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DEPARTMENT OF ENERGY

Final Report

Crosshole Geotomography in a Partially Depleted Reservoir

Grant DE-FG05-89ER14058

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1. Project

Title: Crosshole Geotomography in a Partially Depleted Reservoir
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2. Patentable or Potentially Patentable Inventions: Not Applicable

3. Principal Project Personnel

John A. McDonald

- A) Role in the project: Principal Investigator
- B) Principal areas of research and expertise: Exploration geophysics, reflection seismology, reservoir characterization
- C) Percentage of time: 15%
- D) Education: Grad. Inst. P. (Inst. of Physics), M.S. Physics (S.M.U.), Ph.D. Geophysics (S.M.U.)
- E) Relevant professional employment history: Atomic Weapons Research Establishment UK, Teledyne Geotech, S.M.U., Gulf Research & Development (Section Director), University of Houston (Professor & Director)
- F) Relevant professional activities and honors: Member SEG, AGU, EAEG. Fellow of the Institute of Physics (London)
- G) Relevant publications not emanating from this project:
Over 100 publications over the last 30 years including:
Ass'ad, J.M., Kusky, T.M., McDonald, J.A., and Tatham, R.H., 1992, Implications of scale-model seismology in the detection of natural fractures and microcracks: J. of Seismic Exploration, 1, 61-76.
Cruse, E., Pica, A., Noble, M., McDonald, J.A., and Tarantola, A., 1990, Robust elastic nonlinear waveform inversion: application to real data: Geophysics, 55, 527-538.
Ebrom, D.A., Tatham, R.H., McDonald, J.A., Sekharan, K.K., and Gardner, G.H.F., 1990, Hyperbolic traveltimes analysis of first arrivals in an azimuthally anisotropic medium: A physical modeling study: Geophysics, 55, 185-191.
Kinsland, G.L., McDonald, J.A., and Gardner, G.H.F., 1991, High resolution three dimensional seismic survey of a thin sand at depth: Geophysics, 56, 2036-2047.
Uren, N.F., Gardner, G.H.F., and McDonald, J.A., 1990, Dip moveout in anisotropic media: Geophysics, 55, 863-867.

Ernst L. Leiss

- A) Role in the project: Co-Principal Investigator
- B) Principal areas of research and expertise: Parallel and vector processing, inversion algorithms, theory of formal languages
- C) Percentage of time: 20% (first two years)
- D) Education: M.M. Comp. Sci., (Waterloo), Dr. tech. (Vienna)
- E) Relevant professional employment history: University of Houston (Professor & Director)
- F) Relevant professional activities and honors: Faculty senate, undergraduate council, presentations at various US universities and in Italy, Brazil, Russia, Germany, PRC
- G) Selected publications not emanating from this project:
Over 130 papers, presentations and abstracts including:

- Leiss, E.L., 1992, Exploiting parallel computing for high-performance seismic processing: SEG/Moscow, July 27-31.
- Leiss, E.L. and L.T. Shih, 1992, Autotasking on the Cray Y-MP: a performance evaluation on seismic codes: ACM/SIGAPP Symp. on Applied Computing, March 1-3, 225-230.
- Leiss, E.L., 1992, Experiences in programming high-performance parallel systems: XIII Congresso IBERO Latino Americano sobre Metodos Computacionais para Engenharia, Porto Alegre, Brazil, November 23-25, Proceedings Vol. 1, 1-17.

Hua-wel Zhou

- A) Role in the project: Adjunct faculty
- B) Areas of research expertise: theoretical seismology, inversion theory
- C) Percent time devoted to project: 15%
- D) Education: M.S. Geophysics (Cal State, Long Beach), PhD geophysics (CalTech)
- E) Professional employment history: University of Houston (Assistant Professor)
- F) Selected recent professional activities: AGU, SEG, Sigma Xi
- G) Selected relevant publications not emanating from this project:
 - Allen, C.A., Lou, Z., Qian, H., Wen, X., Zhou, H., and Huang, W., 1991, Field study of a highly active fault zone: the Xianshuihe fault of southern China: Geol. Soc. Am. Bull., **103**, 1178-1199.
 - Zhou, H., 1990, Observations on earthquake stress axes and seismic morphology of deep slabs, Geophys. J. Int., **103**, 377-401.
 - Zhou, H., 1990, Mapping of P wave slab anomalies beneath the Tonga, Kermadec and New Hebrides arcs: Phys. Earth Planet. Inter., **61**, 199-229.

Harry Deans & G.H.F. Gardner

- A) Role in the project: Originally Co-principal investigators, but both Deans and Gardner left the University of Houston early in the project and made no significant contribution.

4. Additional Project Personnel

A) Research & technical support:

<i>B.J. Evans:</i>	Visiting Adjunct Faculty, Curtin University, Perth, M.S., WAIT, RVSP and one-D inversion
<i>C.L. Elford:</i>	B.S. University of Houston, ray tracing and inversion
<i>O.G. Johnson:</i>	Professor, Computer Science, University of Houston: interactive applications, wave equation modeling
<i>C.A. Link:</i>	PhD candidate, University of Houston, crosswell tomography & converted modes
<i>D. Stankovic:</i>	B.S. University of Belgrade, inversion algorithms
<i>Dan Ebrum:</i>	Research assistant professor, University of Houston, PhD University of Houston: fracture anisotropy
<i>J. Jech:</i>	Post-Doctoral Fellow, PhD Prague, ray tracing and inversion
<i>J. Mendoza-Amuchastegui:</i>	M.S. University of Houston, arrival time picking
<i>M.A. Morford:</i>	M.S. University of Houston, shallow CDP & VSP
<i>T.W. Yang:</i>	PhD University of Houston, algorithm optimization & interactive applications

B) Collaboration

<i>D.S. Hamilton:</i>	Research Associate, Bureau of Economic Geology, Austin, PhD University of Sydney, structure and stratigraphy of Seventy-Six West field
<i>G.B. Asquith:</i>	Professor of Geology, Texas Tech University, petrophysics, well-logging
<i>R.P. Major:</i>	Research Scientist, Bureau of Economic Geology, Austin, PhD Brown, geology of Seventy-Six West field.
<i>S.C. Ruppel:</i>	Research Associate, Bureau of Economic Geology, Austin, PhD Tennessee, sequence stratigraphy and diagenesis in the Monahans field
<i>T.E. Owen:</i>	Senior Scientist, Southwest Research Institute, PhD University of Texas, Austin: vibratory source developments

5. Project Overview

A) Specific Project Objectives

1) Past

Characterize downhole seismic sources

Show the applicability of crosswell tomography as a tool for reservoir characterization in depleted reservoirs

2) Current

Use crosswell methodology to make Q estimates

Use crosswell methods for lithology prediction and fluid detection

3) Planned future work

Combine crosswell methods with VSP and high-resolution 3-D surface seismic methods to characterize lithology

B) How this project relates to the DOE's program mission

The work done on this project has contributed to advances in methodology and basic knowledge that can directly influence the production and development of hydrocarbon resources.

Crosswell tomography is an emerging technology that has great potential for improving our understanding of reservoir heterogeneities. A basic component of geotomography is matching the appropriate seismic downhole energy source with the imaging goals. Initial work on this project was directed at characterizing the capabilities of different downhole sources and their capabilities in a lossy medium; such as found in shallow, clastic reservoirs.

As with all imaging techniques, crosswell tomography requires a prodigious amount of data manipulation. Considerable effort on this project was devoted to the development of algorithms for the various stages of data processing. Examples of algorithms include:

- Random noise reduction
- Coherent noise reduction
- Coherent signal enhancement
- First arrival time picking from raw data
- Curved raypath raytracing
- Inversion methods for sparse matrices

Geotomography is a powerful technique for providing a high resolution image of the variation of seismic wave propagation velocities between boreholes. However, other parameters such as attenuation (Q) are sometimes more sensitive to changes in lithologic characteristics than velocities. Part of this project was devoted to using high frequency crosswell methods for determining Q estimates of the lithology between boreholes. Q measurements using crosswell techniques are able to distinguish lithologic variations on a scale an order of magnitude smaller than previous methods.

A study in a carbonate reservoir using crosswell methods provided estimates of the ratio of compressional wave velocity to shear wave velocity. This ratio is another sensitive indicator of lithological conditions and the use of crosswell methods to derive these estimates can provide information on lithological changes over much smaller depth intervals than previously possible.

C) How this project relates to other projects funded by DOE

This project is related to the problem of reservoir characterization. Remote sensing of reservoir rock properties from the surface is largely a low resolution technique. Clearly, reservoirs are heterogeneous and the heterogeneities can be due to fractures, irregular distribution of permeability, and similar variations in rock properties. These heterogeneities control fluid occlusion and fluid flow. In many reservoirs, particularly tight carbonates, recovery of oil in place is less than 20% at abandonment. Therefore high resolution remote sensing seismic techniques need to be developed to map these patterns of heterogeneity. We feel the research under this grant has shown great promise for producing information about these heterogeneities

Complementary DOE programs include those of Berryman (LLNL), Elbring (SNL), Larner (CSM), Turpening and Toksöz (MIT), and Nur (Stanford). This work also complements research supported by GRI being conducted by Harris (Stanford).

D) Project History

- 1) Previous and current funding
Cross-Hole Geotomography in a Partially Depleted Reservoir, DOE, \$814,904, 8/15/89 - 8/14/92, [No Cost Extension through 8/31/93]
- 2) Previous and current complementary contracts or grants with start and end dates
 - AGL Industrial Income: 1991-92 \$268,405
1992-93 \$203,565
 - Annex III to Agreement, DOE and State of Texas - Field Laboratory for Improved Oil Recovery, Office of the Governor, \$130,946, 7/1/89 - 7/1/90
 - State Land Energy Resource Optimization (SLERO), University of Texas, \$645,000, 9/1/89 - 8/31/93
 - Maximization of Petroleum Recovery Efficiency, ERAP, Texas Coordinating Board, \$315,000, 2/1/89 - 1/31/93 [No cost extension through 1/31/94]
 - Improving Oil Recovery by Remote Inference of Fracture Characteristics in Reservoirs, ATP, \$61,000, 1/1/92 - 12/31/94
 - Application of Crosswell Seismic Techniques for the Measurement, in situ, of Rock Properties, Energy Laboratory, \$6,140, 9/1/92 - 8/31/93

6. Scientific and Technical Content

A) Relation of this research to other research in this field

The research in this project has the fundamental goal of contributing to improvements in the development and production of existing and new hydrocarbon resources. This can be achieved through advances in a number of different areas such as geochemistry, sedimentary system analysis, rock properties, and geophysical remote sensing methods.

Our work has contributed to improvements in understanding and predicting reservoir distribution as well as lithological variation within reservoirs. The development of crosswell methodology in our work and other projects has provided capabilities for remote sensing of lithological variations on a scale one to two orders of magnitude larger than previously possible.

This work in combination with developments in the areas of fluid flow modeling, fracture analysis and prediction, and sedimentary system analysis all contribute to the goal of enhanced hydrocarbon production from domestic resources.

B) Importance of problem addressed
(See above)

C) Schedule of major research activities

Downhole seismic energy source characterization in a shallow, clastic sequence
Development of data processing algorithms for noise reduction, signal enhancement, first arrival picking, raytracing, and inversion
Crosswell tomography in a clastic sequence in a working oil field
Q estimates in a clastic reservoir.
Lithology indicators in a carbonate reservoir using V_p/V_s and A_p/A_s
Q characterization over a wide depth range in a mixed sedimentary system

D) Scientific or technical issues currently addressed and their significance

Downhole seismic energy source technology-

For a medium with a given velocity value, an inverse relation exists between the frequency of transmitted signals and the wavelength of these signals. That is, wavelengths are shorter for higher frequencies and the wavelength determines the level of resolution achievable in the recorded data.

Crosswell methods have the potential for recording seismic data at frequencies much higher than possible with surface seismic methods. However, sources that are able to produce these desirable high frequencies generally have a much lower overall energy output than sources with lower frequency content. This tradeoff is the dilemma faced by anyone using crosswell methods.

To achieve the resolution potential of crosswell methods requires an energy source that can output the high frequencies produced by sources like the piezoelectric bender but at output energy levels that allow larger well separations. Research into both the development and application of source technology is thus a vital component in a program addressing the energy needs of the future.

Enhancement of the signal-to-noise ratio of raw data before processing-

Improving the signal-to-noise ratio of data is a classic problem that achieves new significance in the context of crosswell seismology. A combination of the low output energy/high frequency characteristics of downhole energy sources used in highly absorptive media such as clastics creates the need for improvements in the data quality before analysis can begin.

Work in this area concentrated on reduction of the level of random noise in both the time and frequency domain. In the time domain, energy criteria were used to diminish random noise levels while in the frequency domain, the signal-to-noise ratio was enhanced by removal of random phase shifts and envelope compression.

Development of automatic or interactive arrival time picking algorithms-

Crosswell tomographic reconstruction of a velocity field requires the use of first arrival times picked from the recorded data. With the large number of data traces required, it becomes infeasible to pick the arrival times by hand. An automatic picking program is required which must have the ability to distinguish subtle changes in data character or amplitude but maintain consistency from trace to trace.

We have developed and implemented picking algorithms which pick arrival times based on trace energy criteria or envelope amplitude criteria. The algorithm based on envelope amplitudes also incorporates an envelope compression routine that provides even greater accuracy in the travel time picks.

In addition to the automatic picking algorithms, an interactive program was developed that uses data with no previous time picks or data which already has had arrival times picked. The program allows the user to view any time picks and either select a new time or modify the previous one.

Development of curved raytracing algorithms-

Tomographic reconstruction requires accurate traveltimes with knowledge of the wave mode recorded and an accurate means of predicting traveltimes in the medium being modeled. To produce accurate model traveltimes it is necessary to mimic the actual propagation path of the transmitted seismic energy. This is done by means of raytracing.

Currently we have been using two methods of raytracing: the shortest path method which is an application of Fermat's principle and the paraxial method which is based on the eikonal equation. Both methods are able to model curved raypaths. The shortest path method is based on network theory and has been developed to use either constant velocity blocks or constant velocity gradients. The paraxial method uses B-splines to provide a smoothly varying velocity field.

Development of stable inversion algorithms-

Once traveltimes have been predicted by raytracing through a velocity model, traveltimes residuals are calculated by taking the difference of the predicted traveltimes and the observed traveltimes. These traveltimes residuals are input into a linearized inversion scheme to produce an updated set of model parameters; i.e. velocity perturbations. This process can then be repeated (raytracing and inversion) to provide a reasonable approximation to nonlinear inversion.

One of the difficulties with inversion problems of this type is the sparseness (prevalence of zeroes) as well as the size of the data kernel matrix. Inversion of sparse

matrices often results in wildly fluctuating values which cause artifacts in the desired image.

Our inversion process makes use of a constrained LSQR method coupled with an initial inversion using SVD. The hard bound constraints used in the LSQR method allow incorporation of *a priori* data from well logs or other sources. This method has proven to be superior to unconstrained methods.

Using crosswell methods to estimate Q-

Typically Q (inverse attenuation) measurements are made in the laboratories at ultrasonic frequencies or in the field with VSP methods. Laboratory measurements are limited to isolated samples of a large object (rock formation) which may not correctly characterize the relevant properties of the object in question. On the other hand, VSP methods use nearly vertical propagating seismic waves to derive Q estimates for typically horizontally layered media. Also, transmitted frequencies for VSP methods are limited due to the absorptive nature of the near surface. This limits vertical resolution.

The use of crosswell methods to estimate Q has advantages of higher transmitted frequencies by avoiding the absorptive near surface and the horizontal propagation paths in media that are usually horizontally layered. This permits measurements at spacing much smaller than is typical with VSP methods. Since Q is a more sensitive indicator of lithological conditions than velocity, crosswell Q measurements have the potential to provide a high resolution mapping of lithological variation that can be directly applicable to reservoir production and development.

V_p/V_s and A_p/A_s from crosshole measurements-

Another sensitive indicator of lithological conditions is the ratio of compressional wave velocity to shear wave velocity or V_p/V_s . Numerous studies have shown that V_p/V_s can be directly related to lithology type and even to fluid content. Generally these studies have been made using surface seismic methods which are subject to attenuative near surface conditions.

Crosswell methods can be used to provide high frequency horizontal estimates of V_p/V_s in horizontally layered media. This allows determination of V_p/V_s on a scale that is much closer to that of well logs. In addition, our work has shown that the ratio of compressional wave amplitude to shear wave amplitude or A_p/A_s is related to fluid content within a formation.

E) Experimental and theoretical approach taken, techniques used, resources applied-

Downhole seismic energy source characterization-

The sources tested were an airgun, a piezoelectric bender, a sparker, and a water gun. All of the sources were tested in the same shallow, clastic producing oil field. The majority of the tests were conducted using a set of four inline wells to provide offsets up to 600 ft. Comparison of the sources was made by analysis of data quality, frequency content, wavelet shape, signal-to-noise ratio, and source generated noise.

Enhancement of the signal-to-noise ratio of raw data before processing-

Methods of signal-to-noise ratio enhancement included bandpass filtering, cross-correlation, f-k filtering, random noise reduction through trace energy analysis, random phase shift removal, and compression of the data trace envelopes.

All data processing was done on a Convex C210 mainframe or IBM RISC 6000 work stations.

Development of automatic or interactive arrival time picking algorithms-

The automatic arrival time picking methods were developed in conjunction with the signal-to-noise ratio enhancement methods listed above. These methods were designed to make first arrival time estimates using statistical measures based on either trace energy criteria (time domain) or compressed envelopes of phase corrected data traces (frequency domain).

In addition to the automatic time picking algorithms, an interactive program was produced for use on a work station. This allows the user to assess the automatic time picks and change them if desired.

Development of curved raytracing algorithms-

Two methods of curved raypath raytracing have been used for our tomographic reconstructions: a shortest path method and a paraxial method based on wavefront curvature changes (eikonal equation).

The shortest path method of raytracing is based on Fermat's principle and uses network theory to predict the shortest travel times possible for a given velocity structure. Modifications to this method include the ability to incorporate hard constraints, constant velocity or constant velocity gradient models, and improvements in the time required for calculations.

The other raytracing method is based on velocity interpolation between nodes by using B-spline functions. Approximate raypaths are calculated by numerical integration of the system of raytracing differential equations. Final raypaths are found by two-point raytracing by the method of paraxial ray approximation.

Development of stable inversion algorithms-

One of the difficulties of travelttime tomography is the inherent nonlinearity of the problem. This is due to the coupling of the raypath to the structure of the velocity medium so that when velocities are updated, raypaths must be updated also.

Our work has shown that inversion based on a modified LSQR algorithm incorporating hard constraints gives stable results. This algorithm is used for either method of raytracing. The travelttime reconstruction problem is solved by raytracing through a starting velocity model, calculating travelttime residuals, inversion for velocity perturbations, and updating the velocity model. This set of steps is repeated until the desired error criteria are met.

Using crosswell methods to estimate Q-

Typically field measurements of Q are done using VSP methods which employ nearly *vertically* propagating seismic waves. One of the difficulties of this approach is that many times the medium being analyzed is *horizontally* layered. Thus the transmitted waves have passed through possibly several rock types. The final Q estimate is thus an average.

The use of crosswell methods which use *horizontally* propagating waves in a *horizontally* layered medium permits measurements to be made within single layers or rock types. Q estimates made from these measurements more closely characterize the types of lithology present over smaller depth intervals than with VSP methods.

Three inline wells were used to make the measurements. Data from a short offset well pair are used for reference amplitudes and data from a longer offset well pair are used for comparison. The spectral ratio method is used to determine attenuation and finally Q estimates. A least squares line fit constraint was used in the spectral ratio method to give more robust results.

Using V_p/V_s and A_p/A_s from crosshole measurements-

The velocity ratio V_p/V_s is a sensitive indicator of lithology type and lithological conditions such as fluid content. V_p/V_s is typically calculated from nearly vertically propagating seismic waves such as used in surface seismic methods. These waves experience attenuation of the higher frequencies after passing through the near surface layer. In addition, these waves experience lithology averaging by vertical propagation through horizontally layered media.

Crosswell methods provide a means to make V_p/V_s estimates using horizontally propagating waves with frequencies one to two orders of magnitude higher than possible with surface seismic methods. These V_p/V_s estimates can provide details of lithological variations on a much smaller scale than possible with surface methods.

Another useful parameter which can be obtained from this same crosswell data is the ratio of maximum P-wave amplitude to maximum S-wave amplitude or A_p/A_s . Since

fluids do not support S-waves, A_p/A_s should be particularly sensitive to lithological variations caused by changes in fluid content.

7. Project Output

A) Major recent accomplishments with supporting data and their significance-

Produced a P-wave velocity tomogram which successfully imaged a 20 ft thick sandstone in a shallow clastic oil field.

A high resolution P-wave velocity tomogram was produced from traveltime data recorded in a shallow clastic working oil field. Even though the recorded frequencies were low by crosswell standards, the zone of the tomogram with the best resolution showed a good correlation with geology interpreted from well logs.

A large amount of downhole energy source testing was conducted prior to recording the data set which resulted in the tomogram. These test results have been invaluable in determining the operational and energy producing characteristics of a variety of sources.

Development and implementation of software for all stages of tomographic reconstruction.

As listed in the section above, a wide variety of software has been developed for use in crosswell data preparation and processing. Some of this software consists of the application of concepts found in recent literature and adapted to our use while other software consists of original algorithms which are extensions of existing concepts and applications.

Notable among these are:

- spatial coherency filtering
- shortest path raytracing improvements
- least squares inversion with constraints
- removal of random phase shifts from multi-trace recorded data

Q study in a shallow clastic reservoir.

A crosswell study of attenuation (in the form of Q) characteristics of a shallow clastic sequence showed a good correlation of Q determined at 10 ft depth intervals with geology as interpreted from a well log. This study was done with a wide range of impulse frequencies and showed an inverse correlation of Q with resistivity from a well log.

Crosswell measurements of Q are able to be determined at much smaller depth intervals than is possible with previously used VSP methods.

V_p/V_s analysis in a carbonate reservoir.

V_p/V_s estimates were determined from a set of crosswell data recorded in the form of a crosswell log (i.e. horizontal raypaths) in a carbonate reservoir in west Texas. These crosswell calculations at a 10 ft depth spacing showed a high inverse correlation of V_p/V_s with porosity from the receiver well indicating a good potential for crosswell methods as lithology indicators.

In addition to the V_p/V_s analysis, calculations of the ratios of maximum P-wave amplitudes to maximum S-wave amplitudes (A_p/A_s) were made which showed an anomalous zone of high values interpreted to be a fluid-filled zone.

B) Bibliography of publications from this project-

Papers published, in press, or submitted:

Chen, G.M., and Zhou, H., 1992, Boundary element modeling of non-dissipative and dissipative waves: submitted to Geophysics.

Link, C.A., McDonald, J.A., and Zhou, H., Q measurements from crosshole seismic data: submitted to Geophysics.

Link, C.A., McDonald, J.A., Zhou, H., and Evans, B.J., 1992, Cross-well tomography in the Seventy-Six West field: Cross-Borehole Geophysics in the Petroleum Industry - Proceedings of the Geophysical Society of Tulsa 1992 Symposium, 79-90.

- Link, C.A., McDonald, J.A., Zhou, H., and Evans, B.J., 1993, Cross-well tomography in the Seventy-Six West field: *The Leading Edge*, **12**, 36-40.
- McDonald, J.A., Link, C.A., Zhou, H., Jech, J., and Evans, B.J., 1992, Crosshole tomography in a working oil field: Seventy-Six West field, south Texas: *Geotomography*, **2**, 159-178.
- McDonald, J.A., Zhou, H., Link, C.A., Jones, T.K., Owen, T.E., Bangs, J.H., and Hamilton, D.S., 1991, Transmission and inversion of very high frequency acoustic wave data in shallow clastic sediments: *Geotomography*, **1**, 105-119.
- Zhou, H., 1993, Travelttime tomography with a spatial-coherency filter: *Geophysics*, **58**, 720-726.
- Zhou, H., Jech, J., Mendoza-Amuchastegui, J., Link, C.A., and McDonald, J.A., 1992, Crosshole tomography in a shallow unconsolidated reservoir: *Cross-Borehole Geophysics in the Petroleum Industry - Proceedings of the Geophysical Society of Tulsa 1992 Symposium*, 91.
- Zhou, H., Jech, J., Mendoza-Amuchastegui, J., Link, C.A., and McDonald, J.A., 1993, Crosshole tomography in a shallow unconsolidated reservoir: *The Leading Edge*, **12**, 32-36.
- Zhou, H., McDonald, J.A., Link, C.A., and Jech, J., 1992, Need for velocity constraints in travelttime tomography: submitted to *Geophysics*.

Papers in preparation:

- Link, C.A., McDonald, J.A., and Ebrom, D.A., Lithology indicators from crosshole seismic data: to be submitted to *Geophysics*.

Papers presented, and to be presented at symposia and meetings:

- Ass'ad, J.M., Riveros, C., Kamel, M.H., and McDonald, J.A., Ultrasonic velocity measurements in a cracked solid: experiment versus theory: to be presented at the 63rd Ann. Interntl. Meeting, SEG, Washington, D.C., September, 1993.
- Chen, G. and Zhou, H., Detection of crack orientation using acoustic waves: to be presented at the 63rd Ann. Interntl. Meeting, SEG, Washington, D. C., September, 1993.
- Chen, G., Link, C.A., Zhou, H., and McDonald, J.A., Crosshole imaging of a small inclusion using diffracted waves: to be presented at the 63rd Ann. Interntl. Meeting, SEG, Washington, D. C., September, 1993.
- Ebrom, D.A., Tatham, R.H., and McDonald, J.A., Cyclic layering and shear-wave dispersion: to be presented at the 63rd Ann. Interntl. Meeting, SEG, Washington, D.C., September, 1993.
- Elford, C.L., Leiss, E.L., and Zhou, H., 1992, Optimizing shortest path calculations: 23rd Int. Conf. on Combinations, Graph Theory, and Computing, Feb 3-7.
- Evans, B.J., 1991, Source wavefield analysis in long-offset cross-well tomography: 61st Ann. Interntl. Meeting, SEG, Expanded Abstracts, 111-114.
- Hamilton, D.S., 1991, Reservoir heterogeneity at Seventy-Six West field, Texas: an opportunity for increased oil recovery from barrier/strandplain reservoirs of the Jackson/Yegua trend by geologically targeted infill drilling: Presented at the 66th Ann. Tech. Conf., Soc. Petrol. Engin., Dallas, Tx, Oct. 6-9.
- Jech, J., and McDonald, J.A., 1991, A new travelttime inversion computer program and its application to crosshole data: 61st Ann. Interntl. Mtg., SEG, Expanded Abstracts, 840-842.
- Jech, J., and McDonald, J.A., 1991, Numerical modeling of the accuracy of crosshole inverse problems: *EOS, Trans. AGU*, **72**, 334.
- Jech, J., Daley, T.M., and Psencik, I., 1992, Numerical modeling of anisotropic structures from Varian well VSP data: 62nd Ann. Interntl. Mtg., SEG, New Orleans, Oct 25-29.
- Jech, J., McDonald, J.A., and Psencik, I., 1992, Linearized and nonlinear anisotropic inversion: 5th International Workshop on Seismic Anisotropy, Banff, Alberta, Canada, May 1-22.
- Johnson, O.G. and Yang, T.-W., Sequential and parallel block-structured shortest-path raytracing algorithms: to be presented at the Mathematical Methods in Geophysical Imaging Technical Conference, July 14-15, 1993.
- Johnson, O.G., 1991, Crosshole tomography animation in X-windows with Convex-2/IBM RS6000 client-server display connection: ASE91, Applications of Supercomputers in Engineering, Boston, MA, August 13-15.
- Leiss, E.L., and Pan, J.-M., 1992, Inverse techniques in geophysical tomography: a comparison on noisy data: 62nd Ann. Interntl. Mtg., SEG, New Orleans, Oct 25-29.

- Link, C.A. and McDonald, J.A., Attenuation measurements using high frequency crosshole seismic data: to be presented at the 63rd Ann. Internatl. Meeting, SEG, Washington, D. C., September, 1993.
- Link, C.A., and McDonald, J.A., 1992, Attenuation from high frequency crosshole data: Third Annual Archie Conference, Galveston, Texas, Nov 2-4.
- Link, C.A., McDonald, J.A., and Ebrom, D.A., Lithology indicators from crosshole seismic data: to be presented at the 10th Geophysical Conference and Exhibition at the Australian SEG, Perth, W. A., February 20-25, 1994.
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