AAPG EXPLORER

GEOPHYSICAL CORNER

Better Resolution Or Coincidence?

The Geophysical Corner is a regular column in the EXPLORER, edited by R. Randy Ray. This month's column is titled "Rejuvenation of a Mature Field Through Application of a Unique Frequency Enhancement Technology."

By MARCUS L. COUNTISS

Many attempts have been made throughout the history of modern seismic to image thin beds (<1/4 of dominant wavelength) by extracting higher frequencies from seismic. In addition to simply imaging zones below normal resolution, two of the more common goals to aid in reservoir development are:

❒ To define pinch-outs of producing zones.

❒ To resolve internal bed geometries.

Techniques to enhance seismic frequencies are critical to achieve optimum thin bed resolution.

The most common post-stack method is spectral whitening or boosting the amplitudes of all frequencies within a certain bandpass to the same level. The problem with this method is that it does not discriminate noise from signal. Noise is boosted along with the subsurface signal and, depending on the signal-to-noise ratio (SNR), whitening may fail to extract the very information we hope to resolve.

Other techniques such as coherence cube technology and seismic inversion also can help define some of the thin bed properties we seek through a different approach but can still be limited by the inherent bandwidth of standard seismic.

This column focuses on application of a method that attempts to separate the signal from the noise while enhancing only the high frequency "earth signal" – a technique that helped identify new well locations in thinly bedded reservoirs that would not have otherwise been drilled.

More importantly, it helped to nearly quadruple daily production rates and add significant new reserves to a 27-year-old Gulf of Mexico field.

* * *

The example used here comes from South Marsh Island Block 128 Field (Figure 1). The discovery well for this prolific field was drilled in June 1974. The field is a stratigraphically complex, salt cored NW-SE trending anticline bounded on the west by a large down-to-the-west fault.

Reservoir age ranges from Angulogerina B (Early Pliestocene) to Lenticulina 1 (Late Pliocene) at depths of 4,500 to 9,000 feet subsea. Paleobathymetry ranges from inner neritic at the shallower levels to upper

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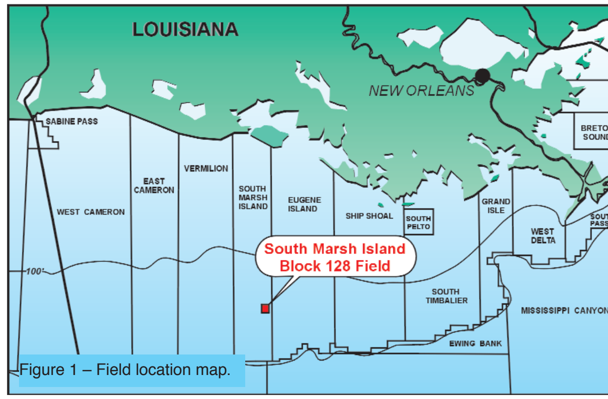

Figure 1 – Field location map.

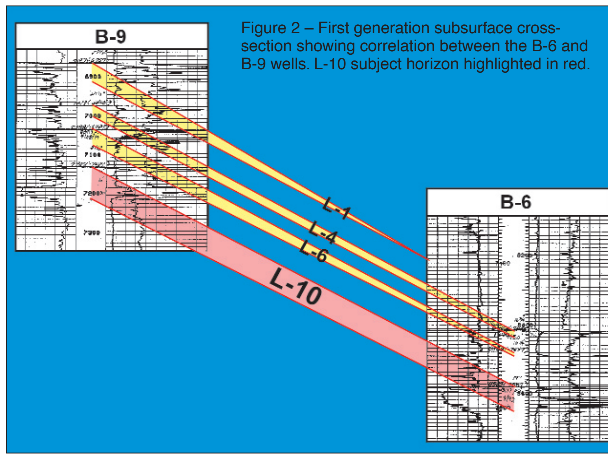

Figure 2 – First generation subsurface cross-section showing correlation between the B-6 and B-9 wells. L-10 subject horizon highlighted in red.

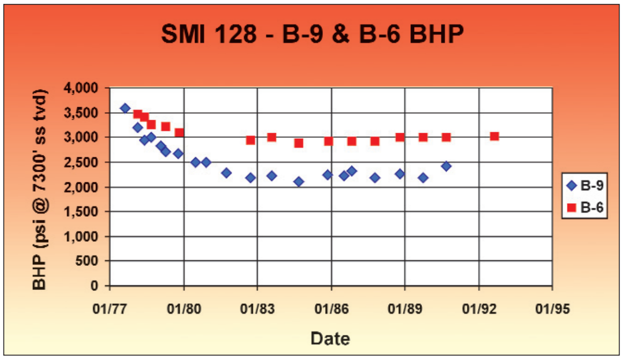

Figure 3 – Chart comparing BHP's from the L-10 reservoir in the B-6 and B-9 wells.

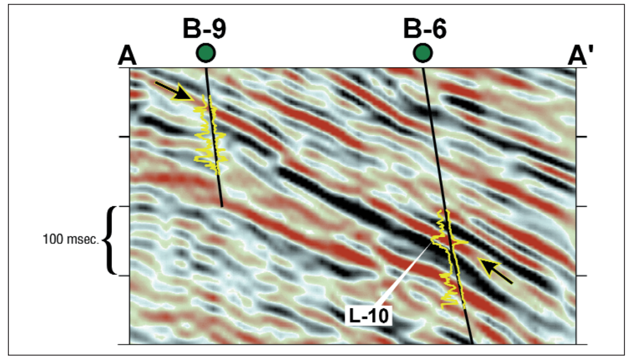

Figure 4 – Standard bandwidth 3-D arbitrary profile (A-A') connecting the B-9 and B-6 wells. Arrows indicate the reflector under investigation. SP log tracts appear to the left of well bore projections with resistivity to the right. Red represents negative reflection coefficients on the seismic color bar.

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bathyl in the deeper zones, with all reservoirs being normally pressured.

The field has seven exploratory wells and 93 development wells, including sidetracks, drilled from four offshore platforms. In January 2000, cumulative production was 115 MMBO and 203 BCF, and average daily production rates were 3,500 BO and 4 MMCF.

Structural interpretation there had been difficult from the outset with various interpreters producing different structural pictures (the lack of seismically mapped faulting was the variable in the interpretations). Even with the acquisition of proprietary, first generation 3-D seismic in 1989, the uncertainties persisted.

The geoscientists working the field were aware of the stratigraphic variations between wells but were hard pressed to visualize this level of depositional complexity with the currently available seismic. Distinguishing between faulting and stratigraphic discontinuities was problematic at best, leading to complex fault patterns that were suspiciously "ungeologic."

Furthermore, many of the reservoir thicknesses were below standard seismic resolution – thus impossible to map with much reliability.

A 1994 vintage speculative 3-D dataset was reprocessed in early 1998, employing target-oriented prestack Kirchoff time migration in an attempt to resolve some of these issues. Field acquisition employed a 4,000-meter streamer with 25-meter group and shot intervals, four millisecond sample rate and an eight second record length. A 15,000-foot migration aperture was selected to optimize imaging of dipping reflectors.

Overall imaging was greatly improved, leading to the conclusion that many of the discontinuities previously interpreted as faulting were in fact stratigraphic variation. Pressure data supported the fact that certain wells were in separate compartments, but this was still not clearly imaged in the 3-D seismic.

In hope of resolving these stratigraphic details, a post-stack frequency enhancement routine was applied to the reprocessed data. This technique employs a branch of mathematics originally developed in quantum mechanics for treating technically unsolvable systems (undetermined equations) in combination with the math evolved for the decoding of encrypted messages.

After all, this is essentially what the seismic trace is.

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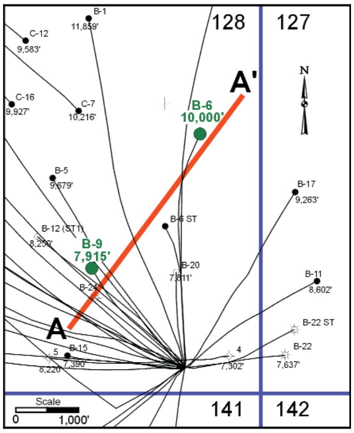

Figure 5 – Location map.

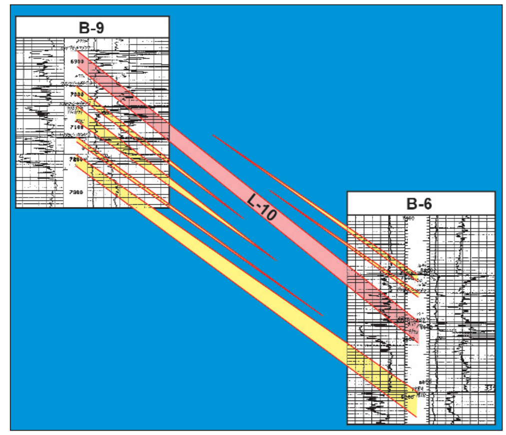

Figure 6 – Revised subsurface cross-section based on standard bandwidth 3-D seismic. Note increased complexity of correlations compared to Figure 2.

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In the data set, two wells were selected as calibration wells. The selection criteria dictated that good quality logs of velocity and density data be available for synthetic seismogram generation.

Velocity survey information also was incorporated. The logs were carefully edited by experienced petrophysicists to compensate for washouts, cycle skipping and any other problems. The consequent reflectivity series were convolved with 50, 60, 75 and 80 hertz Ricker wavelets to produce synthetic seismograms. These served as calibration points and quality control for the seismic processing.

The synthetic traces were compared to the data to optimize parameters of the high frequency data volume. At frequencies approaching 120 hertz, non-geologic "artifacts" or events not correlative to the log-generated synthetic traces appeared in the data, so the data was filtered back to the point where these artifacts disappeared. The resultant high frequency data was integrated with well information to identify and evaluate new drilling targets.

Acoustic impedance inversion was also employed to support the results and, in some cases, was a determining factor for picking drillsites.

In June 2000, the partners initiated a multi-well drilling program to test some of the identified opportunities, including two wells drilled early in the field's development.

❒ The B-6 was drilled in the field's southern portion in April 1976 and encountered 47 feet of net oil pay in two zones.

❒ The B-9 was drilled 2,300 feet to the southwest of the B-6 in June 1976 and encountered 149 feet of net oil pay in four zones.

Both are directional platform wells drilled into generally east dipping strata with no water contacts encountered by either well in any pay zone.

For this article we concentrate on a reservoir referred to as the L-10 zone, a Lentic-1 age horizon.

The first generation interpretation (Figure 2, page 32) shows a geologist's subsurface log cross-section between the B-6 and B-9 wells connecting all of the L series sands (L-1 thru L-10). Note that the L-1 zone in the updip B-9 wellbore is interpreted as absent in the down dip B-6 wellbore. All other L series horizons (L-4, 6 and 10) are shown to be continuous except for variations in

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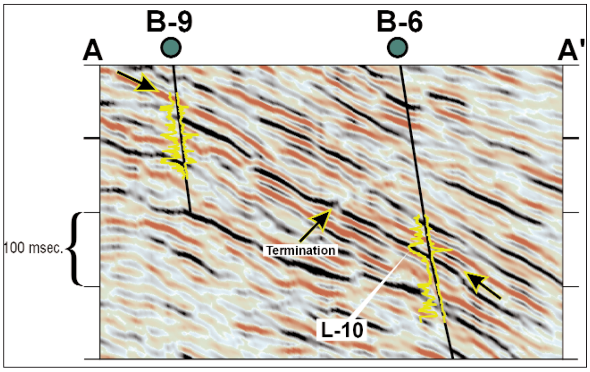

Figure 7 – The same traverse (A-A') as seen in Figure 4 shown in high frequency. Dominant frequency is roughly 80 hz.Arrows indicate equivalent reflector to Figure 4. Reflector termination is also shown by arrow.

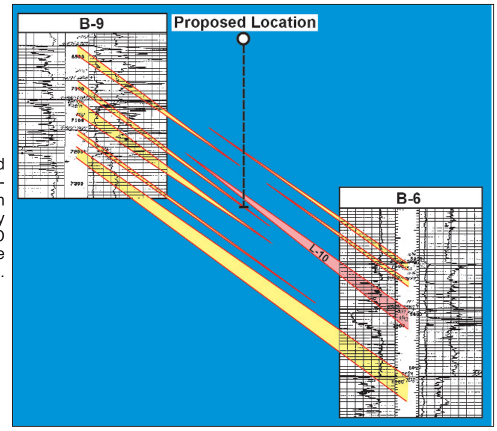

Figure 8 – Revised subsurface cross-section based on frequency enhanced 3-D seismic. Compare with Figure 6.

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thickness and log character.

This correlation generally was accepted by the partners during the early stages of field development. However, after years of production, the bottom hole pressure (BHP) profiles show a divergent trend between these two zones (Figure 3), demonstrating that they could not be in communication with each other. Furthermore, the L-10 zone (-7021 SSTVD) in the B-9 well watered out in September 1991, after producing 2,083 MBO and 2,369 MMCF. The L-10 completion (-7587 SSTVD) in the B-6 well continued to produce until watering out in April 1994 after recovering 539 MBO and 690 MMCF.

How do we explain the fact that the updip well watered out before the down dip well? Clearly some type of stratigraphic separation exists, but can we define it with seismic data?

* * *

Before the application of the frequency enhancement technique, the standard frequency reprocessed version of the 1994 vintage speculative 3-D data (Figure 4) was used to study the accuracy of reservoir correlations. Figure 5 shows the location of an arbitrary seismic line from the 3-D volume as A-A'. It directly connects the B-6 and B-9 wells, showing their SP and resistivity log curves overlain on the data.

The red trough seismic event representing the L-10 is indicated by the arrows.

Note that the reflector is essentially continuous between the B-6 and B-9 wells. This leads to a revised cross-section (Figure 6) where the L-10 sandstone correlation from the B-6 well has shifted to a shallower sand in the B-9 well.

Maintaining the original nomenclature for the reservoirs, the L-4 and L-6 zones in the B-6 well are now shown as absent in the B-9 well. More importantly, the L-10 zone of interest ties to a continuous reflector that now connects it to what was previously identified as the L-1 in the B-9 well.

A revelation? Maybe – but does other information verify this? Records indicate that there is a pressure difference of over 1,000 psi between these two zones, suggesting that they cannot be in the same reservoir.

Once again standard bandwidth seismic fails to resolve the correct correlation.

Remember, we want to image a zone that according to logs is on the order of 20-40 feet in gross thickness. Although our data quality is very good, we are

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limited by the inherent bandwidth of the data. The dominant frequency in the zone of interest is roughly 25 hertz with the high end imaging at 48 hertz. The interval velocity is 8,850 feet/second, making the dominant tuning thickness about 89 feet (1/4 wavelength) with the thinnest possible resolution at 47 feet.

We may expect to see a reflection at the top of the zone, but imaging the base is not achievable – and, due to bandwidth limitations, not resolvable as a separate seismic event. The pay is not associated with a classic "bright spot," so an amplitude extraction does little to reveal any reservoir boundaries.

In addition, the 3-D seismic suggests that the separation is not fault-related. Yet pressure and production data confirm that we are dealing with two separate reservoirs. The separation must be stratigraphic.

It is now time to apply the high frequency version of the 3-D dataset to see if it can image what we know exists.

* * *

Figure 7 (page 35) is the same A-A' arbitrary seismic line shown in Figure 4 (page 33), except that the frequency enhancement technique has been applied. The dominant frequency is now 45 hertz, making the dominant tuning thickness roughly 49 feet. The upper end signal frequencies, however, extend to 80 hertz, allowing resolution of beds as thin as 27 feet.

The individual reservoir units now begin to tie discreet events on the seismic. The zone of interest is again indicated by the arrows. Note that the event that ties the L-10 zone in the B-6 well appears to have a break or termination before it *reaches* the B-9 well. It is interpreted as a stratigraphic pinch-out and explains the reservoir separation indicated by the pressure and production data. This prompts a reinterpretation of the geologic cross-section (Figure 8, page 35) that honors the break in correlation seen by the high frequency data.

This version exhibits more stratigraphic discontinuity than any previous interpretation. It also offers an interpretation that reconciles the pressure and production history and defines a new drilling target.

Is this coincidence or truly the product of higher seismic resolution?

Next month: More successes from the South Marsh Island Field as high frequency seismic targets development drillsites.

(Editor's note: Marc Countiss is with Pogo Producing, Houston.)

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GEOPHYSICAL CORNER

High Frequency Targets New Pay

The Geophysical Corner is a regular column in the EXPLORER, edited by R. Randy Ray. This month's column is the second of the two-part paper titled "Rejuvenation of a Mature Field Through Application of a Unique Frequency Enhancement Technology."

By MARCUS L. COUNTISS

Last month's column introduced a history of the development of South Marsh Island Block 128 Field (figure 1) where, beginning in 1989, interpretations used a first generation 3-D seismic volume that led interpreters to treat seismic terminations as fault related.

This produced interpretations with complex, highly faulted patterns that were geologically suspect.

The addition of a newer vintage of 3-D seismic data with target-oriented reprocessing was an improvement, but still left some questions unresolved. Pressure and production data indicated that some wells originally interpreted to be producing from the same reservoir had to be separated.

This new 3-D seismic seemed to eliminate faulting as the reason, but failed to offer an obvious geologic solution.

The data hinted at a more complex stratigraphic interpretation, but it became clear that the standard bandwidth seismic data would be unable to image the thicknesses of many of the sand units seen in the wells.

Boosting Seismic Signal Frequency

The decision was made to apply a new frequency enhancement technology to the newly reprocessed 3-D seismic data set to see if the vertical resolution could be improved.

In this case, the algorithm works to decode the seismic "message" and extract the acoustic reflectivity series directly from it. The operation is entirely mathematical, with no wavelet estimation or other interpretive input applied. The primary requirement is a seismic trace with reasonably good signal-to-noise ratio.

The high-frequency technique considers the broad-band reflectivity series, or "earth signal," to be convolved with the band-limited embedded wavelet through the process of polynomial multiplication (one-sided convolution). The new method used here takes an alternative approach by describing one-sided convolution as a matrix multiplication with the problem resembling a process used to decode encrypted messages.

This way, the earth reflectivity is not viewed as being filtered but rather "encoded," with the upper portion of the spectrum not removed but encrypted in the lower end of the spectrum, which is still observable.

By treating the seismic trace in this domain, it can be manipulated to increase the high frequency signal without boosting the ambient noise. Consequently, the signal emerges from beneath the noise level and is recoverable.

The resultant signal is very similar to the original "earth signal" or unconvolved reflectivity series, and produces a reasonable estimate of the reflectivity series with greater resolution than the input seismic trace.

Since the entire spectrum is encoded by the embedded wavelet, it is theoretically possible to regain frequencies up to Nyquist frequency (half the sampled frequency) on properly recorded and processed data.

Testing the Updip Pinchout

The reprocessed high-frequency version of the seismic from last month revealed an apparent undrained reservoir in our zone of interest. Recalling that the L-10 zone in the B-6 well was productive, and observing that we can penetrate this reservoir updip to the B-6 take point without a break in continuity, leads to the obvious conclusion that we have defined a new drilling target not previously recognized.

In November 2000 a side-track of the B-6 well was spudded to test the prospect. The well reached total depth and was logged in early December.

Logs revealed oil pay in three zones for a total of 52 feet of net oil pay, 26 feet of which were in the L-10 zone of interest – with no water contact present!

Independent engineering calculations assigned 407 MBO and 183 MMCF of new proved reserve additions to the field, with 203 MBO coming from the zone of interest.

Figure 2 shows a frequency enhanced arbitrary 3-D extracted line, B-B′, that incorporates the new B-6 ST with the older B-6 and B-9 wells. The location of this traverse is shown in figure 3. Again the target horizon is indicated in the B-6 and the new B-6 ST wellbores with the black line tracking the seismic event related to the horizon.

The discontinuity marked by the arrow separates the B-6 and B-6 ST from the updip B-9 well. This interpretation agrees with the separation implied by the pressure data.

In figure 4, the normal bandwidth version of this line is displayed for comparison. The discontinuity visible on the frequency enhanced version is also apparent on this particular profile (highlighted by the arrow), albeit in a less obvious state. Clearly there are places where the separation is visible on the standard bandwidth seismic, but this is something that was never recognized in previous investigations.

(This break in the reflector certainly does not appear on the original processing profile and is laterally discontinuous when viewed in detail. In any event, this prospect was never previously identified.)

Finally we are led to the cross section incorporating the new B-6 ST well (figure 5, page 31), which shows the correlation interpreted on the high frequency 3-D data.

Six Out of Seven

This project generated seven new drilling opportunities, all of which turned out to be commercial producers.

It would be misleading to claim that all of these wells were primarily the product of high frequency imaging. Specifically:

❒ Two wells were essentially production acceleration wells, although the frequency enhanced data helped to optimize the target locations.

❒ One was a side-track of an existing well that had a completion failure and was drilled back into the same zone.

❒ The remaining four wells relied principally on the high frequency data and acoustic impedance inversion.

Only one well had to be sidetracked to obtain a positive result, and this well was completed in a secondary target as a commercial producer; this could be

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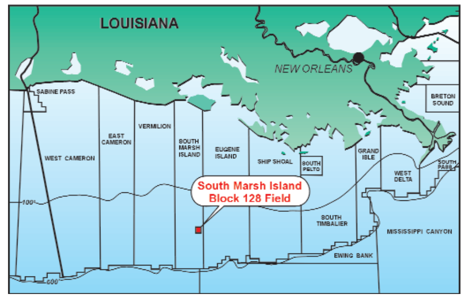


Figure 1 – Field location map for the South Marsh Island Block 128 Field.

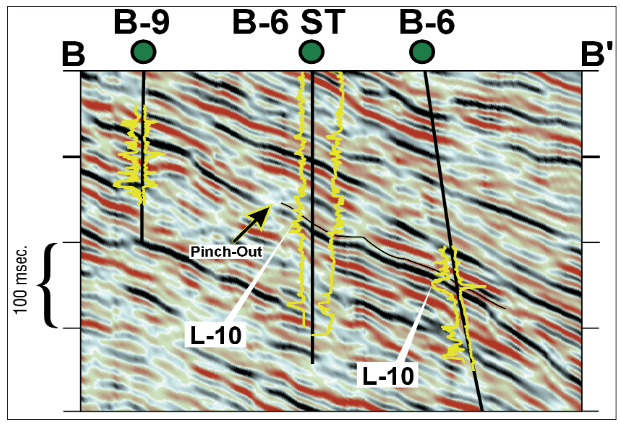


Figure 2 – A high frequency profile (B-B′) incorporating the newly drilled B-6 ST well. The L-10 reflector is tracked by the black line and the stratigraphic separation (pinch-out) is highlighted by the arrow.

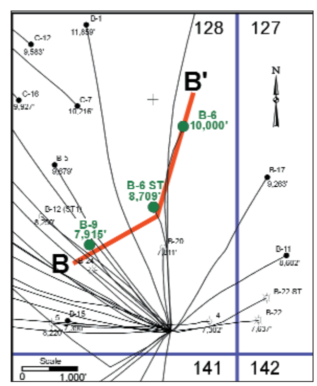
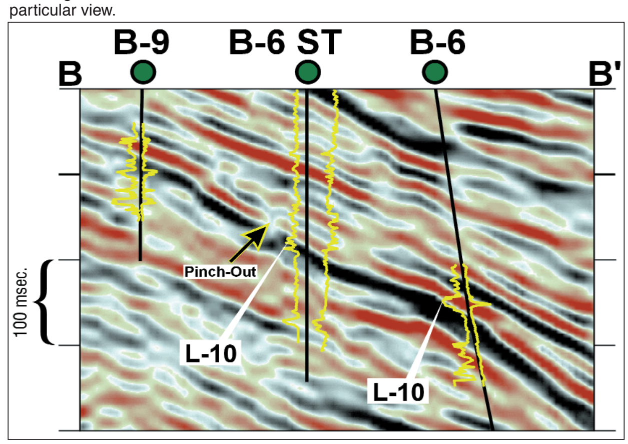


Figure 3 – Location map.

Figure 4 – Shown here is the same profile (B-B′) as seen in figure 2 but in the standard bandwidth format. The stratigraphic separation is still imaged in this particular view.



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counted as a scientific failure, since the primary target was non-commercial.

However, six out of seven is an acceptable success rate for any subsurface method employed.

As of May, total daily field production rates were averaging 11,500 BOPD and 18 MMCFPD, a 328 percent increase in oil rates and a 450 percent increase in natural gas rates! Furthermore, an estimated 3.5 MMBO and 5 BCF of proved reserves were added to the field.

Not a bad day's work in a 27-year-old field.

A Valid Technique

Since the frequency enhancement technique described herein was applied as a post stack process, it is desirable to have the basic processing of the data set in state-of-the-art condition to obtain the best result. Accurate statics, velocities and migration must be applied, since errors in any of these steps affect the high frequencies more so than the low frequencies.

Favorable results were obtained in this example because the basic seismic data quality was good, but inferior acquisition and processing may restrict or eliminate the effectiveness of the method.

Although the clear success of the drilling program supports the validity of the method, good matches with broad band synthetics demonstrate the ability of the technique to extract real high frequency signal.

As with all seismic methods, there is no one "silver bullet" that will achieve all goals – but this is another weapon in the seismic arsenal.

Although the application of the acoustic impedance inversion has not been detailed here, it was beneficial in the course of this program. The combination of multiple techniques is always the best way to improve the reliability of the prediction of a favorable result.

(Editor's note: Countiss is with Pogo Producing, Houston.)

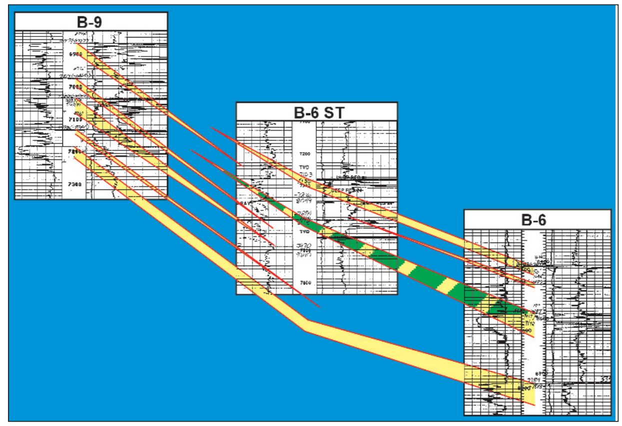

Figure 5. Final cross-section incorporating newly drilled B-6 ST. L-10 reservoir addition proven by B-6 ST is shown by yellow and green hachured area.