P-45 Lawrence Berkeley National Laboratory
Development of Single-Well Seismic Imaging Technology
Success Story Summary

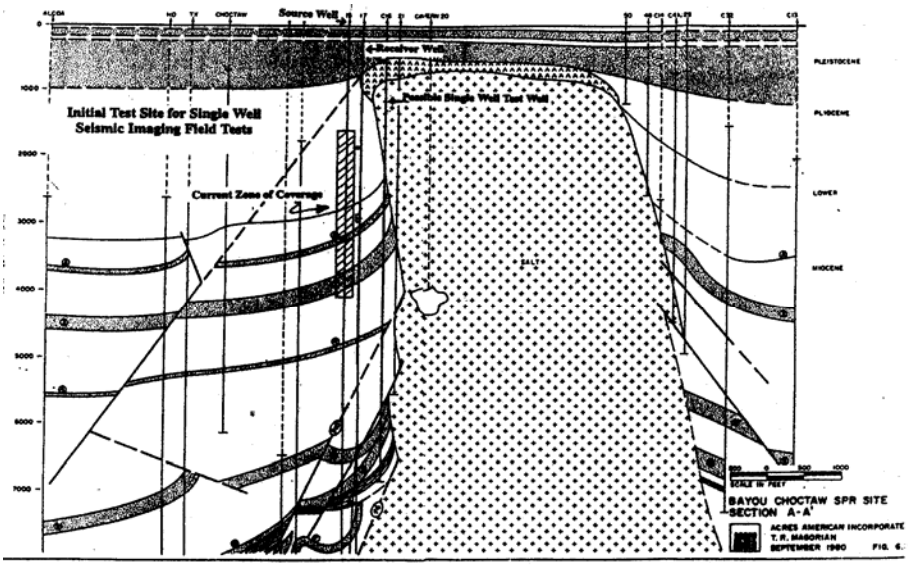


Figure 2a Location map for Bayou Choctaw salt dome.

Single well seismic imaging (SWSI) has been identified in the petroleum industry as an exciting new technology with significant economic potential, particularly in the Gulf of Mexico. Deploying a seismic energy source and receiver string in a single well will allow imaging with higher resolution than can now be achieved with 3D surface seismic or the crosswell seismic techniques as well as providing the economics of single well (as opposed to crosswell) surveys. In a salt basin environment, such images would guide targeted, low-risk drilling for oil and gas trapped against salt dome flanks, overhangs, and fault surfaces (see above example of the Choctaw salt dome). The technology would also yield valuable data in subsalt environment where surface data are often uninterpretable. In this project, the Lawrence Berkeley National Laboratory along with two other national laboratories and the industry (consisting of members of the salt imaging consortium) have pooled their resources in a cooperative venture to develop the SWSI technology. An important objective of this project is to leverage DOE and industry resources in the expeditious development of this useful tool that will address areas of research most beneficial to the industry as a whole.

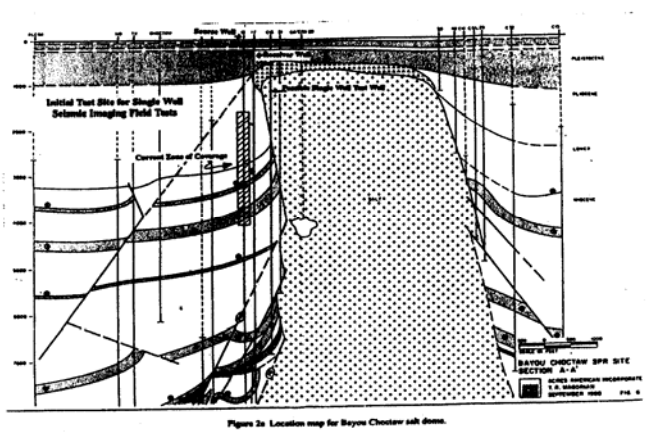
The evolution of SWSI technology from crosswell seismic has been made possible through developments in four independent activities viz., Hardware, Modeling, Field Testing and Data processing and Interpretation. Among the hardware developments, significant improvements in the energy source in a fiber optic source wireline, the receiver system and the tube wave attenuation devices are the most significant. An investigation of the elastic wave propagation led to the development of improved version of 3D finite difference wave propagation algorithm and other software for processing of single well data. Rigorous borehole imaging tests have been conducted at sites such as the Bayou Choctaw salt dome that have been well calibrated and characterized using crosswell imaging and other techniques. The development in single well imaging now allows a larger range of investigations than is possible with standard well logging. Of particular interest in the exploitation of fractured reservoirs is the possibility of imaging subsurface vertical fracturing using this technology. Studies conducted by USGS and the Minerals Management Service indicate that in the Gulf Coast basin alone, the conventional undiscovered oil fields are likely to contain 9.7 BBLS of oil and natural gas liquids and 103.0 TCF of natural gas. Even if a tenth of this conventional undiscovered resource could be exploited using technology developed in this project, then the new tool will help to add 970 MMBLS of oil and 10.3 TCF of gas to the national proved reserves. The considerable economic impact of the new resources

includes generation of 14.7 billion dollars in tax and royalty incomes and 1250 new jobs across all sectors of the economy.

First published 9/01

Development of Single-Well Seismic Imaging Technology (Partnership)

***Problem*:** For low-risk drilling in geologically complex areas, such as oil and gas trapped against salt dome flanks, overhangs, and fault surfaces, high-resolution cost-effective images of the geological structure are needed. The conventional method of gathering subsurface images with 3D seismic has not always been very successful in certain geologically complex areas. What is needed is a technology that increases seismic resolution in areas where there is limited well access. From experience gathered in crosswell seismic, it is becoming clearer that it should be possible to leverage this technology to develop the single-well seismic imaging technology (SWSI). In SWSI technology both the seismic energy source and the receivers are deployed in the same well, thereby allowing imaging of geologically complex areas with much higher resolution than is possible with crosswell seismic.

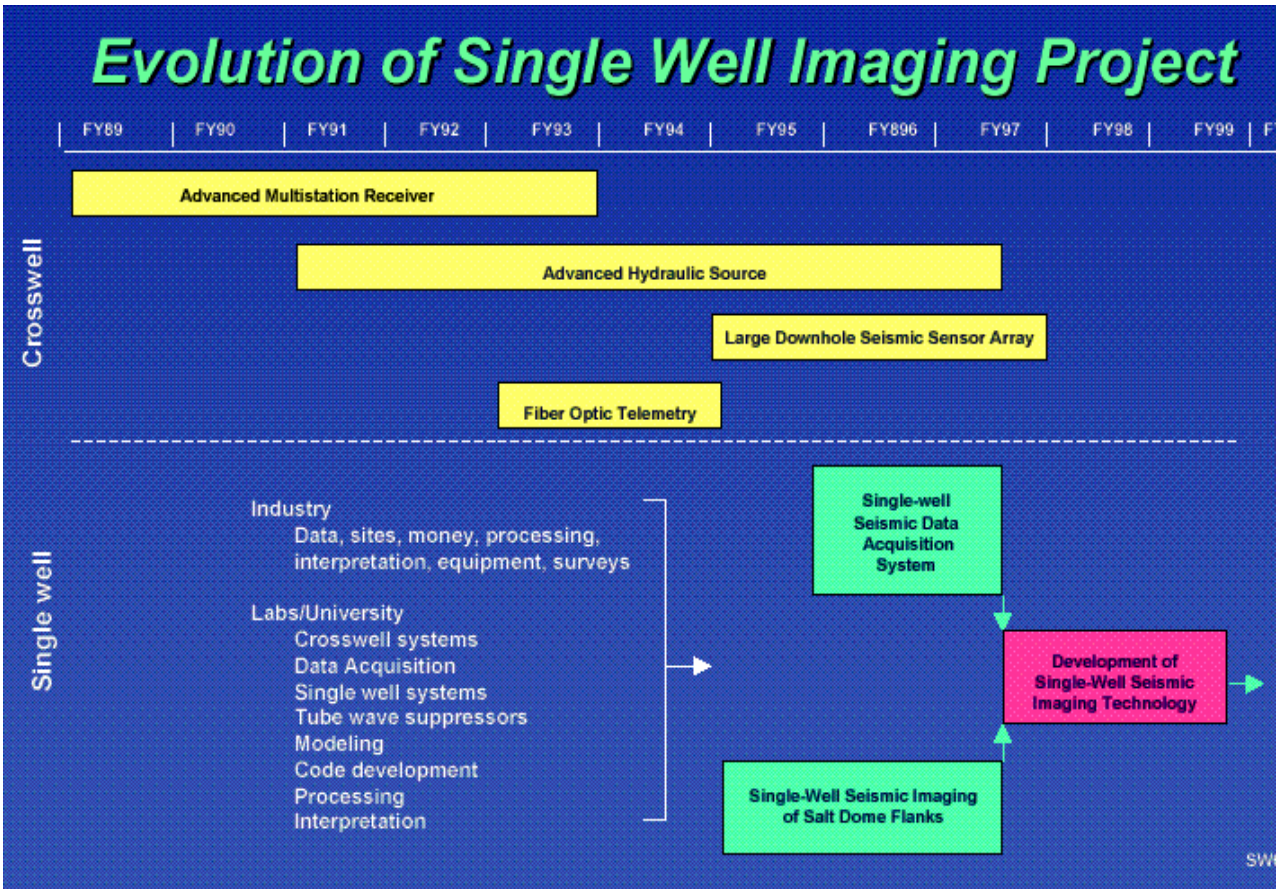


The Bayou Choctaw Salt Dome showing overhangs and other inaccessible areas.

While this technique has long been used for sonic logging, current research is aimed at imaging tens and hundreds of meters away from the borehole while conventional sonic logging is limited to 1 to 10 meters radius around the well bore.

New technologies are also needed that can be applied to areas which are beyond the reach of the present technology, such as the subsalt areas of the Gulf of Mexico. Deployment of a seismic energy source and receiver string in a single well will allow imaging with higher resolution than can now be achieved with surface 3D techniques as well as providing the economics of single well (as opposed to crosswell) surveys. From cost

considerations also, this technology should be within the reach of most independent operators.



The evolution of the single well imaging project from the crosswell seismic imaging technology is shown in the diagram above and the important contributions made by the different sectors of the oil and gas industry to the development of the SWI technology is also illustrated in the diagram.

***Project Objective*:** From past experiences with crosswell seismic imaging applications, it has become clear that that it is possible to leverage this technology to identify and provide solutions to fundamental issues surrounding single-well seismic imaging technology. The work in this project is an integrated, multi-year approach to spur the development and application of a new technology in a time frame much quicker than if left to individuals working separately. An important objective of the project is to leverage resources in order to address issues that would not be addressed by individual companies. The overall philosophy in conducting this project is to seek the best possible leverage of DOE and industry efforts in this technology area and avoid duplication of efforts and at the same time address areas most beneficial to the industry as a whole. This project will address issues that individual companies or labs are unable or unwilling to perform. This

includes working closely with the industry's 12-company Salt Imaging Consortium focused on the use of single well surveys to image salt dome flanks, and drawing upon results from the single-well imaging DOE-ACTI project between Sandia and members of the consortium. This project is also coordinated with and leveraging resources of the Uni-well project in the United Kingdom.
While the SWSI holds great promise, the question is whether the technical challenges in the areas of borehole seismic data acquisition, processing, and interpretation can be overcome. Crosswell seismic has generated many technologies that can be applied. Many new technologies can also be applied in many different modes (e.g. vertical arrays fiber sensing, etc.). An important objective of this project is to leverage as much as possible of the technologies developed earlier in crosswell seismic and other areas. Single well technology will require a parallel approach of diverse technologies. To implement the diverse technologies in a timely manner will require a critical mass of expertise and effort.

The important steps necessary for implementation in the successful development of the SWSI technology are summarized below:

1. Coordinate expertise from national labs, universities, and industry to provide a critical mass to address high priority needs to advance single well seismic imaging
2. Develop an integrated, iterative program of
    - Instrumentation
    - Modeling
    - Field Testing and Data Acquisition
    - Data Processing
3. Leverage DOE and industry (over $3 million cost share in this project) resources to avoid duplication and address areas most beneficial to industry as a whole, driven by industry needs
4. Address issues that individual companies or laboratories are unable or unwilling to perform
5. Use previous and ongoing efforts to optimize methodology in cost effective and timely manner

Project Cost: The total estimated cost for the project is $ 7,235,000 out of which DOE share for the project is $3,553,000 and the rest is from non-DOE sources. Besides Lawrence Berkeley National Laboratory, the project is a coordinated research effort between 2 other national laboratories working closely with the industry and involving university support. The main participants in this project are as follows:

- Idaho National Engineering and Environmental Laboratory
- Lawrence Berkley National Laboratory
- Sandia National Laboratory
- Stanford University

- Salt Imaging Consortium (BP Amoco, Arco/Vaster, Baker-Atlas, Chevron, Conoco, Exxon, ORYX, Phillips, Schlumberger, Shell, SMK Energy, Texaco, and Spirit Energy 76), Hunt Petroleum, OYO, P/GSI, and Tomoseis

Technology Change: LBNL's development of SWSI technology has progressed from initial surveys using multiple cables in shallow wells to a robust, oil-field scale, single cable system capable of utilizing various sources and sensors. The field testing of SWSI systems that indicate development of the single well technology are shown in Table 1.

Table 1. Summary of LBNL SWSI Field Acquisition to date:

Year	Site	Survey Comments
1992	Conoco Oklahoma Test Site	Shallow well with multiple Cables
1994	MIT Michigan Test Site	Deep Well – Piezoelectric Source
1997	Bayou Choctaw Salt Dome	Multiple Sources and Sensors
1998	Texas Humble Test Site	Fiber Optic Telemetry-Orbital Vibrator Source
1998	Bayou Choctaw Salt	Fiber Optic telemetry
1999	Baker-Atlas Houston Test Site	Improved Fiber Optic telemetry-TWS test
1999	Bayou Choctaw Salt Dome	Two wells, Multiple Sources and Sensor

The technique of single well seismic imaging (SWSI) is a hybrid of sonic logging, vertical seismic profiling and crosswell seismic surveys. Unlike in sonic logging, which is limited to 1 to 10 meter radius of investigation, the current SWSI research is aimed at imaging tens and hundreds of meters away from the borehole. The limitations of traditional sonic logging are imposed by source frequency (10 to 50 kHz), source strength (typically small piezoelectric sources) and source-sensor spacing (typically 3 to 5 meters). SWSI surveys have addressed these three limitations of the sonic logging tool.
The successful development of single well seismic imaging technology requires work on the following four independent activities that comprise facets of the technology required for the ultimate successful completion of single-well seismic imaging :

1. Hardware: Source/receivers, telemetry/recording, borehole noise effects, deployment
2. Modeling: Synthetic seismograms, parametric studies, inversion, designs for hardware/surveys
3. Field Testing: Quality data sets, evaluation/validation at well characterized sites
4. Data processing and Interpretation: Algorithms, 3-D imaging, noise reduction, visualization.

Research in SWSI is progressing in different areas such as acquisition, data modeling, data processing and analysis and the major accomplishments are summarized in Appendix –A.

Technology Transfer: The industry participants (see list under project cost) are expected to be the first to benefit from the transfer of technology from the SWSI research because of their direct involvement in the project. General information and results from the project may also be accessed from the following website:

http://www-esd.lbl.gov/GG/CCS/swsi.shtml

The wealth of experience gathered in this project has also been disseminated via a number reports and research publications. A list of these publications as well as a few important references to this project are presented in Appendix-B.

Some of the recent work was presented at the American Geophysical Union Annual Meeting (December, 1999), the University of Utah Cluster Computing Conference (February, 2000) and the DOE Basic Science Geophysical Imaging Workshop (February, 2000).

Technology Implementation: The technology developed in this project will be implemented in many different ways because the project consists of interdependent areas which represent facets of the industry required for successful development of the single-well seismic imaging technology. For example, different hardware developed for acquisition and processing of the single well data will be available to the industry either as direct purchase or as rental for 'fee' basis. Similarly a wide variety of algorithms developed for processing and interpretation of single well data, for 3-D imaging, noise reduction, visualization, etc., will be available to the industry and the technology implementation will be as computer software programs.

End Users: The end users of the technologies developed in this project will be the major and independent oil and gas companies engaged in hydrocarbon exploration in basins around the world. The SWSI technology will be particularly useful for imaging geologically complex and hard to access areas. Imaging of salt dome flanks and overhangs in salt basins, both on and offshore the Gulf of Mexico is a prime example of a potential area where the SWSI technology will find very useful applications.

Impacts:

Reserves Additions: Figures 9 and 10 from the 1995 National Assessment of United States Oil and Gas resources by USGS show the distribution of undiscovered technically recoverable conventional oil and gas resources in different regions of the country in the onshore and the state waters and exclusive of the offshore areas. With advanced technologies, such as the SWSI, some of these technically recoverable reserves could be transferable to the proved reserves category. Of particular interest to us in this project is the Gulf Coast region (region 6) with its several oil producing salt basins where the SWSI technology should find very useful application. The Minerals and Management Services has made a similar estimate for the offshore areas of the country and the estimated reserves for the offshore Gulf Coast basin is 0.959 billion barrels of oil and 5.102 TCF of natural gas. Combining the USGS and the Minerals and Management

Services estimates the total Gulf Coast technically recoverable oil reserves will be 9.705 BBO. A similar calculation for the natural gas indicates that the total gas reserves will be around 103.122 TCF

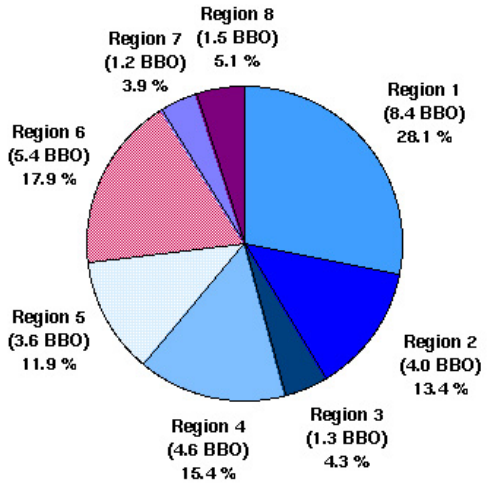


Figure 9. Distribution of undiscovered technically recoverable conventional oil resources, by region, based on mean estimates for the regions

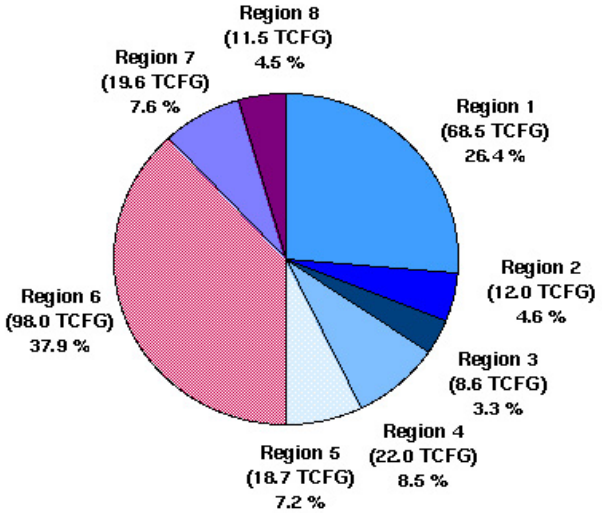


Figure 10. Distribution of undiscovered technically recoverable conventional gas resources, by region, based on mean estimates for the region

The same information is also given in the USGS Table 2 below. This table, in addition, shows the potentially recoverable natural gas liquids (NGL) in different basins that may be quite significant in some basins, such as the Gulf Coast. This table also shows technically recoverable reserves in some other regions, like the West Texas and the Midcontinent, where the SWSI technology will have potential applications.

Table 2. (Continued)

Province number and name	Crude oil (billion barrels)			Gas (trillion cubic feet)			NGL (billion barrels)		
	F_{95}	F_5	Mean	F_{95}	F_5	Mean	F_{95}	F_5	Mean
Region 5—West Texas and Eastern New Mexico									
042, Pedernal Uplift	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
043, Palo Duro Basin	0.01	0.07	0.03	< 0.01	0.02	0.01	0.00	0.00	0.00
044, Permian Basin	1.59	4.50	2.88	10.53	23.21	16.40	0.41	0.92	0.64
045, Bend Arch–Fort Worth Basin	0.29	1.13	0.64	1.19	3.36	2.15	0.08	0.23	0.15
046, Marathon Thrust Belt	< 0.01	0.04	0.02	0.06	0.29	0.15	< 0.01	0.02	0.01
Total, Region 5	**2.22**	**5.26**	**3.57**	**12.89**	**25.67**	**18.71**	**0.55**	**1.10**	**0.80**
Region 6—Gulf Coast									
047, Western Gulf	0.73	4.54	2.29	44.27	96.68	68.41	1.17	2.59	1.83
048, East Texas Basin[3]									
049, Louisiana-Mississippi Salt Basins	0.86	5.24	2.69	18.64	41.83	29.57	0.68	2.61	1.50
050, Florida Peninsula	0.05	1.20	0.42	< 0.01	0.11	0.04	0.00	0.00	0.00
Total, Region 6	**2.66**	**8.80**	**5.39**	**70.88**	**130.31**	**98.02**	**2.22**	**4.70**	**3.32**
Region 7—Midcontinent									
051, Superior	0.00	0.44	0.05	0.00	2.95	0.42	0.00	< 0.01	< 0.01
052, Iowa Shelf	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
053, Cambridge Arch–Central Kansas	0.04	0.43	0.20	0.08	1.04	0.41	< 0.01	0.04	0.02
054, Salina Basin[4]									
055, Nemaha Uplift	0.03	0.29	0.12	0.17	0.97	0.48	0.01	0.06	0.03
056, Forest City Basin	0.00	0.06	0.02	0.00	0.19	0.07	0.00	0.01	< 0.01
057, Ozark Uplift	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
058, Anadarko Basin	0.20	0.63	0.38	8.72	21.29	14.21	0.14	0.31	0.22
059, Sedgwick Basin	0.02	0.11	0.06	0.13	0.48	0.30	< 0.01	0.03	0.01
060, Cherokee Platform	0.02	0.17	0.08	0.07	0.35	0.19	< 0.01	0.02	0.01
061, Southern Oklahoma	0.05	0.57	0.24	0.47	1.78	1.01	0.01	0.05	0.03
062, Arkoma Basin	0.00	0.07	0.01	1.18	4.26	2.50	0.04	0.16	0.09
Total, Region 7	**0.75**	**1.82**	**1.18**	**13.61**	**27.51**	**19.58**	**0.31**	**0.54**	**0.42**

Economic Impact and Job Creation: Even if a hundredth of the income generated from the sale of oil and gas resources discovered by the application of the SWSI technology is ploughed back into the exploration and production sector of the oil industry, then it will have a ripple effect in the economy by creating new earnings and generating new jobs in different sectors of the economy. To estimate these indirect benefits, the Regional Input-Output Modeling System (RIMS II) economic multipliers developed by the Bureau of Economic Analysis within the Department of Commerce can be utilized. In this report they have adopted a set of multipliers from the "Calculated Oil and Gas Industry Multipliers" published in Marginal Oil and Gas: Fuel for Economic Growth, 1997 Edition, from the Interstate Oil and Gas Compact Commission (IOGCC). These multipliers have been used to approximately calculate the indirect economic benefits in the state of Texas as a result of investment of 147.1 million dollars (1/100 of the income generated from oil and gas production in this state).

Estimate of Indirect Economic Benefits Using Final Demand Multipliers in the State of Texas

Total Investment	=	$ 147.1 millions
Addition to Texas Economy	=	$ 232.3 millions
Creation of Earnings in Texas	=	$ 31.6 millions
Total No. of Jobs created in all sectors of economy in Texas	=	1250

Cost Savings: An important advantage of the single well technology over the crosswell technology or 3-D surface seismic technology is the better economics of these surveys since measurements will be essentially confined to one well. SWSI will involve deployment of fewer pieces of equipment inside the well compared to a crosswell survey. The net effect should be an overall reduction in costs from single well surveys.

Environmental Benefits: The successful development of SWSI technology will result in enhanced capability to map subtle geological features in difficult to access areas This will automatically reduce the number of wells needed to drain reservoirs in inaccessible areas. Reduced number of wells also implies overall reduction in footprints and consequently less damage to the environment.

Appendix-A

Major Accomplishments

Task 1- Instrumentation Design and Development

Source /Receivers, telemetry/recording
Sea Con Inc. completed and delivered to SNL and LBNL for testing and deployment, the modified Conoco source for use on a fiber optic source wireline. Successfully addressed was the design, fabrication, and testing of fiber optic connectors, transmission and acquisition operations near a seismic source (Conoco AC orbital vibrator) in a borehole environment.
Sea Con Inc. completed the adaptation of the AC orbital vibrator such that it can be used with commercially available P/GSI fiber optic wireline (20,000 ft) in addition to the LBNL fiber optic wireline (10,000 ft).

LBNL acquired OYO fiber optic system that will accommodate the different receiver systems providing great flexibility in data acquisition capability. The system was upgraded to a 24-channel system with bandwidth increased to 3600Hz.

Tube Wave Attenuation
For tube wave attenuation, a variety of devices (packers, inflatable bladders, and trapped bubbles) and passive (partial and full blockage) devices fabricated from various materials were tested at INEEL's "laboratory borehole". It was observed that--

1. At shallow depths, simple inflatable bladders or trapped bubbles provided up to 10 DB of attenuation.
2. The performance (reflectance) of gas filled bladders and trapped bubbles degrades rapidly with depths as the density of the gas increases,
3. Conventional packers can provide significant tube wave attenuation even at depth (15 DB attenuation at 1,000-2,000 ft), and
3. The attenuation seems to be primarily due to the geometry and the material from which the packer is fabricated and is less dependent on the means of inflation. Passive attenuation in the form of right circular cylinders that closely match the well bore diameter were also tested. The materials from which these were fabricated include sintered brass beads and stainless wool. The attenuation characteristics of a typical sonde were also evaluated. All exhibit attenuation in the zero to 5 dB range.

Borehole Source Comparison of Vertical Vibrator and Orbital Vibrator
The above two borehole sources were tested using crosswell data in the same well pair over the same depth range. The data was recorded in June, 1997 at Bayou Choctaw near Baton Rouge, Louisiana. The sources were well locking vertical hydraulic vibrator, operated by Paulsson Geophysical Services, Inc. (P/GSI) and an orbital vibrator (also known as O.V. source), operated by Lawrence Berkeley Laboratory (LBNL). The conclusions from these tests were as follows:

- The P/GSI source provides more elastic energy (at least 9 dB better signal-to-noise ratio) and more low frequency energy (below 75 Hz)
- The orbital vibrator source allows better separation of P and S-waves because it generates in-line and cross-line polarizations.
- The O.V. has a higher dominant frequency content for P-wave (320 Hz, in-line) and S-wave(225 Hz, cross-line)
- The P/GSI source was found to generate more tube waves

Deployment of equipments in wells

A single well (MIT.Stech #1-21) seismic imaging was employed by Conoco and LBNL as part of the DOE/Industry cooperative program in a deep, oil field type borehole using a high voltage, piezoelectric Orbital vibrator, a digitally telemetered string of borehole hydrophones and a single armored cable. The well is 6500 ft deep with 8 5/8" casing to 2500 ft. and 7" liner to 6500 ft. Three sections of the well were surveyed, a shallow section for equipment testing, an Antrim Shale section, and a deep section to cover the Brown Niagran Reef interval.

Task 2 – Modeling of wave propagation in complex media

An inversion of the elastic wavefield produced by a line source of finite length was conducted (a better representation of certain borehole sources than a point source) yielding a unified treatment of an axial torque, an axial force, and a radial pressure.
Improvements have been made to a finite-difference computational algorithm for simulating seismic wave propagation in a three-dimensional isotropic elastic medium.
Sandia performed travel time analysis of events observed in seismograms recorded with a dual-well acquisition geometry at the Bayou Choctaw La. field test site. A parallel version of a 3D elastic wave propagation algorithm was sited on a 36 node distributed cluster of processors and memory. This algorithm was used to simulate full waveform reflected and refracted arrivals from the sediment/salt boundary of a 3D Bayou Choctaw Salt dome model.

Task 3- Field Testing and Data Acquisition

Performed crosswell surveys from outside to inside salt at Bayou Choctaw field to validate salt flank location that was coincident with crosswell using outside wells with multicomponent receivers (3C receivers). A second full-scale single well test was at Bayou Choctaw Field adding piezoelectric source in additional wells that were coincident with the crosswell surveys.
Deployed and tested tube wave suppressors during single well surveys in deep environment.

Appendix-B

A number of important references to this project are given below:

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