GC What Causes those Annoying Stair-Step Artifacts on Coherence Volumes?*

Tengfei Lin[1] and Kurt J. Marfurt[1]

Search and Discovery Article #42036 (2017)
Posted March 13, 2017

*Adapted from the Geophysical Corner column, prepared by the authors, in AAPG Explorer, March, 2017. Editor of Geophysical Corner is Satinder Chopra (schopra@arcis.com). Managing Editor of AAPG Explorer is Brian Ervin.

[1]University of Oklahoma, Norman, Oklahoma (kmarfurt.ou.edu)

General Statement

Since its original introduction 20 years ago, coherence remains, along with bright spots, to be one of the most popular seismic attributes used by interpreters. During this time, there have been significant advances in algorithmic implementation, data preconditioning and most importantly, interpretation workflows. Nevertheless, the stair-step artifacts seen on many coherence volumes has haunted its developers and annoyed interpreters throughout this time. Specifically, while time slices through coherence volumes provide excellent images of the continuity and orientation of faults, the lateral location of these faults are often shifted from one manually picked on vertical slices through the seismic amplitude data by a human interpreter.

Eigenstructure-, semblance-, variance-, and gradient structure tensor-based coherence, as well as Sobel-filter estimates of discontinuities, are all computed in an oblique window centered about each voxel consisting of five or more traces and zero to as many as two dozen time samples. Since the size of the analysis window is oriented vertically along traces, folk wisdom has been that the stair steps are caused by the vertical extent of the analysis window, where larger vertical extent results in larger, smoother stair-step artifacts.

For this reason, a best practice is to limit the vertical analysis window to approximately the dominant period of the seismic data, thereby avoiding mixing discontinuities from deeper or shallower horizons. For listric faults, the stair-step artifacts become worse than annoying, with the gentler stair steps intersecting a time slice multiple times, resulting in a broad incoherent zone rather than in a single sharp image of the fault.

Attempted Remedies

We evaluated two remedies to this problem, neither of which worked. First, we balanced the amplitude of each sample vector within the analysis window to have approximately the same contribution. Such balancing reduced, but did not eliminate the contribution of the stronger discontinuities within the analysis window. Second, we reduced the vertical size of the analysis window. As shown in Figure 1d, even a window size of 1-sample results in a stair-step artifact, which suggests the artifact is due to the seismic amplitude data and not to the size of the coherence window.

Recent publications by the diffraction imaging community have provided some insight into the cause of these artifacts. While the typical migration algorithm assumes that each subsurface image point is a point diffractor, those algorithms that explicitly include an obliquity factor actually assume each subsurface point is part of a specular reflector. In prestack migration, the obliquity factor is a function of the unit vector from the source to the image point, ps, the unit vector from the receiver group to the image point, p_g, and the normal to the hypothesized reflector, n (Figure 2). In diffraction imaging, one explicitly computes n, defining the normal to the reflector dip, from a previous image of specular (or conventional) imaging. In this case, the obliquity factor, Ω, is simply the mean of the vectors p_s and p_g times n, which geometrically gives the cosine of the angle between the average of the angle of incidence and reflection and the normal. Examination of Figure 2 shows that for specular reflections, the angle of incidence equals the angle of reflection about the normal, such that $\Omega = 1$.

Furthermore, migration ray pairs, p_s and p_g, skewed to the left of the specular angle will generally be accompanied by migration ray pairs skewed to the right. In most migration algorithms, the seismic image is built up point diffractor by point diffractor. The net result is that the seismic wavelet will be oriented perpendicular to the reflector, parallel to n. The root cause of the problem is that the earth is composed of a sparse collection of reflecting interfaces. Interpreters recognize faults by alignment of discontinuities in the reflections. Discontinuities in these interfaces are represented by a seismic wavelet normal to the interface, not parallel to the (unimaged) fault plane.

Since we do not believe this phenomenon is well recognized by most interpreters, we generate a suite of synthetic shot gathers using a finite difference algorithm, prestack migrate the results to obtain images in both time and depth domain, and compute coherence (Figure 3). Note that the seismic wavelets near the fault edges are aligned perpendicularly to the horizontal reflectors. Since these terminations occur at discrete layer boundaries, the result is a discrete stair step, with the vertical extent of the stair step defined by the size of the seismic wavelet.

Conclusion

There is no easy algorithmic solution to this problem. The best solution is to improve the resolution of the seismic data, thereby imaging more fault discontinuities at weaker reflectors. Barring this option, one can "enhance" the fault discontinuities by smoothing coherence anomalies parallel and sharpening coherence anomalies perpendicular to the fault as described in a previous article in this column. In spite of our disappointment in fixing footprint artifacts, recognizing its root cause may help more clever developers to construct a solution.

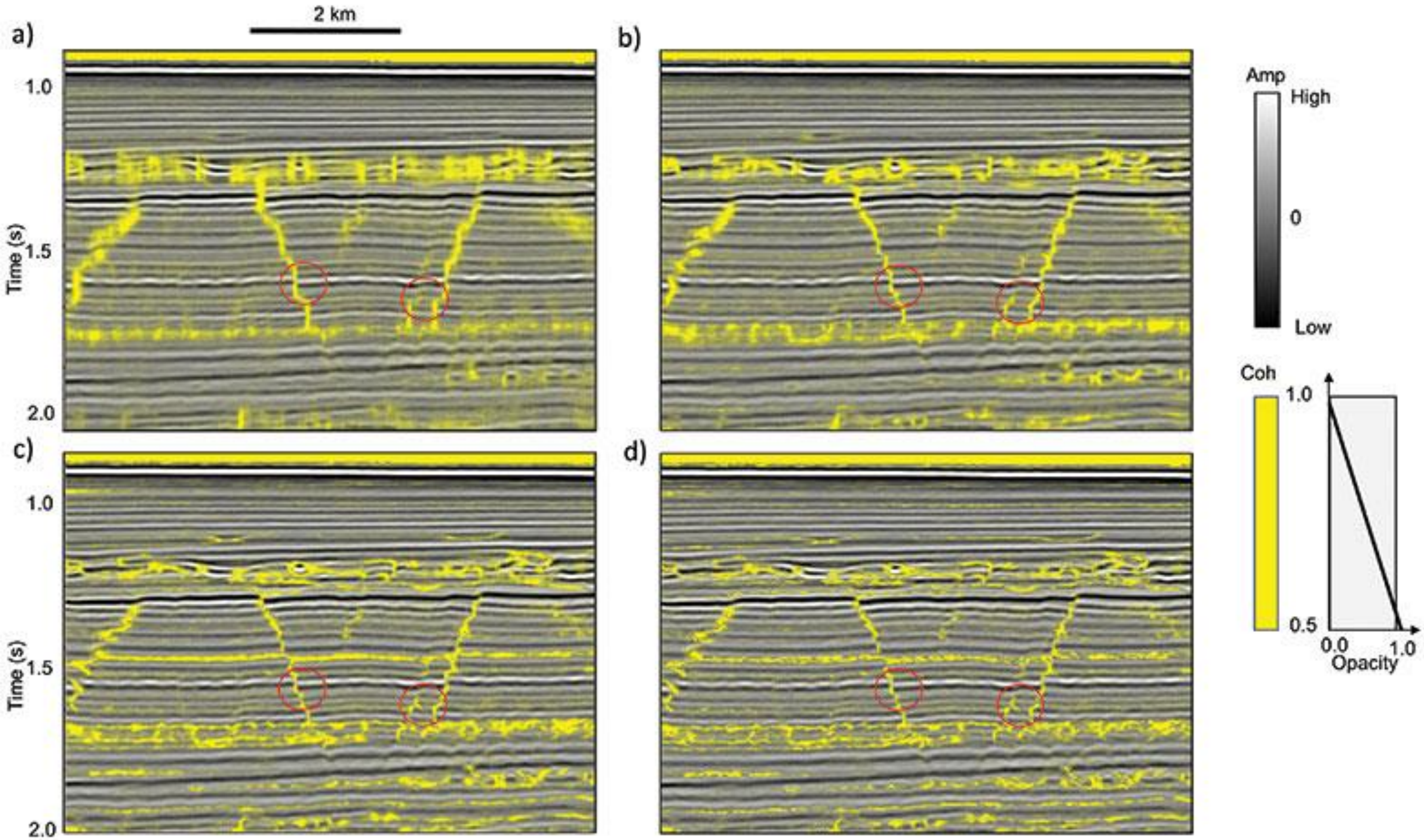

Figure 1. A suite of vertical slices through co-rendered seismic amplitude and coherence volumes where the coherence was computed using five traces and (a) ±40 ms, (b) ±20 ms, (c) ±4 ms, and (d) ±0-ms vertical analysis windows. Sample increment = 4 ms, bin size =12.5 m x 25 m. Note the stair-step artifacts indicated by the red circles. The stair-step anomalies shifts the location of faults seen on coherence time slices laterally. While such inaccuracies on the time slices are not catastrophic, it can be quite annoying. Folk wisdom attributes the stair-step anomalies to the size of the vertical analysis window, which while oriented along structural dip, typically consists of vertical trace segments. However, note that the stair step persists even when the coherence window size is a single sample, as seen in (d). In each image, the stair step is due the vertical orientation of the seismic wavelet, perpendicular to the nearly horizontal reflector. (Data courtesy of NZPM.)

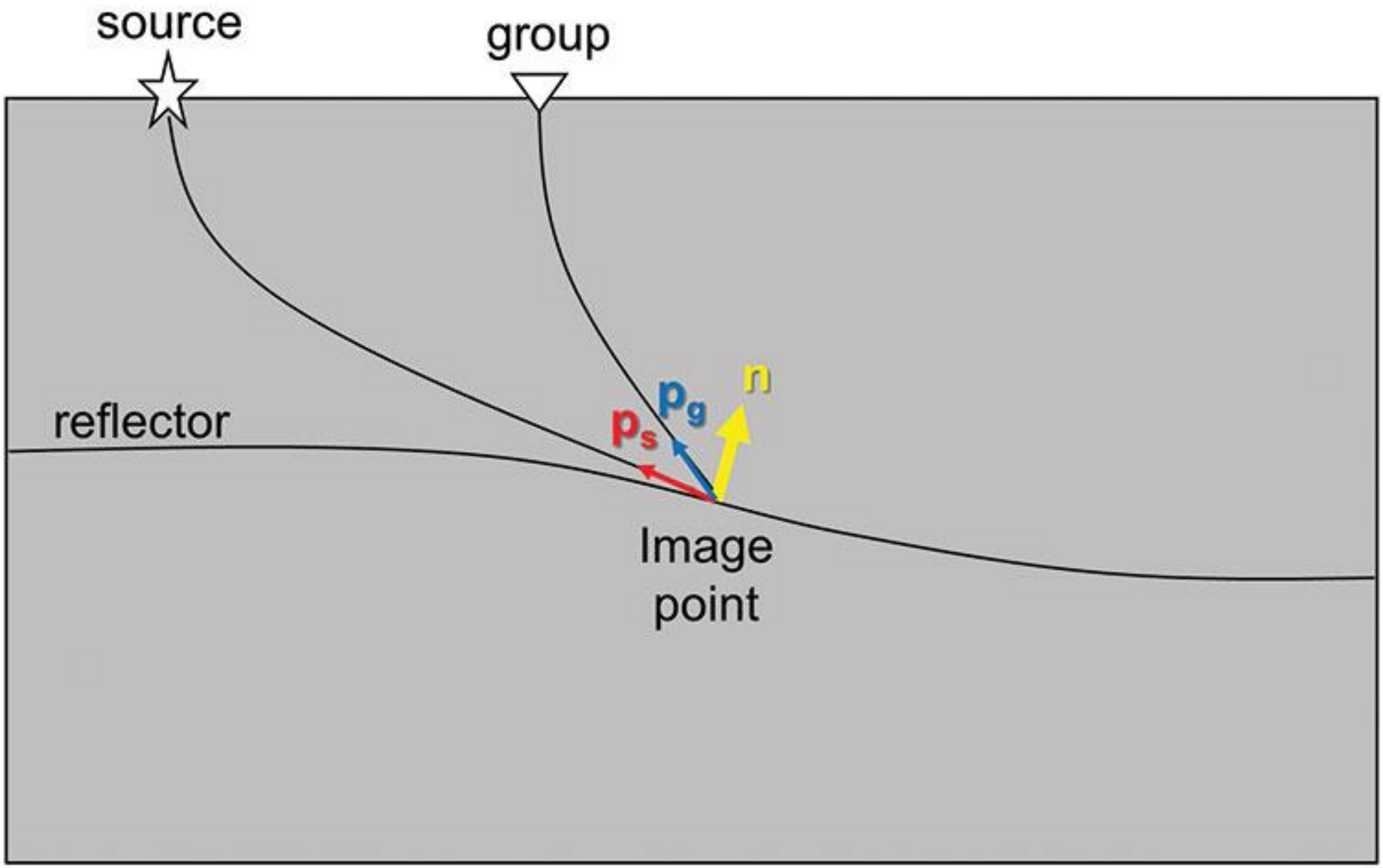

Figure 2. The geometry of seismic migration, using the notation of the diffraction imaging community, n defines the normal to the hypothesized reflector at the image point. If no hypothesis is made, most algorithms assume n to be vertical, while some eliminate the obliquity factor completely. p_s and p_g define unit vectors at the image point. The obliquity factor is the cosine of the angle between the yellow vector and the average of the blue and red vectors.

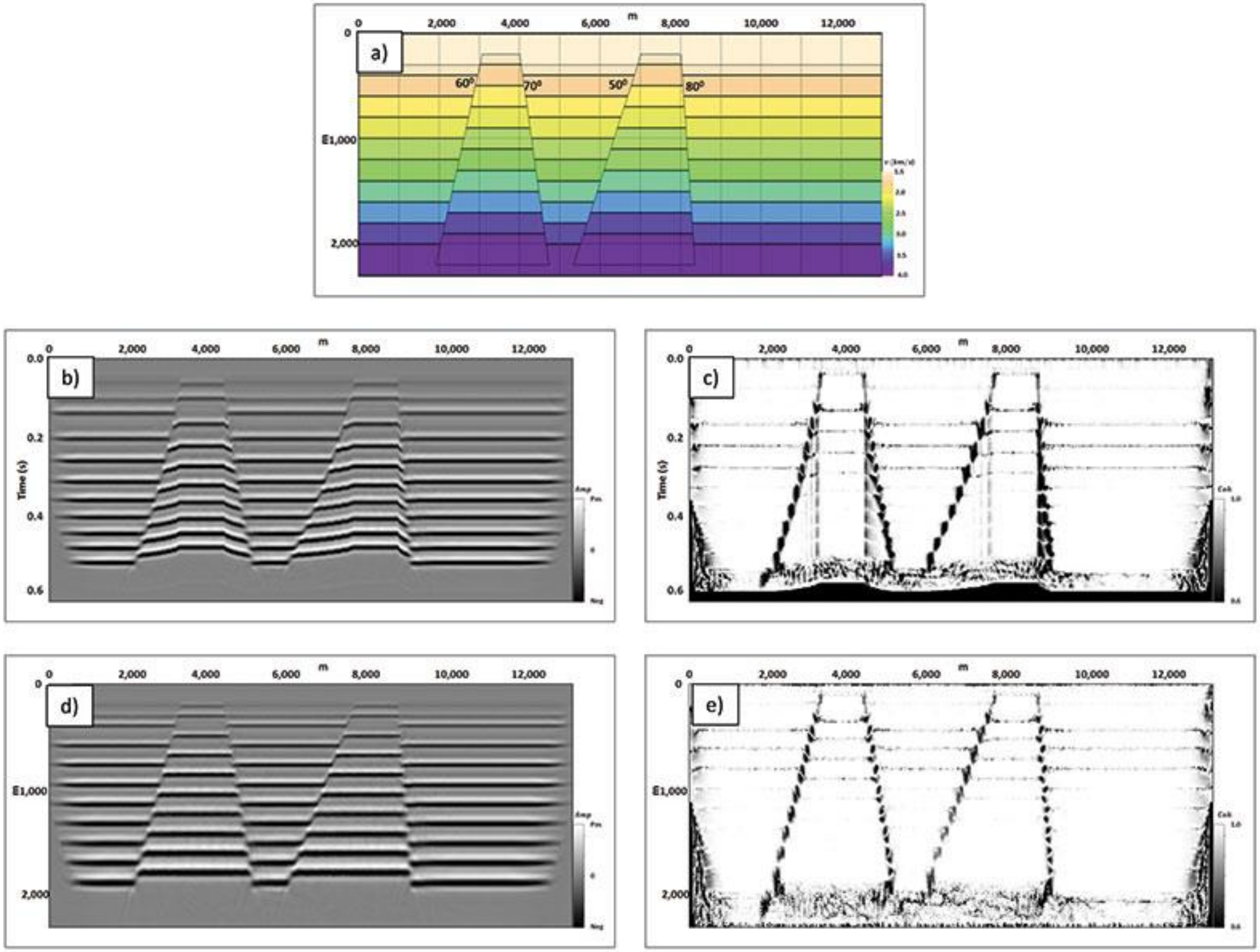

Figure 3. (a) A simple reflectivity model showing faults with dips of 500, 600, 700 and 800. Synthetics were generated using a 2-D finite difference solution of the wave equation. (b) The resulting prestack time-migrated image. Note that the seismic wavelets are perpendicular to the reflector, including near the fault edges. The images suffer from fault shadows. Fault plane reflectors were not imaged due to the finite migration aperture of 2000 m. (c) The coherence image computed from the seismic data (b) displayed in (a) using a vertical analysis window of one sample. (d) The resulting prestack depth-migrated image. (e) The coherence image computed from the seismic data (d) displayed in (a) using a vertical analysis window of one sample. Note the stair-step artifacts are about the size of the seismic wavelet seen in (d). Depth migration has eliminated the fault shadows. (Modeling and migration software courtesy of Tesseral LLC.)