A Proposal Submitted to a
Consortium of Companies on

Seismic Quantification in Reservoir Delineation and Characterization

By

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Institutional Approval: Lee Boozer, Director
Office of Grants and Contracts
University of Houston

Executive Summary

This starts our second year of a three-year proposal for the Reservoir Quantification Laboratory (RQL). Our long-term research mission is a better understanding of the physical processes that affect seismic amplitude so that improved delineation and characterization of reservoirs are possible. With a better understanding of the physical processes that effect amplitude, more accurate estimations of porosity, permeability and fluid saturation for the reservoir compartments will follow. We are happy to report our initial successes in this effort.

We have investigated frequency-dependent amplitude losses associated with hydrocarbon reservoirs. Through a DOE alliance, LBNL and the University of California developed a wave theory for solid-fluid material that incorporates both matrix and fracture porosity with the fluid volume being held by the matrix porosity but the major permeability being through the fractures. The theory yields an asymptotic expression for the frequency-dependent reflectivity and attenuation. In order to provide quantitative amplitude measurements of the reflectivity from seismic data, we have empirically formulated two rock-property transforms that allow conventional seismic horizon maps to be converted into reflectivity maps. As a by-product, an estimate of water saturation is produced.

Our effort to quantitatively evaluate reservoir geometry with seismic reflectivity at different incident angles and frequencies was accomplished with our first physical modeling experiments across a vertically fractured reservoir. Several diagnostic tools for evaluating the density and azimuth of fractures resulted. In this experiment, the frequency dependency of the propagating wavelet has been preserved with wide-angle processing to permit a more accurate characterization of the fractured reservoir. While we are still investigating new processing and interpretation procedures for fractured reservoirs, it is encouraging that our results are immediately applicable to conventional seismic PP field data.

2005 Work Summary

Our three-year plan for the “Seismic Quantification in Reservoir Delineation and Characterization” project is multi-fold with nine different areas of research. The time schedule, which was presented at the beginning of this project, is listed in Appendix A for the various research tasks. Appendix B provides additional details of the individual tasks. Our accomplishments in the individual research areas are summarized by the oral and poster presentations listed in Appendix C. Copies of articles, abstracts, reports, and posters are supplied on a CDROM to the 2005 sponsors of RQL.

The following are brief descriptions of our 2005 research that is included on the CDROM.

Wave Propagation

One of our major research areas involves the wave-theory development of fluid flow in porous media that accounts for the unexplained changes in frequency and amplitude losses associated with seismic reflection surveys across hydrocarbon-saturated reservoirs. The theory is an extension of the Biot-Barenblatt double porosity theory and it establishes a frequency-dependent analytical relationship between permeability and attenuation. The new theory shows more loss due to attenuation than the original Biot theory, an aspect that is desired. In addition, the new theory provides a solution for the normal-incident reflection and transmission coefficients. This work was done at LBNL and the University of California.

Physical Modeling

Before any meaningful physical modeling experiments were conducted it was necessary to calibrate the transducers. This was done several times during the last year as transducers were damaged due to our inexperience with the linkage between the mechanical movement and the specified parameters in the software. The transducers have excellent omni-directional responses. However, post acquisition shaping filters are necessary to broaden the source spectrum (i.e. source pulse rings). Several pairs of transducers have been ordered to replace the damaged ones.

Last year, we proposed to generate acoustic data across a meandering porous channel. However, the complication of the geometry and non-welded surfaces led to the rejection of this model. Instead, a simple HTI model composed of thin sheets of Plexiglas (approximately 180 sheets with thickness of 0.1 wavelength) bolted together was chosen. Over twenty-one 3D surveys and numerous expanded spreads were collected across this model and are still being investigated. Over 3 months of data acquisition has been generated. We are extremely pleased with our preliminary observations and the ability to predict fracture density and azimuth based on post-critical reflections and head waves. Other seismic wave fields associated with the fracture density and azimuth are reported at the annual meeting and are included on the CDROM.

Computer Programming

Our initial efforts to apply new data-processing algorithms to the physical modeling data using commercial software were not too encouraging. Therefore, a suite of programs was developed (and are continuing to be developed) based on a PC windows compiler and free software. These programs are available to sponsors and to students for their research. The PC programs are easily converted into UNIX-based versions. The programs include:

1. Various 2D and 3D time migrations (including non-NMO migration),
2. Gabor spectral decomposition and applications,
3. Various wavelet shaping and design programs,
4. Section, horizon and alternate screen displays,
5. AVO ray-theory synthetics, display and analyses with fluid substitution, anisotropy, perturbation of properties, etc., and
6. Auxiliary programs for data handling.

Numerical Modeling

AVO synthetics based on PP-only ray theory are misleading when large source-receiver offsets are investigated as our research demands. It is not only the magnitude of the rock property variations across the boundary but also the vertical profile of the variations that affect the AVO response. The results and conclusions from the reflectivity synthetics are captured in a poster that is included in the CDROM. Results from this study also assisted in identifying the additional ray modes that are needed to make the ray-theory synthetics better match the reflectivity synthetics.

A shallow reflectivity study was conducted to illustrate the convergence of reflection and head wave events at large offsets. The reason for this research is that during the physical modeling experiments, the mapping of the head wave time arrival and amplitude became diagnostic of fractures. Our initial reflectivity synthetics have illustrated the relationship of head wave amplitude to the medium's Poisson ratio, a fracture indicator.

While working with AGL, there was concern about the S/N quality of a reflection event mapped beneath a thick low-velocity shale layer with a 3D attribute. Our study with numerical stratigraphic modeling with all internal multiples explained the loss of S/N ratio and the false hydrocarbon indication.

Initial numeric tests were conducted on the Biot-Barenblatt theory for typical reservoir properties. These tests are still preliminary. With the theoretical portion finished, new physical models have been designed to emphasize the seismic differences to be observed from the double-porosity theory versus the conventional elastic theory.

Imaging

The theory of non-NMO migration was extended with a quantitative analysis of the wavelet stretch. Both 2D and 3D migration computer programs based on non-NMO migration have been written. Then, Fourier analyses of waveforms with and without non-NMO migration from various synthetic models were compared.

We have done significant research into designing migration weights with and without NMO corrections and have tested them with synthetic data. Our initial tests indicate that our migration weights are stable out to offsets that are 3 times the depth and up to 30-degree dips. We have not found any published migration weights that are that robust. Because of time limitations, we have not reported these results. They will be in the second year report.

Calibrate Borehole to Seismic

From the petrophysical studies of 500 sand reservoirs conducted by Geophysical Development Corporation in the Gulf of Mexico, we discovered two rock-property transforms. These transforms are useful in numerous applications. For instance, the transforms convert seismic horizon maps (near and far offsets) into normal-incident reflection coefficient values. Then, estimates of water saturation are possible. A preliminary application to real data from a field in the Louisiana shelf assisted in identifying areas where additional calibration research is needed.

Interpretation

For over fifty years, geoscientists who are involved with attenuation measurements have said, " We still can't tell the difference between scattering and intrinsic attenuation". However, there are seismic data processing techniques that allow the recognition and to some extent the prediction of amplitude and frequency loss caused by scattering. One scattering mechanism that has been recognized in the Gulf of Mexico is shallow channel slumps. What other structure or stratigraphic features will produce frequency or amplitude losses through scattering? Using pre-stack and post-stack seismic, we are currently investigating 3D attributes that detail anomalous amplitude and frequency values beneath Miocene reservoirs and then cataloging these with respect to their structure and stratigraphic styles.

Seismic Data Processing

We tried several times to reprocess 3D long-offset seismic data in an area that we know has large amplitude far-offset signatures related to both hydrocarbons and clean sands. Unfortunately, our attempts to have "clean" 3D common-offset gathers before migration have not been successful. Or it might be, we are judging our data quality too strictly based on what we feel our S/N for amplitude needs to be for application as a function of frequency and incident angle. However, a preliminary processing flow has been established.

2006 Tentative Work Plan

Appendix D contains a short description of our intended plan for the various research areas as of December 5, 2005.

Additional work in the Inversion and Rock Physics Measurement Research areas will be conducted if sufficient funds are obtained.

Deliverables

- Copies of seismic data from numerical and physical modeling.
- Petrophysical measurements from borehole and physical models.
- Synthetics and anisotropic measurements derived from field data.
- Algorithms for wave-propagation in porous media
- Methodology (model and field data)
    - ❖ Target-oriented frequency-preserved seismic data processing
    - ❖ Identification of impulse response for various physical processes
    - ❖ Tomographic inversion for velocity, attenuation and anisotropic parameters.
    - ❖ Interpretation of structure and composition based on non-NMO corrected data and seismic reflectivity at different frequencies and incident angles (AVAF)
- One final report per year

Deliverables will be presented in form of annual reports in digital format. In addition to the report and annual review meeting, if requested, we will make visits to sponsor work sites for shorter presentations to a wider audience.

2005 Sponsors

BP, Devon, ExxonMobil, GeoData, Geophysical Development Corporation, and Unocal, Fairfield, Paradigm and Apex Metalink.

Students

Supported: Julius Doruelo, Zhengyun Zhou, and Connie VanShuyver
Students: Duan Li, Haitao Ren, Matt van Wie, and Sean Lewis

Research Alliance Investigators

Dr. Valery Korneev	Staff Geological Scientist, Lawrence Berkeley National Lab Seismic wave propagation
Dr. Tad Patzek	Professor of Geo-Engineering, Univ. of California, Berkeley Mulitphase flow and hydrofracture dynamics
Dr. Dmitry Silin	Associate Researcher, Univ. of California, Berkeley Reservoir fluid flow and wave propagation
Dr. Robert Wiley	Apex Metalink In kind Research Geophysicist

Appendix A
Seismic Quantification in Reservoir Delineation and Characterization
RQL Time Schedule

Projected Work Time Schedule

		Year 1						Year 2						Year 3					
		2	4	6	8	10	12	2	4	6	8	10	12	2	4	6	8	10	12
Seismic Data Processing																			
Task 1	Select 3-D data	■	■																
Task 2	First 3-D processing			■	■	■	■	■											
Task 3	First attribute processing					■	■	■	■	■									
Task 4	TOP on 3-D data					■	■	■	■	■	■	■	■	■	■	■	■		
Computer Programming																			
Task 1	TOP NMO and migration	■	■	■	■														
Task 2	Trim parabolic NMO stactic				■	■	■												
Task 3	Link TOP to Workstation		■	■	■	■	■	■											
Task 4	Recognize, quantify, decompose amplitude				■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Task 5	Wavefront distortion impulse response				■	■	■	■	■	■	■	■	■						
Wave Propagation																			
Task 1	Develop wave propagation - porous media	▒	▒	▒	▒	▒	▒	▒	▒	▒									
Task 2	Develop AVAF reflectivity eqs. - 3 models				▒	▒	▒	▒	▒	▒	▒	▒	▒						
Task 3	Numeric AVAF synthetics						▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒		
Phys. & Numeric Modeling																			
Task 1	Calibrate source-receiver & H2O attenuation	■	■	■															
Task 2	Physical 3-D seismic for 3 models		■	■	■	■	■	■	■										
Task 3	Numerical 3-D seismic for 3 models				■	■	■	■	■	■	■	■	■	■	■	■	■		
Task 4	TOP of seismic from 3 models			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Task 5	Develop extended ray theory	■	■	■	■														
Rock-Physics Measurements																			
Task 1	Measure borehole rock properties			■	■	■	■	■	■	■	■								
Task 2	Measure physical model properties			■	■	■	■												
Imaging																			
Task 1	Develop imaging based on AVAF models					▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒		
Task 2	Extend AVAF imaging technique to field										■	■	■	■	■	■	■		
Inversion																			
Task 1	Velocity and anaisotropy inversion							■	■	■	■	■	■	■	■	■	■		
Task 2	Attenuation inversion							■	■	■	■	■	■	■	■	■	■		
Task 3	Characterization by inverse scattering													■	■	■	■	■	■
Task 4	Forward modeling of 3D by scattering				■	■	■	■	■	■	■	■	■						
Calibrate Borehole to Seis																			
Task 1	1D and AVO synthetics			■	■	■	■	■	■	■									
Task 2	Weak anisotropy parameter estimation							■	■	■	■	■	■						
Task 3	Trend and anomaly rock-property modeling				■	■	■	■	■	■	■								
Task 4	Rock properties vs depositional environment							■	■	■	■	■	■	■	■				
Interpretation																			
Task 1	Build structure abd strat models +++					■	■	■	■	■	■	■	■	■	■	■	■	■	
Task 2	Coherency - Conventional vs TOP					■	■	■	■	■	■	■	■	■	■	■	■	■	

▒ Univ. Cal. and National Lab Work

Appendix B
Project Tasks

Seismic Data Processing

Task 1. Select 3-D seismic field data set that has sufficient borehole control to facilitate validation of interpretation. Preference will be given to data sets that exhibit events near the reservoir that exhibit frequency-dependent amplitude variations.
Task 2. Perform preliminary processing of 3D field data with conventional anisotropic and pre-stack time migration for *Stage 1 Output*.
Task 3. Perform preliminary attribute processing for known reservoir.
Task 4. Start TOP of 3-D field data

Computer Programming

Task 1. Develop non-stretch pre-stack 3-D time migration and target-oriented NMO.
Task 2. Develop CMP static correction for far-offset traveltimes not define by anisotropic NMO equation. Static corrections might be softly related to parabolic curvature.
Task 3. Develop links between TOP processing package and interpretation workstation.
Task 4. Develop multi-channel programs for the recognition, quantification and decomposition of seismic amplitude variations to different physical processes.
Task 5. Develop slant stack process and impulse response of wave front distortion to define structure caused by lateral heterogeneities.

Wave Propagation

Task 1. Develop the asymptotic model and governing equations describing seismic wave propagation in fluid-saturated porous and fractured rocks. Investigate the interaction between the solid skeleton and the fluid at the transition between permeable and impermeable zones.
Task 2. Describe the reflectivity equations for AVAF imaging of reservoir properties for models with:

- Porous (micro porous) medium
- Fractured medium, and
- Dual-porosity / Dual-permeability medium (Dual = matrix + fractures)

Task 3. Formulate the algorithms for the numerical modeling, AVAF imaging and quantitative analysis of the AVAF images.

Physical and Numerical Modeling

Task 1. Calibrate source and receiver for directionality and water attenuation.
Task 2. Conduct physical modeling to investigate wave attenuation by frequency-dependent reflectivity on long-offset 3D seismic for the following models:

- Porous (micro porous) medium
- Fractured medium, and
- Dual-porosity / Dual-permeability medium.

Task 3. Conduct numerical modeling for the three physical models with and without loss-mechanism parameters.
Task 4. Process physical and numerical data conventionally and with TOP.
Task 5. Extend conventional PP ray theory to include PPSP, PPPP and other modes for long offset.

Rock-Physics Measurements

Task 1. Measure rock properties from borehole data.
Task 2. Measure properties of physical model for inclusion in numerical modeling.

Imaging

Task 1. Create and investigate a new technique of seismic reservoir imaging based on the AVAF models of

- Porous (micro porous) medium
- Fractured medium, and
- Dual-porosity / Dual-permeability medium.

Task 2. Extend reservoir-imaging techniques from AVAF models to 3-D filed data.

Inversion

Task 1. Develop tomographic estimations of velocity and weak-anisotropy fields above, within and below reservoir zones from TOP processing.
Task 2. Estimate attenuation field with tomographic inversion of TOP data.
Task 3. With best estimate of reservoir structure, apply inverse scattering theory to estimate reservoir compartment properties.
Task 4. Investigate possibility of applying forward scattering theory to model the three porous reservoirs.

Borehole to Seismic Calibration

Task 1. Generate 1D and AVO synthetics, ray-theory, reflectivity (SOLID) and anisotropic from available borehole data.
Task 2. Estimate the weak anisotropic trends from seismic and borehole data.
Task 3. Develop rock-property trend statistics and anomalous lithology statistics.
Task 4. Catalog rock properties as function of reservoir and depositional environment.

Appendix C - 2005 Work Accomplishments

Seismic Data Processing	
Connie VanSchyver	Processing Flow Development
Computer Processing	
Fred Hilterman and Haitao Ren	Preliminary modeling software
Fred Hilterman and Haitao Ren	PC software for frequency dependent analyses
Wave Propagation	
Tad Patzek	Biot for Dummies
Dmitry Silin	Biot-Barenblatt double-porosity theory
Gennady Goloshubin	Reflectivity of double-porosity model - Practical application
Bob Wiley and Scott Peters	Wavelet Energy Absorption
Bob Wiley,Scott Peters,Peter Wilson	WEA in western China deltaic channel
Physical Modeling	
Julius Doruelo and Fred Hilterman	Examining the physical modeling system: Amplitude calibration and directivity tests of transducers: System time delay study
Julius Doruelo and Bob Wiley	Proposed physical models for investigating wave attenuation by frequency-dependent reflectivity
Julius Doruelo and Fred Hilterman	Common-offset physical modeling of HTI fractures for 3 azimuths
Julius Doruelo & Fred Hilterman	3D physical model volumes across HTI fractures
Numerical Modeling	
Connie VanSchuyver and Fred Hilterman	Seismic responses to shallow near-surface variations
Fred Hilterman and Connie VanSchuyver	AVO reflectivity responses: Pitfalls of high-velocity layers
Haitao Ren, Fred Hilterman, and Charlotte Sullivan	Interpretational aspects of internal multiples from Australia to West Texas
Julius Doruelo, Gennady Goloshubin and Fred Hilterman	Numerical examples of double-porosity reflectivity effects and proposed physical modeling
Imaging	
Fred Hilterman and Connie VanSchuyver	Seismic wide-angle processing to avoid stretch
Mingya (Susan) Chen and Fred Hilterman	A Study on non-NMO migration
Calibrate Borehole to Seismic	
Zhengyun (Jenny) Zhou, Fred Hilterman, Haitao Ren & Mritunjay Kumar	Water-saturation estimation from seismic & rock-property trends
Zhengyun (Jenny) Zhou, Fred Hilterman, Haitao Ren and Mritunjay Kumar	Water saturation estimation - Preliminary field application in Louisiana Shelf, GOM
Interpretation	
Matt van Wie, Fred Hilterman, Charlotte Sullivan and Kurt Marfurt	Structural and stratigraphic analysis of Miocene aged sands, Offshore Gulf of Mexico
Sean Lewis	Stratigraphic styles of hydrocarbon reservoirs: How they affect various 3D seismic attributes

Appendix D
2006 R&D Plan

Seismic Data Processing	
Apply AVAF theory to 3D field data.	Connie VanSchuyver, Gennady Goloshubin and Fred Hilterman
Computer Programming	
Convert PC software to UNIX base with SEGY interface.	Zhengyun (Jenny) Zhou, AGL student
Continue program development for large offset processing interpretation. Computer Programming Tasks 2, 4 and 5.	Fred Hilterman and RQL students
User-interface for attenuation-AVO modeling	Duan Li
Wave Propagation	
Extension of double-porosity model to non-normal incident reflections. Wave Propagation Task 2	Gennady Goloshubin, U.California and LBNL
Theoretical development and application of reflectivity as function of offset and frequency. Wave Propagation Task 3 and Imaging Task 1.	Gennady Goloshubin, Fred Hilterman, U.California and LBNL
Add five additional ray modes to PP ray theory to match reflectivity thin layer synthetics.	Fred Hilterman, RQL student
Physical Modeling	
Finish processing, data acquisition and document results for HTI fracture detection.	Julius Doruelo and Fred Hilterman
Construct models with smaller property contrasts to simulate real earth. Work with AGL to define spatial attributes to enhance seismic wavefields found in earth models. Interpretation Task 2.	Julius Doruelo, Kurt Marfurt
Evaluate reflection and refraction amplitude as function of offset and curvature of boundary for fracture models.	Julius Doruelo, Gennady Goloshubin, Fred Hilterman
Develop wave theory description of coda scattering for inline fracture detection.	Gennady Goloshubin and Julius Doruelo
Construct two porous models and generate physical modeling synthetics for comparison to theoretical dual-porosity model. Physical and Numerical Modeling Tasks 2 and 3.	Julius Doruelo, Gennady Goloshubin, RQL student
Imaging	
Finish and document research on “true” amplitude migration weights and phase compensation filters for very large offset data.	Zhengyun (Jenny) Zhou, Fred Hilterman, Gennday Goloshubin
Calibration Borehole to Seismic	
Continue field data application of water-saturation estimation with pore-fluid and slope rock-property transforms.	Zhengyun (Jenny) Zhou and Haitao Ren
Develop attenuation and complex reflection coefficient depth trends for several Biot-Barenblatt, White, etc. models that include fluid diffusion.	Haitao Ren, Gennady Goloshubin, LBNL, U. California and Fred Hilterman
Interpretation	
Develop methodology for the processing and interpretation of 3D field data in GOM with very far offsets. Seismic Data Processing Tasks 2 and 3 and Interpretation Task 1.	Connie VanSchuyver, Fred Hilterman RQL student

Rock calibration of attributes on common offset volumes. How is depositional environment, facies and rock properties manifested in attributes?	Sean Lewis, AGL student
Stratigraphic and structural styles related to rock properties in Class 2 Miocene sediments exhibiting anisotropic and large offset reflections	Matt van Wie, AGL student