Advanced Reservoir Imaging Using Frequency-Dependent Seismic Attributes

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EXECUTIVE SUMMARY

Our project goal is to develop innovative seismic-based technology that quantifies frequency- and angle-dependent seismic amplitude attributes in terms of the reservoir's composition, in particular in terms of rock properties such as permeability and fluid viscosity. These attributes, coupled with multi-trace seismic attribute technology will also increase the accuracy and resolution of the reservoir's delineation. Our new technology also includes improving target-oriented processing to preserve the frequency content of the propagating wavelet for wide-angle reflections.

Our proposal to develop an advanced imaging and interpretation technology includes *development of theory and processing algorithms, laboratory experiments and the verification of results using field data provided by industrial partners.* Our 3-D seismic data come from three offshore Gulf of Mexico areas (deep-water East Breaks, shelf High Island and shelf South Marsh Island), and from the onshore region of the eastern Central Basin Platform in West Texas.

During this first reporting period, from January 1, 2004 through June 30, 2005, the project focused on the following tasks:

- Gather 3-D seismic, and petrophysical data for the four study areas: a Devonian chert and carbonate reservoir in Crane County, Texas, and Neogene reservoirs in the offshore Gulf of Mexico,
- Develop an asymptotic model and governing equations describing low-frequency wave propagation in porous media,
- Develop algorithms for extracting low-frequency signal from seismic data,
- Develop target-oriented normal-moveout and migration 3-D processing algorithms,
- Calibrate the physical modeling system and generate seismic synthetics to validate the new target-oriented processing and ultimately validate the theoretical models, and
- Develop numeric code to validate theoretical models and calibrate well data to seismic.

Except for the numeric code for the theoretical models, we have accomplished the tasks and, in addition, are ahead of schedule in generating multi-trace geometric attributes and seismic interpretation of structure and stratigraphy. We have developed and applied algorithms for extracting low-frequency signals from seismic data, but it will always be a major research effort to differentiate the anomalous low-frequency amplitude as caused by scattering effects or by intrinsic attenuation or by other mechanisms.

In the study areas, we have generated multi-trace seismic attribute volumes, including coherence, maximum positive curvature, and maximum negative curvature for the west Texas and South Marsh Island surveys. We have created synthetic seismograms and have tied the logs to seismic in all four seismic surveys. We have four MSc graduate students who are at various stages in mapping horizons and faults, and are beginning to delineate target reservoir intervals, sand body geometries and sequence stratigraphy.

In activities related to theory, we reviewed a linear poroelasticity model from the point of view of basic principles of flow in porous media. We then applied a low-frequency asymptotic analysis of this model to the interpretation of the frequency-dependent reflection coefficient component at low-frequency ranges.

The 3-D directionality impulse responses of the physical modeling system, mainly the transducers, have been measured. With the artifacts of the physical modeling system known, we are designing new physical models including glass bead layers with different pore fluids for verifying the new reflectivity theory. Our new algorithms for target-oriented processing and spectral decomposition will play an important part in analyzing the results from these physical modeling experiments.

After examining the reflectivity theory on the physical model synthetics, processing and interpretation of the seismic data from well-documented productive fields is the next important part of *verifying our technology*. We have run preliminary post-stack attenuation attribute analysis of the west Texas data and will process the pre-stack seismic data to generate frequency-dependent and angle-dependent attributes (AVO), and will integrate these data to build geologic reservoir models. We will calibrate and validate our frequency- and angle-dependent seismic attributes against the geologic model and against reservoir parameters determined from petrophysical and engineering data. We expect the analysis of frequency-dependent AVO attributes and low-frequency imaging will lead to more accurate predictions of pore-fluid production by mapping fluid contacts and mobility. This will represent a major step in the goal of developing seismic-based method of mapping reservoir permeability.

We have recently applied frequency-dependent seismic attributes to the analysis of fractures in an oil field in west Siberia. Processing of the 3D low-frequency seismic data produced an accurate delineation of fractured hydrocarbon-bearing zones. We (Goloshubin and Silin, 2005) investigated P-wave propagation, reflection and transmission at an impermeable interface between elastic and dual-porosity poroelastic media. We concluded that the reflection and transmission coefficients are functions of the frequency. At low frequencies, the frequency-dependent components are asymptotically proportional to the square root of the product of frequency, reservoir fluid mobility, and fluid density.

WAVE THEORY DEVELOPMENT

Milestones:

The proposed milestones for wave-theory development in the first year are

- Algorithms for extracting low-frequency signal from seismic data,
- Asymptotic model and governing equations describing low-frequency wave propagation in dual porous media (both skeleton and fracture porosity),
- Tortuosity parameter evaluation for typical reservoir rocks,
- Numerical and analytical analysis of dependence of reflection amplitudes on tortuosity and dual porosity and formulation of correspondent imaging algorithms, and
- Formulation of reflectivity equations, development of algorithms and computer codes for numerical modeling and frequency-dependent seismic imaging for porous permeable layered medium.

Approach and Accomplishments:

Estimation of low-frequency signal

Several spectral decomposition programs evaluated for estimating the low-frequency content of seismic field data. The short-window Fourier transform (SWFT) and the wavelet-matching algorithm (WMA) were converted into DISCO (commercial software package) routines that are callable from our 3-D seismic processing package. SWFT computes a Fourier transform at every sample point of a trace using a truncated time window that is padded with zeros to provide smoothness in the spectra. The spectra from overlapping windows are averaged. WMA determines a single dominant amplitude and phase from the Hilbert transform to construct a Ricker wavelet that is subtracted from the trace. The process is repeated on the residual trace until a tolerance limit is reached.

When running the spectral decomposition programs SWFT or WMA, a 2-D arbitrary line selected from a 3-D seismic volume generates a 3-D volume. A spectra magnitude value is written in each cell of the 3-D volume that has the axes of CMP location, time and frequency. We evaluated the algorithms on 2-D lines from four 3-D data sets, which are defined in the Data Gathering section. Based on our best estimate, lines were selected that traversed major hydrocarbon reservoirs. The spectral decompositions will be evaluated again once the geological interpretation and geophysical calibration of the reservoirs are completed so that a meaningful interpretation of the results in terms of the reservoir's petrophysical properties can be made.

Initial work on estimating spectra derivatives of the propagating wavelet has been tested. The significance of these tests is related to the empirical observations that oil production rate can be correlated to seismic attributes that are proportional to spectral derivatives.

Our goal is to continue research and development of algorithms for extracting and analyzing low-frequency signal from seismic data and to be able to differentiate scattering effects from intrinsic attenuation. It was concluded at the 2005 SEG Production and Development Forum that this goal has not been reached by the geophysical industry.

Dual porosity models and equations
Previously, the asymptotic solution of the reflectivity for a granular porous model had been formulated, theoretically analyzed and found to be a function of frequency, fluid mobility and density. A similar formula of the reflectivity for fractured porous models has now been developed. Goloshubin and Silin will present this new theory at the 2005 SEG meeting. Numerical tests will be conducted to determine what physical effects and the magnitude this theory would show for the four data tests in house.

Tortuosity parameter evaluation for typical reservoir rocks
We investigated the dependence of scaling on the dynamic Darcy's law relaxation time, which turns out to be linearly related to Biot's tortuosity parameter. This parameter must be very large to enter first-order asymptotic formulae.

Numerical and analytical analysis of reflection amplitudes
We derive wave propagation equations from the basic principles of the theory of filtration, particularly to verify that both the filtration and poroelasticity theories have a common foundation. In addition, such an approach facilitates establishment of a relationship between seismic imaging attributes and hydraulic reservoir parameters.
In this study, we obtain a simple asymptotic expression, in which the role of the reservoir fluid mobility is transparent. We focus on the simplest case of P-wave normal-incident reflection.

At low seismic frequencies, viscous fluid flow in pore space results in anomalous reflection of the signal. The reflection coefficient has been asymptotically expressed as a sum of constant and frequency-dependent component. The latter is proportional to the square root of the frequency of the signal. The proportionality coefficient includes the reservoir rock and fluid flow properties. The frequency-dependent component also includes a phase shift of the reflected wave.

The results suggest that for frequency-dependent reflection imaging, one should exploit accurate extraction of the frequency-dependent component of the reflection coefficient. Development of suitable methods and algorithms is a part of future work.

To date, the formulization has been for normal-incident reflections. We are working on the extension of this theory for oblique reflections and hopefully could extend this to post-critical angle reflections.

Formulation of computer codes for numerical modeling
Amplitude-versus-offset (AVO) programs for generating offset source-receiver synthetics for isotropic and VTI anisotropic layered models have been developed and tested. The programs are based on ray theory and handle industry-standard well-log suites. These programs will serve as a first basis for testing the new theoretical models and comparison to field data.

TARGET-ORIENTED PROCESSING

Milestones:
None specified.

Approach and Accomplishments:
Though no tasks or milestones were specified for target-oriented processing (Hilterman and VanSchuyver, 2003), it is a major tool needed to accomplish our goals. Considerable effort has been spent in quantifying wavelet stretch in target-oriented processing and developing weights for Kirchhoff migration in order to obtain true amplitude processing without frequency (wavelet stretch) distortion. The weighting factors currently described in literature (Dillenger et al., 2000) are inaccurate for Kirchhoff common-offset migration when offsets are greater than offset equal to depth. We have developed a closed-form solution for Kirchhoff weights that incorporate dip and wavelet stretch caused by normal-moveout (NMO) and migration. We tested our algorithms against published results and ours are more accurate for large source-receiver offsets. The accuracy is obtained unfortunately by more intensive computations. Zhengyun (Jenny) Zhou (PhD student) has assisted Gennady Goloshubin and Fred Hilterman in developing the new migration algorithms.

Figure 1 depicts stretch as a function of incident angle and dip, where the left side is for conventional migration and the right side target-oriented processing. If the dip is large and the incident angle is small, then wide-angle processing does not reduce migration stretch (lower right of Figure 1d). Outside this large dip and small incident-angle region, wavelet stretch is between 0.8 and 1.2 if the sum of the dip and incident angles is less than 80°.

Figure 2a is the first of two synthetic models with target-oriented migration that is presented in this report. The common-offset synthetic contains 301 traces at 50-ft (15-m) intervals. Figure 2b illustrates a portion of the synthetic line. After conventional migration (Figure 2c), the wavelet period is approximately 50 ms, which relates to a predicted stretch of 1.58. With wide-angle processing (Figure 2d), the wavelet period essentially maintains its original time duration of 32 ms.

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The second synthetic involves a reflectivity CMP gather generated from an acoustic model (Figure 3). The synthetic was repeated 301 times to simulate CMP gathers at 30-ft (9.2 m) intervals. Reflection crossover is difficult to preserve in routine processing as is illustrated by the pre-stack time migration in Figure 4a. The migrated synthetic in Figure 4b was generated using target-oriented processing. The flat event at 2.25 s is the target horizon. What is significant is that true amplitude has been preserved though migration including the crossover event.

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We are still evaluating the target-oriented algorithm on synthetic lines generated in the physical modeling tank. By the end of the year, the migration algorithm should be commercially available in the software package FOCUS and DISCO (product from Paradigm Geophysical Company).

PHYSICAL MODELING

Milestones:

The proposed milestones for the first year of physical modeling are:

- Acquisition of seismic data across existing 3D porous channel model filled with different fluids

Approach and Accomplishments:

During the past six months we have focused on repairing, acquiring and testing hardware for the tank experiments. We have spent considerable time calibrating the various transducers with respect to their 3-D directionality in terms of their time-domain impulse responses rather than their factory-provided scalar directionality plots. It is imperative that the 3-D impulse responses are known so that measured reflectivity as a function of offset angle and frequency are not confused with instrument properties instead of the desired medium properties.

Graduate students involved in acquiring experimental seismic data are Julius Doruelo (PhD) and Bryon Golden (MSc) under the guidance of Dr. Wiley. We have:

- Repaired physical model acquisition equipment,
- Calibrated transducers and computed shaping filters, and
- Collected and processed multi-offset data across two physical models

We are initially acquiring data over the 3-D anisotropic fractured model that was listed as a Year 2 Milestone rather than the 3-D porous channel model. The switch in models was made because the calibration of the physical modeling system can be more accurately confirmed on this model than the 3-D channel model. In addition, this is an excellent model for verifying the results from target-oriented processing.

Dr. Robert Wiley at the time of our proposal was a research professor at UH but has since accepted a full-time position off campus. However, Dr. Wiley still works at UH one-day a week on this DOE project.

THEORY VERIFICATION WITH FIELD DATA

Milestones:

The proposed milestones for the first year are:

- Reprocess 3D seismic data from the reservoirs of the Central Basin Platform in West Texas. Estimate AVO and other seismic attributes.

The AVO seismic response for our West Texas data is Class 1, which means the rock-properties of the skeleton dominate the stack amplitude and AVO response and the fluid properties have little influence on the seismic signature. Since our goal is to detect fluid mobility from seismic signatures, seismic data in areas that respond to fluid properties were desired such as Class 2 and Class 3 AVO anomalies (Rutherford and Williams, 1989). Thus, we acquired through our industry sponsor, several data sets where the seismic responses are Class 3 (bright spot) and Class 2 (amplitude increase with offset).

In addition, these data sets have large source-receiver offsets for examining the effects of target-oriented processing across known reservoirs.

Data Gathering

Three-D seismic, geologic, petrophysical, and engineering data have been acquired for the project study areas. Our four 3-D seismic data come from three offshore areas (Figures 5 and 6) East Breaks, High Island and South Marsh Island in the Gulf of Mexico, and from the onshore region of the Central Basin Platform, West Texas. We have loaded all 3-D data sets in the interpretation system, Geoframe, and all near, far and full stacks into the seismic processing system, Focus. We are still acquiring digital logs for the offshore surveys, but have enough to generate initial synthetics for each survey. Details for each study area are provided below.

West Texas

Burlington Resources has provided 104 sq. km (65 sq. mi.) post-stack 3-D seismic survey along with digital LAS well-log curves and production data for more than 50 wells in the Devonian microporous chert reservoir of Waddell Field, Crane County, Texas (Figure 6). Devon Energy has provided digital logs and resistivity-based image logs for additional wells in the Devonian fractured-carbonate reservoir in the northern part of the Waddell East Ranch survey. The image logs will be especially valuable in calibrating fracture-related multi-trace attributes.

East Breaks

Kerr-McGee and Seitel donated post- and pre-stack seismic data covering offshore East Breaks Blocks 642,643,644,686,687, and 688. An offshore block is approximately 9 square miles. The West Boomvang, East Boomvang and North Boomvang fields lie within this coverage. Kerr-McGee has provided digital well-log curves for 16 wells along with a detailed interpretation of the pay intervals in the three fields. Olufemi Akanbi (MSc candidate) is conducting an amplitude calibration study in this area. The research goal is to quantify the accuracy of predicting water saturation as a function of stack amplitude for a Class 3 rock-property environment. This knowledge will benefit our study when attenuation properties are examined in the same fields.

South Marsh Island

Fairfield (our DOE industry sponsor) contributed 3-D pre-stack and post-stack seismic data covering six offshore blocks around South Marsh Island 238 and 239. Anadarko and Geophysical Development Corporation have donated digital well-log curves. Sean Lewis (MSc candidate) has done preliminary structural and stratigraphic interpretations. Additional trend curves and elastic wave-theory amplitude calibration studies will be conducted.

High Island

Fairfield contributed pre-stack and post-stack 3-D seismic data for High Island Block 129 that includes a surrounding migration halo of 5000 ft. GDC and Anadarko are contributing wireline logs. Matt Van Wie (MSc candidate) is doing a geologic and geophysical study of this area. Connie van Schuyver (PhD candidate) has processed

(with anisotropy considerations) a far-offset 2-D line. Initial well-tie calibrations have been conducted.

Approach:
In order to properly interpret the seismic data, additional objectives were defined. These objectives are:

- Gather 3-D seismic, petrophysical, and engineering data on all fields,
- Interpret surveys to identify reservoir zones of interest,
- Generate preliminary frequency attribute analyses on the west Texas and offshore data 3-D data sets,
- Assemble appropriate equipment for conducting West Texas physical models,
- Acquire preliminary data for an isotropic physical model and an anisotropic physical model of a West Texas reservoir, and
- Re-process offshore data where source-receiver offsets are greater than twice the reservoir depth.

We have run geometric attributes on both the West Texas data set and the South Marsh Island dataset. Preliminary frequency analysis of the Devonian reservoir indicates that there are frequency differences between water-filled and hydrocarbon-filled reservoirs, but that interbed multiples affected our initial results.

Accomplishments:
In this section, we report on the initial structural and stratigraphic interpretation of the various seismic volumes, on the frequency analysis of the Devonian reservoirs, and on the initial geometric attribute analysis of the South Marsh Island seismic volume. Seismic interpretation has started on all data sets. Four graduate students are each using a data set for a seismic interpretation research project. Other graduate students involved with this project are as follows. Horizons in the west Texas data set were picked as part of Donjun Fu's recently completed MSc thesis that tied rock physics to multi-trace seismic attributes. Jenny Zhou, PhD geophysics student, is conducting the frequency analysis of the Devonian reservoirs. Connie VanSchuyver, PhD geophysics student, is working on various processing aspects of the entire project.

Introduction to Geometric Attributes
One of the innovative parts of this project is to generate multi-trace seismic attributes, recently developed at CAGE/AGL, on all seismic volumes. This will be the first time these attributes have been run on target-oriented migrated data. In contrast to conventional amplitude extractions, geometric (also called multi-trace) attributes are a direct measure of *changes* in seismic texture. Many of these seismic attributes, such as dip/azimuth, were first applied to maps, and then generalized to work on an uninterpreted 3-D seismic volume. Others, such as coherence, were first applied to 3-D seismic volumes and later reworked to apply to flattened horizons.

While sensitive to vertical changes in reflectivity, most geometric attributes are designed to enhance *lateral* changes in reflectivity. In contrast, spectral decomposition and the

recently introduced SPICE algorithm (Liner, et al., 2004), while sensitive to lateral changes in reflectivity, are designed to enhance *vertical* changes in reflectivity. Likewise, a warped seismic horizon may show significant changes in dip (and also curvature, which is a spatial derivative of dip), and show no lateral change in waveform (coherence), amplitude, or thickness (amplitude gradients and spectral decomposition). Understanding which attributes are sensitive to different types of geologic changes is key to intelligent attribute interpretation, whether by a skilled geoscientist, or with the aid of modern pattern recognition and geostatistical software. One of the best-accepted geologic models for determining deformation is the relation between reflector curvature (Figure 7) and the presence of open and closed cracks. Reflector curvature is fractal, with geologic detail versus field scale folds illuminated by short wavelength and long wavelength scales, respectively. Until now, such curvature estimates have been limited to the analysis of picked horizons. In contrast, the spectral estimates of reflector curvature used in this study allow us to examine broken reflectors within the entire seismic volume. We find that the maximum positive and maximum negative curvatures are particularly useful in mapping lineaments including faults, folds, and flexures (Nissen, et al., 2004; Sullivan et al., 2005).

Multi-trace seismic attribute volumes, including maximum positive curvature and maximum negative curvature at both long and short spectral wavelengths, have been generated for the west Texas survey and for the South Marsh Island survey.

West Texas - Fractured carbonate and microporous chert reservoirs

We have constructed synthetic seismograms, tied logs to seismic, and have assembled production data, normalized to the first 12 months of production, and have interpreted horizons (Figure 8) and some of the faults. We have run a suite of some 14 multi-trace attributes on these data, and show an example in Figure 9. Preliminary frequency analysis of the Devonian reservoir indicates that there are frequency differences between water-filled and hydrocarbon filled reservoir, but that interbed multiples from the Pennsylvanian limestones and the Mississippian Woodford shale affected our initial results (Figures 9-12).

Interpretation East Breaks

Olufemi Akanbi (MSc candidate at the University of Houston) has generated synthetic seismograms, tied wells to seismic, and constructed preliminary maps of faults and major horizons at East Breaks. Olufemi will conduct a case history study of several fizz water (low gas saturation) reservoirs in six blocks in the deep-water East Breaks area. He has obtained 16 suites of well-log curve suites and will be involved in developing a workflow for estimating gas saturation from seismic stack amplitude data. Olufemi's research will include well-log editing, generation of rock-property trends, generation of synthetic seismograms with various gas-saturation states, mapping of reservoir intervals, sandstone reservoir geometries, and quantifying seismic and synthetic amplitudes in several hydrocarbon zones. In the upcoming six months, Olufemi will continue structural and stratigraphic mapping, and will begin to build reservoir and depositional models.

Interpretation South Marsh Island

Preliminary interpretation by MS student Sean Lewis has identified channel systems that will be investigated for potential as hydrocarbon-filled and water-filled seismic analogs (13-15). The seismic data include features deposited in a rich variety of deltaic, continental, and slope environments, and is expected to yield a good suite of stratigraphic features for study.

At South Marsh Island we have used multi-trace geometric attributes, coherence, and spectral decomposition to begin to identify channels that have potential for saturation analysis (figures 16-18).

Seismic coherence is a measure of waveform similarity. Our coherence estimates use cross-correlation and eigenstructure techniques and are only sensitive to the waveform phase of the seismic data, and not to its amplitude. In contrast, semblance, variance, and Manhattan distance estimates of coherence are sensitive to both waveform *and* amplitude. Given a choice, we prefer the former two estimates of coherence, since we can attribute any anomalies to only one cause – change in waveform, since the eigenstructure algorithm provides more robust images in the presence of noise than cross-correlation. Coherence has been used to illuminate faults, channels, diapers, reefs, and drilling hazards in nearly every basin on the planet.

However, not all seismic features of interest exhibit themselves through coherence. In Figure16a, we show a time slice at 1.3 s through a coherence volume generated from the South Marsh Island 3-D seismic volume. We immediately recognize several channels and faults through the time slice. In contrast, the Most Negative curvature image shown in Figure 16b shows little information of stratigraphic interest. The reason is geological rather than algorithmic. The channels seen in Figures 15 and 16 and in the vertical slice in Figure 18c are neither structurally controlled nor do they generate any differential compaction. The only curvature 'anomalies' we can easily interpret are associated with faulting (also seen on the coherence). We illustrate lateral changes in amplitude in Figure 17. In Figures 17a and 17b we display both NS and EW components of the coherent energy gradient, where the coherent energy is basically the RMS energy of a +/-10ms window of seismic data that has the same waveform (Marfurt, 2005). In essence, we show how energy tunes in and out as we pass laterally along a thin channel. A mathematically independent measure of tuning is through spectral decomposition, originally presented by Partyka et al. (1999). In our analyses, we are using a slightly different matched pursuit wavelet-based spectral decomposition presented by Liu et al. (2004). One disadvantage of spectral decomposition for volumetric (vs. horizon-based) interpretation is the multiplicity of attribute volumes that can easily fill all available disk space. The 'SPICE' approach (Liner et al., 2004) is to examine spectral discontinuities. We address this challenge by using a 2-D color bar and plotting the peak frequency against hue (blue being low and red high frequency) and the amplitude of this peak frequency above the spectral average against lightness (Figure 18). In this manner, we note that the two channels seen as bright orange in Figure 18a are tuned in at approximately 65 Hz, giving us an indication of both their thickness and reflection strength**.** Geometric attributes and spectral decomposition are powerful tools that can

accelerate the interpretation of very large seismic volumes and can extract subtle structural and stratigraphic features. Since they are mathematically independent, geometric attributes and spectral decomposition are best used in combination with each other and with the original seismic data to more fully exploit the seismic signal (Marfurt and Sullivan, 2005).
During the next six months, Sean Lewis will continue to construct structural, stratigraphic and depositional models for key intervals, and will begin to model seismic response to a variety of reservoir parameters.

Interpretation High Island
Graduate student Matt Van Wie has loaded digital well curves, has tied the logs to seismic by synthetic seismograms and has begun mapping key horizons and faults. PhD student Connie van Schuyver has begun to process near and far gathers and to model seismic responses to saturation changes. The preliminary results are shown in Figures 19-25.

Interpretation Vermilion
For the offshore seismic volumes, part of our reservoir characterization research will include improving the seismic-based estimation of water saturation in thin blanket sandstone bodies. A reservoir is often called "fizz" when the gas percentage in the pore space is 25 percent or less. Normally, a small amount of gas in a reservoir lowers the P-wave velocity dramatically, and then as the gas saturation increases the primary velocity does not change significantly. The pore-fluid prediction becomes more difficult if reservoir properties such as porosity undergo slight changes. These possible reservoir scenarios make the prediction of fizz and gas from AVO problematic. To address this problem, pre-stack and post-stack 3-D seismic data and analog well-log curves were made available to us at Seismic Micro Technology (SMT). These data were in offshore Louisiana northern Vermilion area. Using this data, we have introduced two rock-property transforms that assist in the discrimination of gas from fizz (Zhou et al., 2005) and assist in estimating reservoir thickness. These transforms are derived from rock-property trends that are local to the prospect. With these two transforms and the AVO gathers at the prospect and at the down-dip water-equivalent reservoir, a test statistic is developed that differentiates economic gas from fizz saturation. This new methodology doesn't require a calibration well that ties the seismic unless the bed thickness is desired.

CONCLUSIONS

Our objective is the development and application of a new technology that will improve both the delineation and characterization of a hydrocarbon reservoir using variations of seismic amplitude as a function of incident angle and frequency. To this end, we have secured necessary seismic and well-log data to evaluate the reflectivity algorithms developed and those under development. The data sets, which are already loaded onto our new disk system, cover three offshore areas and one onshore west Texas area. We have verified that the field seismic represents all three classes of AVO anomalies from the frame-dominant to the pore-dominant seismic signatures and each data set contains multiple hydrocarbon reservoirs with different rock and fluid types and saturation

conditions. The wide range of rock properties covered by the four 3-D data sets provides ample test material for the new reflectivity algorithms.

We have started geologic interpretation on all data sets, and have begun frequency and multi-trace geometric analysis of three data sets: the west Texas microporous reservoir, and the Tertiary siliciclastics in the South Marsh Island and High Island data sets. Once the reservoir structures are defined and calibrated to well data, then the frequency characterization of the seismic horizons surrounding the reservoirs will be evaluated. While initial spectral decomposition volumes across a 3-D data set indicate frequency variations associated with hydrocarbons, we are waiting on the geologic and geophysical interpretations for further evaluation.

Parallel to the preliminary field-data results, we have satisfactory tests on our target-oriented migration code for both theoretical and physical model data. This code preserves the wavelet frequency content that is normally altered in normal-moveout corrections and/or migration. The next step is the parallelism of this code so our 3-D field data sets can be target-oriented processed for evaluation of reflectivity variations as a function of frequency.

The physical modeling experiments have been altered from the proposal to allow us to evaluate our target-oriented processing on models more simple than the originally proposed meandering porous channel. Solid and VTI fracture models constructed out of Plexiglas have been used for verification of our processing computer codes. Design has begun on glass bead models for testing the recently developed reflectivity codes. Glass bead models were selected because analytic solutions for elastic wave propagation are known for different pore-fluid properties. In addition, physical modeling artifacts will be easier to remove from the glass bead models than from the originally proposed porous channel model.

Ray-theory numerical modeling has been developed that includes anisotropy and target oriented processing procedures for assisting in the calibration of well-log data to the re-processed 3-D seismic.

On the theoretical side, we have developed an asymptotic model and governing equations describing low-frequency wave propagation in fractured as well as porous media. As part of our work, we will develop a methodology to determine the reservoir properties using the frequency dependence of seismic reflections and will develop and validate the low-frequency asymptotic analytical solutions for seismic waves reflected from fluid-saturated layers. We will investigate scalability relations between field and laboratory model parameters.

A major goal is to quantitatively evaluate effects of liquid and gas hydrocarbon phases, as well as the effects of reservoir geometry on seismic reflectivity at different incident angles and frequencies (AVAF – *A*mplitude *V*ersus *A*ngle & *F*requency).

We are consistent with our schedule and should finish all milestones proposed for the first year.

Seven graduate students are currently working on some aspect of this project as part of their research required for the Masters or PhD degree.

SIGNIFICANT ACCOMPLISHMENTS

- Previously, the asymptotic solution of the reflectivity for a granular porous model had been formulated, theoretically analyzed and found to be a function of frequency, fluid mobility and density. A similar formula of the reflectivity for fractured porous models has now been developed. Goloshubin and Silin will present this new theory at the 2005 SEG meeting.

- Two new rock-property transforms have been found that facilitates the prediction of water saturation and thickness from pre-stack seismic data. Zhou et al. will present this theory at the 2005 SEG meeting.

- The wavelet stretch associated with target-oriented processing was quantified and validated. This will allow us to remove any frequency variation artifacts from target-oriented processing. Hilterman and VanSchuyver have a paper describing the method accepted (2005) for Geophysics.

COST

Progress Report - 2005 (YEAR 1, as of 8/12/2005)				
	Budgeted	**Expensed**	**Encumbered**	**Cost-Share**
Salary & Wages	56,175.00	26,750.00	2,344.11	
Fringe Benefits	11,540.00	2,609.89	0.00	
Capital Outlay	5,000.00	6,522.00	0.00	
Travel	7,464.00	2,924.89	0.00	
Indirect Cost	60,712.00	22,834.31	8,458.69	
Subrecepient payout	110,000.00	6,431.06	103,568.94	
Maint. & Operations	0.00	1,843.21	0.00	
Cost-Share / Fairfield Industries, Inc.				56,000.00
Cost-Share / Shell Oil Company				70,000.00
Total	250,891.00	69,915.36	114,371.74	126,000.00

Salaries:			
Zhengyun Zhou (PhD Student) (1/16/05 - 5/31/05)			
Julius Doruelo (PhD Student) (1/16/05 - 5/31/05)			
Connie VanSchuyver (Research Staff) (3/01/05 - 8/31/05)			
Charlotte Sullivan (Research Professor) (4/01/05 - 4/30/05)			
Capital Outlay:			
Raid Arena HD (9x400G) Electronix Corp.			
Travel:			Registration
Fred Hilterman / New Orleans / 5/27/05 - 5/27/05		$297.90	200.00
Fred Hilterman / Austin, TX / 5/15/05 - 5/18/05		694.92	780.00
Gennady Goloshubin / San Fran. / 12/04/04 - 12/17/04		633.88	180.00
Gennady Goloshubin / Denver / 10/10/04 - 10/14/04		1298.19	395.00
		$2,924.89	
Subrecepient Payout:			
University of California			
Maint. & Operations:			
MatLab Software			192.00
UPS / Ship to Electronix Corp.			22.30
Shoreline Grill / 5/17/05 / Austin, TX			73.91
			$1,843.21

SCHEDULE STATUS

During the summer, Dr. Gennady Goloshubin, research professor at University of Houston, was required to return to Russia for a re-issue of his visa. His visa was re-issued but this resulted in his absence for three months. Even with Dr. Goloshubin's absence, we do not anticipate any delays in meeting our milestones.

Dates have been modified from the proposal to reflect actual starting date of 01/2005

Year 1 (01/2005 - 11/2005)

A. Development of algorithms for low-frequency information extraction from seismic data (UH, LBNL, 1/2005 - 04/2005).
   Finished. Two spectral decomposition techniques have been implemented. Additional work will continue on this aspect throughout the project.
B. Development of asymptotic model and governing equations describing low-frequency wave propagation in porous media (UCB, LBNL, 1/2005 - 04/2005).
   Finished. Asymptotic model and equations have been developed for both porous and fractured models.
C. Tortuosity parameter evaluation for typical porous reservoir rocks (UCB, 1/2005 - 04/2005).
   Still under investigation. Anticipate finishing 11/2005.
D. Numerical and analytical analysis of dependence of reflection amplitudes on tortuosity and formulation of correspondent imaging algorithms (UH, UCB, LBNL, 05/2005 - 11/2005).

Still under investigation. Anticipate finishing 11/2005.

E. Formulation of reflectivity equations, development of algorithms and computer codes for numerical modeling and frequency-dependent seismic imaging for porous permeable layered medium (UCB, LBNL, UH, 05/2005 - 11/2005).
Still under investigation. Anticipate finishing 11/2005.

F. Acquiring of seismic data with different observation system designs for the existing 3D porous channel physical model filled with different fluids (UH, 04/2005-08/2005).
Have delayed 3-D porous channel and are investigating a simpler model. Anticipate finishing 11/2005.

G. Reprocessing of the existing 3D seismic data from the reservoirs of the Central Basin Platform in West Texas. Estimating of the AVO and other seismic attributes (UH, 04/2005-11/2005).
Have finished majority of post-stack attributes on west Texas data. Waiting on delivery of pre-stack data. Have loaded three other pre-stack 3-D data sets and have begun pre-stack AVO processing. Anticipate finishing one of the pre-stack offshore 3-D surveys by 11/2005.

H. Analysis of the results. Preparation of the report (UH, UCB, LBNL, 10/2005-11/2005).
Anticipate finishing on time.

TECHNOLOGY TRANSFER

The following abstracts, presentations and papers have been submitted:

Hilterman, F. and C. VanSchuyver, 2005, Seismic wide-angle processing to avoid NMO stretch, Accepted for publication in Geophysics

Zhou, Z., F.J. Hilterman, and H. Ren, 2005, Water-saturation estimation from seismic and rock-property trends: *to be presented at the* 75th Annual International Meeting of the Society of Exploration Geophysicists.

Goloshubin G. M. and D. Silin, 2005, Using frequency-dependent seismic attributes in imaging of a fractured reservoir zone: *to be presented at the* 75th Annual International Meeting of the Society of Exploration Geophysicists Expanded Abstracts.

Several petroleum-related companies have joined the Reservoir Quantification Laboratory (RQL) at the University of Houston. The goal of RQL is similar to this DOE project. The RQL sponsors are Unocal, ExxonMobil, Devon, Geophysical Development Corporation, BP, Paradigm, and Fairfield. Shell is an industrial sponsor of this DOE project.

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Fu, D., C. Sullivan, K.J. Marfurt, and D.W. Han, 2005, Rock properties and seismic analysis of chert reservoirs in the Devonian Thirtyone Formation, west Texas, Geophysics, *in review*

Goloshubin G. M. and D. Silin, 2005, Using frequency-dependent seismic attributes in imaging of a fractured reservoir zone: *to be presented at the* 75th Annual International Meeting of the Society of Exploration Geophysicists Expanded Abstracts.

Hilterman, F. and C. Van Schuyver, 2003, Seismic wide-angle processing to avoid NMO stretch, 73rd Annual International Meeting Society of Exploration Geophysicists, Expanded Abstracts, 215-218.

Hilterman, F. and C. VanSchuyver, 2005, Seismic wide-angle processing to avoid NMO stretch, Accepted for publication in Geophysics.

Liner, C., C.-F. Li, A. Gersztenkorn, and J. Smythe, 2004, SPICE: A new general seismic attribute: 72nd Annual International Meeting of the Society of Exploration Geophysicists Expanded Abstracts, 433-436.

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Sullivan, E.C., K. J. Marfurt, A. F. Lacazette, and M. Ammerman, 2005, Application of new seismic attributes to collapse chimneys in the Ft. Worth Basin: submitted to Geophysics.

Zhou, Z., F.J. Hilterman, and H. Ren, 2005, Water-saturation estimation from seismic and rock-property trends: *to be presented at the* 75th Annual International Meeting of the Society of Exploration Geophysicists.

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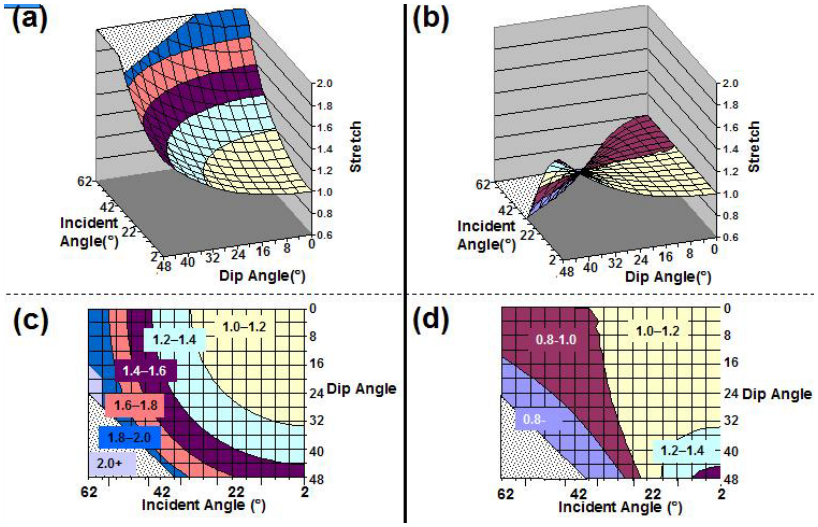

Figure 1. NMO stretch versus incident angle and reflector dip. (a) and (c) Kirchhoff migration, (b) and (d) Wide-angle processing. Dotted areas have (dip angle + incident angle) > 80°, that is, reflected raypaths have emergence angles greater than 80°.

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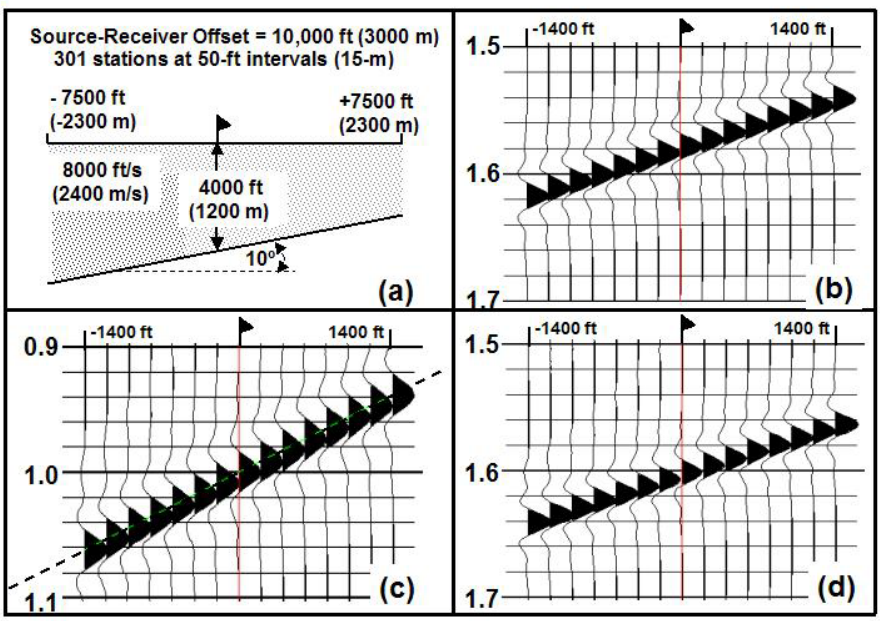

Figure 2. Kirchhoff migration versus wide-angle processing for 10° dipping reflector. (a) Model, (b) Portion of synthetic common-offset gather, (c) Kirchhoff migration of common-offset gather, and (d) Target-oriented Kirchhoff migration.

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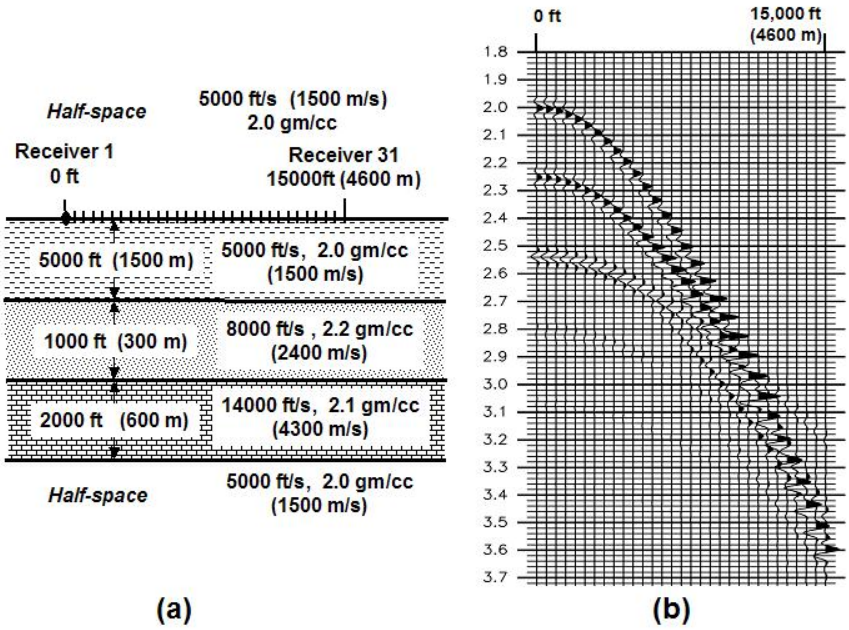

Figure 3. Acoustic model (a) and Reflectivity CMP synthetic gather (b). Depth model has large velocity contrasts that give rise to crossing events on the reflectivity synthetic. Divergence corrections based on 1/r are applied to synthetic gather.

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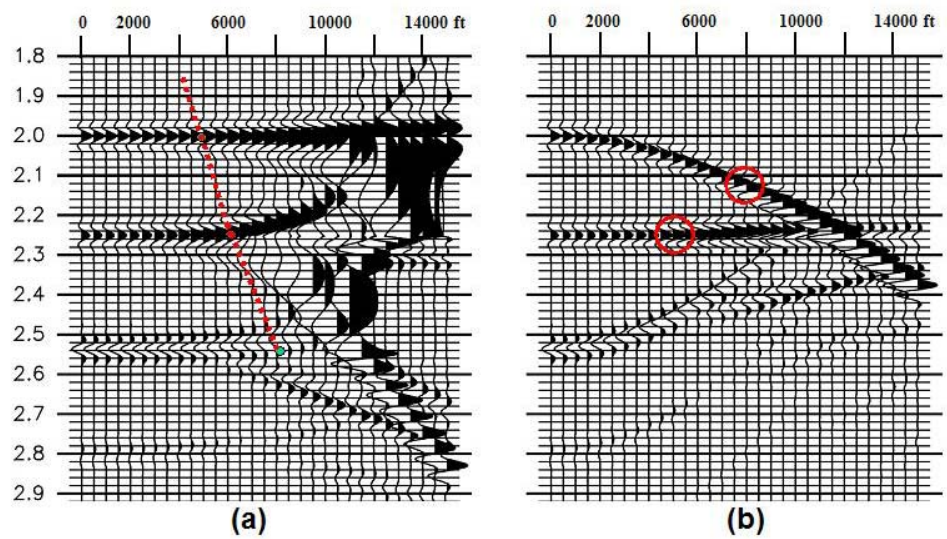

Figure 4. (a) Conventional Kirchhoff migration of reflectivity gather from Figure 3 versus (b) Target-oriented migration and NMO correction of reflectivity gather. Dash line in (a) is typical mute pattern of offset equal depth. Circles in (b) locate critical-angle distances.

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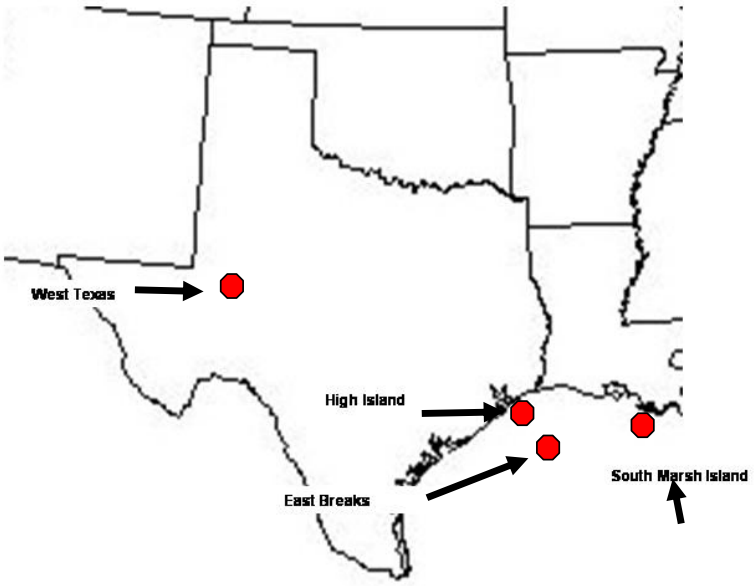

Figure 5. Location map of study areas.

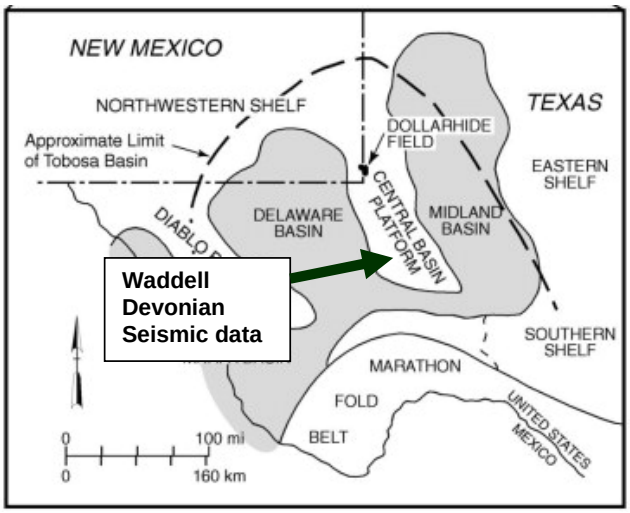

Figure 6. Permian Basin paleogeographic map with location of 3-D survey over the Waddell Devonian field. The dashed line marks the extent of the Lower Paleozoic depocenter, in which Devonian carbonates and cherts form basin-filling deposits (Ruppel and Hovorka, 1995). The Devonian carbonate and microporous chert reservoirs examined in this study are in the Waddell and South Jordan fields, Crane County, Texas (after Saller et. al. 2001).

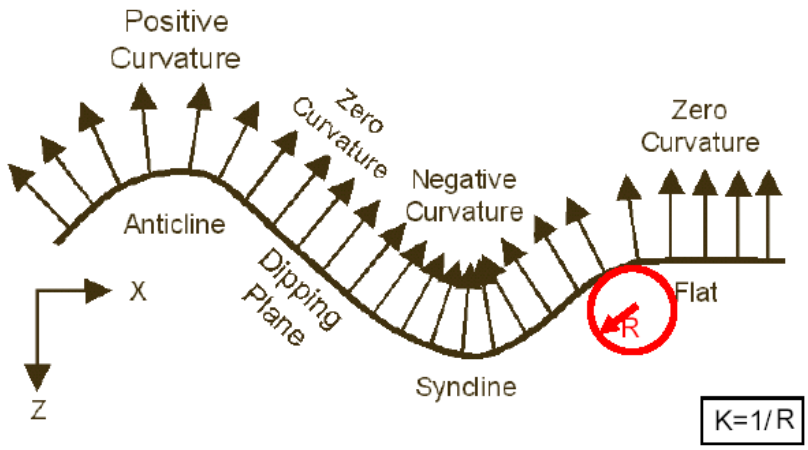

Figure 7. Curvature in two dimensions. Curvature (K) is defined as the inverse of the radius of a circle that is tangent to the surface at any point; positive curvature is concave downward and negative curvature is concave upwards. The curvature algorithms used in this study operate on the entire 3-D seismic volume, and do not require pre-interpretation of horizons. This is particularly helpful in areas of small, enechelon growth faults. (After Roberts, 2001.)

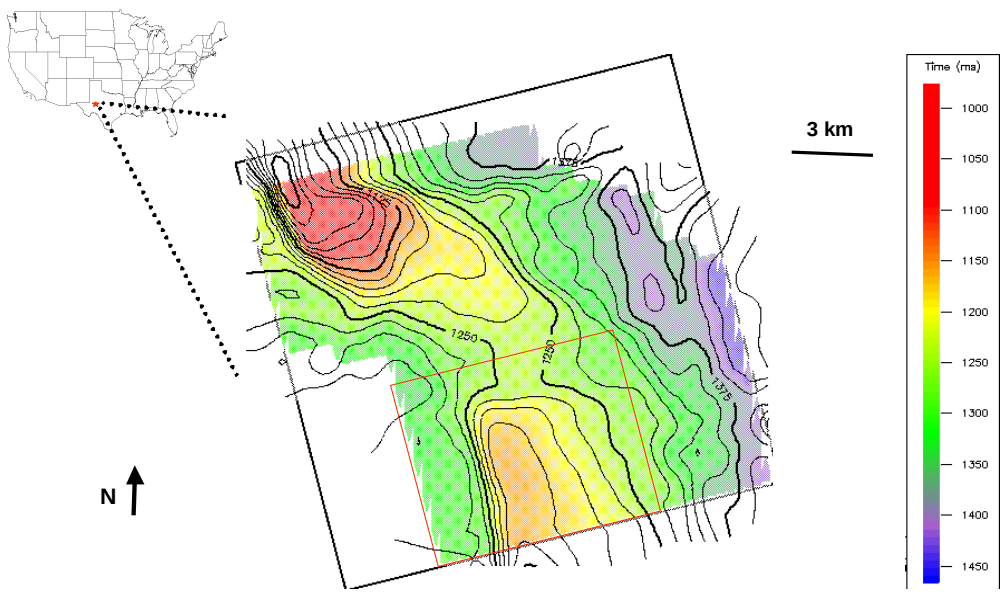

Figure 8. Time structure map on top of the Devonian Thirtyone Formation. This data set is from the eastern edge of the Central Basin Platform in west Texas. The area outlined in red is characterized by bioclastic carbonates and channelized microporous, spiculitic chert reservoirs. This is the area of focus in Figures 9-10 (From Fu, 2005).

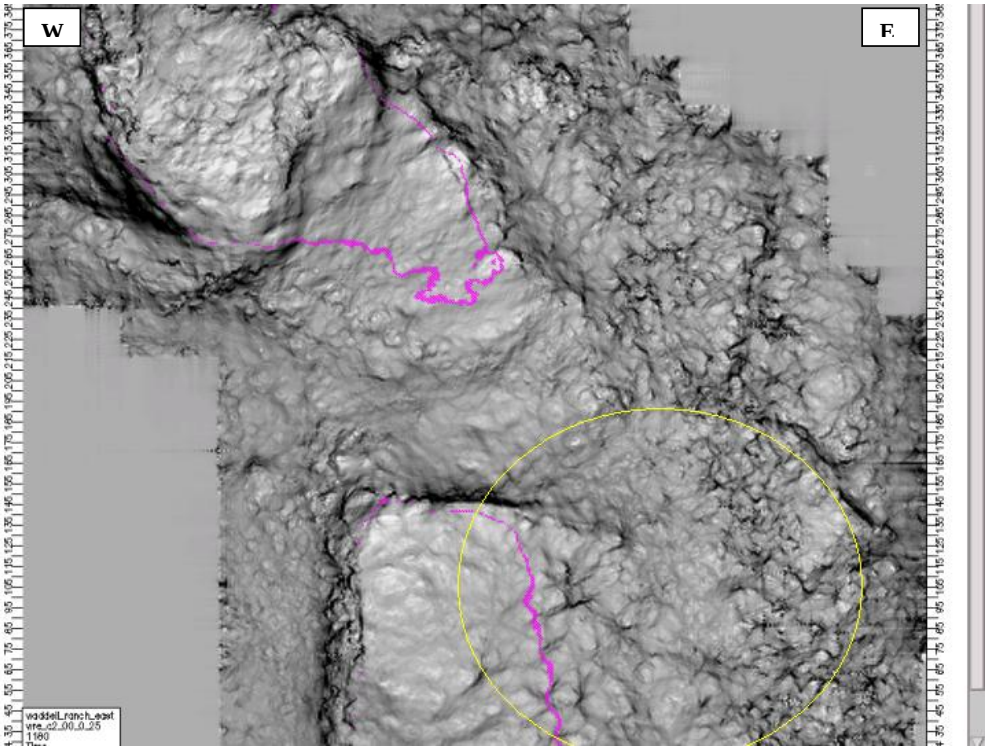

Figure 9. Time slice through the long wavelength Most Positive curvature volume within the Devonian interval of our west Texas 3-D seismic data. Dark areas mark regions of anticlinal curvature; the irregular pink line is the top of the Devonian Thirtyone Formation. Fractured carbonate reservoirs occur in the northern part of the survey. Microporous channelized chert reservoirs are largely confined to the southern part of the survey (yellow circle), but are not well imaged by the curvature attribute because of lack of differential compaction over channels. Volumetric curvature attributes are particularly useful in establishing stress regimes and most likely azimuth of open fractures and non-sealing faults (Blumentritt et al, 2005, Nissen, 2005). East to west field of view about 15 km.

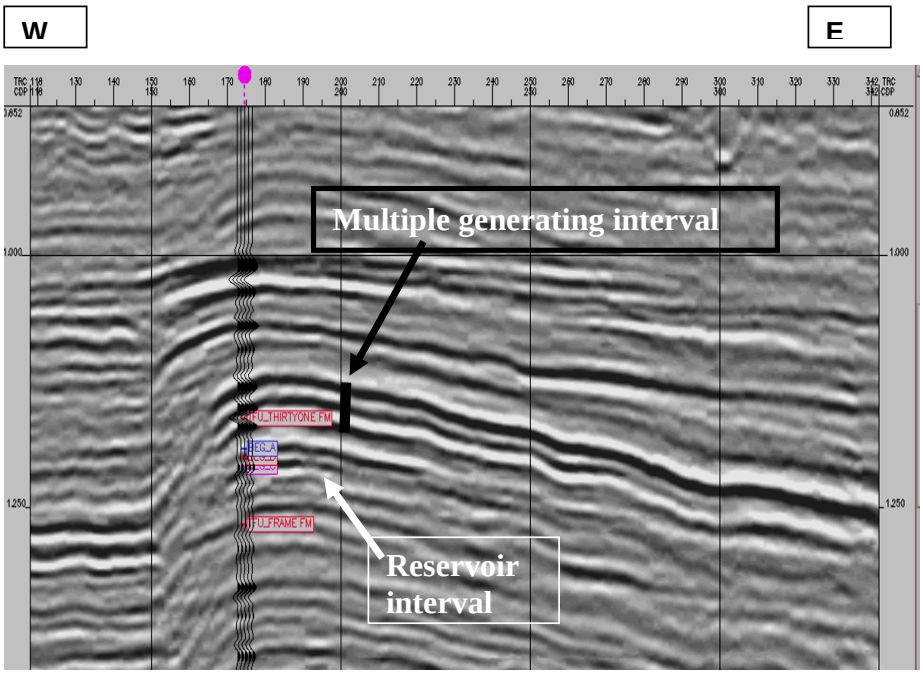

Figure 10. Synthetic tie to seismic, Waddell Devonian field, west Texas. This East-West seismic line is across the area circled in yellow in Figure 9. White arrow points to top of channelized, spiculitic chert reservoir zone. Field of view is about 6 km. Modeling indicates that interbed multiples are present in the data, and are generated within the interval marked by the black bar.

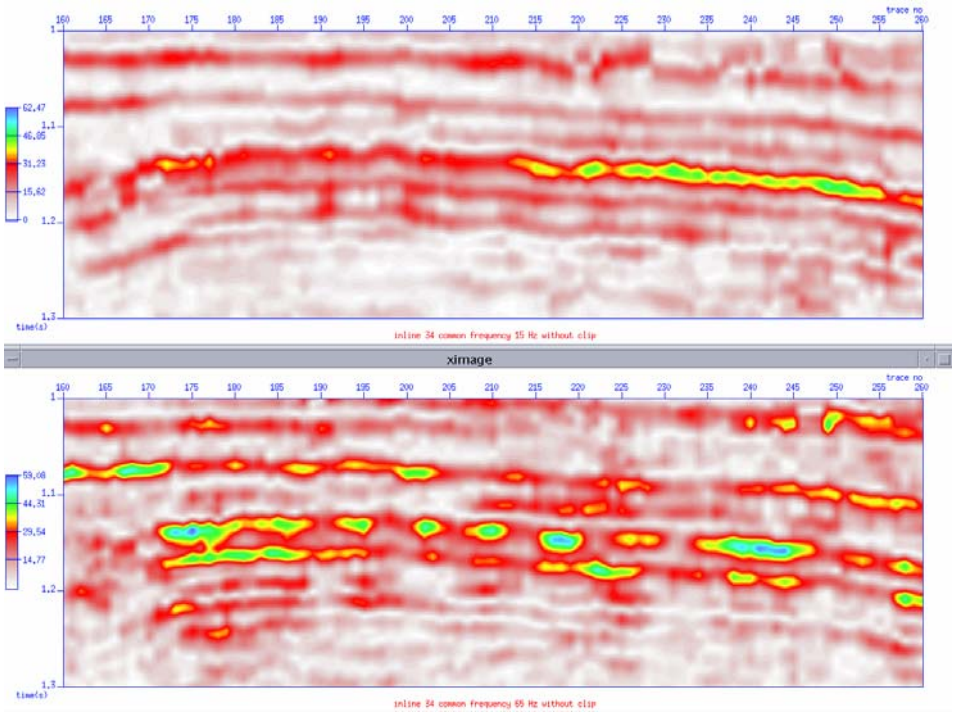

Figure 11. Preliminary generation of frequency attributes, Waddell Field. Figure 11a is generated from a frequency of 15 hertz; Figure 11b is from a frequency of 65 hertz. The reservoir occurs at about 1.2 s.

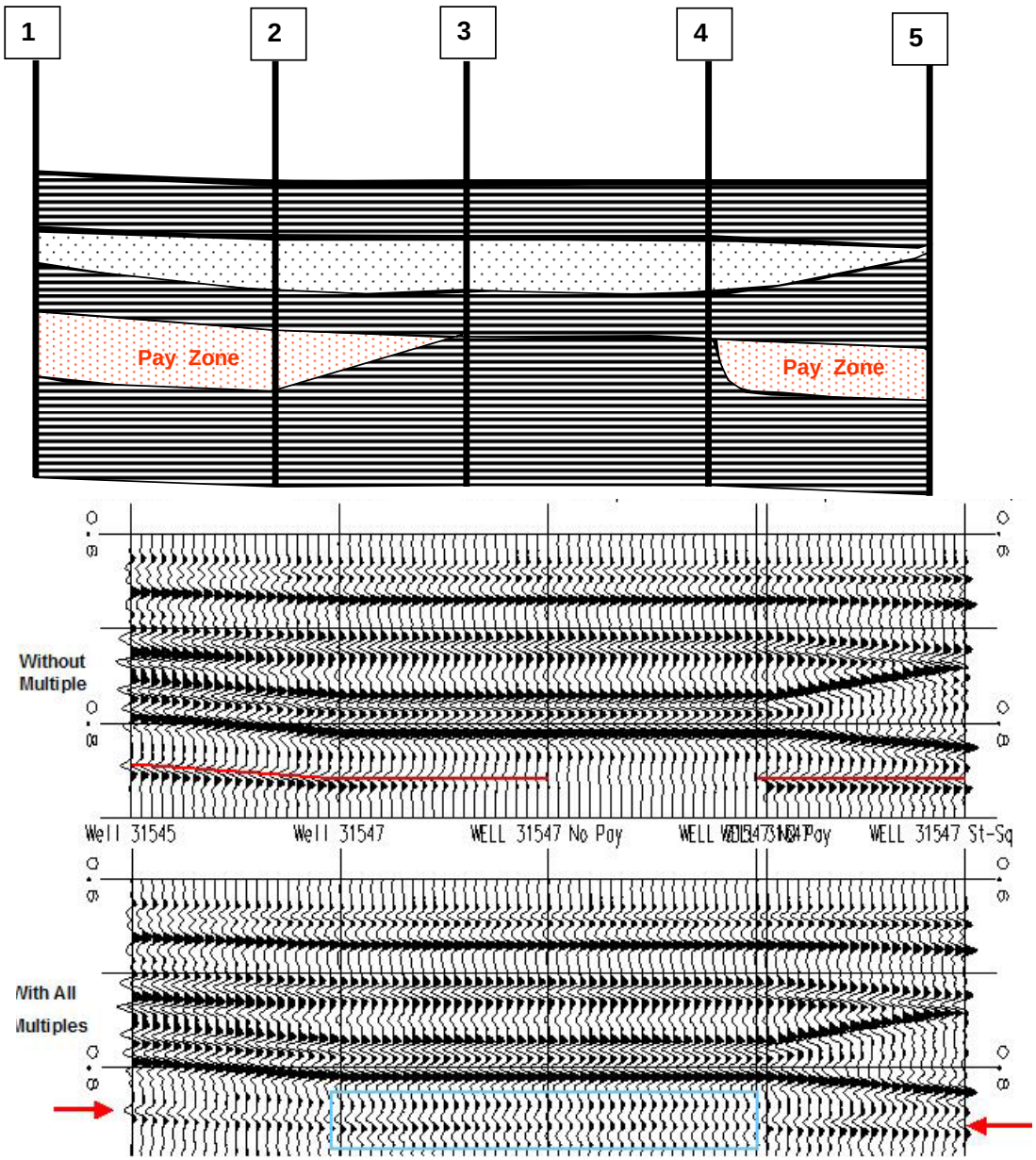

Figure 12. Effects of interbed multiples on detection of channelized microporous pay zones in the West Texas 3-D survey. Wells 3 and 4 have no pay as indicated in the stratigraphic model in Figure 12a, and have no associated seismic impedance contrast when modeled without multiples (upper panel). When multiples are added (lower panel), the seismic signature indicates an impedance contrast associated with a channel boundary.

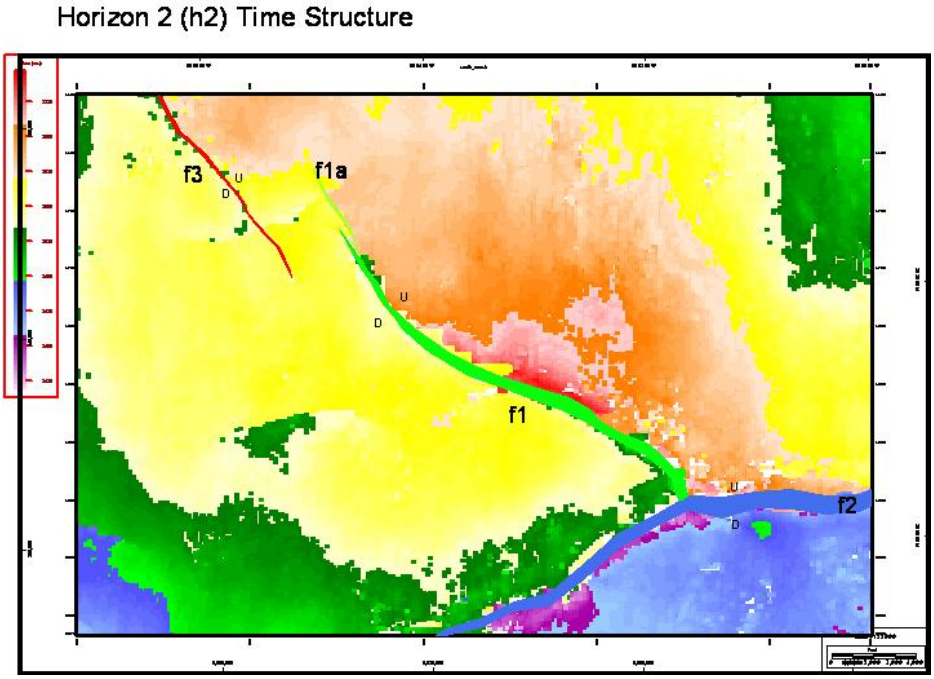

Figure 13. Time structure on Horizon 2 from the South Marsh Island seismic volume. The shelf offshore Louisiana is characterized by piercement salt dome structures, normal faults, and thin pay sands. Time slices above this horizon are shown in Figure 15. Field of view is 12 km.

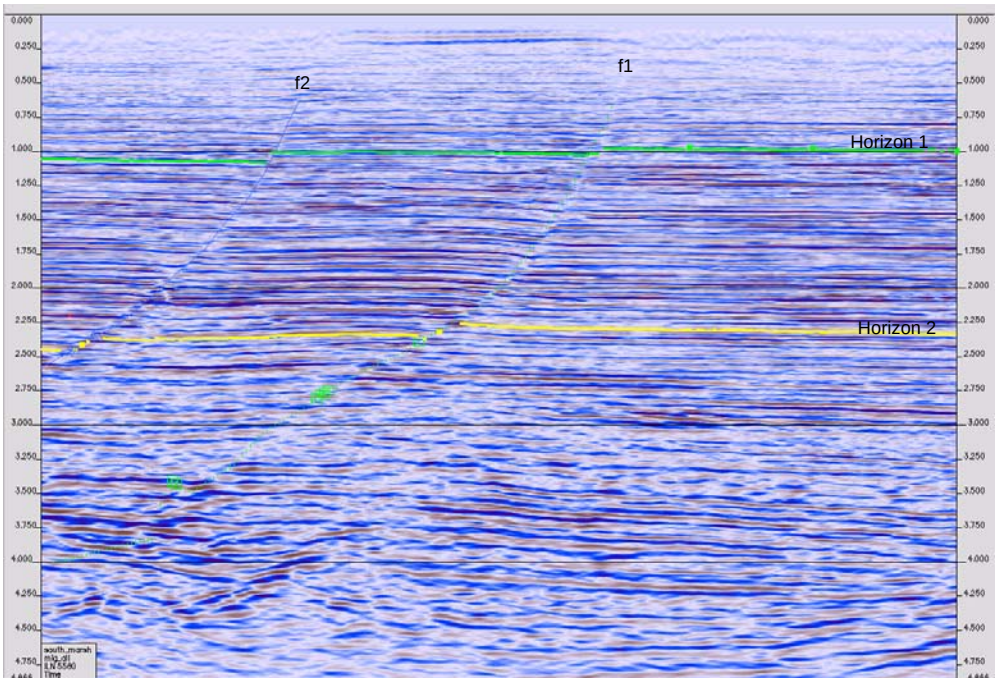

Figure 14. Seismic line extracted from the South Marsh Island seismic. Faults f1 and f2 are normal faults. The time structure shown in Figure 13 is mapped on Horizon 2. Time slices above this horizon are shown in Figure 15. Field of view is 12 km.

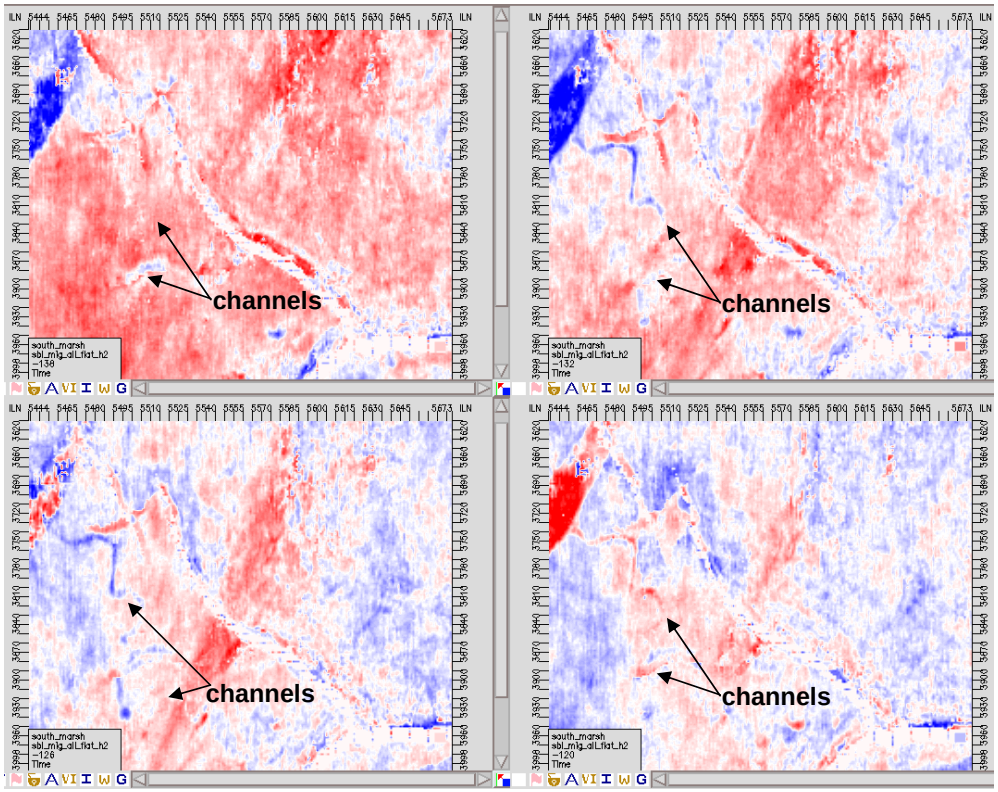

Figure 15. Channels in time slices in the South Marsh Island seismic volume. Time slices are taken every 6 ms from 138 ms to 120 ms, above flattened Horizon 2 (around 2250 ms), shown in Figure 14. Mapping of selected horizons and sand bodies by graduate student Sean Lewis is one of the first steps in constructing a structural and stratigraphic model for South Marsh Island. Field of view is 12 km.

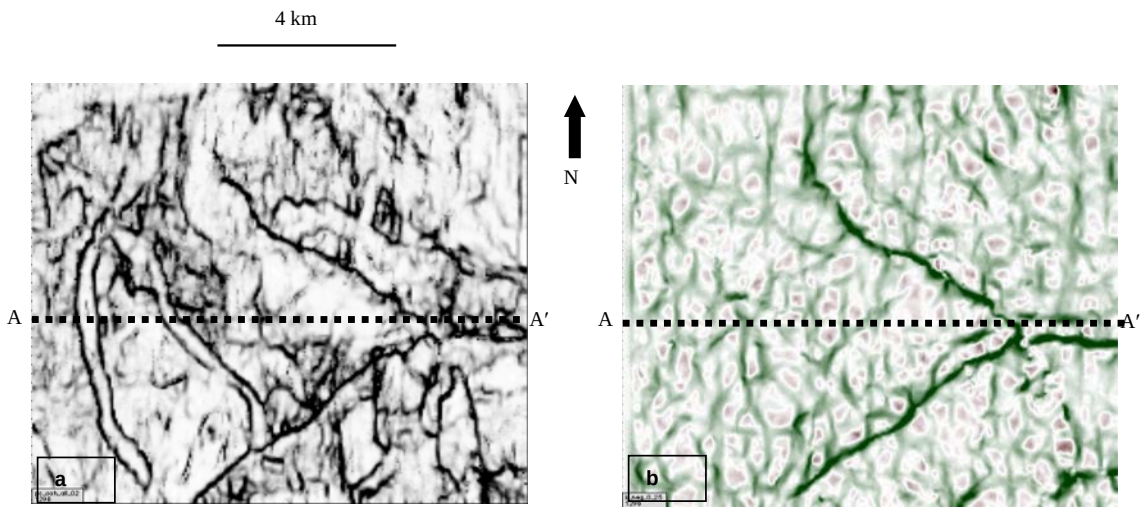

Figure 16. Comparison of coherency and curvature on imaging channels at South Marsh Island. Time slice at t=1.3 s through a coherence volume (a) generated for the South Marsh Island survey and the Most Negative Curvature volume (b). Discontinuities caused by channels and faults are better imaged by coherency. Because differential compaction within the channels is not evident, channels do not form images in the curvature volume (from Marfurt and Sullivan, 2005). View =12 km.

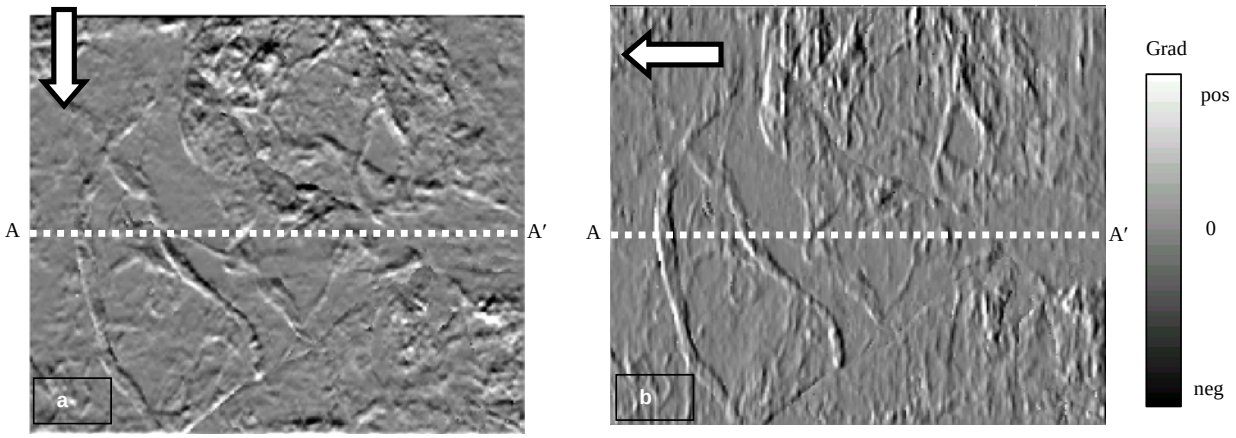

Figure 17. Comparison of components of the coherent energy gradient attribute. The time slice at t=1.3s through the NS component (a) of the coherent energy gradient corresponding to Figure 16 illuminates east-west oriented features. The time slice at t=1.3 s through the EW component (b) of the coherent energy gradient illuminates north-south oriented features. Dark features have a negative amplitude gradient (from Marfurt and Sullivan, 2005).

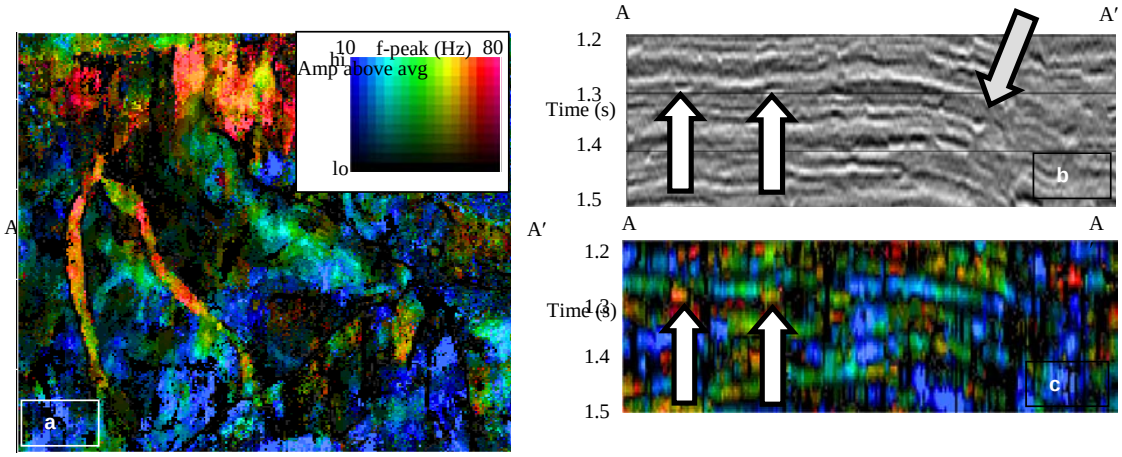

Figure 18. Spectral decomposition images of channels in the South Marsh Island seismic volume. The time slice at t=1.3 s through the peak spectral component cube (a) corresponding to Figures 16-17. Channels tune at 65 Hz. Vertical slices (b and c) through the seismic data and peak spectral component volume corresponding to line AA' shown in Figures 16-18a. White arrows indicate the two channels seen in Figures 16-18a, gray arrow (18b) indicates a fault.

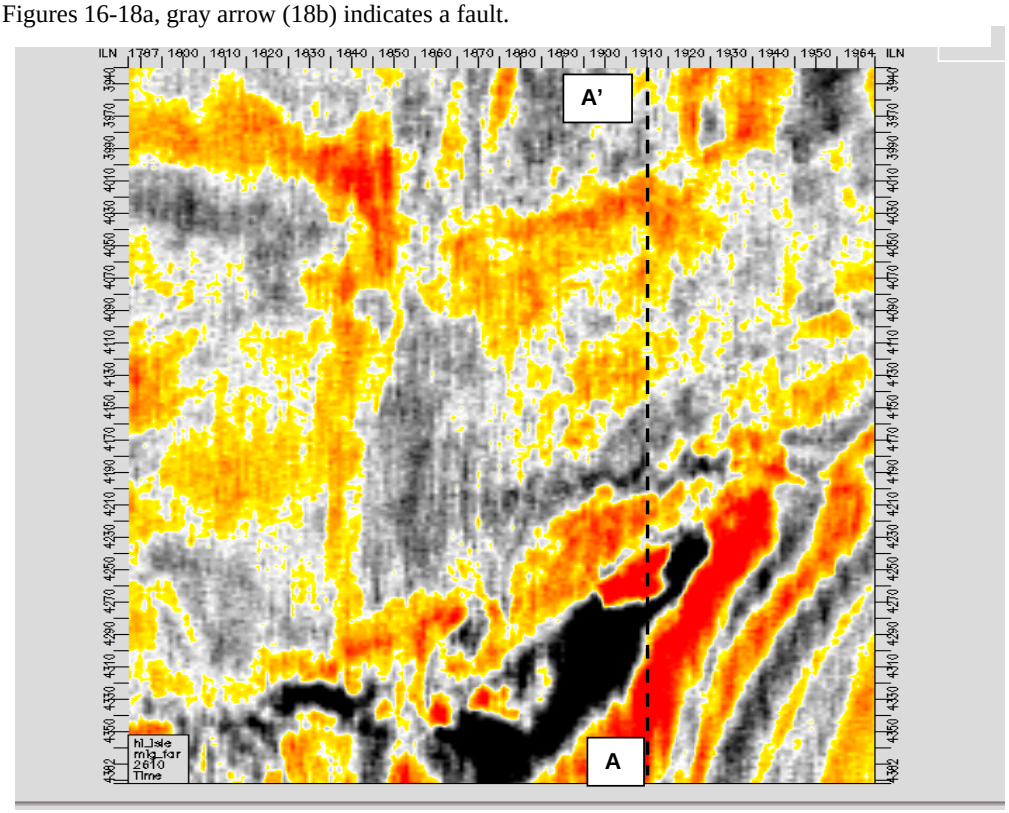

Figure 19. Time slice of High Island 3-D data, through pay interval shown in Figures 20-23. Dashed line indicates position of seismic line shown in following figures

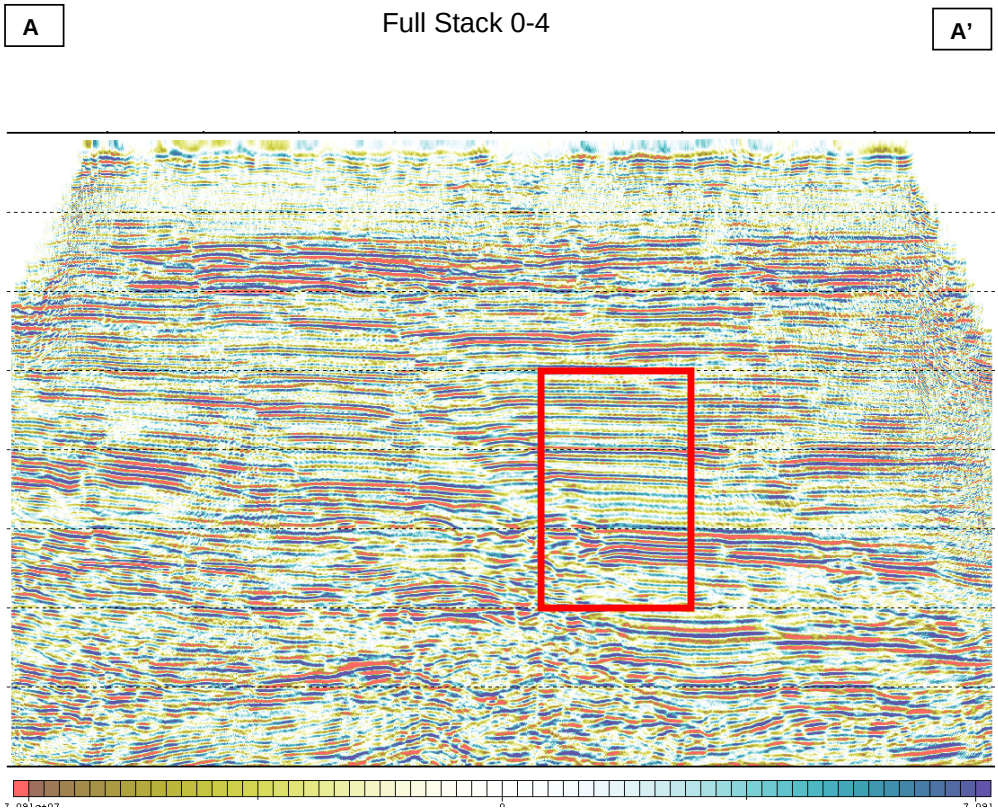

Figure 20. Full-stack seismic line extracted from the High Island 3-D survey, displayed from zero to four seconds. The red box shows area examined closer in Figures 21-23. Field of view is about 11 miles.

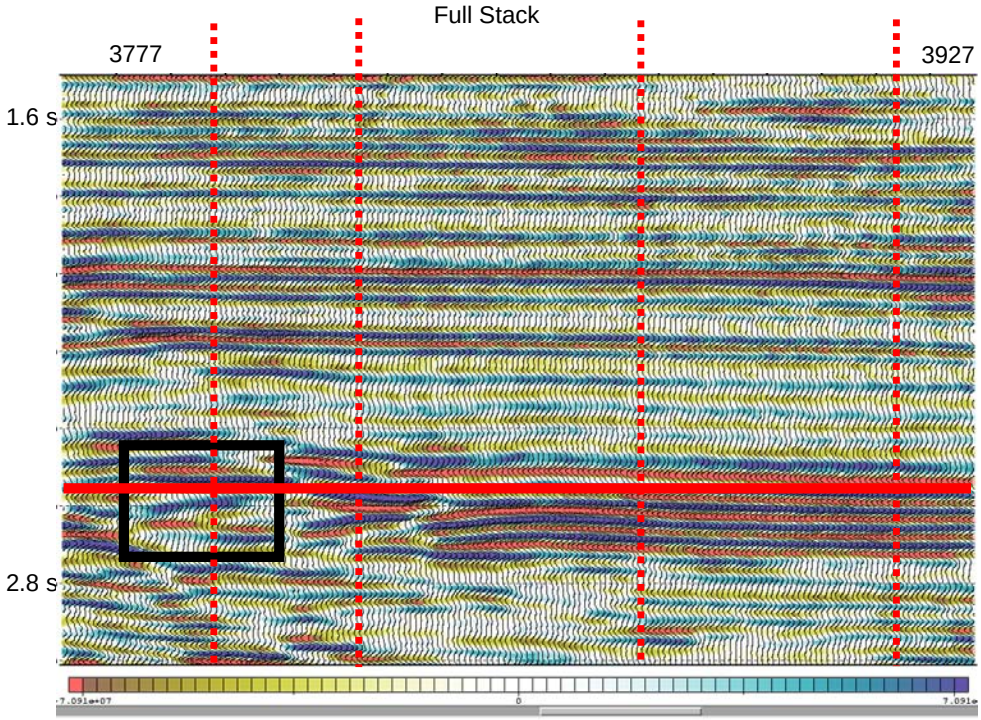

Figure 21. Zoomed view of red box area in Figure 20. Red horizontal is reference seismic trough for later slides. Vertical lines are gathers displayed in later figures. Black box highlights area of drilled well with known hydrocarbons.

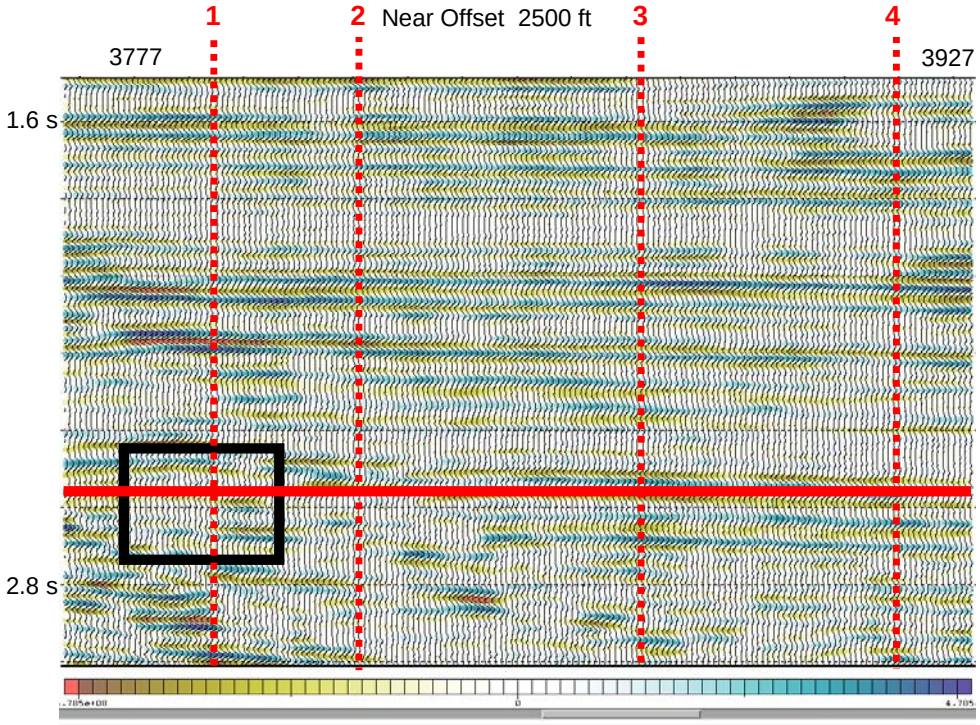

Figure 22. Common offset stack of 2500 ft for red box in full stack Figure 20. No strong amplitudes are present above or below reference trough (red horizontal line) within black box in this figure. In contrast, there is a strong amplitude event below the reference trough in previous Figure 21 and in the following figure of a far offset stack. Known hydrocarbons exist only at location 1.

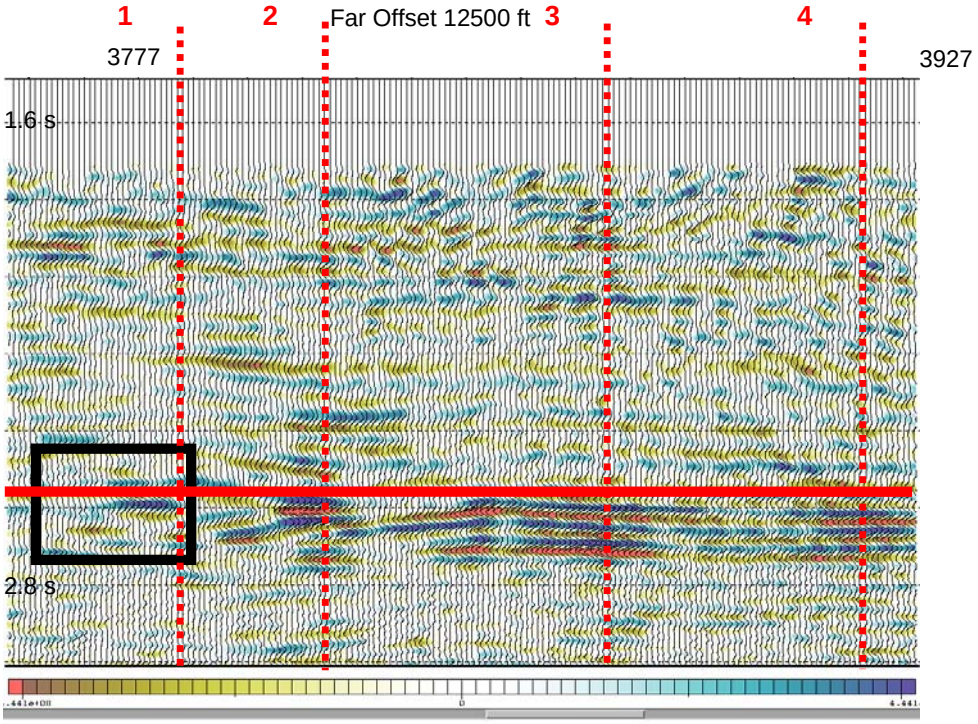

Figure 23. Far offset stack of 12,500 ft over same area as in previous figures. Note strong amplitudes below reference trough (red line) at each of the four locations.

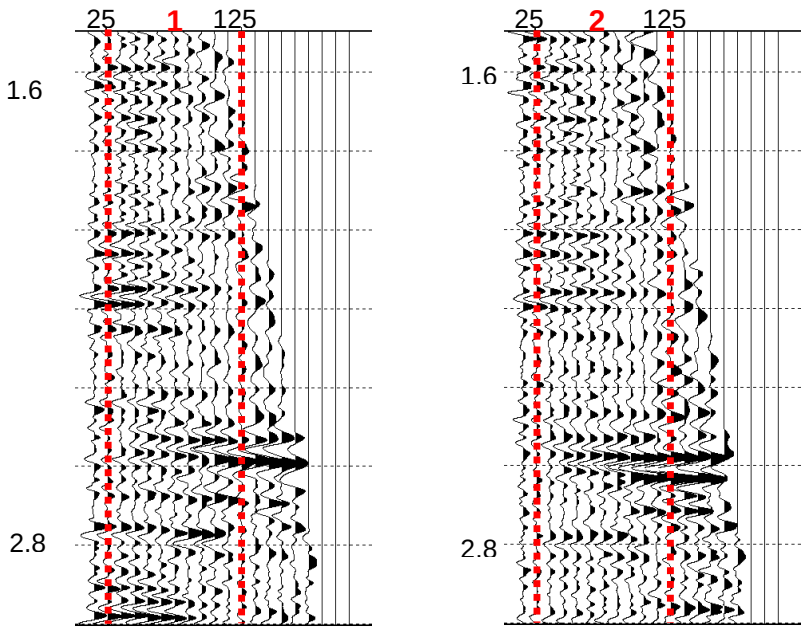

Figure 24. Gathers from locations 1 and 2 on seismic line shown in Figures 21-23. Location one has known hydrocarbons in reservoir at about 2.6 seconds. Strong amplitude at location 2 suggests presence of hydrocarbons here as well.

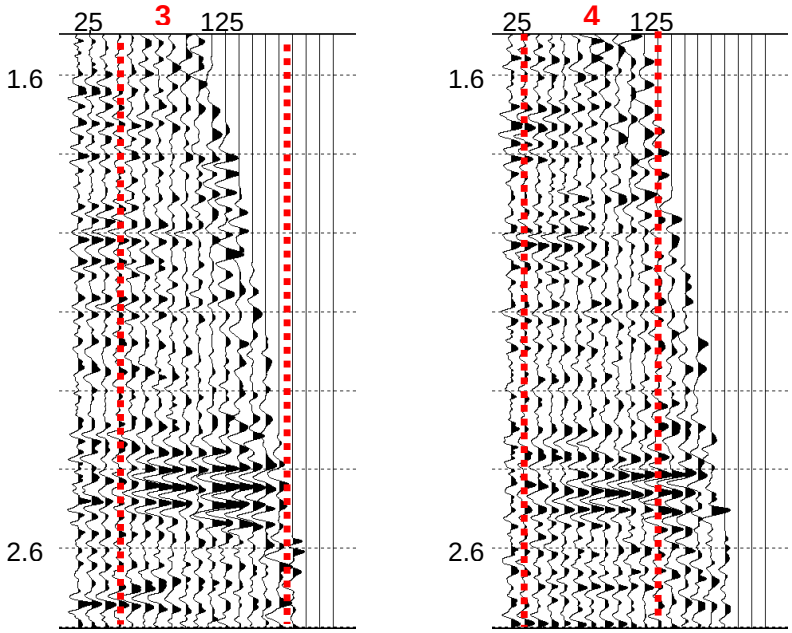

Figure 25. Gathers from locations 3 and 4 on selected line shown in Figures 21-23. Response is different from that of hydrocarbon bearing zone, even though the far-offset stack showed strong amplitudes. This signature suggests the presence of clean wet sand.