Multi-spectral volumetric curvature adding value to 3D seismic data interpretation

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Abstract

Volumetric attributes computed from 3D seismic data are powerful tools in the prediction of fractures and other stratigraphic features. Geologic structures often exhibit curvature of different wavelengths. Curvature images having different wavelengths provide different perspectives of the same geology. Tight (short-wavelength) curvature often delineates details within intense, highly localized fracture systems. Broad (long wavelength) curvature often enhances subtle flexures on the scale of 100-200 traces that are difficult to see in conventional seismic, but are often correlated to fracture zones that are below seismic resolution, as well as to collapse features and diagenetic alterations that result in broader bowls. We present a number of examples demonstrating the interpretational value of such multi-spectral volumetric estimates of curvature.
List of keywords:

Attributes, curvature, coherence
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Introduction

Computation of volumetric curvature attributes is a significant advancement in the field of attributes. Curvature computed from 3D seismic horizons have been used for prediction of fault and fractures for over of decade; some of these curvature measures have been shown to be correlated with open fractures measured on outcrops (Lisle, 1994) or through production data (Hart et al., 2002). Horizon-based curvature is limited not only by the interpreter’s ability to pick, but also the existence of horizons of interest at the appropriate level in 3D seismic data volumes. Horizon picking can be a challenging task in datasets contaminated with noise and where rock interfaces do not exhibit a consistent impedance contrast amenable to human interpretation. Very recently, volumetric computation of curvature has been introduced, which dispels the need for consistent horizons in the zone of interest (Al-Dossary and Marfurt, 2006). By first estimating the volumetric reflector dip and azimuth that represents the best single dip for each sample in the volume, followed by computation of curvature from adjacent measures of dip and azimuth, a full 3D volume of curvature values is produced. There are many curvature measures that can be computed, but the most-positive and most-negative curvature measures are the most useful in that they tend to be most easily related to geologic structures. Volumetric curvature attributes are valuable in mapping subtle flexures and folds associated with fractures in deformed strata. In addition to faults and fractures, stratigraphic features such as levees and bars and diagenetic features such as karst collapse and hydrothermally-altered dolomites also appear to be well-defined on curvature displays. Channels appear when differential compaction has taken place.
In Figure 1 we show a comparison of the most-positive and most-negative curvature attributes computed along a marker horizon from a 3D volume from south-central Alberta, Canada (Figures 1b and d), with the equivalent displays extracted along the horizon from the most-positive and most-negative curvature volumes (Figures 1b and d). Notice that while the NW-SE fault patterns are seen on all these displays, we also see a strong acquisition footprint on Figures 1b and d. Most typically, seismic horizons indicate peak, troughs, or zero-crossings of the seismic wavelet corresponding to the reflector of interest. These picks are contaminated by ground roll and other noise, which in turn are often correlated to source and receiver directivity, fold, and azimuthal variability of a given bin to the acquisition design. Lateral changes in the times of these picks used in dip magnitude, dip azimuth, and curvature maps exacerbate this noise and thus enhance the appearance of acquisition footprint. In general, volumetric computations of dip and azimuth (the input to volumetric curvature computations) are performed using a vertical analysis window (+/- 10 ms in Figures 1c and e), and are thus less sensitive to noise. The fault lineaments are seen as better focused and well defined in Figures 1c and e, while the footprint artifacts we see in Figures 1b and d are somewhat suppressed.

In Figure 2, we show strat-cube displays through volumetric estimates of coherence (Figure 2a), most-positive curvature (Figure 2b) and most-negative curvature (Figure 2c). A strat-cube is a subvolume of seismic data or its attributes, bounded by two not necessarily parallel horizons. Notice the clarity with which most of the NS faults stand out on the coherence display. In general, coherence maps lateral changes in seismic waveform that may be associated not only with reflector offset across a fault, but also with syntectonic deposition, diagenetic alteration, pressure compartmentalization, and fault gauge. In contrast, volumetric curvature enhances the
more subtle features associated with faults, including reflector rotation about a fault, reflector drag along a fault, subtle faults that have displacements that falls below seismic resolution, and a rich suite of fold and flexure phenomena associated with faulting, including roll-over anticlines, fault-bend-folds, and relay ramps (Xiao and Suppe (1992), Suppe et al (2004) and Ferrill and Morris (2008)). For this reason, there is considerably more detail on the most-positive and most-negative curvature displays when compared to the coherence display. In this data set, the lineaments in red seen on the most-positive curvature display will correlate with the up-thrown signatures that we see on the seismic. Similarly, the lineaments in blue seen on the most-negative curvature display will correlate with the down-thrown signatures. Such information comes in very handy for interpreting the seismic data. In order to correlate our attribute interpretation to the seismic data we show a zoomed image of the most-positive curvature horizon slice seen intersected with a seismic crossline in Figure 3. Notice how the red positive curvature features associated with the fault trends (running almost north–south) correlate with the up-thrown anticlinal signature on the seismic (indicated with the blue arrows). Similarly, the down-thrown edges on both sides of the faults are seen on blue color which indicates negative values of most-positive curvature (yellow arrows). Other similar features tend to stand out on the horizon slice and correlate as expected on the seismic section.

**Multi-spectral volumetric estimation of curvature**

Multispectral curvature estimates introduced by Bergbauer et al. (2003) and extended to volumetric calculations by Al Dossary and Marfurt (2006) can yield both long and short wavelength curvature images, allowing an interpreter to enhance geologic features having different scales. Tight (short-wavelength) curvature often delineates details within intense, highly localized fracture systems. Broad (long wavelength) curvature often enhances subtle flexures on the scale of 100-200 traces that are
difficult to see in conventional seismic, but are often correlated to fracture zones that are below seismic resolution, as well as to collapse features and diagenetic alterations that result in broader bowls.

Al Dossary and Marfurt (2006) introduced a ‘fractional derivative’ approach for volume computation of multispectral estimates of curvature. They define the fractional derivative as

$$F_{\alpha}(\frac{\partial u}{\partial x}) = -i(k_x)^{\alpha} F(u),$$

where the operator $F$ denotes the Fourier transform, where $u$ is an inline or crossline component of reflector dip, and where $\alpha$ is a fractional real number that typically ranges between 1 (giving the first derivative) and 0 (giving the Hilbert transform) of the dip. The nomenclature ‘fractional derivative’ was borrowed from Cooper and Cowans (2003); however, an astute mathematician will note that the $i$ is not in the parentheses. In this manner we can interpret equation 1 as simply a low pass filter of the form $k_x^{(\alpha-1)}$ applied to a conventional first derivative. Figure 4 shows filters for values $\alpha=0.80$ and $\alpha=0.25$. Given the spectral response, particularly when multiplied by the spectral response of the derivative operator, we will call the resulting images “short-wavelength” and “long-wavelength” curvature in the figures that follow.

The space domain operators corresponding to different values of $\alpha$ mentioned above are convolved with the previously computed dip components estimated at every sample and trace within the seismic volume. In additional the directional derivative is computed using a circular rather than linear window of traces, thereby avoiding a computational bias associated with the acquisition axes. Lower values of $\alpha$ decrease the contribution of the high wavenumbers, thereby shifting the bandwidth towards longer wavelength. Thus full 3D curvature attribute volumes are available for analysis at different scales, which helps extract meaningful and subtle information from seismic data.

**Examples**
In Figure 5 we show the strat-cube displays of long-wavelength and short-wavelength curvature of a fault/fracture system from Alberta. The surface displayed is at 1620 ms. Figure 5a shows the long-wavelength most-positive curvature strat-cube surface display correlated with the seismic crossline. Notice, the broad definition of the fault trends seen in bright red, correlating nicely with the upthrown signature on the seismic. The short-wavelength version of the most-positive curvature is shown in Figure 5c. Notice the higher resolution of the fault definition. The wider red lineaments as seen on the long-wavelength display is seen here as resolved into two or more lineaments. Such detail is useful for picking up fracture information on curvature displays. Similarly, Figures 5b and d depict the long and short-wavelength versions of the most-negative curvature and the blue lineaments correlate with the downthrown signatures on the seismic sections.

Curvature attributes are useful for not only faults and fracture interpretation, but also for stratigraphic features such as levees and bars as well. In the Gulf of Mexico and the North Sea, where the effect of differential compaction on deeper stratigraphic features propagates upward, it may be necessary to first flatten the seismic volume on a horizon below the target of interest before compute vector dip and curvature. In Alberta, the existence of structurally competent carbonate formations either as or below the target of interest ameliorates this problem.

In Figure 6 we show a comparison of coherence with the long-wavelength and short-wavelength versions of the most-positive and most-negative curvature. Notice a meandering channel seen on the coherence display (Figure 6a), which has its levees seen clearly at some points but not so well defined at others (yellow arrows). In Figure 6b showing the long-wavelength version of the most positive curvature, we see some of the levees of the channel developed as indicated by the yellow arrows. The axis or the thalweg of the channel is seen very clearly on the long-wavelength version of the most-positive curvature in Figure 6c. As expected, enhanced resolution in terms of definition of the channel is seen on the short-
wavelength version of both the most-positive and negative curvature as seen in Figure 6d and e. Building on this preliminary analysis, and inspecting the seismic data, we anticipate that the channel axes will appear as valleys and the levees by ridges (Figure 7). Details on these shape volumes can be found in Al-Dossary and Marfurt (2006). In Figure 7 we show images corresponding to Figure 6.

We show another comparison of coherence with the long-wavelength and short-wavelength versions of the most-positive and negative curvature in Figure 8. Again, notice that the thalweg of the channel is well-defined on the most-negative curvature and the edges or the levees of the channel can be clearly marked on the most-positive curvature. The stratigraphic details within the channel can be examined by focusing on the short-wavelength version of the most-negative curvature (Figure 8e). As emphasized above, the seismic signatures of the different portions of the channel can be studied by closely correlating the attribute and the seismic profiles as is shown in Figure 9 for the most-negative curvature.

In Figure 10 we show an inline and a crossline from a 3D seismic volume from Alberta. This data volume was used for the study of fractures at the level indicated with the blue vertical arrow. The fractures in the indicated formation manifest on the seismic in the form of broken down reflections. Consequently, the coherence display (Figure 11a) shows low coherence in this zone on the time slice. The long-wavelength most-positive curvature (Figure 11b) indicates the main reflection trends in the form of red lineaments. This pattern is interspersed with blue broken trends which are seen very clearly on the long-wavelength most-negative curvature display in Figure 11c. The short-wavelength version of the two curvature displays as seen in Figure 11c and e show these lineaments in a lot more detail as would be expected for fractured zones.

**Calibration with well-log data**

It is always a good idea to calibrate the interpretation on curvature displays with log data if possible. One promising way is to interpret the lineaments in a fractured zone and then transform them into a rose diagram. Such rose diagrams can then be compared with similar rose diagrams that are obtained from
image well logs to gain confidence in the seismic-to-well calibration. Once a favorable match is obtained, the interpretation of fault/fracture orientations and the thicknesses over which they extend can be used with greater confidence for more quantitative reservoir analysis. Needless to mention such calibrations need to be carried out in localized areas around the wells for accurate comparisons.

In Figure 12 we show how the generation of rose diagrams from the long-wavelength and the short-wavelength displays. Notice the rose diagram generated from the short-wavelength curvature display leads to a more robust display, than the sparse lineament seen on the long-wavelength display.

Conclusions

Multispectral volumetric curvature attributes are valuable for prediction of fracture lineaments in deformed strata. Several applications of volume curvature have been completed in different geological settings, which are found to be useful for different stratigraphic features, ranging from imaging of channel boundaries, small scale faults to highly fractured zones.

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List of References


List of captions

**Figure 1.** (a) Time surface from a 3D seismic data volume from Alberta, and horizon-based (b) most-positive and (d) most-negative curvature computed from the picked horizon in (a). Volume-based (c) most-positive and (e) most-negative curvature extracted along the picked horizon shown in (a). Notice that the acquisition footprint artifact is not seen on the volume-based curvature displays. (*Data courtesy of Arcis Corporation.*)

**Figure 2.** Strat cubes through (a) coherence, (b) most-positive, and (c) most-negative attribute volumes. While some N–S faults are seen on the coherence display, the level of detail is much higher on the curvature displays. (*Data courtesy of Arcis Corporation.*)

**Figure 3.** Zoom of the most-positive curvature attribute horizon slice shown intersected with a seismic crossline. Notice that the peaks of the upthrown fault planes indicated with blue arrows correlate with the bumps in the horizon times on the seismic horizon. Similarly, the peaks of the downthrown fault planes indicated with yellow arrows correlate with the lows in the horizon times on the seismic horizon (*Data courtesy of Arcis Corporation.*)

**Figure 4.** Fractional derivatives visualized as filters applied to the conventional first derivative operator. The idealized derivative is proportional to the wavenumber (k) and inversely...
proportional to the wavelength ($\lambda$). The dotted line represents a filter applied to the derivative operator $\delta/\delta x$ that would perfectly reproduce $\delta/\delta x$. Any numerical operator needs to go to zero at Nyquist, or $\lambda=2\Delta x$. We compensate for coarser sampling artifacts at $45^\circ$ to the grid by tapering the derivative after $\lambda=4\Delta x$. The 0.80 derivative slightly enhances the long wavelength components, while the 0.25 derivative greatly enhances the long wavelength components. The filters are normalized such that the area under the filtered spectrum (the product of the filter times the idealized first derivative) is equal to 1.0.

**Figure 5.** Zoom of chair-displays where the vertical display is a portion of a crossline through the original 3D seismic amplitude volume while the horizontal displays are strat slices through (a) coherence (b) most-positive (long-wavelength) (c) most-negative (long-wavelength) (d) most-positive (short-wavelength) and (e) most-negative (short-wavelength) attribute volumes. The lineament detail on the short-wavelength attribute displays is higher and crisper than similar lineaments on the long-wavelength displays. The fault lineaments correlate with the upthrown and downthrown signatures on the seismic. (Data courtesy: Arcis Corporation, Calgary).

**Figure 6:** Comparison of strat-slices from (a) coherence (b) most-positive (long-wavelength) (c) most-negative (long-wavelength) (d) most-positive (short-wavelength) and (e) most-negative (short-wavelength) attribute volumes. The definition detail on the long-wavelength curvature attribute displays is higher and focused than similar lineaments on the coherence display. Stratigraphic detail within the channel is seen as crisper and well-defined on the short-wavelength curvature displays. (Data courtesy: Arcis Corporation, Calgary).

**Figure 7:** Stratal slices through various attribute volumes. (a) Coherence shows a main channel along with what appear to be incised valleys feeding into it. (b) Structural ridges appear to be blue. Areas that have no ridge component are white. These appear to correlate to what we interpret to be low coherence interfleuve zones. (c) Structural valleys appear as red further supporting our interpretation of incised valleys feeding into a major channel. Areas that have no valley component are white. (d) Display of structural ridges and valleys together. Other structural shapes (domes, saddles, and bowls) also exist but are not displayed. (e) Coherence plotted on top of the structural valley image, where the most coherent values (c=1.0) are set to be transparent, showing that the channel axis is both valley-shaped and highly coherent. (f) A complementary image but now with the lowest ridge values set to be transparent, allowing us to see that high coherence (white) corresponds to the absence of ridges. Such correlations suggest improved delineation of channels through multiattribute cluster analysis or neural networks. Basically, channels in this survey appear to have both high coherence and a valley shape.

**Figure 8:** Comparison of strat-slices from (a) coherence (b) most-positive (long-wavelength) (c) most-negative (long-wavelength) (d) most-positive (short-wavelength) and (e) most-negative (short-wavelength) attribute volumes. The definition detail on the long-wavelength curvature attribute displays is higher and focused than similar lineaments on the coherence display. Stratigraphic detail within the channel is seen as crisper and well-defined on the short-wavelength curvature displays. (Data courtesy: Arcis Corporation, Calgary).

**Figure 9:** Enlargement of a chair-display in which the vertical display is an inline from the 3D seismic volume and the horizontal displays is the strat-slice through most-negative curvature...
(long-wavelength) volume. The channel feature correlate well with their expected seismic signatures. *(Data courtesy: Arcis Corporation, Calgary).*

**Figure 10:** An inline and a crossline from a 3D seismic data volume from Alberta. The vertical blue arrow indicates the fractured zone on the seismic section. *(Data courtesy: Arcis Corporation, Calgary).*

**Figure 11:** Zoom of chair-displays where the vertical display is a portion of a crossline through the original 3D seismic amplitude volume while the horizontal displays are time slices through (a) coherence (b) most-positive (long-wavelength) (c) most-positive (short-wavelength), (d) most-negative (long-wavelength) and (e) most-negative (short-wavelength) attribute volumes. The fractured zone shows low coherence but the lineament detail on the short-wavelength attribute displays is higher and crisper than similar lineaments on the long-wavelength displays. *(Data courtesy: Arcis Corporation, Calgary).*

**Figure 12:** (a) A time slice through the most-positive curvature (long wavelength) volume with the individual lineaments interpreted in black. The Rose diagram prepared for this set of lineaments in black is shown to the right of this figure, (b) A time slice through the most-positive curvature (short-wavelength) volume with the individual lineaments interpreted in black. The Rose diagram prepared for this set of lineaments in black is shown to the right of this figure *(Data courtesy: Arcis Corporation, Calgary).*