Generation of a 3D seismic “Wheeler Diagram” from a high resolution Age Volume

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Summary

Wheeler diagrams, or chronostratigraphic charts, provide a useful way to look at stratigraphic temporal relationships, particularly with regards to understanding the location and timing of erosional and non-deposition events. Such diagrams typically must be constructed by hand and therefore are only generated for a select few lines. Conventional Wheeler diagrams just contain line drawings of the extent of each chronosome. This paper presents a method of generating a seismic Wheeler-like “diagram” for a 3D volume. This “diagram” is actually a seismic volume with dimensions of inline, crossline, and relative age. It contains the seismic response along the chronosomes similar to a stratal slice volume, except that in this new volume hiatus occurrences are denoted. The generation of this Seismic Wheeler Volume is accomplished by using a high resolution Age Volume.

Introduction

The generation of the Seismic Wheeler Volume was prompted by a request/challenge from Jim Benson, a Santos stratigrapher, and encouraged by Dennis Cooke, Chief Geophysicist at Santos, and Cedric Griffiths of CSIRO.

This paper has five sections. I will begin with a review of the Wheeler diagram, drawing material from USC’s web site. Next I will review the Relative Geologic Time (Age) Volume that was described by Stark (2003, 2004). The Age Volume and its histogram is what prompted the Santos Challenge. The third section contains the Santos Challenge as relayed to me via email correspondence. I will follow this with a description of two methods used to generate a Seismic Wheeler Volume. The last section contains conclusions and a brief look to the future.

Wheeler Diagram

The lower portion of Figure 1 is a Wheeler diagram. According to the USC web site: “Chronostratigraphic charts, also called Wheeler diagrams after the geologist who initially formalized this time-stratigraphy concept in 1958, display both the horizontal distribution of the component sedimentary layers of a sequence but also the significant hiatuses in sedimentation. This diagram is derived from sedimentary successions and is used to show the time relationships of both the depositional systems and system tracts, and their relationship to surfaces of non-deposition (Emery et. al, 1996).”

Figure 1: Stylized stratigraphic section and corresponding Wheeler diagram (Chronostratigraphic Chart). (This figure is Baum’s stratigraphic-chrono chart solution taken from http://strata.geol.sc.edu/ss-chrono.html, 2005)

“The basic units of the charts are “chronosomes”, horizontal ribbons that represent sedimentary rock units bounded by time planes. Chronostratigraphic charts are best constructed from interpreted seismic sections and help understand how sedimentary sections develop through time. The horizontal axis of the chart matches the horizontal dimension of the seismic section and vertical axis represents [geologic] time...” (adapted from http://strata.geol.sc.edu/ss-chrono.html, 2005)

Age Volume

To generate a Seismic Wheeler Volume, two input volumes are required: a seismic (or attribute volume) and a Relative Geologic Time (Age) Volume. Figure 2 contains a portion of a 3D seismic volume over which the Age Volume shown in figure 3 was generated. This Age Volume was generated by interactively unwrapping the instantaneous phase in 3D using the procedure described by Stark (2003, 2004). These two volumes are used to construct the Seismic Wheeler Volume shown later in figure 5.

The Age Volume has the same spatial dimensions of inline, crossline and traveltime (or depth) as the seismic volume. The value at each sample in an Age Volume represents relative geologic time. Points of the same color have the same age and are therefore part of the same horizon. The relative age values always increase with traveltime (depth) (in normal sections) just as the geologic age increases. The age values are relative in that if age value A is greater than age value B, we know that A is older than B, but we don’t know how much older.
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The calibration from relative geologic time to “true geologic time” requires a non-linear function that will vary with travel time and possibly position. The Seismic Wheeler Volumes describe herein are a function of relative geologic time.

Figure 2: Portion of seismic volume over which Age and Seismic Wheeler Volumes were generated. This dataset covers approximately 100 km² and contains 501 inlines and 501 crosslines (from Stark 2004).

The interactive three-dimensional phase unwrapping method of generating the Age Volume produces a high resolution Age Volume. When the Age Volume is converted to 8-bit, such as that seen in figure 3, the age resolution is degraded, but still useful.

Figure 3: Relative Geologic Age Volume corresponding to seismic data shown in figure 2. This Age Volume was generated by interactively unwrapping the instantaneous phase in three dimensions within an 800 ms window. (from Stark 2004).

Figure 4: Histogram of the Relative Geologic Age Volume shown in figure 3. The vertical axis is relative geologic time, while the horizontal axis is the number of seismic samples in the volume for each relative geologic age. The horizontal axis also represents the lateral extent of the horizons.

Santos Challenge

In late 2004, after reviewing the Age Volume and its associated histogram (figures 3 & 4), Jim Benson of Santos described the benefits of generating a Seismic Wheeler Volume and requested/challenged me to build such a volume. Rather than paraphrase him, below are slightly edited excerpts from his emails. I have added those words not in italics for clarity, to obscure basin names, or to editorialize.

“Dennis Cooke has just introduced me to your proprietary software featuring phase unwrapping and “Relative Geologic Time Volume Generation”.”

“Based on the application of your technique in the Name Removed 3D (figure 2) it appears that the software may provide us with an invaluable tool to interpret 3D seismic volumes using a sequence stratigraphic approach first outlined by Nordlund and Griffiths (1993).”

“Your software effectively maps out every “chromosome” (see Nordlund & Griffiths 1993) within a 3D seismic volume making it possible to generate very accurate maps of depositional system architecture in time and space, invaluable for delineation of play fairways.”
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“It also provides a unique way to associate time gaps in proximal parts of the basin (unconformities) with correlative conformities in the basin depocentre.... setting up a framework to predict the timing of sand delivery into a basin. Very exciting to say the least.”

“Your chronostratigraphic chart (figure 4) shows the relative ordering in time of each reflector in the time volume. This is significant because it means you have been able to assign a unique identifier to each reflector and then stack them in a layer cake with the oldest layer at the bottom and the youngest at the top. Presumably this means that on any line from the volume you can determine if any of the individual reflectors are missing. (Yes!) If carried through the volume then, these intervals of missing reflectors would correspond to unconformity surfaces.”

However...

“At the moment your chronostratigraphic chart display (figure 4) is too generalized. A more effective way of interpreting and displaying these relationships was outlined by Nordlund & Griffiths (1993 a, b).”

“You need to redisplay your data set so that the time series of reflectors can be identified on the seismic data itself. Effectively it would be like taking a 2d line and tracing each and every one of these reflectors with a pencil, creating a discrete line segment on paper for each unique reflector. (I can do this already.) As an example see Nordlund & Griffiths (1993a) Figure 2, where they have digitized individual reflectors from a 2D line. This is like a cosine of instantaneous phase display where the continuity of each reflector is enhanced and the geometric (onlap/offlap) relationships are shown.”

“The next step would then be to take all of these line segments, rank them from oldest to youngest (oldest at the bottom, youngest at the top) and display the distribution of each of the line segments against stratigraphic time (which simulates a Wheeler diagram or 2D chronostratigraphic diagram as shown in Figure 5B of Nordlund and Griffiths).”

“Would you be able to generate these displays from your algorithm? Automated generation of Wheeler diagrams using such a framework would be an immensely powerful tool for setting up predictive sequence stratigraphic models.” (Benson, 2004, personal communication).

Seismic Wheeler Volume Generation

Given an Age Volume, it turns out to be very easy to generate the Seismic Wheeler Volume. Below is a description of the two methods that I have used. The data in figure 5 was generated using the second method.

The first method takes advantage of the Age Volume being converted to 8-bits for display purposes. It is faster but not as accurate as the second method. For an 8-bit Age Volume there are 256 possible relative geologic time values. Therefore, the output Seismic Wheeler Volume will have the same inline and crossline dimensions of the input volume but only 256 vertical age samples. The conversion is performed one trace at a time, for all desired traces. The first step is to initialize to zero an output trace and a count trace. Next, the seismic amplitude (attribute) value of each two-way time sample is added to the current value in the output trace at the location equal to the age value of the particular two-way time. The count trace at this age location is also incremented. After all of the two-way time samples have been processed, all of the 256 age values are post-processed. If the count value is zero for any age value, then the seismic amplitude output value is set to the desired “hiatus value”. The 8-bit conversion can cause two vertically adjacent (in two-way time) points to have the same age, so either an average or user defined “undetermined” value is used whenever the count value is greater than one. The last step is to save this output trace, and get another trace to process until all desired traces are completed.

The advantages of this method is that it is fast and works with 8-bit data, but it has two disadvantages. First, since it is using the 8-bit Age Volume, it is does not utilize all of the available seismic amplitude or relative age resolution. Second, it does not distinguish between hiatuses that are caused by unconformities and those caused by an incomplete Age Volume (which can occurred in poor data quality areas).

The second method is a bit slower, but it does not have the two disadvantages of the first method. It starts with selecting a start age, an end age, and an age increment to determine the vertical size of the output Seismic Wheeler Volume. It also is a one trace at a time process. The first step is to initialize the output trace to a desired “no data available” value (to handle locations for which an age value was not determined due to windowing or data quality reasons.) Next, for each of the desired output age values between the start and end age, the travel time samples whose ages bracket the desired output age are located. These samples are used to interpolate the seismic amplitude (attribute) to obtain the seismic value to be placed at the desired relative age sample in the output volume. If the relative age difference between the two bracketing ages exceeds some threshold (that will depend upon how the age volume is generated) a hiatus value is used instead. This process is repeated for every desired trace.
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Figure 5 is a “Seismic Wheeler Volume”. It is the result of applying this second generation method to the floating-point age volume represented by figure 3. The green colored regions denote hiatus locations, while the magenta regions are the “no data available” points due to the bottom of the Age Volume generation window.

The top of this cube has been trimmed to a constant relative age slice. Note the channel like feature on the right hand side of this slice. This constant age slice is similar to the stratal slices described by Zeng et al (2001). However, the slice in figure 5 contains hiatus locations, which are not present in the stratal slices generated by others.

Although this volume is similar to the stratal slice volumes of others, I believe this is the first published example of a stratal slice volume containing imbedded hiatus locations.

In the future, the usefulness of the Seismic Wheeler Volume for delineating sand delivery timing and play fairways will increase significantly with increasing seismic volume size. More knowledge/information will be gained by exploring such a volume with advanced volume visualization techniques.

References


Stark, T.J., 2004, Relative geologic time (age) volumes—Relating every seismic sample to a geologically reasonable horizon: The Leading Edge, 23, no. 09, 928-932.


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