Delaware Basin Horizontal Wolfcamp Case History: H2S and extraneous water linked to graben features mapped by HTI analysis

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The Geologic Problem:

Vertical fracturing within the Wolfcamp underlying Lamar limestone graben features (has been shown to act as a conduit) has demonstrated a fracture stimulation connection to excessive extraneous water and H_2S in Wolfcamp horizontal wells within Reeves County of the Delaware Basin. Bridge plugs located on the heal side of these fractured intervals have successfully isolated the excessive water and H_2S, confirming the location of the problem. The working model assumes Lamar limestone grabens caused by late Cretaceous Laramide extension with faults terminating at various depths: often directly beneath the Lamar limestone, but sometimes into the Bone Springs and even the Wolfcamp.

The Seismic Solution:

Post-stack seismic structural analysis has been unsuccessful at predicting the depth of fault penetration, most likely because vertical displacement is too small to show a significant change in dip at the Wolfcamp level (Figure 1). By looking at relative travel-time changes instead of absolute, pre-stack velocity-based HTI analysis successfully detected the abundant fracturing caused by the small fault displacement.

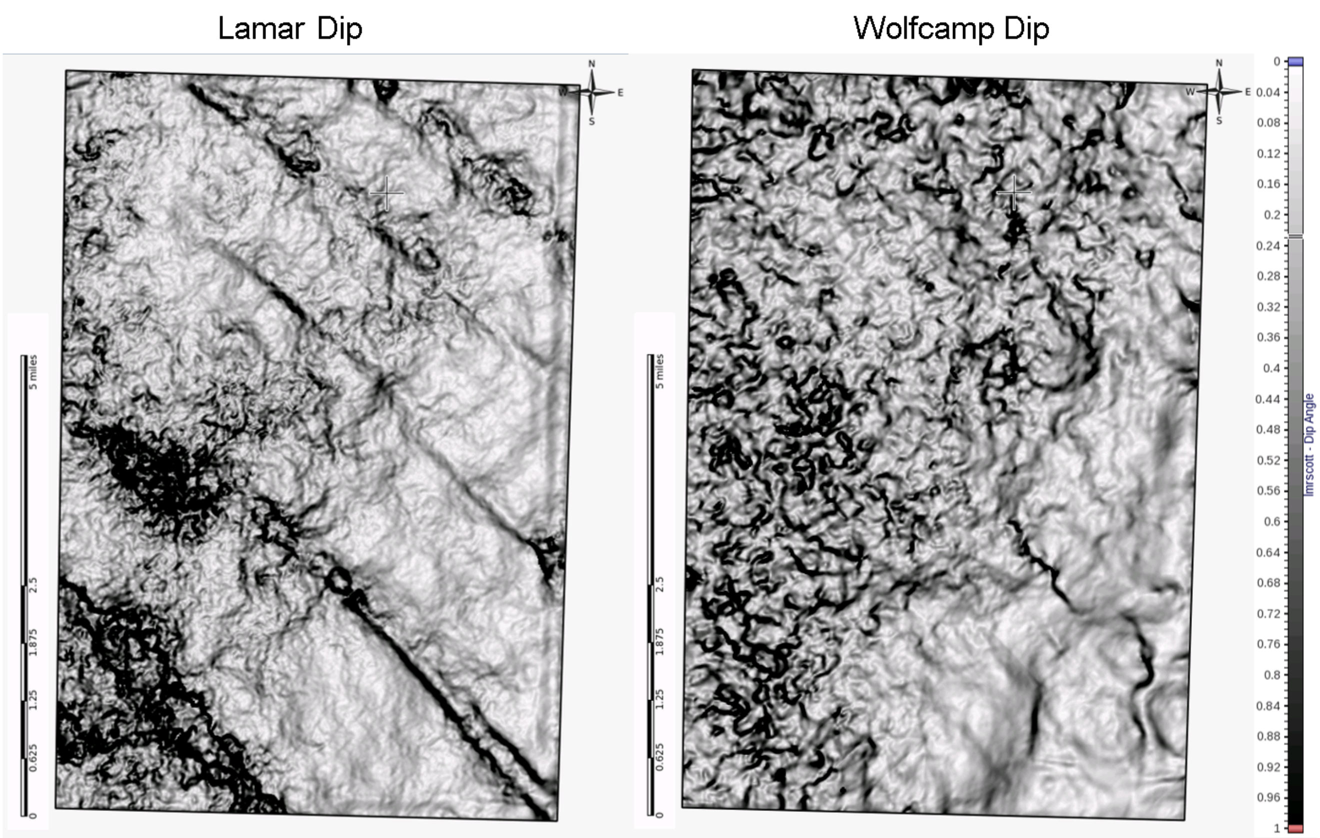

Figure 1: Lamar Dip (left) shows very clear NW to SE faulting. Wolfcamp Dip (right) does not clearly show a continuation of these same faults down to the Wolfcamp level.

Wide azimuth acquisition and azimuth-preserving processing are necessary to record and preserve azimuth information for HTI analysis. Azimuths were acquired evenly out to 9000', which is adequate for a target depth of ~10,000' (maximum reflection angle at the Wolfcamp B in the narrow azimuth direction is ~25° which is greater than the minimum of 20° required for HTI). The study area was selected away from survey edges and surface skips, so that all CMP's contained similar fold at all azimuths. To preserve azimuth and offset information during migration, the data was binned into offset and azimuth ranges, with each bin PSTM migrated separately. After migration an additional pass of gather conditioning further cleaned the data for azimuthal velocity analysis.

Velocity-based HTI analysis of the conditioned gathers highlighted the Lamar limestone graben features as clear changes in fast azimuth coincident with Lamar faults. Moveouts were measured with a modified Swan technique that found the percent anisotropy and fast azimuth that best flattened the gather. The RMS fast azimuth extracted along the Wolfcamp B shows a sharp change from the background azimuth of 160° to a local azimuth of 70° at the graben boundaries (Figure 2). Also evident are increases in % RMS ansitropy along the outside edges of the grabens and a decrease in anisotropy within the grabens. Finally, western and northwestern portions of the survey were dominated by noise and not usable for HTI analysis. The high level of noise encountered is corroborated by the chaotic dip measured in these portions of the map.

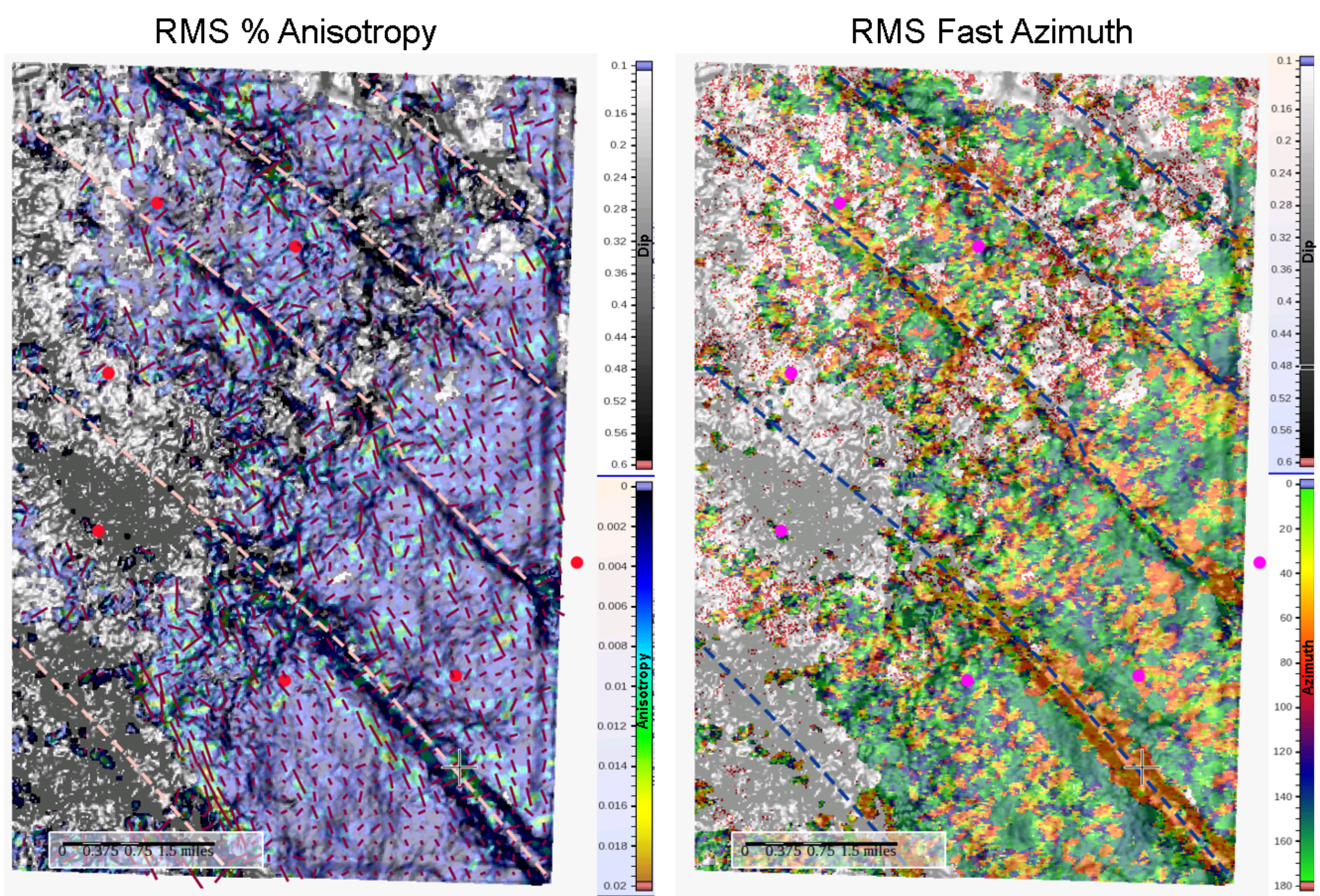

Figure 2: Wolfcamp B RMS % Anisotropy (left) tends to be low inside grabens and high outside graben edges. Wolfcamp B Fast Azimuth (right) changes abruptly at graben

boundaries from the background azimuth of 160° to the local azimuth of 70°. Shading indicates dip.

While RMS anisotropy successfully identified the highly fractured zones of the Lamar limestone grabens, the values measured were not predicted by standard fracture theory. For example, well treatment data suggests a highly fractured zone within the graben, with little to no fracturing outside; contrarily the percent anisotropy - which is supposed to correlate to fracture density - was higher outside than inside the grabens. Similarly, the fast azimuth is supposed to be parallel to maximum horizonal stress and open fracture orientation. Thus, the maximum horizontal stress inside the grabens should be perpendicular to the graben axes and so too the orientations of open fractures. Such a scenario might be likely in a compressional environment with reverse faulting, but not in the extensional environment of the Delaware Basin, where normal faulting requires that the maximum horizontal stress and corresponding open fracture direction be somewhat parallel to the faults (and graben axes).

A more likely explanation of the data is that, because the underlying assumption of uniformly distributed fractures has been violated, a non-standard interpretation of azimuthal moveout distribution is needed. Figure 3 shows a plausible explanation for the unusual RMS anisotropy results. The host matrix is largely unfractured and considered seismically “fast”. The graben feature is highly fractured and considered seismically “slow”. For a CMP located within the graben, the vast majority of rays will arrive at the fast velocity. Snell’s law tells us that rays will bend to spend the least amount of time possible inside the graben, so even rays non-perpendicular to the graben will experience little of the slow down. Only rays with both shots and receivers within the graben will be forced to experience the full impact of the slow down. The resulting moveout pattern is not sinusoidal (as it is for uniformly distributed fractures) but a stair-step function. The sinusoid that the software attempts to fit to stair step will have a low peak-trough amplitude, because of the overall flatness, and a trough lined up with the graben axis. This explains the low anisotropy and non-fracture-parallel azimuth despite a high concentration of fractures. The high anisotropy just outside the grabens can be explained similarly. Rays non-parallel to the graben will experience the slow down, while rays parallel to the graben will not. The wider range of rays experiencing the slow down due to the location outside the graben may cause a wider sinusoidal trough and better match to a sinusoidal shape, resulting in a higher anisotropic fit. In summary, while the interpreter cannot interpret the fractures using standard HTI theory, he can still locate them by looking for sudden changes in azimuth that coincide Lamar faulting and are flanked by high % anisotropy.

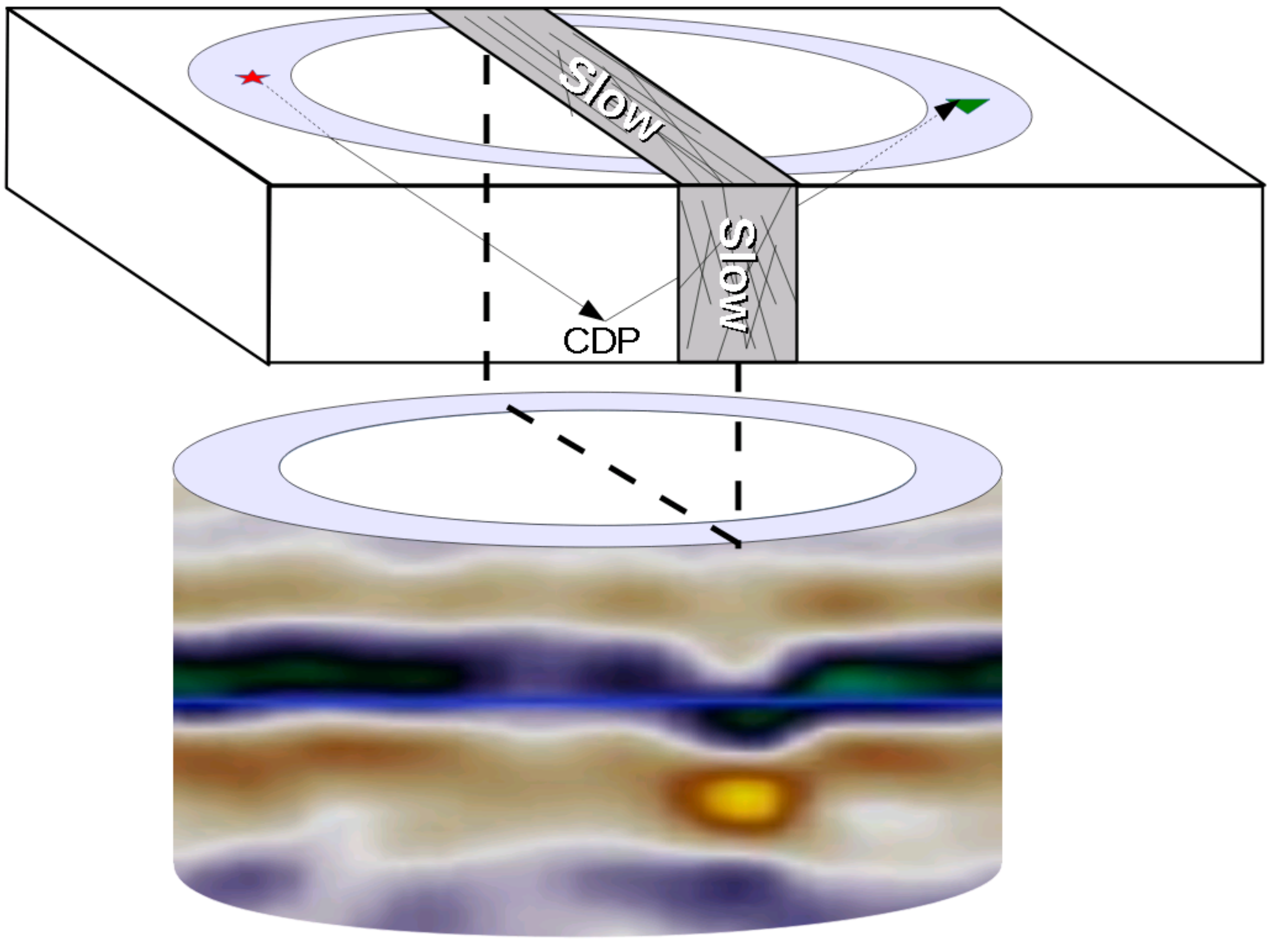

Figure 3: Cartoon of impact of linear slow feature on azimuthal variation of reflection arrival times.

Adding confidence to the non-uniform fracture distribution interpretation mentioned above, are pre-stack and post-stack seismic evidence. Figure 4 shows a gather taken from within a graben feature. Azimuth sectors non-parallel to the graben are overcorrected at the Wolfcamp B, indicating the actual rock was faster than the migration velocity. Azimuth sectors parallel to the graben are flat, meaning that they arrived at the migration velocity, and more slowly than the other sectors. If the fractures were evenly distributed, there would be a more gradual change from flat to non-flat. The sudden change indicates that the slow feature is only associated with a narrow band of azimuths, as would be expected from a narrow, fractured graben. Secondly, the stacked section to the right shows push-downs below the graben features. This is consistent with a narrow band of slow rock distorting the image. Both phenomena suggest a long narrow section of slow rock consistent with a fractured Lamar limeston graben feature.

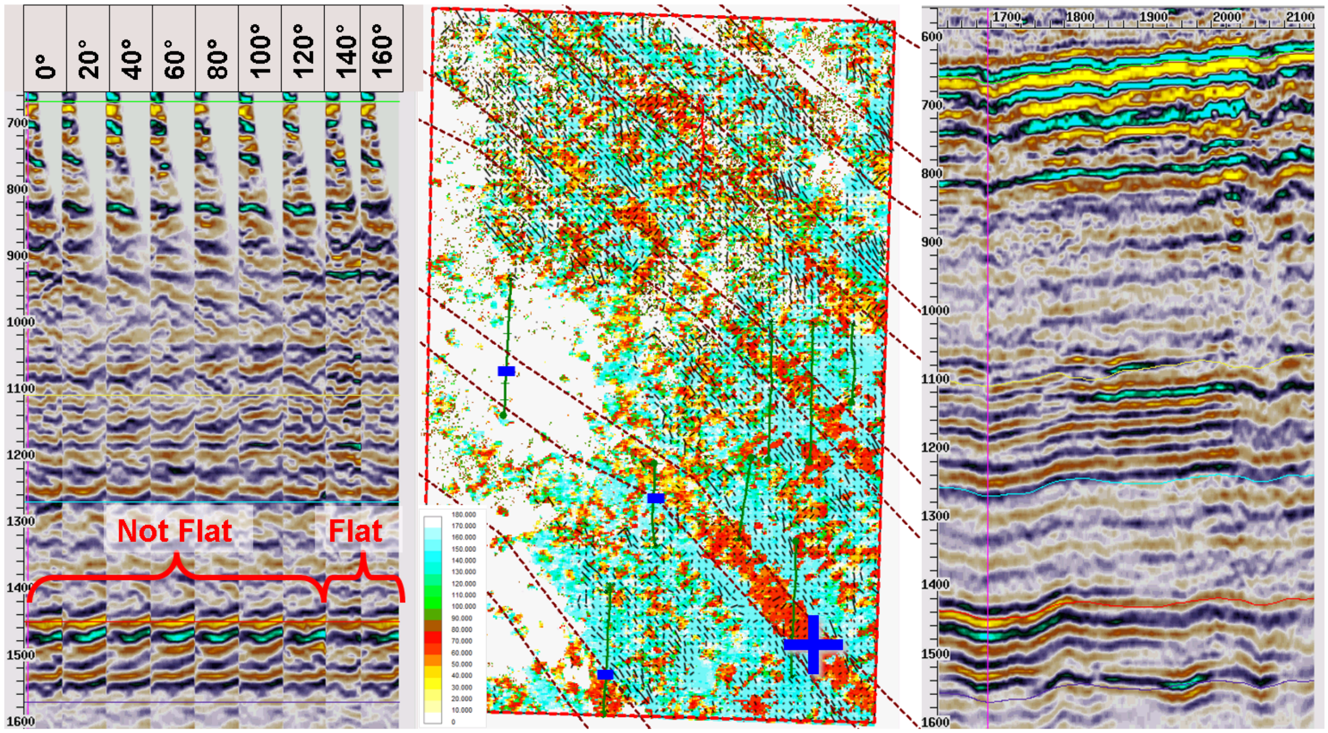

Figure 4: Azimuth sectors (left) from within graben feature (center – blue cross) show overcorrection non-parallel to graben axis and flat moveout parallel. Stacked section (right) shows Wolfcamp B push-down under graben feature. Vertical pink line indicates gather location.

The usual step of HTI RMS-to-interval inversion to vertically isolate the location of fracturing was unsuccessful, but the fractures could still be attributed to the Wolfcamp B via gather inspection. RMS anisotropy is the average anisotropy of the entire overburden. In order to find out where along the raypath the anisotropy occurred, the values are extracted along horizons and compared for changes. If the average anisotropy didn't change between horizons, then no interval anisotropy was found. If the anisotropy did change, then local anisotropy should be placed within that interval. Figure 4 shows that reflection strength at the top and bottom of the reservoir was too weak for reliable anisotropy measurements, so no comparison of anisotropic change with depth could be made. RMS anisitropy could only be reliably measured from the center of the reservoir, which is not conducive to interval anisotropy calculation. On the other hand, gather inspection shows that a change in amplitude with azimuth is occurring along with the change in moveout at the Wolfcamp B. Amplitudes are not the result of an average along the raypath, but the impedance contrast at the reflection depth, so the amplitude change places the fracture location at the Wolfcamp B. Finally, the coinciding lateral location of the azimuth changes with the Lamar graben faults and horizontal well Bridge Plug locations suggests of a local origin of the anisotropy.

Results/Conclusions:

Fast RMS azimuth maps at the Wolfcamp C successfully identified where Lamar graben features penetrate down to the Wolfcamp. Such features tend to occur where sudden changes in azimuth coincide with mapped grabens in the Lamar limestone. By successfully locating these features, future wells can be planned such that they don't intersect them, avoiding costly H_2S remediation and excessive water.

coincide with Lamar faults.