3D geologic modelling of channellized reservoirs: applications in seismic attribute facies classification

Renjun Wen,[*] president and CEO, Geomodeling Technology, presents a new methodology for modelling stratigraphic heterogeneity in channellized reservoirs.

Geological models are usually used qualitatively in seismic interpretation. This paper illustrates that quantitative representations of detailed geological models can significantly enhance seismic attribute interpretation through facies classification. When applying seismic attribute classification to reservoir facies mapping, one often faces such typical questions as:

- Which attributes should be used as input to classification?
- How many classes should be used in the unsupervised classification method?
- How many levels of hierarchy should be selected in the hierarchical classification method?
- Does the seismic facies correspond to the geological facies?
- How can attribute-derived facies models be validated?

There are no unique and easy answers to the above questions. In this study, we aim to create a more accurate representation of the reservoir by using 3D synthetic Earth models to guide seismic attribute classification. We consider a channellized reservoir for which seismic attribute analysis has proven to be very useful, but results can be difficult to interpret. The next section describes a 3D stratigraphic modelling approach for the channellized reservoir. The major channel components and parameterizations are illustrated with examples. This is followed by a summary of seismic attribute analysis and classification workflow applied to a synthetic seismic volume. Results of attribute classifications using a self-organized map (SOM) (Kohonen, 1989) and waveform correlation maps are compared in relation to different input attributes and classification parameters. The lessons learned from this synthetic example are summarized and the selection of attributes for facies classification is discussed.

3D stratigraphic models of channellized reservoirs

There are several computer-based methods to build 3D reservoir model flow simulations, such as object-based methods or cell-based geostatistical methods (Dubrule and Damsleth, 2001). However, none of these methods are able to reproduce stratigraphic heterogeneity patterns at sub-seismic scale, which can be major controlling factors for fluid flow and spatial variations of acoustic properties. In this paper we report a new modelling method to generate 3D stratigraphic architectures of channellized reservoirs. The method is an extension of the bedding structure modelling method developed by Wen et al. (1998) and is being further developed in the SBED Joint Industrial led by Geomodeling Technology. The stratigraphic features within channellized reservoirs to be modelled in this study are below the resolution limit of conventional seismic data. The cell size is about 20 x 20 x 1 m^3. At such a modelling scale, detailed geological features must be modelled, based on their formation process so that their 3D structures can be correctly represented in the geological model.

Models of single channel geometry

A channel's 3D geometry at any given time in its development can be parameterized by its platform and section parameters. The channel platform location is represented by its central line. This line can be a sine-wave or a list of points that are digitized based on seismic data or a conceptual model, or simulated from

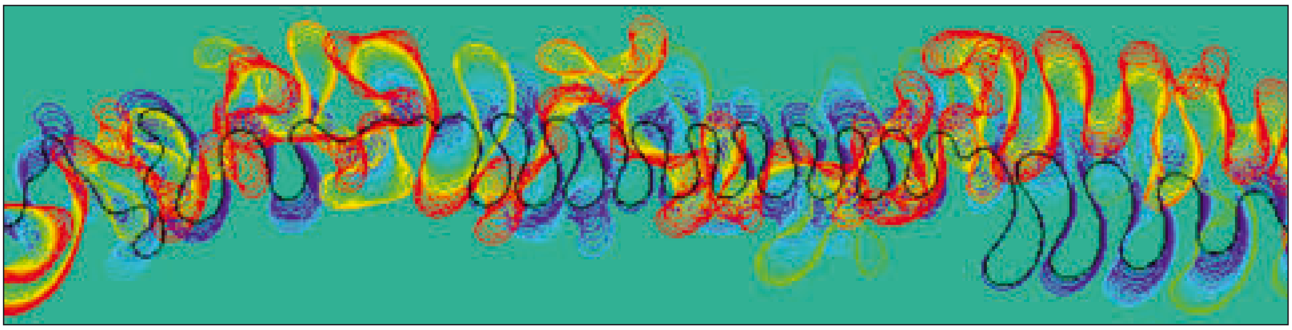

Figure 1 *Meandering channel central lines used for 3D modelling in channellized reservoir.*

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[*] *renjun@geomodeling.com*

other programs, such as the meandering channel central lines shown in Figure 1.

The section parameters (Figure 2) of a channel include: 1) maximum depth, 2) width, 3) asymmetrical index, and 4) shape factors. These four parameters normally vary along the central line. This variation can be modelled based on deterministically derived rules (e.g. the steep side of the channel must be on the outer band), rules specified by a trend (e.g., channel depth decreases or increases in a certain direction), or rules with a stochastic component (e.g. a one-dimensional Gaussian random function parameterized by a variogram model, mean, and standard deviation). A surface representing the top of a channel system is constructed based on the channel-central line, its section parameters and the levee parameters describing the decay of elevation as a function of distance away from the channel central line (Figure 3).

Modelling components of channel deposits

What we regard as a channellized reservoir is formed by channel deposition, migration and erosion processes during its 'active' time. While these processes can be very complicated and involve both physical and chemical processes, we only modelled the geometrical aspects in our computer model. This is justified because our modelling objective is to reproduce a realistic 3D stratigraphic framework at the sub-seismic scale. We modelled channel deposits using four components (Figure 4):

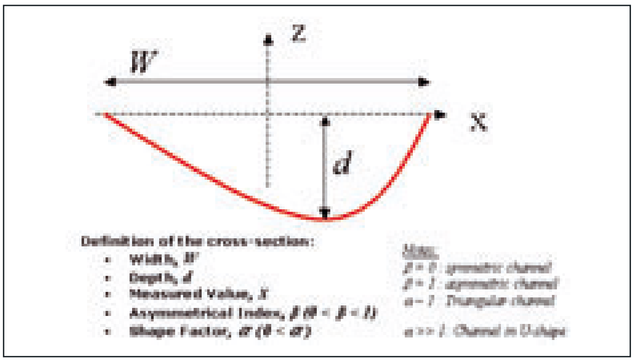

Figure 2 *Channel section parameters: maximum depth, width, asymmetrical index, and shape factors.*

Lateral accretion: These are point bar deposits formed by lateral channel migration. The lateral accretion is further modelled by four sub-components: channel lag deposits in the bottom, cross-bedded sandstone in the middle, ripple laminated sandstone on top, and shale layers. Lateral accretions that have shale layers are called inclined heterolithic stratification (IHS) and are usually formed in tidal influenced channel systems. Figure 5 shows an example of lateral accretion simulated by SBED.

Abandoned channel fill: These deposits occupy the last remaining spaces in the channel when it is abandoned (Figure 4). Depending on the geological setting, the abandoned channel fill pattern can be quite different.

Overbank deposits: These are regarded as background facies in the modelling software. These include crevasse splays.

Channel boundary layers: To model the transmissibility between channel deposits and background facies or other channels, our channel model can include two types of boundary layers within the channel deposits (Figure 4): a layer below all

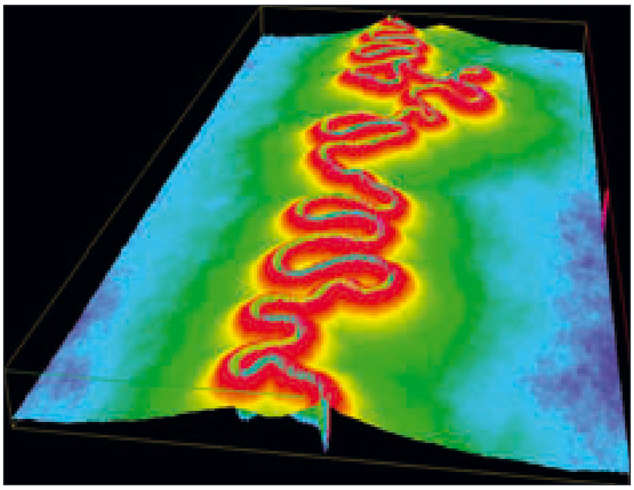

Figure 3 *Constructed channel surfaces based on channel central line and section parameters. Colour represents relative elevation. Red is higher, blue is lower. Stratigraphic architecture of channellized system is created by migrating multiple channel surfaces, and includes the processes of erosion and the stacking of multiple channels.*

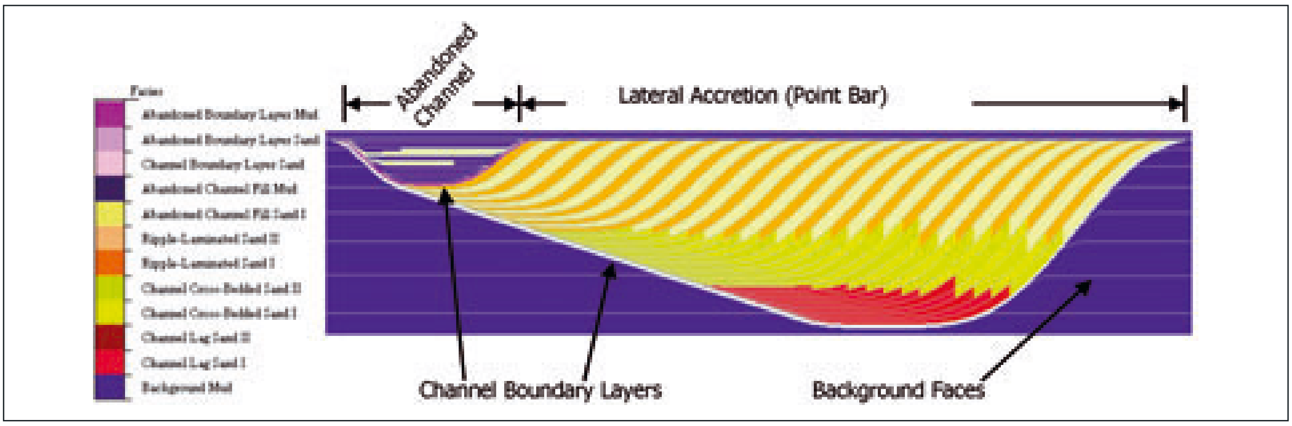

Figure 4 *Modelling components of channel deposits.*

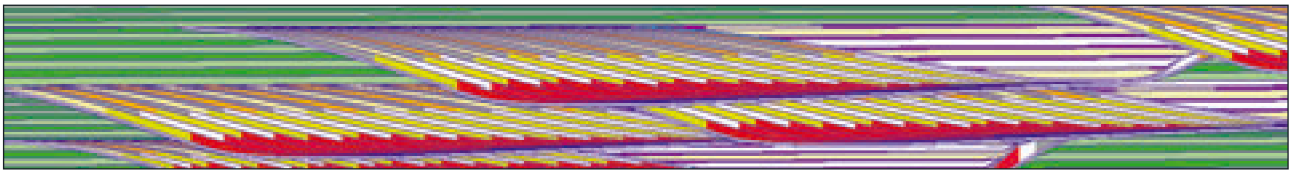

Figure 5 *Examples of simulated lateral accretion deposits. Spatial distribution pattern of inclined heterolithic stratification (IHS) can be represented in 3D (Image generated in SBED).*

deposits of a channel and a layer below abandoned channel infill. If there is no lateral accretion component, only one layer is required to model the boundary. The reason to include a boundary layer as a separate modelling component is to explicitly represent model flow properties across one channel to another. Seismically, channel boundary layers could be reflectors if the seismic resolution is sufficient, since there tends to be a large acoustic contrast between sandy channel deposits and background mud facies.

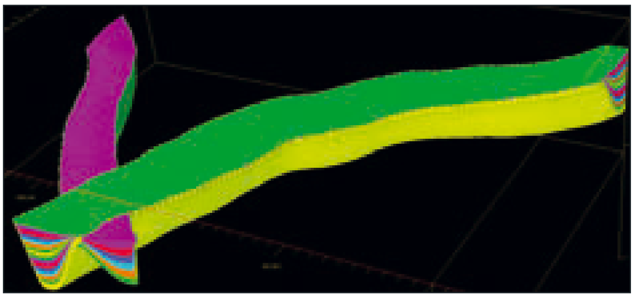

Figure 6 *Examples of simulated channel reservoirs excluding the over-bank deposits (Image generated in SBED).*

Stacking patterns of multiple channels

A channellized reservoir consists of deposits formed by multiple channels. Depending on base-level variation and tectonic setting, channel deposits are vertically stacked in different patterns. Although different schemes are used to describe and classify channel stacking patterns, we model the stacking patterns based on channel amalgamation curves.

Figure 6 shows two channels with asymmetrical convergent infill patterns (without displaying the overbank deposits). The bounding surfaces and internal stratigraphic variations within this model are below the resolution of conventional seismic data. Computer-based modelling that mathematically represents geological processes is the only way to realistically capture these detailed stratigraphic features in the 3D model.

Synthetic seismic volume and its attributes

Figure 7a is a high-resolution litho-facies model of a channellized reservoir (each sample is 20 x 20 x 1 m^3). The model was simulated using the SBED software based on the principles described above. By assigning representative velocities and densities to each litho-facies, we then calculated an acoustic imped-

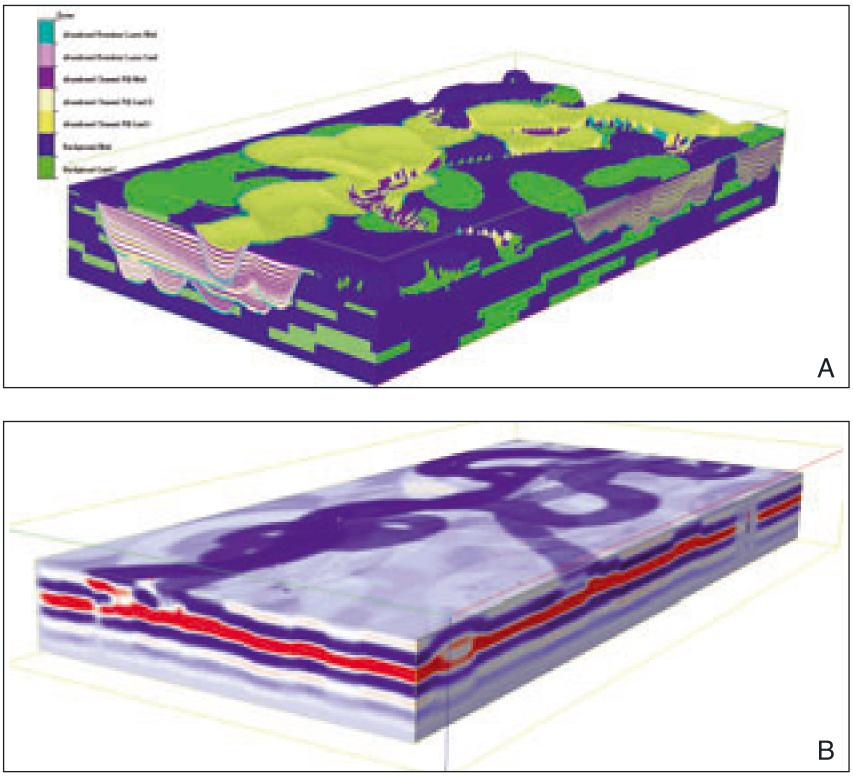

Figure 7 (**a**) *Reservoir facies simulated from SBED as the basis to generate (b) synthetic seismic volume used in the attribute analysis and facies classifications.*

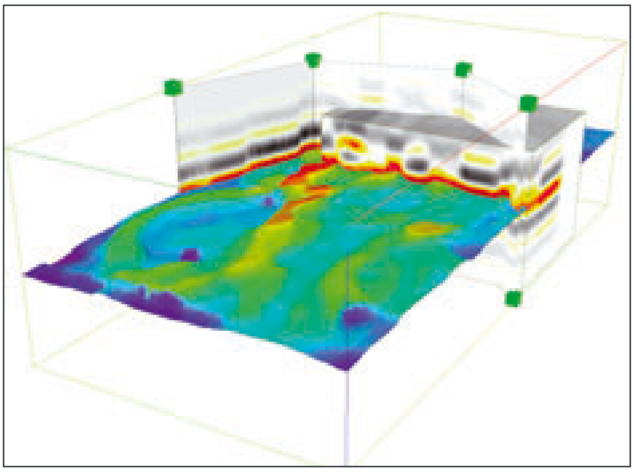

Figure 8 *A seismic horizon in the synthetic seismic volume. A strata-grid with a constant thickness is defined based on this horizon. Both trace-based and voxel-based seismic facies classification are applied to the same strata-grid. Note that a strata-grid does not necessarily need to have a constant thickness. Both classifications (trace-based or voxel-based) are applicable to strata-grids with varying thicknesses.*

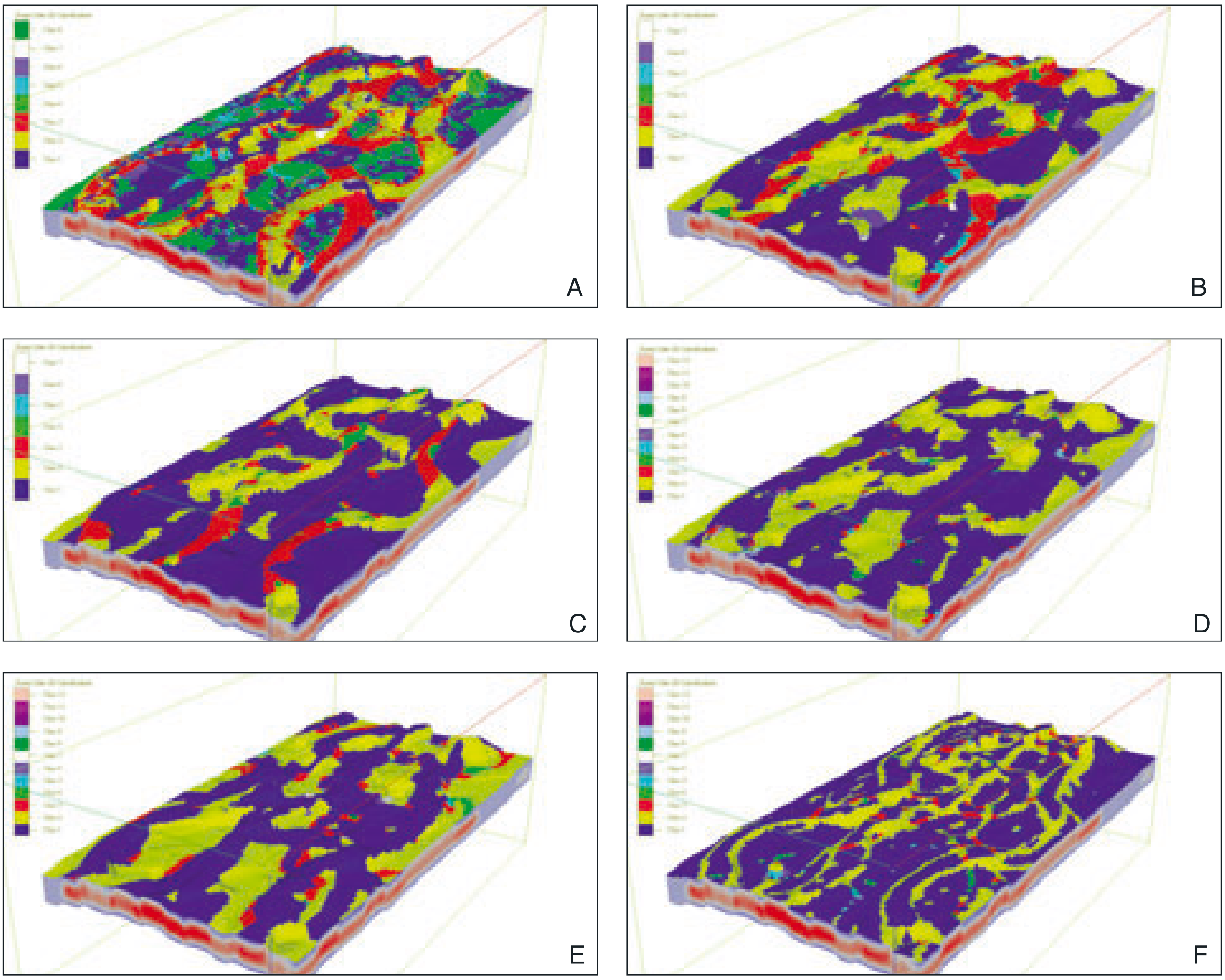

Figure 9 *Trace-based classification of a strata-grid volume based on six individual attributes: (a) average weighted frequency; (b) instantaneous amplitude; (c) instantaneous phase; (d) post-stacked amplitude from which the other five attributes are calculated; (e) relative amplitude impedance; (f) semblance. Whereas a 2D facies map is not sufficient to represent the heterogeneity of facies variation below the seismic resolution, it nevertheless reflects a general trend on a map view. It can be observed that facies maps classified from average weighted frequency and instantaneous amplitude are the best among the six attributes. Facies from instantaneous phase are sensitive to interval definition. It is not surprising that facies maps derived from the semblance attribute reflect more boundary information for the channels than the litho-facies information (Images generated in VisualVoxAt).*

ance cube, which was convolved with a Ricker wavelet with a peak frequency at 40 Hz. The resulting synthetic seismic volume is shown in Figure 7b.

Six post-stack attribute cubes were generated from the synthetic seismic volumes using VisualVoxAt software. They are instantaneous amplitude, weighted instantaneous frequency, instantaneous phase, relative acoustic impedance, and semblance. These attributes are easy to calculate. We did not consider any pre-stack attributes in the following comparison study. It is just a matter of CPU time to compute more attributes. The major challenge in the application of seismic attributes to reservoir mapping is how we interpret the multiple attributes, i.e. link what we see on seismic attributes to reservoir properties such as lithology and, ideally, fluid content.

Seismic facies classification

Seismic facies classification is a computation process to assign each trace in an interval or each sample to a facies code. Depending whether training data are used in the classification procedure, there are supervised and unsupervised classification methods. In this study we considered an unsupervised classification method based on the SOM method, which is preferable to the traditional clustering method (Coléou et al., 2003). Since we have the synthetic seismic volume for comparison (Figure 7), we should be able to identify which attributes are more effective than others when they are used as input to the classifier.

Depending on whether classification algorithms are applied to a trace in an interval or each sample (a voxel) in the seismic volume, the seismic facies classification can be trace-based or voxel-based. We examined both trace-based and voxel-based SOM methods applied to the six attributes calculated for the synthetic seismic volumes.

Strata-grid

The first step in our seismic classification method is to define a stratigraphic volume, which we call a strata-grid. A strata-grid is a sub-volume bounded by two horizons, which are not necessarily parallel. Figure 8 shows the seismic horizon tracked from the synthetic seismic volume. It is

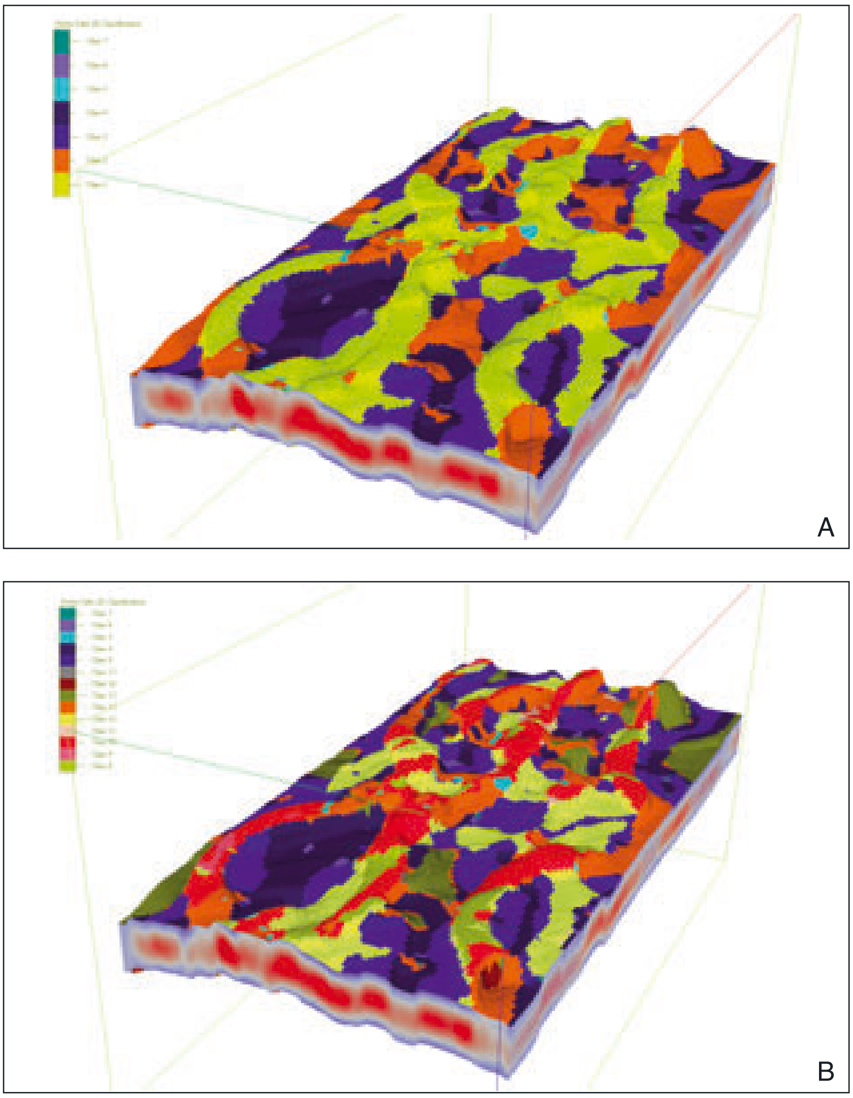

Figure 10 (a) *Seismic facies map from multi-attribute trace-based classification using both average weighted frequency and instantaneous amplitude. The facies pattern looks more consistent with our 'synthetic' geological model Figure 7a. (b) Seismic facies map from an interactive hierarchy classification scheme applied to facies 1 and 2 in (a), which correspond to channel-infill facies. Internal facies variations can be mapped through hierarchy classification of two attributes (Images generated in VisualVoxAt).*

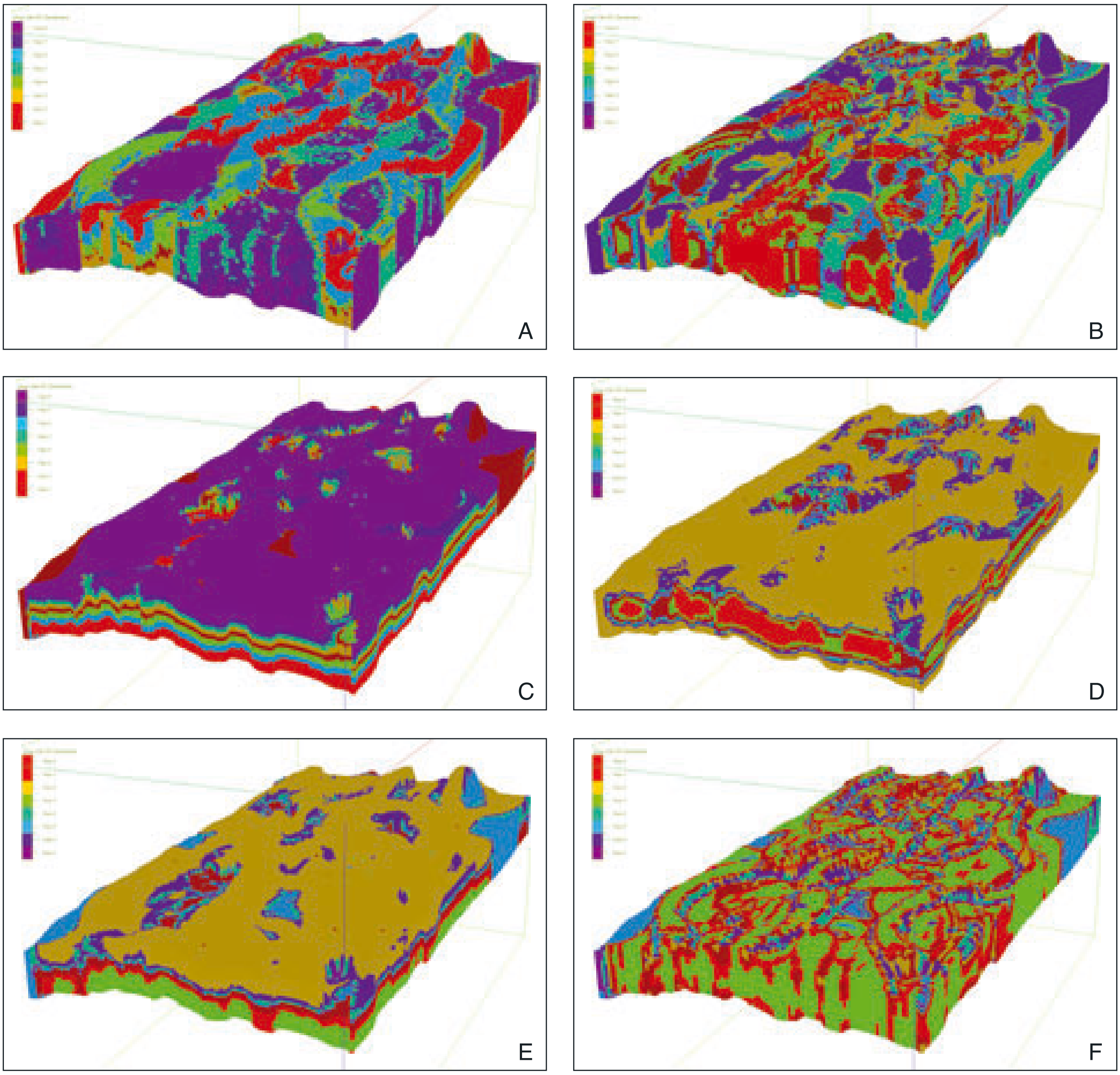

Figure 11 *Voxel-based seismic facies classification using six individual attributes. (a) average weighted frequency; (b) instantaneous amplitude; (c) instantaneous phase; (d) post-stacked amplitude from which the other five attributes are calculated; (e) relative amplitude impedance; (f) semblance. Only the seismic facies volumes from average weighted frequency and instantaneous amplitude are more consistent with the synthetic litho-facies volume in Figure 7a. This is consistent with the trace-based classification results shown in Figure 10 (Images generated in VisualVoxAt).*

a strong reflector in the middle of the channellized reservoir. A strata-grid with a constant thickness of 20 milliseconds was defined around this horizon. We then applied both trace-based and voxel-based SOM classification methods to the data set.

Trace-based seismic facies classification

In a trace-based seismic facies classification, we assign one facies code to each trace within a strata-grid; hence vertical variations of facies within the interval would be unmappable. This may be acceptable in consideration of the seismic resolution limit compared with the scale of vertical facies change. But in areas where vertical changes in facies are detected (not necessarily resolved) by the attributes, a facies map from trace-based classification would not be sufficient.

Figure 9 displays six seismic facies maps that are wrapped on the top-surface of the strata-grid. Only one attribute is used in each classification in order to examine the effectiveness of individual attributes. Whereas a 2D facies map is not sufficient to represent the 3D heterogeneity of facies variation

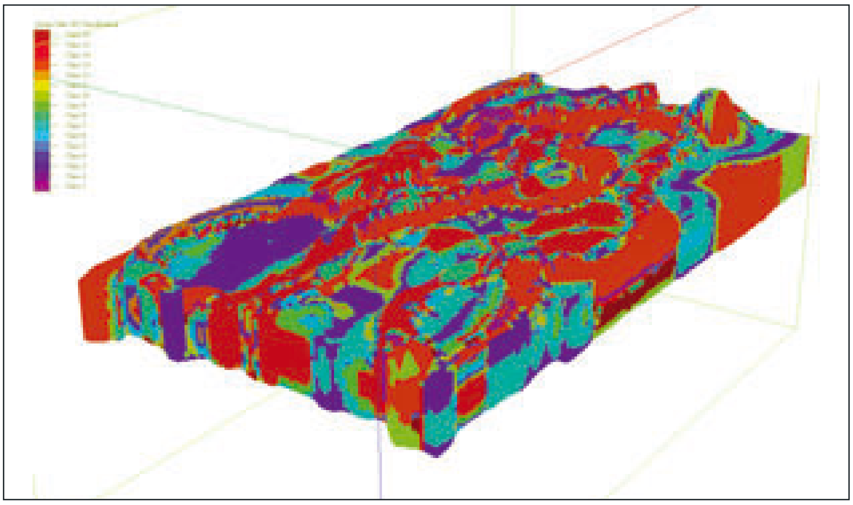

Figure 12 *Seismic facies volumes classified from average weighted frequency and instantaneous amplitude. Some detailed facies zones are better defined than in the facies volumes classified from each individual attribute (Image generated in VisualVoxAt).*

below the seismic resolution, it nevertheless reflects a general trend on a map view. It can be observed that facies maps classified from average weighted frequency and instantaneous amplitude are the best among the six attributes. Facies from instantaneous phase is sensitive to interval definition. It is not surprising that the facies map derived from the semblance attribute provides more boundary information for the channels than the litho-facies information.

Our method of trace-based classification can utilize multiple seismic attributes within a strata-grid. Since single attribute facies maps from average weighted frequency and instantaneous amplitude look more meaningful, we then used both attributes in a multi-attribute trace-based classification. The resulting facies map is shown in Figure 10. The seismic facies pattern looks more consistent with our synthetic geological model in Figure 7. However, internal variations within the channel infill deposits are not reflected in Figure 10. An interactive hierarchical classification scheme is then selectively applied to facies 1 and 2, which correspond to channel infill facies. The hierarchical classification scheme is an effective approach to mapping internal facies variation, provided the top-level facies map is properly derived.

Voxel-based seismic facies classification

In the voxel-based seismic facies classification, each sample (a voxel) is assigned a facies code based on one or multiple attributes at the sample. Results from voxel-based classifications are facies volumes. Given that a seismic data set has enough resolution, voxel-based facies classification would be able to map vertical facies variations within a reservoir.

In the same procedure as the trace-based classification, we first use each of six individual attributes to derive a seismic facies volume (Figure 11). The result is consistent with what we observed from the trace-based classification map (Figure 9). Facies patterns derived from only average weighted frequency and instantaneous amplitude are comparable to the synthetic litho-facies cube in Figure 7. We find that using more attributes in a seismic facies classification does not necessarily improve the classification results. In fact, some of the input attributes have no direct link to what is to be classified. By combining multiple attributes that are related to the reservoir properties we want to map (in this case litho-facies), we defined facies zones that were not included in the facies volumes classified from each individual attribute (Figure 12).

Summary

In this paper we presented a geological modelling method to generate detailed 3D stratigraphic architectures of channellized reservoirs. Using this detailed model as the synthetic, we created a synthetic seismic volume to which the attribute analysis and seismic facies classification were applied. Both trace-based and voxel-based seismic facies classification procedures were applied to the synthetic data. By comparing the seismic facies classification results with the 'synthetic' lithofacies model, we observed that average weighted frequency and instantaneous amplitude are more effective than other attributes considered in this study as input to the seismic facies classification for mapping litho-facies. This modeling method can be applied to reservoir characterization workflows to simulate and correlate stratigraphic heterogeneity in channellized units.

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sification. The three products are trademarks of Geomodeling Technology Corp.

SBED is a joint industrial project with three phases of development. SBED member companies include BG International, BHP Billiton, ConocoPhillips, ENI, ExxonMobil, Hydro, Shell, Statoil and Total. SBED is also the name of the geological modelling software developed by Geomodeling Technology Corp. within this joint industrial project.

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