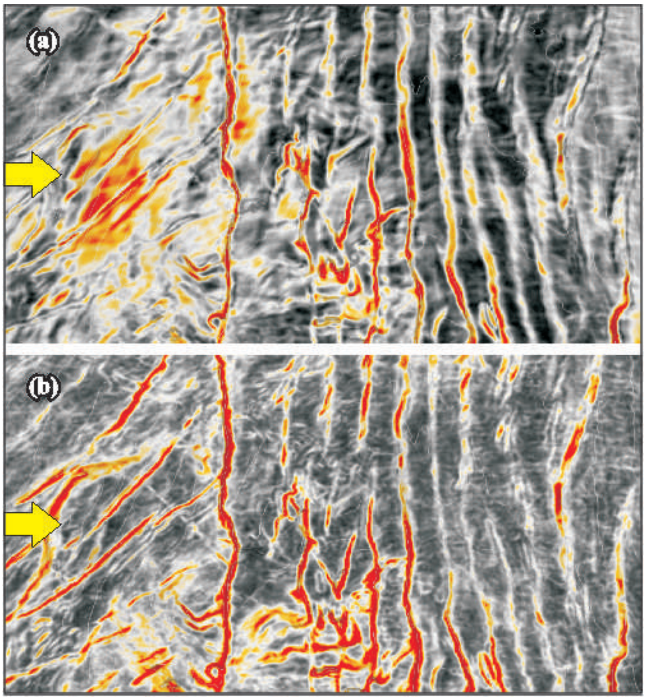

Fig. 2: A horizon slice for (a) non-steered similarity and (b) dip-steered similarity. Note that the dip-steered similarity is essentially showing correct definitions of the fault patterns.

Semi-Automated Stratigraphic Interpretation The HorizonCube

The second advanced seismic interpretation technique discussed in this paper is semi-automated stratigraphic interpretation. One example of semi-automated interpretation using dip-steering and which generates a number of crucial attributes is dGB's HorizonCube.

The HorizonCube is a set of densely mapped seismic horizons within a zone of interest. These horizons are automatically tracked between a given set of framework horizons and faults. The tracking is done using SteeringCube (see also Qayyum et al., 2013).

There are two types of HorizonCube: Continuous and Truncated. In the continuous HorizonCube, horizons stay together when they converge and never cross each other. Such horizons consist throughout the area of computation and thus help in defining near-zero isochron regions between two horizons to highlight unconformities and condensed sections. This type is useful in 3D attributes visualization and reservoir modeling.

In a truncated HorizonCube, a horizon may stop when it meets another horizon in space based on a user-defined threshold (see Qayyum et al., 2014 for further illustrations on the differences and applications of the two types of Horizon

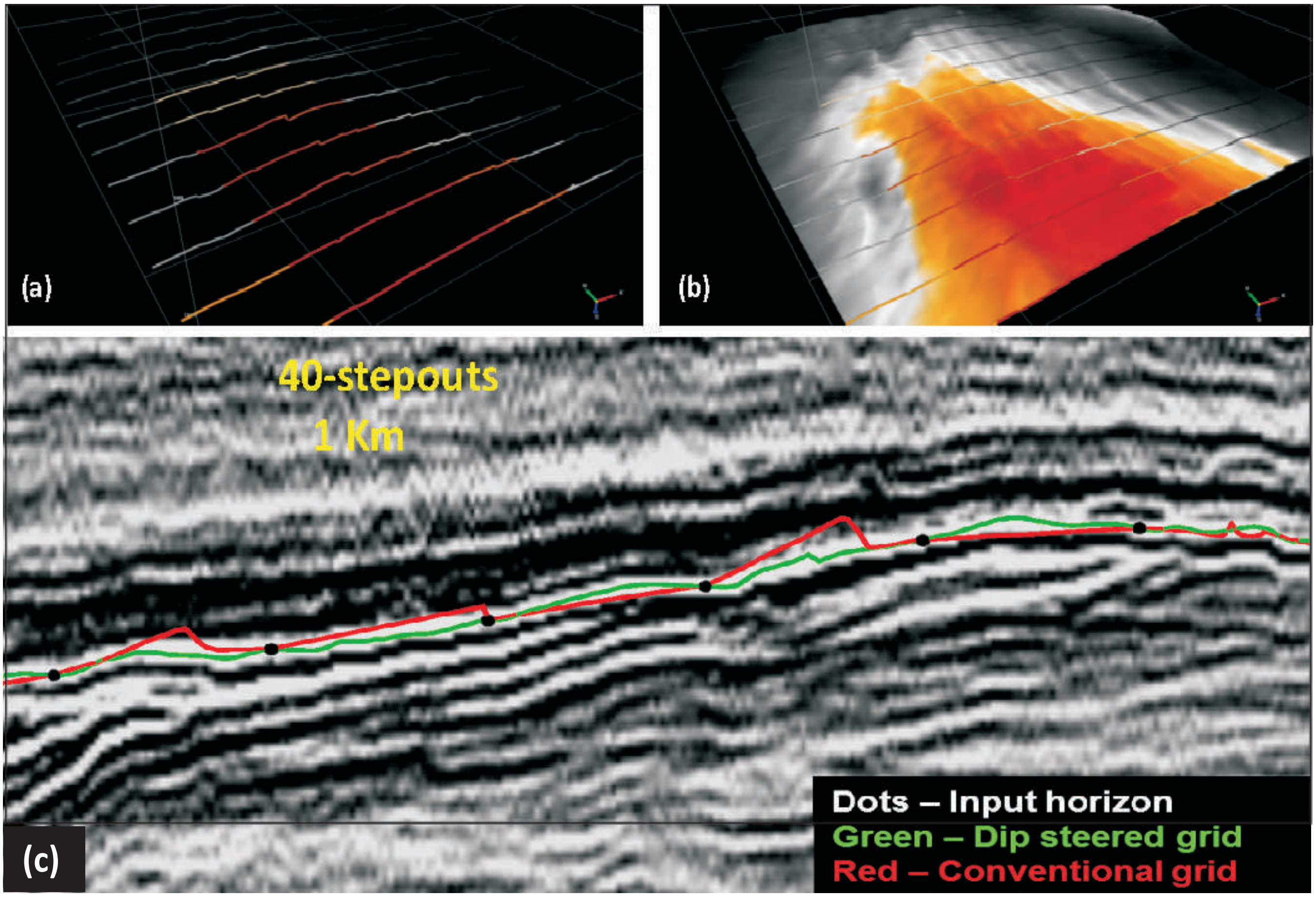

Fig. 3: An example of dip-steered gridding: (a) sparsely-interpreted seismic horizon;(b) its dip-steered grid; and (c) seismic section with comparison of conventional and dip-steered gridding.

Cube). Such type of Horizon Cube helps in identifying stratigraphic lapouts (onlaps, downlaps and toplaps). The latter type is also useful to create Wheeler diagrams and perform sequence stratigraphic interpretation.

4D Wheeler Transformations

Wheeler diagrams form the heart of sequence stratigraphic interpretation. However, these diagrams mostly reflect area-time instead of space-time relationship of a stratigraphic unit (Qayyum et al., 2012; 2014).

This advantage of preparing complete Wheeler diagrams is that one can adequately identify the causes of depositional shifts in 3D (Figure 4). These diagrams are becoming routine practices in seismic stratigraphic interpretation. However, these diagrams are mostly prepared for 3D seismic datasets. The applications of these diagrams in case of outcrops and full calibration to an absolute geological time scale require further work.

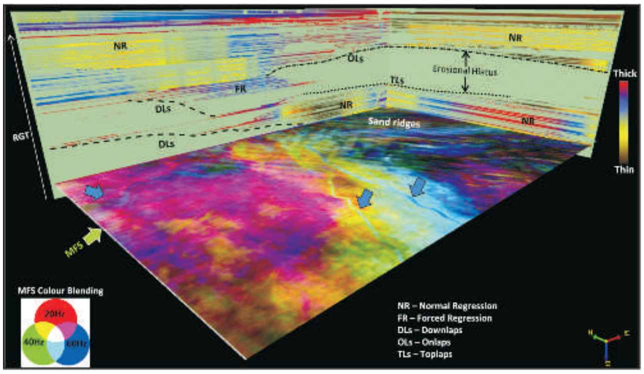

Fig. 4: An illustration for 4D Wheeler Diagram allowing a comprehensive investigation of depositional environments in space and their development through geologic time. The systems tracts isochron attribute display on sections (or volume) helps define a unit completely (space-time). The horizontal slice (colour blended spectral decomposition responses) represents a particular depositional surface (maximum flooding surface) along which detailed patterns are enlightened.

New Stratigraphic Attributes Derived from the HorizonCube

From a continuous Horizon Cube a new family of attributes can also be computed that help to visualize geologic features that have previously remained hidden in the seismic data. These attributes can be computed directly from the Horizon Cube.

Such attributes include: *Event Thickness* attribute (highlighting not only sedimentary bodies but also local pinch-outs, condensed intervals and local unconformities); *HorizonCube Density* attribute that helps define the zones of pinch-outs, condensed sections and unconformities; *Arbitrary Layers* that divide mapped seismic horizons into fix layers with a unique ID for each layer; and *Derivatives* that can measure subtle geometrical changes and discontinuities. Table 1 provides an overview of such attributes, definitions and applications.

In our experience we found the HorizonCube density, Unit IDs, and isochron volumes are the most important seismic attributes for stratigraphic exploration (Figure 5).

Table 1: A brief summary of new stratigraphic attributes.

Attributes	***Definition and Applications***
HorizonCube Attributes	***No up-front interpretation is required.***
HorizonCube Event Thickness	Isochron thickness between two consecutive HorizonCube events. This attribute highlights sedimentary bodies but also picks up local pinch-outs, condensed intervals and local unconformities.
HorizonCube Dip	Geometrical 3D dip attribute computed from the HorizonCube. This dip tends to be smoother than the dip computed directly from an input SteeringCube. It helps define structural and geomorphologic features.
HorizonCube Curvature	Represents a family of 3D volume curvature attributes (eleven sub-attributes) that are computed from the HorizonCube. This attribute can also be used for delineating structural and geomorphologic features.
HorizonCube Density	A measure of number of HorizonCube events per time gate. It is a single trace based attribute. High-density values correspond to horizons convergence. These are indicative of pinch-outs, condensed sections and unconformities. Low-density values correspond to divergence, suggesting relatively thicker deposition and/or preservation.
HorizonCube Layers	This attribute divides a HorizonCube into fix layers with a unique ID for each layer. A HorizonCube generally consists of hundreds of horizons. Visualizing all of them in 3D can be very slow and laborious. This attribute can be used for quality control visualization purposes.
Instantaneous Derivatives	First or second derivatives on a set of HorizonCube events to understand local geological changes. They can also be extended to perform a derivative on an isochron between a given range of events from a HorizonCube. These attributes are used to measure subtle geometrical changes and discontinuities. The latter application is more practical than a simple time derivative.
SSIS Attributes	***These are defined after performing stratigraphic interpretation.***
Common ID	It assigns a common number to each interpreted sequence stratigraphic unit (sequence, systems tract or a parasequence). For instance, if three highstand system tracts are interpreted using a HorizonCube, all three units will have one common number. The common ID is also an identifier of stratigraphic interpretation with the attribute used to volume render a particular systems tract with seismic property cubes, or to apply mathematical and logical manipulations per system tract to build a better reservoir model.
Unique ID	It assigns a unique number to each sequence stratigraphic unit (sequence, systems tract or a parasequence), counting from top to bottom. Each unit will always have only one ID for the entire HorizonCube. This attribute can also be used in visualization and geobodies extraction or to perform stratigraphic and reservoir modeling.
Isochron	It is a sequence stratigraphic unit thickness. The unit of this attribute depends on the seismic survey type (TWT or in depth). This is a key attribute to understand how sedimentation filled a sedimentary basin as a function of geologic time.
Relative Rate of Preservation	It is the ratio between a SSIS Isochron volume and a known geologic time-span for a particular unit. The results are relative measurements of rate of preservation per geological time unit. This attribute is a key geologic quantity. For good confidence, this attribute requires a good calibration of HorizonCube with well data (chronostratigraphy, biostratigraphy, paleontology etc.).
Isochron Differences	An attribute that defines the difference between two isochron grids as a volume at a certain trace location. Numerically, it can be expressed as: Isochron Difference = Unit A thickness - Unit B thickness. It has an additional application compared to the isochron volume per systems tract. It can be used to qualitatively differentiate an overlying unit from an underlying unit. This helps to build an understanding of deltaic lobes switching, by-pass and relative rate of sediments preservation within a given spatiotemporal framework.
Preserved Volume per Unit	An attribute that is derived from an isochron and the spatial area that a certain stratigraphic unit covers. Numerically, it is a product of isochron and preserved area after deposition. If an interval is structurally distorted, the exact volume can only be obtained after structural restoration.

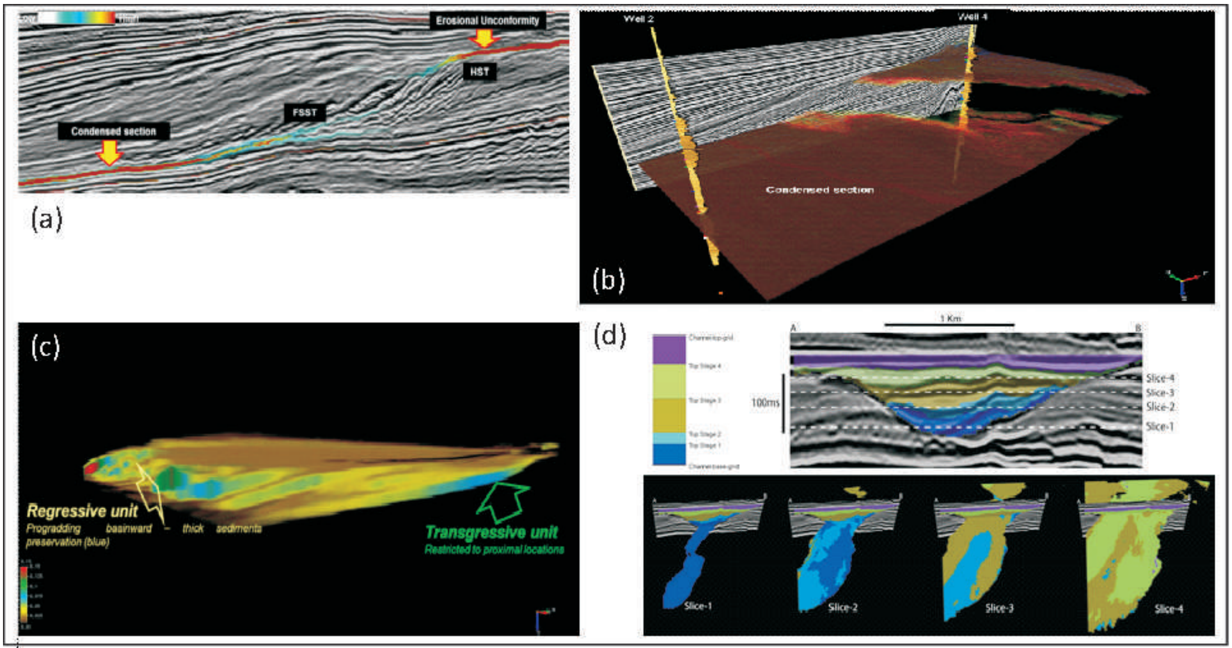

Fig. 5: An illustration for key stratigraphic attributes evolved. (a) HorizonCube Density attribute is overlain on a seismic section;(b) the same attribute is displayed in 3D; (c) extracted isochron volume; and (d) the results of slicing performed through interpreted sequence stratigraphic units.

Slicing and Dicing

Geologic information can also be unlocked through new methods for dicing and slicing seismic volumes. Based on HorizonCube, this can be achieved through the attributes described above and a 3D Slider - a workflow that combines 2D and 3D visualization techniques with interactive analysis.

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

The calculation speed of modern CPU's and GPU's allows the interpreter to use interactive 3D sliders - Horizon Cube based sliders that slice through the seismic data in a geologically meaningful way, i.e. by slicing along (relative) 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.

In the 3D slider module, on-the-fly computations of isopach maps are 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 geobodies for further assessment, property assignment and exported to downstream applications, such as reservoir models (Figure 6).

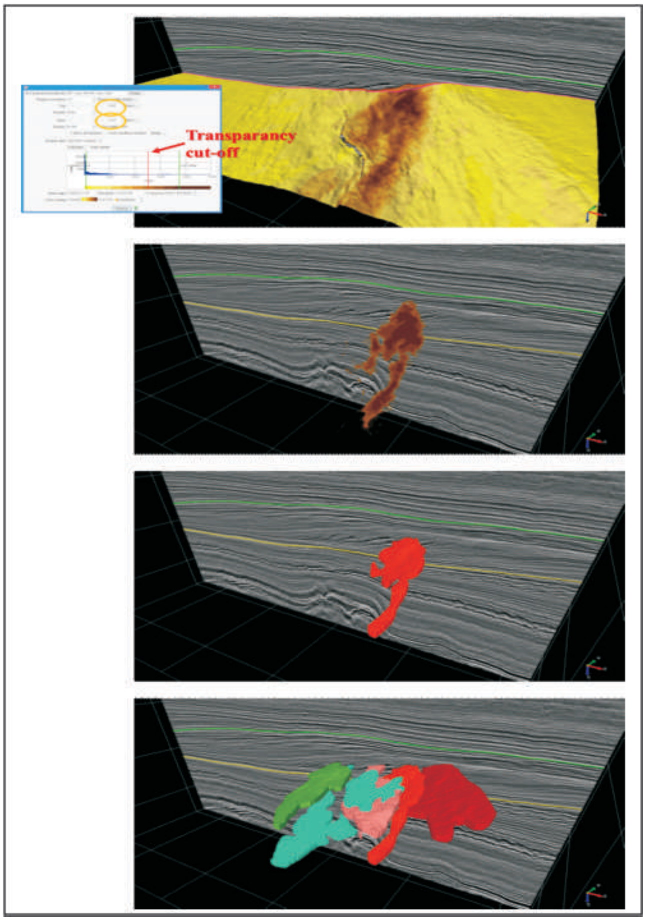

Fig. 6: An example of geobodies extraction: (a) isochron map of a package delineated using 3D slider; (b) the same map with thinner area clipped; (c) a geobody extracted using RMS amplitude attribute, and (d) geobodies extracted within neighboring packages.

Trend Logs

Seismic interpretation without incorporating well information can often be cryptic. Trend logs - the third advanced seismic interpretation technique - are therefore crucial tools for performing sequence stratigraphic interpretation and integrating with the HorizonCube.

Such logs have a tendency to enlighten a transgressive-regressive nature of an observed stratigraphic section (Figure 7). A reliable stratigraphic framework can be built if these logs are integrated with care along with the stratal stacking patterns observed using HorizonCube.

Qayyum and Smith (2014) illustrated a figure taken from a Middle East carbonate section, which shows an improvement in lithostratigraphic results based on the observed trends of tens of kilometers. They also showed its integration with the seismic data and Wheeler transformation (see Figure 5 in Qayyum and Smith, 2014).

Geobodies Based on Connected Voxels

For the exploration phase of hydrocarbon production cycle, it is essential to get as close as possible to the real-world architecture of a reservoir. Conventional methods of seismic interpretation, such as the analysis of tracked surfaces, are not sufficient for spatial modeling of an object. In recent decades, visualization of geological features has been performed as part of a three-dimensional solution by extracting geobodies within a seismic volume. This approach found its application in different geological areas - one of them being sequence stratigraphic interpretation.

There are several methods of creating geobodies. The one that is shown in this article called *Voxel Connectivity Filter* (from a 'voxel' being defined as a cell in a seismic volume with a given threshold/ranges of a seismic attribute). The filter uses user-defined amplitude selection to compute geobodies. The samples interconnection is computed based on an amplitude criteria and geometrical spreading settings. It is a very useful tool that can visualize important features of hydrocarbon reservoir characterization as 3D geobodies. An essential benefit of this tool is that it allows getting a volume of several bodies and visualizing them in 3D or using it as an input to supervised neural network.

Figure 8 shows high amplitude connected bodies within the Paleocene interval of the Porcupine basin. These bodies are developed during the enlargement of the delta in the Porcupine basin and development of fan complexes. The bodies contain bright amplitudes due the presence of porous channelized sands(For further details, refer to Johannessen and Steel, 2005; Ryan et al., 2009).

Discussion & Conclusions

In this article, we summarize some of the key interpretation techniques that have emerged around sequence stratigraphy and which are today providing interpreters and operators with a more complete understanding of the subsurface.

We have described in detail at the interpretation techniques of Dip-Steering, Semi-Automated Stratigraphic Interpretation, Trend Logs, and Geobodies based on Connected Voxels and how methodologies, such as HorizonCube can generate new sets of attributes and rapidly scan thousands of auto-tracked horizons using a new 3D slider.

It is clear that these specialized interpretation techniques represent just the starting point and give a new perspective to

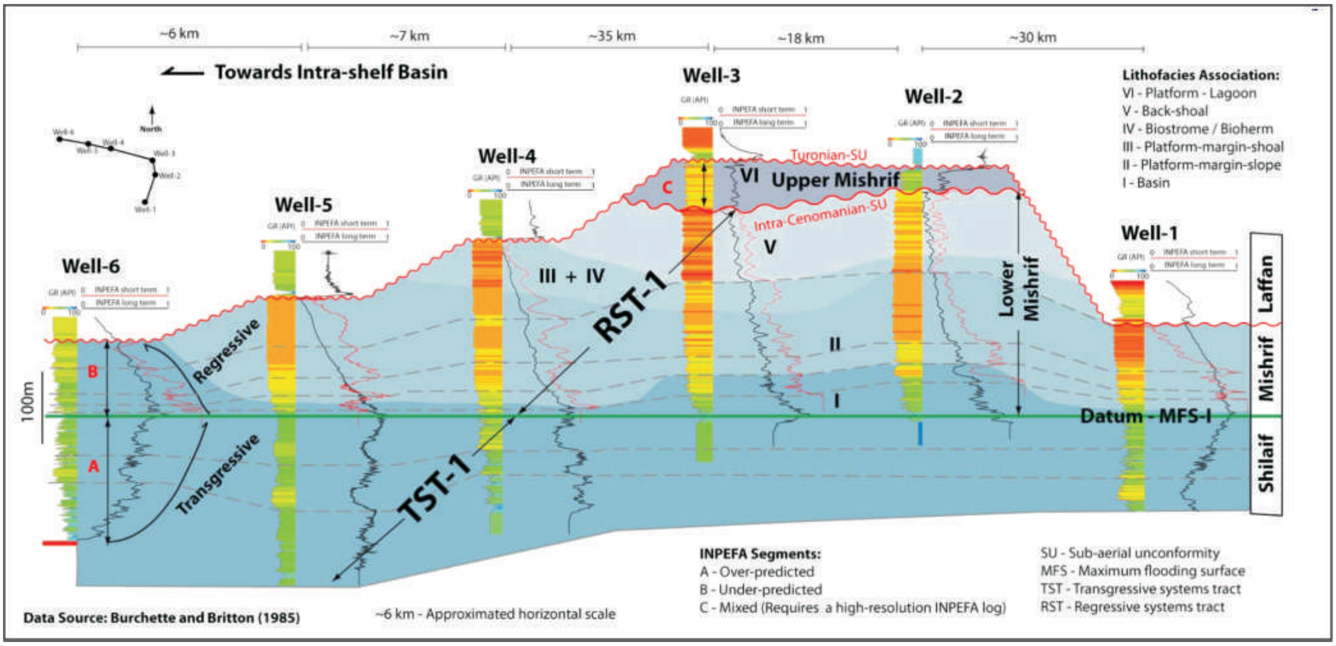

Fig. 7: Trend logs interpretation (Middle East) showing correlated transgressive and regressive units.

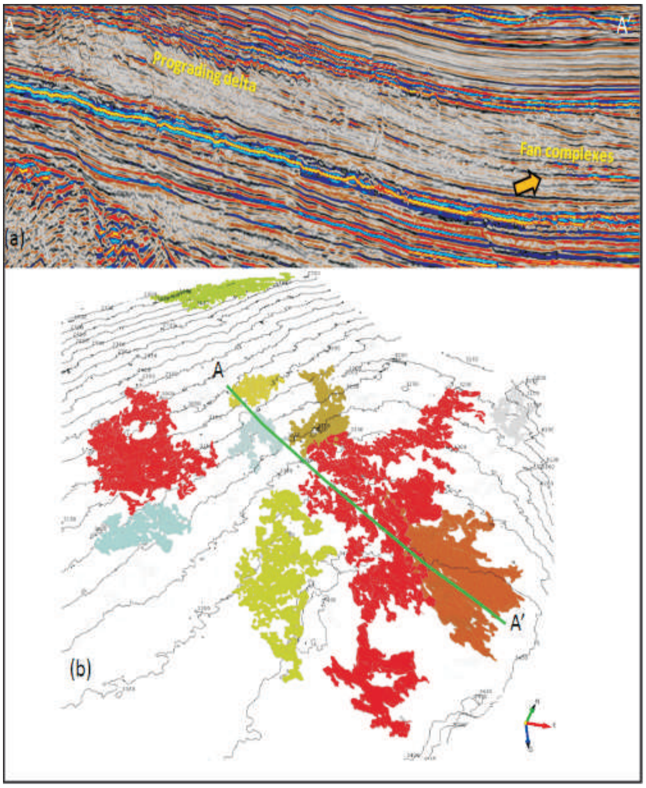

Fig. 8: Seismic section (a) showing high amplitude bodies located within overall low amplitude package and (b) geobodies extracted using RMS amplitude criteria.

seismic stratigraphy. Once these techniques become common, one would start seeing a significant impact on future drilling, well and reservoir management strategies.

References

Brouwer, F., and A. Huck, 2011, An Integrated Workflow to Optimize Discontinuity Attributes for the Imaging of Faults: GCSSEPM p. 496-533.

Burchette TP, Britton SR (1985) Carbonate facies analysis in the exploration for hydrocarbons: a case study from the Cretaceous of the Middle East. Geol Soc Lond Spec Publ 18:311-338. doi: 10.1144/GSL.SP.1985.018.01.13

Chopra, S., and K. J. Marfurt, 2007, Seismic Attributes for Prospect Identification and Reservoir Characterization: SEG Books, 518 p.

De Groot, P., 2013, Global Seismic Interpretation Techniques are coming of age: DEW Journal, p. 41-47.

Johannessen, E. P., and R. J. Steel, 2005, Shelf-margin clinoforms and prediction of deepwater sands: Basin Research, v. 17, no. 4, p. 521-550, doi:10.1111/j.1365-2117.2005.00278.x.

Qayyum, F., P. de Groot, and N. Hemstra, 2012, From 2D to 4D Wheeler Diagram, in Strata and Time: Probing the Gaps in our Understanding, London, England: Search and Discovery, p. 1-3.

Qayyum, F., P. F. . De Groot, N. Hemstra, and O. Catuneanu, 2014, 4D Wheeler diagrams: concept and applications: Geological Society, London, Special Publications, v. 404, p. SP404.1, doi:10.1144/SP404.1.

Qayyum, F., N. Hemstra, and R. Singh, 2013, A Modern Approach to Build 3D Sequence Stratigraphic Framework: Oil and Gas Journal, v. 111, no. 10, p. 46-65.

Qayyum, F., and D. Smith, 2014, Integrated sequence stratigraphy using trend logs and densely mapped seismic data: First Break, v. 32, no. 12, p. 75-84.

Ryan, M. C., W. Helland-Hansen, E. P. Johannessen, and R. J. Steel, 2009, Erosional vs. accretionary shelf margins: the influence of margin type on deepwater sedimentation: an example from the Porcupine Basin, offshore western Ireland: Basin Research, v. 21, no. 5, p. 676-703, doi:10.1111/j.1365-2117.2009.00424.x.

Stark, T. J., H. Zeng, and A. Jackson, 2013, An introduction to this special section: Chronostratigraphy: The Leading Edge, v. 32, no. 2, p. 132-138, doi:10.1190/tle32020132.1.

Tingdahl, K. M., and P. F. M. de Groot, 2003, Post-stack dip- and azimuth processing.: Journal of Seismic Exploration, v. 12, no. 2, p. 113-126.

Author's Profile

Farrukh Qayyum

Farrukh Qayyum is Senior Geoscientist at dGB Earth Sciences a company he has been at for over eight years. Farrukh has published numerous papers and has MSc and M Phil in Geology and Geophysics from Quaid-e-Azam University in Islamabad.

Jan Stellingwerff

Jan Stellingwerff Beintema is Executive Vice President Asia - Pacific and a Geoscientist with over 30 years of experience in various aspects of geology, geophysics and reservoir evaluation. He is specialized in the petrophysical interpretation of full-waveform sonic data. He also became involved in the marketing and commercialization of in-house geophysical software package. He holds Msc in geology from Polytech' Montpellier. From 2006 to 2011 Jan was based in Enschede as Senior Sales Manager.

Victoria Romanova

Since 2014, Victoria Romanova has been working at dGB Earth Sciences in the position of geoscientist participating in the sequence stratigraphic interpretation projects within the G&G team. Victoria graduated from Kazan State University in Russia in 2010 with an MS equivalent in geophysics. Prior to joining dGB, she also worked for oil and gas service company, TNG-Group, dealing with 2D and 3D seismic interpretation within the Libyan and Volgo-Ural Russian basins.