ON THE HORIZON

Paul de Groot and Farrukh Qayyum, dGB Earth Sciences, The Netherlands, introduce a new series of seismic attributes and give examples of applications.

Tury Tanner, one of the founders of seismic attribute analysis, defined seismic attributes as "all of the measured computed or implied quantities obtained from the seismic data."

Under this definition, it should come as no surprise that seismic attributes have been around since the arrival of digital computing in seismic acquisition, processing and interpretation.

In the early days - the 1960s - the focus was on improving seismic processing. This changed, however, when interpreters realised that seismic anomalies were often linked to hydrocarbon-bearing structures and could thus be used as direct hydrocarbon indicators.

Based on this, a whole group of seismic attributes were developed and a new specialism emerged - Quantitative Seismic Interpretation. Quantitative Seismic Interpretation integrates geology, geophysics and rock-physics and aims to predict rock properties from seismic measurements. In parallel, computer-aided interpretation became the norm and more and more attributes became available to assist in generating mainstream seismic interpretation workflows.

The two main drivers for using seismic attributes in seismic interpretation projects are:

▶ To improve visualisation. Seismic attributes are a qualitative application aimed at removing extraneous information in the hope of revealing trends or patterns that are not visible in the original data.

▶ To integrate data. Seismic attributes are also a quantitative application aimed at obtaining information carriers from different sources that can be integrated by statistical methods.
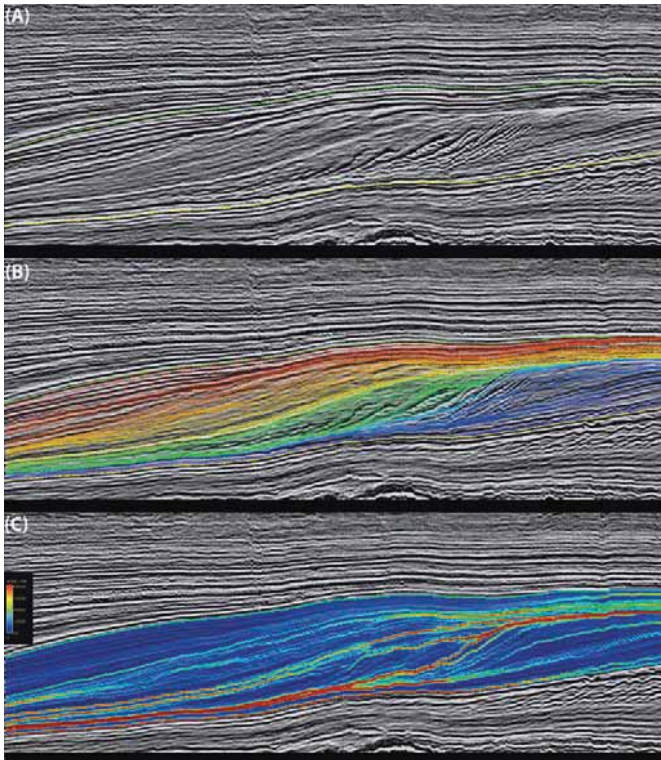
The set of attributes introduced in this paper falls in the first qualitative category. These attributes provide a different view of the seismic information and are
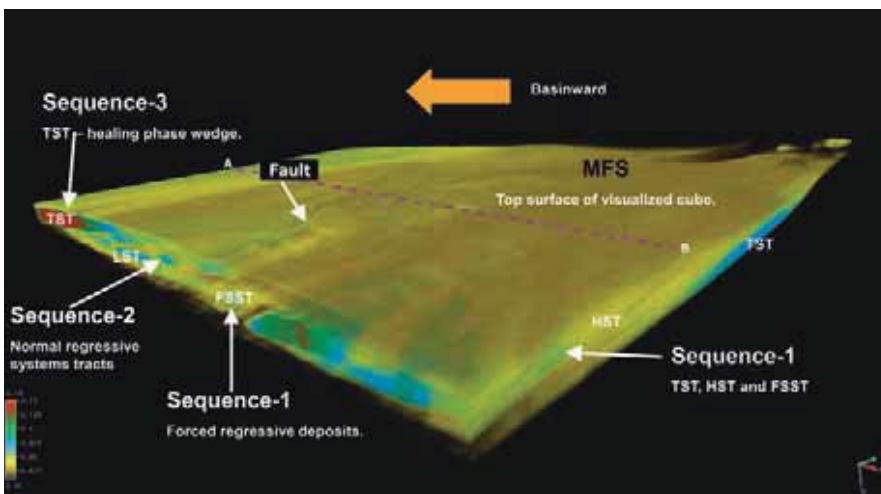
used to highlight unconformities, condensed sections and various stratigraphic features. In this case, the attribute set is derived from a HorizonCube, which consists of a dense set of auto-tracked horizons.

Attributes

A HorizonCube is generated in two steps. Firstly, a (dip-) SteeringCube is generated, which calculates local dip and azimuth values of the seismic reflectors. The SteeringCube is the main input

to a 3D auto-tracker algorithm that tracks the dip/azimuth field to generate a dense set of horizons throughout the 3D seismic volume.

At the tracker starting position, horizons are typically spaced one sample rate apart. Horizon spacing increases and decreases as the horizons grow away from the start position but horizons will never cross each other. The tracker can stop horizons if the vertical spacing falls below a certain threshold to generate a truncated HorizonCube.

Alternatively, the tracker can be instructed to continue tracking throughout the volume even if horizon spacing becomes infinitely small. This results in a continuous HorizonCube in which all horizons exist at every X/Y position (Figure 1b). All horizons within a truncated and continuous HorizonCube represent correlated 3D stratigraphic surfaces that are assigned a relative geological time.

The HorizonCube can thus be seen as a stack of horizons, which are ordered according to (relative) geologic age. They are used, among other things, to assist in well correlations, in unravelling depositional histories and finding stratigraphic traps using sequence stratigraphic interpretation principles. Through this, detailed geologic models can be built and model-driven seismic inversion results improved.

From a continuous HorizonCube a new family of attributes can be computed that help to visualise geologic features that have hitherto remained hidden in the seismic data. The following attributes can be computed automatically from the HorizonCube:

▸ Density: a measure of the number of events per user-defined time gate. Density is calculated on a trace-by-trace basis and high-density values correspond to intervals where horizons converge. These are indicative of pinch-outs, condensed sections and unconformities.

▸ Thickness: an isochron thickness between two consecutive HorizonCube events. This attribute highlights sedimentary bodies but it also picks up local pinch-outs, condensed intervals and local unconformities.

▸ Dip: is a geometrical 3D dip attribute computed from the HorizonCube. This dip tends to be smoother than the dip computed directly from the SteeringCube.

▸ Curvature: represents a family of 3D volume curvature attributes (11 sub-attributes) that are computed from the HorizonCube. These curvature attributes tend to be smoother than conventional volume curvature attributes, computed from the SteeringCube.

Figure 1. *3D seismic data from offshore, The Netherlands (F3 Demo data set): a) inline showing seismic response of the fluvio-deltaic interval of interest; b) overlay of horizons from the continuous HorizonCube. Colours indicate relative geologic time. All horizons are tracked in 3D and are present throughout the volume. Note the laterally varying vertical spacing between horizons; c) density attribute (-4,+4 ms), note that high density values coincide with unconformities and condensed sections.*

In addition to attributes computed directly from the HorizonCube, another set can be computed that require interpretation input. The dense set of horizons are then first used to decompose the interval of interest into packages with different seismic response patterns. If the packages correspond to base level variations, the units represent systems tracts, but this is not a requirement. Any decomposition into geologically meaningful packages can also be used. Based on this, the following set of semi-automated attributes can be computed:

▸ Systems tracts ID attribute: these assign either a unique number or a common number to each systems tract. The attribute can be used, for example, to volume render a particular systems tract or to apply mathematical and logical manipulations per system tract.

Figure 2. *3D visualisation of systems tracts thicknesses reveal depositional trends in the fluvio-deltaic interval of interest. Thicknesses are in seconds TWT. A-B corresponds to the seismic section displayed in Figure 1.*

► Systems tract isochron: a sequence stratigraphic unit thickness. This is a key attribute in understanding how sedimentation filled the basin as a function of geologic time.

Application examples

The density and event thickness attribute examples are demonstrated on the public domain 'F3 Demo' data set.

This 3D seismic data set covers part of a block in the Dutch sector of the North Sea. The interval of interest is a sequence in the upper 1200 ms in which a number of interesting stratigraphic features are observed. The most striking feature is the large scale sigmoidal bedding, with textbook quality downlap, toplap, onlap, and truncation structures (Figure 1a). The interval consists of sand-shale deposits with some carbonate streaks deposited by a large fluvio-deltaic system that drained large parts of the Baltic Sea region during the Miocene, Pliocene and Pleistocene eras.

Figure 1b shows the continuous HorizonCube as a colour overlay over the interval of interest. Colours indicate relative geologic time. Note the laterally varying vertical spacing between individual horizons. Horizons tend to merge together along unconformities and condensed sections. This property becomes apparent when the density of horizons is computed in an 8 ms time gate centred on each evaluation point. The density attribute displayed in Figure 1c is an excellent attribute to guide interpreters in sequence stratigraphic interpretations.

The following attribute is the systems tracts thickness attribute. This requires an interpretation step in which the user sub-divides a sequence into packages with similar depositional characteristics.

Boundaries are set with the aid of a slider tool. The interpreter displays the dense set of horizons on seismic sections in the normal (structural) domain and optionally also in the Wheeler transformed (flattened seismic) domain. The slider removes horizons from the display such that packages can be isolated.
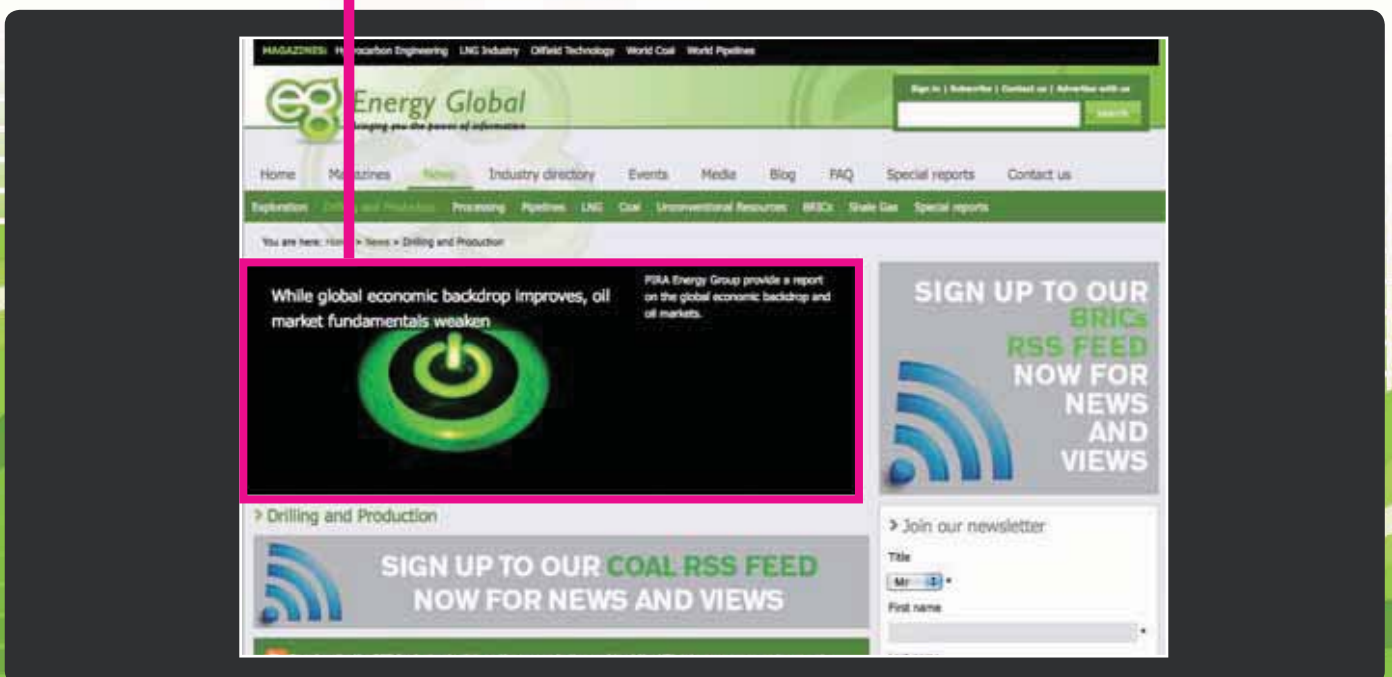
Classification is based on external knowledge and/or the direction of horizon stacking patterns e.g. basinward (progradational), landward (transgressive), upward (aggradation) etc. In F3, the interval of interest is divided into three incomplete third order sequences with Highstand, Falling stage, Transgressive stage and Lowstand systems tracts (Depositional Sequence Model IV). The systems tracts thickness attribute, computed at every sample position in the interval, allows visualisation of depositional trends in 3D (Figure 2).

The 3D volume rendering of the systems tracts thickness attribute captures the depositional trends of the entire second order prograding system. The lower sequence-1 starts with a transgressive systems tract (TST) that is overlain by normal regressive deposits during a highstand (HST).

The normal regression is outpaced with increasing sediment influx. This is reflected as a thick prograding set of parasequences, visible as blue coloured units. The uplift in the landward direction caused a large scale landward erosion and subsequent fall in base level at the shoreface. This phase is interpreted as the falling stage systems tract (FSST) of sequence 1.

Further regression formed a lowstand wedge that contains high frequency cycles – not shown in this illustration. Sequence 2 primarily consists of normal regressive systems tracts. Sequence 3 is a healing phase, a transgressive systems tract (TST) that is

capped by a distinct maximum flooding surface. The healing wedge is more distally restricted and very thin in the middle area of the survey. The thin region that extends from the slope to the landward margin is interpreted as a transgressive lag with more wave-tidal erosion.

The clear advantage of the systems tracts thickness attribute is that it allows for the studying of 3D depositional trends in sequences, or systems tracts. The thickness variations reveal spatial distribution of depocenters and show how accommodation spaces were filled and destroyed over geologic time.

In the next example, event thickness and systems tracts ID attributes are used to study the depositional architecture of a tertiary channel system in the Carnarvon Basin (Northwestern Australian shelf). The study area lies in the vicinity of the Chandon Field and covers an area of approximately 875 km^2.

The tertiary interval contains several deepwater channel systems that have incised deepwater pelagic chalk or ooze deposits. Conventional mapping of internal reflection geometries for building a depositional framework is a labour intensive and difficult exercise. The workflow used in this study utilises a local HorizonCube that was created between conventionally mapped horizons marking the top and bottom of the channel complex.
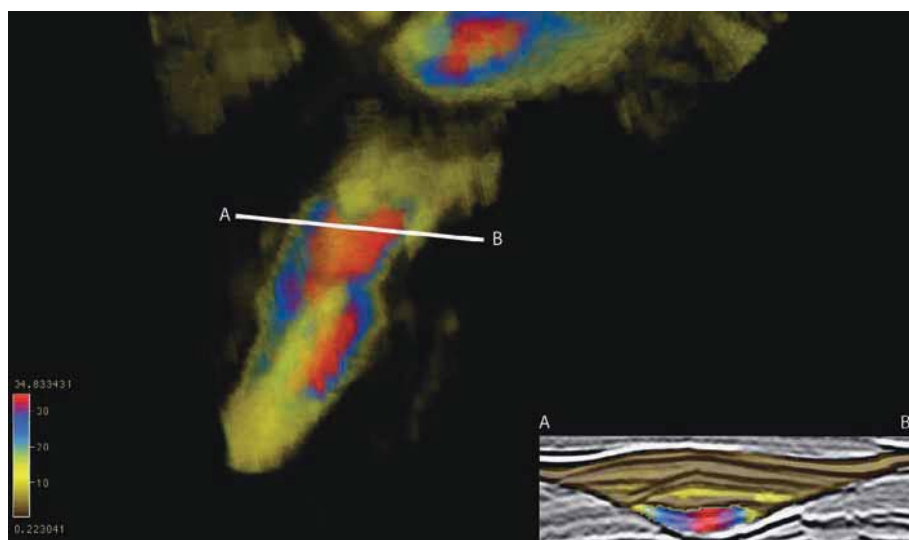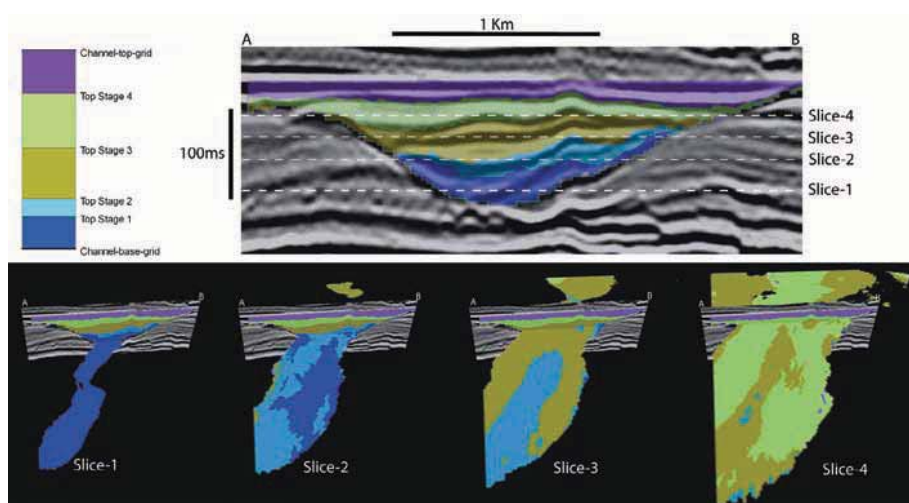
The entire workflow including interpretation of the channel stages took less than one hour.

Figure 3 shows the event thickness attribute in 3D using volume rendering. The yellow-to-red colours trend shows seismic thicknesses in the range of 10 – 40 ms. The section view in the same display shows that event thickness in the upper part of the channel is rather thin with only the basal part of the channel system exhibiting large thickness values.

The 3D volume rendering shows a nice straight channel trend with the thicker parts located in the channel centre. Such regions could contain numerous intra channel bars and should thus be considered as potential stratigraphic traps. The thinner levees of this system are located at the outer boundaries of the system (yellow).

For the next attribute, the channel system was first sub-divided into five different stages. The sub-division was based on observed reflection patterns using the HorizonCube slider technique explained before. Next, in order to better understand the depositional architecture, a systems tracts ID (actually channel stage ID) attribute was computed and visualised (Figure 4).

Each stage in the display is represented by a unique ID that is colour coded. Time-slicing through the attribute volume helps to unravel the depositional history from stage 1 to stage 5. Slice 1 shows the initial channel stage that is slightly meandering. This is characteristic of a high-gradient slope environment that was filled with turbiditic deposits. Slice 2 shows a transitional phase from stage 1 to stage 2. Slice 3 shows that channels are now sweeping as well as swinging in the area. This means that the channel systems are becoming more stable vertically (less incision) and more unstable laterally (more meanders and distributaries). Slice 4 shows distributary channels that overlie the stage 3 deposits. Stage 5 is the last stage of the system after which no further channelisation occurred.

Figure 3. Volume rendering of the event thickness attribute reveals depositional trends of a deep-marine channel system (Carnarvon basin, Northwestern Australian Shelf).

Figure 4. HorizonCube 'systems tracts id' visualises four interpreted channel stages and helps to study evolution of the channel complex in 3D.

Conclusions

In this article a new family of seismic attributes have been introduced that can be used to visualise geologic features such as unconformities, condensed sections, depositional trends and depo-centres. The attributes are computed from a HorizonCube, a dense set of auto-tracked horizons. Two groups of attributes were discussed: attributes that can be computed directly from the HorizonCube and attributes that require some upfront interpretation. **OT**