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Rejuvenation of a Mature Field Through Application of a Unique Frequency Enhancement Technology

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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 and 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 band-pass 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 can also 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 paper focuses on the application of a method that attempts to separate the signal from the noise while enhancing only the high frequency “earth signal”. The technique helped to 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.

Field History

The example used here comes from South Marsh Island Block 128 Field. 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 4500’ to 9000’ subsea. Paleobathymetry ranges from inner neritic at the shallower levels to upper bathyl in the deeper zones with all reservoirs being normally pressured. The field has 7 exploratory wells and 93 development wells, including sidetracks, drilled from 4 offshore platforms. In January 2000, cumulative production was 115 MMBO and 203 BCF and average daily production rates were 3500 BO and 4 MMCF.

Structural interpretation of the field had been difficult from the outset with various interpreters producing different structural pictures. The presence of seismically mapped faulting was the variable in the interpretations. Even with the acquisition of a 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. This led to some quite 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 4000 meter streamer with 25 meter group and shot intervals, 4 millisecond sample rate and an 8 second record length. A 15,000 foot migration aperture was selected to optimize imaging of dipping reflectors.

Boosting Seismic Signal Frequency

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. 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. Here 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 sampling frequency) on properly recorded and processed data.

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 was also 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 set 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 drillsite selection for one of the partners.

Identifying the Problem

In June 2000, the partners initiated a multi-well drilling program to test some of the identified opportunities. Focus is on two wells drilled early in the development of this field. The B-6 was drilled in the southern portion of the field in April 1976 and encountered 47 feet of net oil pay in two zones. The B-9 was drilled 2300 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 the purposes of this example, concentration will be on a reservoir referred to as the L-10 zone, a Lentic-1 age horizon. The first generation interpretation treated the L series horizons (L-4, 6 and 10) as being continuous except for variations in thickness and log character. The L-1 zone in the updip B-9 wellbore is interpreted as absent in the down dip B-6 wellbore. This correlation was generally 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 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 2083 MBO and 2369 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 can the fact that the updip well watered out before the down dip well be explained? Clearly some type of stratigraphic separation exists, but can it be defined with seismic data?

Applying the Frequency Enhancement

Before the application of the frequency enhancement technique, the standard frequency reprocessed version of the 1994 vintage speculative 3-D data was used to study the accuracy of reservoir correlations. The L-10 reflector is essentially continuous between the B-6 and B-9 wells. This leads to a revised interpretation 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 believed to be 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. However, records indicate that there is a pressure difference of over 1000 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.

In review, the object is to image a zone that according to logs is on the order of 20'- 40' gross thickness. Although data quality is very good, it is 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 8850 ft./sec. making the dominant tuning thickness about 89' (1/4 wavelength) with the thinnest possible resolution at 47'. A reflection at the top of the zone may be expected, 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.

Using the frequency enhancement technique, the dominant frequency is now 45 hertz making the dominant tuning thickness roughly 49'. However, the upper end signal frequencies extend to 80 hertz allowing resolution of beds as thin as 27'. The individual reservoir units now begin to tie discreet events on the seismic. The event that ties the L-10 zone in the B-6 well exhibits a break or termination before it reaches the updip 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 that honors the apparent correlation seen by the high frequency data. This version is more stratigraphically discontinuous than any previous interpretation. It also offers an interpretation that reconciles the pressure and production history.

Testing the Results

This new interpretation reveals an apparent undrained reservoir in the zone of interest. Recalling that the L-10 zone in the B-6 well was productive and observing that this reservoir can be penetrated updip to the B-6 take point without a break in continuity leads to the obvious conclusion that a new drilling target not previously recognized has been defined. In November 2000, a side-track of the B-6 well was spud to test the prospect. The well reached total depth and was logged in early December 2000. Logs revealed oil pay in 3 zones for a total of 52 feet of net oil pay, 26 feet of which was 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.

In summation, 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. Two 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 counted as a scientific failure since the primary target was non-commercial. However, six out of seven can be viewed as an acceptable success rate for any subsurface method employed. As of May 2001, total daily field production rates were averaging 11,500 BOPD and 18 MMCFPD, a ***328%*** increase in oil rates and a ***450%*** increase in natural gas rates! Furthermore, an estimated ***3.5 MMBO*** and ***5 BCF*** of proved reserves were added to the field.

Conclusions

Since the frequency enhancement technique described herein was applied as a post stack process, it is desirable to have the basic processing of the dataset 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 the example presented 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 AI inversion has not been detailed in this paper, 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.