Relative geologic time (age) volumes—Relating every seismic sample to a geologically reasonable horizon

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The age volume described in this paper can significantly increase the amount of useful geologic information extracted from a seismic data volume.

This paper has three goals. The first is to introduce and describe the relative geologic time volume, referred to herein as either an RGT volume or an age volume. Every seismic sample in an age volume contains an estimate of the relative geologic time for that sample, which automatically relates every sample to a geologic horizon. The second goal is to discuss some of the applications and advantages of using a RGT volume to store and access seismic interpretation. For example, it can be used to sculpt a seismic volume along a desired horizon, or view depositional changes as a function of geologic time. The third goal is to describe two methods for generating such a volume, the first employing standard interpretation techniques, and the second relying on unwrapping instantaneous phase. Unwrapping the instantaneous phase is a new, holistic approach to interpreting seismic data that can produce a very detailed seismic interpretation.

Background. The goal of building and using an RGT volume is to extract significantly more geologic information from the seismic data than is available from conventional methods. The RGT volume is both a way of storing and retrieving seismic horizons. To generate such a volume each seismic sample needs to be assigned an estimate of relative geologic time, which in essence connects it to a geologically reasonable horizon. In “normal sections” these relative geologic time values will increase with depth (or traveltime). High gradients in the RGT volume could be indicative of faults, unconformities, fluid contacts, or interpretation errors, while a constant value surface in a RGT volume is a seismic horizon.

Figure 1 contains a portion of the seismic data used to illustrate the age volume and some applications. This particular volume comprises 501 inlines by 501 crosslines with 200 4-ms time samples and covers about 100 km². In the seismic cube, the data sample values oscillate around zero and are displayed using a standard red-white-blue color scale. The data are of fairly good quality with several apparently laterally continuous reflections.

Figure 2 contains an age volume corresponding to the seismic data in Figure 1. The age volume has the same dimensions and coordinates as the seismic data volume, but instead of seismic amplitude, each sample contains an estimate of relative geologic time, determined using methods described below. The volume is displayed using a rainbow color scale in which each hue becomes progressively darker with increasing relative geologic time. Just like the seismic amplitude volume, the age volume contains significantly more resolution than can be represented by a color scale.

The phrase relative geologic time should be interpreted as: “If relative geologic time A is greater than relative geologic time B, then the rocks of relative geologic time A were deposited before rocks of relative geologic time B.” Thus, using this volume, we can tell if a data sample A is younger or older than the same age as data sample B, but we cannot say how much older or younger A is than B until a calibration step is performed.

Any time slice taken from the age volume in Figure 2 will contain a geologic map corresponding to that time. Similarly, any inline or crossline display (faces on the cube) represents a geologic cross-section. A constant color represents essentially a constant age. Therefore, areas on the time slice in Figure 2 that have the same color will belong to the same horizon; this can be exploited using visual correlation between Figure 1 and Figure 2, or the applications discussed next.

Applications. In this section I will discuss three methods that use an RGT volume to help better understand the seismic volume and identify stratigraphic features. All three methods make use of the fact that in an RGT volume a constant value surface is a constant relative geologic time and therefore a seismic horizon. Seismic amplitude along a surface of constant relative geologic time is analogous to Henry Posamentier’s “proportional slice” or Hongliu Zeng’s “stratal slice” (Zeng et al., 2001). I will use the term stratal slice. They have documented the usefulness of these slices for identifying stratigraphic features.

In the first method the stratal slice and its associated structure map are selected and updated using a spatial reference. This user-defined spatial reference point (i.e. inline, crossline, traveltime location) can be interactively changed several times per second to obtain a stratal slice and structure map which...
contains this point. The second method uses the RGT volume to sculpt the seismic volume, such that all seismic samples that are younger than a user-defined relative geologic time are made transparent. The third method utilizes the RGT volume to sculpt a formation out of the volume, in which all seismic samples that are either younger than, or older than, a user-defined relative geologic time range are made transparent. Two ways of generating and displaying the sculpted volumes will be discussed. One uses movie loops generated using conventional volume-rendering software, and the other uses a special volume-rendering graphics board.

**Spatial referenced horizons.** Figures 3 and 4 illustrate stratal surfaces generated from the seismic and RGT volumes (shown in Figures 1 and 2) and passing through user-selected reference positions. Each figure contains the following five display windows: inline, crossline, time slice, horizon structure and horizon attribute (amplitude). The black X in these figures represents the user-defined reference point that determines the currently displayed horizon. The relative age at the reference point is used to extract a surface from the age volume that is connected to the reference point and is everywhere at substantially the same relative geologic time. The structure of this extracted surface is shown in the horizon structure display (each color band darkens downdip) and the seismic amplitude along this surface is shown in the horizon attribute (amplitude) display.

As the interpreter repositions this point on a seismic section, the displays are immediately updated to correspond to the relative geologic time surface that passes through the new reference position. The yellow box marked on both the inline and crossline displays indicates the region (i.e. subvolume) in which the high-resolution age volume is available, and thus, these stratal slices.
There are many advantages to this method. For instance, the interpreter does not need to remember a name to display a horizon (although a name can be associated with a particular relative geologic time). The relative geologic time of an existing map can be either incremented or decremented to obtain a new surface in either a single frame or movie loop fashion. The relative geologic time increment between maps can be very small, allowing several maps to be generated per seismic wavelet. These methods allow the interpreter to rapidly scan through the volume perpendicular to the bedding planes to look for stratigraphic features of interest. Some features are very hard to see if the data are not viewed at least approximately parallel to the bedding.

The horizon in Figure 4 is approximately 1/2 cycle below that of Figure 3. By moving the reference point down one half cycle, parts of the channel system are more visible, while other portions disappear. Note that the stratal amplitudes are not all the same polarity—both horizons have some positive and some negative values. Figure 3 has several strong red meandering stream channels and possibly a blue incised valley.

The structure maps indicate that the two structural highs on the inline section are part of local four-way closures. Due to the way the age volume is generated, an isopach between the two horizons would show spatial variations in the bed thickness, since Figure 4 is not a simple static or proportional function to achieve the desired cut surface. The view can then

The last frame in this sequence (lower right) is at approximately the same level (relative age) as the stratal slice in Figure 3, and the potential blue incised valley appears to run along a present-day high. The relationship of this “blue event” and the structural high would be more apparent if the images were in stereo or could be animated. If a movie were generated in stereo or such that the cube rotated slightly with each frame, then viewing such a movie would better convey both the stratal amplitude variations as well as the local structural variations.

Once generated, the movie can be viewed at several frames a second or it can be interactively scanned up and down in geologic time to select a particular frame of interest. This is significantly faster than the several minutes it takes to sculpt and render the two volumes for each frame.

Instead of just generating the movie, the sculpted volumes can be studied using the regular volume-rendering tools, such as rotation, translation, zoom, clipping, opacity filtering, etc. It takes several seconds per volume to rerender a volume of this size using standard rendering software on a standard desk side workstation.

Figure 6 is similar to the last frame of Figure 5 (lower right image) but generated using prototype software, a special volume rendering board, and a sculpting technique that is significantly different and faster than that used to generate the Figure 5 displays. (This sculpting and rendering only takes a fraction of a second versus minutes.) This technique combines with the age volume and seismic volume to create a two-field voxel. The seismic data are used to control the color of the resultant display while the age data are used to control the opacity. In this case, all voxels less than age A are transparent while all voxels greater than age B are opaque. A linear opacity function is used for the few age values that fall between A and B. This transition in the opacity curve allows for a range of relative geologic time voxels to be seen at once on the top of the sculpted volume. A simple change in the opacity curve produces a new sculpted volume in just a fraction of a second. The user interactively manipulates the opacity function to achieve the desired cut surface. The view can then
Either the movie loop or interactive program can be used to formation-sculpt the volume to just a narrow range of relative geologic time using techniques similar to those just described. Once the desired geologic time slab is found, the volume can be rotated, translated, and zoomed to find the proper viewing location.

The special graphics board can take advantage of the fact that most of the data are not being rendered in order to significantly increase the frame rate. Alternatively, a larger formation sculpted volume can be rendered at about the same frame rate.

**Age volume generation.** In this section I will discuss two ways of generating an RGT volume. The first method uses interpolation and standard horizon interpretation techniques to store the interpretation in an RGT volume. The second method generates an RGT volume by unwrapping the instantaneous phase.

**Interpolation method.** The interpolation method of generating an RGT volume uses standard horizon interpretation techniques. Each interpreted horizon is assigned a constant age value, or in the case of unconformities, spatially varying relative age values. The only constraint is that these values follow the law of superposition. (If available, actual geologic time values can be used.) The RGT volume is then populated by interpolating age values between the picked horizons. The resultant RGT volume has the same dimensions as the seismic data, but each sample contains an estimate of relative geologic time. This method is faster (given the interpreted horizons) but not as detailed as the phase unwrapping method described next.

**Unwrapping instantaneous phase.** This is a new, holistic approach to performing seismic interpretation that is particularly suited for generating an RGT volume. Both RGT volume generation methods generally make the same assumptions; however, phase unwrapping creates an RGT volume with significantly more detail than is obtained from the interpolation method.

Phase unwrapping involves adding integer multiples of $2\pi$ to the phase in order to reduce the number of discontinuities in the resultant sum (unwrapped phase). It is not a new concept for the geophysical industry; the synthetic aperture radar (SAR) literature contains many 2D phase unwrapping techniques. However, to the best of my knowledge, I am the first to apply phase unwrapping to instantaneous phase.

The concept of unwrapping instantaneous phase to generate an RGT volume will be illustrated using the synthetic data shown in Figures 8 and 9. Figure 8 contains the input and output of unwrapping a single trace while Figure 9 contains the section from which this trace was taken.

Referring to Figure 8, the instantaneous phase (yellow line) is generated from the seismic trace (cyan line). The instantaneous phase is a cyclic function that wraps, just like Fourier phase and SAR phase, at $\pm \pi$. But unlike Fourier phase and SAR phase, the instantaneous phase will (or, by flipping its polarity, can be made to) generally increase with traveltime except for where it wraps.

The cycle number trace (blue step-function line) represents the number of times the instantaneous phase has wrapped. It will normally always increase with traveltime. Notice that every time the instantaneous phase wraps from $+\pi$ to $-\pi$, the cycle number increments by at least one ($2\pi$) unit. In general, every time the instantaneous phase decreases, the cycle number is incremented by at least one. There is one location where there is a local decrease in instantaneous phase,
but not a full $+\pi$ to $-\pi$ change in phase. The cycle number still increments, and this is said to be a local unconformity. In the center of the figure an unconformity is denoted and the cycle number experiences a large step. The entire 2D section is required to determine the size of this step. If a shorter line segment had been used, the step might have been smaller, and if a longer line segment had been used, the step might have been larger—hence it is relative geologic time.

The relative geologic time (red line) equals the unwrapped phase and is the combination of the instantaneous phase and the cycle number. The seismic data are in the upper left, followed by the instantaneous phase in the upper right. The cycle numbers in the lower left are derived from the instantaneous phase. Cycle number boundaries occur everywhere the local instantaneous phase gradient is negative as well as a few other locations that are required to generate a geologically consistent result. The unwrapped phase (or relative geologic time) is in the lower right. It is the combination of the cycle number and instantaneous phase.

Conclusions. There are several advantages to generating an RGT volume. For instance, horizons can be retrieved using spatial referencing. There is no need to look up a name in a list—simply touch a point on a section to display the relative geologic time surface that contains that point. It facilitates interactively slicing through a volume as a function of relative geologic time or animating an isochore as a function of relative geologic time. Additional volumes can be generated from the RGT volume; for example, calculating its temporal and spatial derivatives provides a quality measure along with faults and unconformities. Alternately, since every time sample is connected to a horizon, a closure volume can be generated to provide a detailed evaluation of the survey area’s trap potential. Such a volume could indicate whether or not a sample is part of a closure, and some attributes of the closure. The RGT volume allows for new, holistic ways of interpreting our data, such as unwrapping the instantaneous phase. This new technique essentially generates all horizons at once. The end result is a complete and consistent interpretation that cannot easily be obtained by working on just one reflection at a time.

Truly, the relative geologic time volume is a starting point for obtaining a fully interpreted seismic cube.


Acknowledgments: I thank those who have supported me in this endeavor.

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