Domain transform: A tool for imaging and interpreting geomorphology and stratigraphy in seismic volumes

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The presence of complex structure on seismic data often makes it difficult to recognize and interpret depositional systems in the volume. A number of techniques, under the broad topic of chronostratigraphy, have been developed in recent years to address this problem and enable more complete imaging and interpretation of seismic geomorphology and stratigraphy. A “domain transform” (DT) is an interpretation-guided process designed to remove some or all structural deformation from a seismic volume. It improves the imaging of paleo-depositional systems by creating a volume that consists of approximations of paleo-depositional surfaces. Such volumes are ideal for imaging, analysis, and interpretation of seismic geomorphology and stratigraphy.

For clarity, the following definitions are used in this paper:

- Structure volume: A typical 3D seismic volume, which includes all of the imaged geologic structure, obtained from processing and used in interpretation.
- Stratal volume: Any seismic volume that has in some fashion been adjusted so that each horizontal slice in the volume approximately represents a paleo-depositional surface.
- Relative geologic time (RGT) volume: Any seismic volume where a relative geologic time has been assigned to each sample in the volume. An RGT volume is not necessarily a stratal volume, but the RGT values in a structure volume can be used to create a stratal volume by creating a volume where each surface of constant RGT is flat.
- Wheeler volume: A volume based on an extension of concepts for analysis of chronostratigraphic sequences in Wheeler (1958) to three dimensions and applied to seismic data. Some definitions of a Wheeler volume include any stratal volume that honors hiatuses, whether nondepositional or erosional in nature. In this paper, such a volume will simply be called a stratal volume in which discordant surfaces are honored. Inclusion of discordant surfaces is essential to create a stratal volume from any seismic interval that contains anything more complicated that differential sedimentation or compaction.

The earliest attempts to create paleo-depositional surfaces included horizon slicing or volume flattening in the late 1980s, and proportional slicing (also called stratal slicing) in the mid 1990s (Zeng, 1994; Posamentier et al., 1996). The stratal slicing (or proportional slicing) process generates a “stratal time volume” which Zeng et al. (1998 a, b) claimed to be a relative geologic-time volume.

Stark (2004) developed the concept of and methods to derive an RGT volume from a seismic volume. Stark describes two methods of generating RGT volumes, the first based on interpolation between interpreted horizons, and the second based on phase unwrapping of seismic data. An RGT volume retains all of the structure of the original seismic volume, but surfaces of constant RGT extracted from the seismic volume represent approximations of stratal-slices.

Lomask et al. (2006) and Lomask and Guitton (2007) describe a processing method for flattening 3D seismic volumes with no interpretive control, and a hybrid process that may include some interpretation constraints to improve the results in the presence of various structural complexities. A volumetric estimation of local dip at each point in the seismic volume, is converted into vertical shifts (time or depth shifts) in the volume, creating a volume in which the reflection events have been flattened.

Several of these algorithms assume that surfaces of constant phase represent paleo-depositional surfaces. As Zeng (2010) has pointed out, this is not always the case. A reflection in the seismic volume may or may not represent a surface of constant chronostratigraphic time, and conversely a surface of constant chronostratigraphic time may cross phase in the seismic volume.

Domain transform

Hammon and Dorn (Hammon et al., 2008; Dorn et al., 2008; Dorn, 2011a; Dorn 2011b) have developed an interpretation-guided approach to removing the three-dimensional effects of structure from 3D seismic volumes called a domain transform (DT). The DT is most closely related to horizon based volume flattening and proportional slicing. These two previous techniques account for folding, vertical faults, and, in the case of proportional slicing, differential sedimentation. Dulac et al. (2009) have developed a closely related interpretation guided transformation based on an application of geomodeling techniques.

DT substantially extends the capabilities of interpretation-guided structural transformation. In addition to folding and differential sedimentation, it includes algorithms to remove the effects of faults, parallel unconformities, angular unconformities and other discordant surfaces, carbonate buildups (e.g., pinnacle reefs), canyons, and mass transport complex boundaries.

A DT volume created to remove all structure from the input structure volume is ideal for imaging and interpreting depositional systems because every horizontal slice closely represents a paleo-depositional surface. Depositional systems are readily recognized from their morphology on these slices. Other stratigraphic details are placed in the approximate position and relationships that they had at the time of deposition. Since the transformation is interpretation-guided, non-autotracked surfaces that accommodate situations where a surface of constant chronostratigraphic time crosses phase in the volume can be used in the transform.
DT volumes may also be created to remove some of the structure in a volume, but retain other structure. As an example, a DT volume designed to remove only post-depositional structural deformation (folding, faulting, rotation, etc.) may be used to view a stratigraphic feature (e.g., a prograding fan) in the approximate geometry it had at the time of deposition.

A second DT volume could also be created that removes the internal “structure” of the stratigraphic feature (e.g., flatten the progrades). The two linked DT volumes better support integration of the interpretation of seismic stratigraphy on vertical slices of the first DT volume with seismic geomorphology on horizontal slices of the second DT volume. When this type of analysis is conducted by creating the second DT volume directly from the first DT volume, the second DT is referred to as a “cascade” domain transform.

Once the DT is calculated for a specific set of input surfaces, the 3D transformation matrix can be stored and used to transform colocated volumes, surfaces, well paths, well logs, formation tops—essentially any data represented in the 3D space to which the transform applies. The transformation matrix can be used to transform these data from the structural domain to the stratal domain, and to inverse transform any data (e.g., interpretation, attribute volumes, facies classifications) from the stratal domain to the structural domain.

Although a domain transform can be used to generate a 3D Wheeler volume if all key sequence boundaries are interpreted, that is not its primary application. It is primarily a flexible tool to assist in the interpretation of structure, seismic geomorphology and seismic stratigraphy at any scale from prospect to regional, depending on the area of 3D seismic coverage.

Removing structure from a volume
In the DT process, proportional slicing is used to remove the effects of differential sedimentation and differential compaction. The assumption is made that slices that are proportionally spaced between pairs of horizons approximate stratal slices or paleo-depositional surfaces between those control horizons. Differential compaction can be removed so long as a surface that captures the differential compaction is included in the transformation.

Parallel unconformities may be handled in a number of ways. Zero-thickness intervals can be defined when syndepositional faulting results in an interval of deposition on the downthrown side of a growth fault that is not represented on the up-thrown side of the fault. The definition of intervals in DT also enables the events above and below the unconformity to be flattened, whereas the unconformity surface (the horizon) is itself not flattened. The unconformity may be shifted to accommodate flattening of the events below or above the unconformity.

The processing of angular unconformities in DT is illustrated schematically in Figure 1. Figure 1a shows a simple model consisting of a set of flat-lying horizons that overlay a set of steeply dipping horizons. The horizon separating these two zones of varying dip is an angular unconformity. DT shifts the data below the unconformity so the horizons above and below the unconformity surface are horizontal in the output stratal volume (Figure 1b). This introduces a three-dimensional “null” or no-data zone into the output volume (gray space in Figure 1b), which represents the volume eroded from the deeper sedimentary layers before deposition of the overlying sediments.

A carbonate reef is transformed through a combination of discordant and concordant surfaces. The top of the reef is considered discordant with clastics above and around the reef, concordant or discordant with the interval below the top (depending on reef growth patterns), and the shape of the top of the reef may be maintained through the transformation. Any velocity pull-up at the base of the carbonate is also flattened (Dorn, 2011b).

At this time, the only effective way to manage a salt body in a DT is to use the interpreted salt boundary to isolate the three-dimensional salt body from the rest of the input volume, and apply DT on data outside the salt body.

Interpreted boundaries of canyons and mass transport complexes (MTCs) can be included in the transform to properly isolate the canyon fill or MTC. After transformation to the stratal domain, the horizons in both the canyon fill/MTC

Figure 1. A schematic cross section through a model showing the effect of the domain transform on an angular unconformity. (a) The structural cross section. (b) The corresponding transformed stratal cross section.

Figure 2. Schematic cross sections showing the effects of the domain transform on models containing two different types of faults. (a) and (b) The structural cross section and the stratal cross section for a normal fault. (c) and (d) The structural cross section and the stratal cross section for a listric normal fault.
and the surrounding sediments are flat. Sufficient null space is inserted into the stratal volume to separate the canyon fill and overlying sediments from the older sediments into which the canyon or MTC were cut.

Faults represent one of the more complicated aspects of DT. Ideally, 3D fault displacements are removed for all interpreted fault surfaces. This is shown schematically for two example fault geometries in Figure 2. “Before” and “after” sketches illustrate the effect of applying a 3D transform to each of these geometries. In both cases, the DT not only removes the vertical and horizontal components of displacement along the dipping fault surfaces, but it also makes the interval between horizons A and B have equal thickness on both sides of the fault. Although none of these fault models in Figure 2 illustrate it, if a fault block is rotated with respect to the horizontal, that rotation is also removed in the DT.

In the next three sections, examples are presented for the application and use of the domain transform on data sets from different geographic regions with different depositional environments.

Example 1: Unconformities and deep-water turbidites (North Sea)
The first example data set is from an area where the Paleocene deposits include several deep-water turbidite channels. Figure 3a is a vertical slice through the seismic volume showing the 13 horizons used in the transformation. Although there is not much faulting in the area, there are a large number of angular unconformities. Most horizons were autotracked in 3D through the volume. However, in the middle of the volume, there is a very thick shale sequence in which there are no trackable events. The pink horizon in the middle of the section in Figure 3a was “phantomed” to provide some control over the stratal slicing in that thick shale interval. The Paleocene is represented deeper in the section with the Top Paleocene in orange, Intra Paleocene in blue, and Base Paleocene in red.

Figure 3b is the same vertical slice as Figure 3a extracted from the DT volume created using the 13 horizons. The discordant relationships have been honored, and null points have been inserted in the stratal volume to accommodate flattening of the events above and below discordant surfaces. The Intra Paleocene event in the stratal volume (green horizon, second from the base of the section in Figure 3a and Figure 3b) has distinct breaks and vertical shifts in the transformed section, suggesting that the interpretation of that horizon needs to be refined to remove cycle skips in several areas. This is an example of the utility of a DT volume as a tool for quality control of a structural interpretation.

Figure 4a shows a stratal slice from the DT volume from within the Paleocene interval. Instantaneous amplitude (IA), frequency (IF), phase (IP) and horizon edge stack (HES) (Dorn and Kadlec 2011; Dorn et al., 2012), an edge attribute, are corendered. The corendering is mixed-mode with IA (blue intensity) and IF (green intensity) corendered additively, IP (circular variable-hue color scale) corendered using transparency, and with the edge attribute (HES) controlling the lighting of the voxels in the volume. The boundary of a deep-water turbidite channel is clearly visible on the stratal slice, and has been interpreted (two black lines). Two areas of known production are highlighted approximately by the red ovals.

Figure 4b shows the structural horizon created by inverse DT of the stratal slice from Figure 4a. The inverse transform of a stratal slice is, by definition, a structural horizon. The
inverse transform takes the flat slice in the stratal domain and puts all of the structure back into the slice, creating a horizon in the structural domain. In Figure 4b, the new horizon is shown in 3D perspective view with color showing the highs in red and the deeper portions of the horizon in blue. The interpreted boundary of the turbidite channel has also been inverse-transformed (black lines); the position of the known fields is shown approximately by the red ovals. For the field in the center of the survey, the display clearly shows a structural high with four-way closure where the field is located. In the lower right edge of the survey, the available data show a structural high with at least a three-way closure at the location of the second field.

This turbidite channel is at a level in the volume that is between the Top and Mid Paleocene events. By using a DT volume, we were able to view a slice that imaged the entire channel, and interpret its boundaries. By inverse transforming that stratal slice, we were able to very quickly obtain a structural horizon at the level of the turbidite channel and answer the question of whether there were closed highs that included the channel that might represent potential reservoirs. In this case those highs actually correspond to existing fields.

Example 2: Differential sedimentation and faulting (GOM)

This data set is from the US continental shelf in the Gulf of Mexico. The area has a high density of normal faults downthrown to the south, and intervals exhibit growth across these faults. Stratigraphically, there are a large number of stacked fluvial and shallow marine channel systems. In order to image and interpret these channels, it is very useful to remove the structural effects of regional dip, minor folding, faulting, and the effects of differential sedimentation.

Figure 5a shows a typical inline from the 3D survey, including a number of normal faults. Figure 5b shows the same inline from a “formation volume” or sculpted volume between the shallowest horizon (pink) and the deepest horizon (red) used in the transform. Figure 5c shows the same inline from the stratal volume created by a DT. Six horizons and 71 faults were used to create the transformation. Figure 5b is included for ease of comparison with the stratal volume in Figure 5c. The DT succeeded in flattening most of the events.

Figure 6a and Figure 6b show two different multi-attribute corenderings of the same stratal slice. Figure 6a is a corendering of IA, IF, IP with HES combined in the manner described above for Figure 4a. Figure 6b is IA^2/IF in a variable hue color scale corendered using transparency with HES in a gray scale. In both cases the instantaneous attribute volumes were created in the structural domain and then transformed to the stratal domain. This workflow is necessary because the transform interpolates or stretches the traces in a growth environment. This changes the bandwidth, frequency, and amplitude spectrum of the data as it transforms them into the stratal domain. As a general rule, attributes based on the waveform should be calculated in the structural domain and transformed to the stratal domain. Attributes based on the “structure” of the volume (e.g., horizon edge stack or coherence) may be calculated directly in the stratal domain.
The details of the depositional systems shown on the slices in Figure 6a and Figure 6b are significantly different. Different combinations of attributes reveal different aspects of the depositional systems. Figure 6c shows a corendering of the same attributes as those in Figure 6a, but at a slightly deeper slice in the volume.

Example 3: Salt, faults and stacked fluvial systems (GOM)

The third example is from a Gulf of Mexico volume that includes a salt dome, and an associated complex fault pattern with both normal and listric normal faults. Figure 7a is a crossline from the seismic volume. Five horizons and a few of the 62 faults used in calculating the DT are shown. Fault block rotation, the vertical and horizontal components of dip slip along the faults, and the effects of differential sedimentation across the faults were all removed in the transformation. Figure 7b shows the same crossline extracted from the resulting stratal volume. Overall, the reflection events have been flattened and there are no gaps at the faults. Reflections in first two intervals (starting at the top of the volume, red-yellow and yellow-green) both seem to be properly tied across the faults.

To the right of the orange listric fault, the entire third interval (green-light blue) appears to be properly tied and transformed (events flattened). However, the reflections on the left side of the fault (e.g., in the red oval), do not properly tie with those to the right side of the orange fault. Looking at the fourth interval, again it seems to be properly tied and flattened to the right of the orange listric fault. The mis-tie across the orange fault appears to be fairly small at the base of the interval (dark blue horizon), and the mis-tie gets worse nearer to the light blue horizon.

These observations illustrate one of the benefits of performing a DT in regions of complex structure. The transformed volume (the stratal volume) provides an excellent environment to assess the accuracy of the structural interpretation. Problems in the structural interpretation (whether it is mis-tied across faults as is the case here, or there are faults that were not interpreted) cause disruptions in the stratal volume that are easily identified. In the case of this data set, at the very least it appears that the light blue horizon has been
mis-tied across the orange fault and should be corrected.

Figure 8 shows four stratal slices in map view. These slices show only a small subset of the stacked channel systems present in this volume. In Figure 8, we are again corendering, in the manner described earlier, IA, IF, and IP along with the HES attribute.

Once the channels are imaged, the three-dimensional bounding surfaces of the channels may be interpreted in the stratal volume, as in Figure 9a. These bounding surfaces may then be inverse-transformed into the structural domain (Figure 9b). Not only can depositional systems be identified more rapidly and thoroughly, they can also be interpreted in greater detail with this type of workflow.

**Conclusions**

A domain transform is an interpretation-guided approach to creating stratal volumes. It is a flexible 3D spatial transform of the seismic volume into a stratal domain. This transform simultaneously handles the effects of differential sedimentation and compaction, horizon dip, folds, angular unconformities, carbonate reefs, canyons, mass transport complexes, and 3D fault displacement. It extends the ability to create stratal volumes to complex structural environments, which could not be properly addressed by earlier techniques based on proportional slicing. Since it is interpretation-guided, it also allows the creation of the stratal volume to include the effects of constant geologic time surfaces (or horizons) that cross phase in the seismic volume.

Application of this transform to 3D seismic volumes has lead to the development of new workflows for interpretation. The stratal volume may be used to check the quality and accuracy of the structural interpretation. If deficiencies in the structural interpretation are found, the stratal volume supports rapid correction of the problem, using the depositional features on stratal slices to ensure the correct structural ties across faults. The improved structural interpretation can then be used to improve the domain transform and stratal volume, further refining the imaging of depositional systems.

Combinations of attributes can greatly enhance the imaging of the overall depositional system and highlight changes in and around them. Once the colocated attribute volumes are corendered, the corendered slices may be used to interactively “explore” for depositional systems in the stratal volume. Once a depositional feature is imaged and interpreted, the interpretation may be inverse transformed back to the structural domain and merged in with the structural interpretation.

**References**

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