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Numerical Simulations of 3D Seismic Data Final Report CRADA No. TC02095.0

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Numerical Simulations of 3D Seismic Data

Final Report
CRADA No. TC02095.0
Date Technical Work Ended: April 13, 2009

Date: May 22, 2009 Revision: 1

A. Parties

This project was a relationship between Lawrence Livermore National Laboratory (LLNL) and Schlumberger Cambridge Research (SCR).

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B. Project Scope

This was a collaborative effort between Lawrence Livermore National Security, LLC (formerly The Regents of the University of California)/Lawrence Livermore National Laboratory (LLNL) and Schlumberger Cambridge Research (SCR), to develop synthetic seismic data sets and supporting codes.

The main goal of this project was to develop synthetic seismic datasets similar to the datasets acquired for hydrocarbon exploration and reservoir characterization. This technology is being adopted now outside of the North Sea, in particular in the Gulf of Mexico. The use of seismic multi-component (4C) data is not yet widespread and the synthetic data generated in this project should contribute to advances in acquisition and processing methods for multi-component exploration.

The objective of this collaborative research project was to create synthetic seismic datasets and perform controlled numerical experiments and analysis. These data enable performance metrics to be determined on innovations in seismic processing. The synthetic datasets allow a "controlled dataset of truth" against which benchmarking can be performed. Specifically, the ability of the sampling density and analysis to predict the complete "controlled dataset of truth" can be gauged for accuracy and precision when these complete synthetic datasets act as the known truth.

This project consisted of the following tasks and major deliverables:

Task 1: 3D datasets over acoustic, isotropic slab (2.5D) model, North Sea prospect

Task 2: 3D datasets over acoustic, isotropic (3D) model, Barents Sea prospect

The tasks/deliverables from the original project proposal were slightly modified to best meet the needs of the industry partner. The original proposal contained three tasks. Task 1 from the original proposal did not change. This is represented by Task 1 above. The computational complexity of Task 2 and the physical parameterization of Task 3 from the original proposal were combined. This is represented by Task 2 above. These revisions were discussed and agreed to by project participants.

Deliverables:

Deliverables are the data and the jointly developed code. The data are the wavefields sampled during the simulations. We distinguish *standard data* and *non-standard data*. Standard data are the (1) pressure wavefield at one depth level, e.g., 7.5 m below a free surface, and (2) four-component (4C) data, including pressure and three components of the particle velocity recorded at the sea bottom. Non-standard data are all other types of data, e.g., 4C data recorded elsewhere than on the sea bottom, or pressure wavefields sampled at two or more closely spaced surfaces. The deliverables from each task are described below, along with provisions for non-disclosure of the deliverables according to Article VIII.B of the CRADA. The non-standard data are predicted to have proprietary implications. Hereafter we will refer to non-standard data as proprietary and derivative proprietary data.

1. **3D datasets over acoustic, isotropic slab (2.5D) model**
   - Gridded representation of material properties for North Sea 2.5D model (SCR)
   - Selection of parameters and run validation (SRC/LLNL)
   - 3D synthetic seismic volume for 2.5D acoustic model (LLNL)
   - Sampling of synthetic model wavefields, including 4C seismograms (LLNL)
   - Description of model runs (LLNL)
   - Technical reporting on Task 1 package effort (LLNL)

   Standard data from Task 1 shall remain Protected CRADA Information during the first five (5) years from the date the data is produced, unless the Parties agree in writing after the data are generated to an earlier release of such data. After five (5) years, standard data from Task 1 shall be released to the public domain. Proprietary and derivative proprietary data from Task 1 shall remain Protected CRADA Information from the date the data are produced until both Parties agree in writing to a release of such data. The final technical report on Task 1 shall be Protected CRADA Information until both Parties agree in writing to a release of the report.

2. **3D datasets over acoustic, isotropic slab (3D) model**
   - Gridded representation of material properties for Barents Sea 3D model (SCR)
   - Selection of parameters and run validation (SRC/LLNL)
   - 3D synthetic seismic volume for 3D acoustic model (LLNL)
   - Sampling of synthetic model wavefields, including 4C seismograms (LLNL)
   - Description of model runs (LLNL)
   - E3D installation at Schlumberger/WesternGeco locations (LLNL/SCR)
   - Technical reporting on Task 2 package effort (LLNL)

   An intended use of standard data from Task 2 is in joint research between SCR and Statoil. SCR will release the standard data from Task 2 as soon as available to Statoil for tests of depth migration algorithms as described in the introduction.

   With respect to other third parties, standard data from Task 2 shall remain Protected CRADA Information during the first five years from the date the data is produced, unless the Parties agree in writing after the data is generated to an earlier release of such data. After five years, standard data from Task 2 shall be released to the public domain. Proprietary and derivative proprietary data from Task 2 shall remain Protected CRADA Information from the date the data is produced until both Parties agree in writing to a release of such data. Parts of the final technical report of Task 2, agreed upon in advance in writing by both Parties, may be disclosed to Statoil. With respect to other third parties, the final technical report on Task 2 shall be Protected CRADA Information until both Parties agree in writing to a release of the report.

3. **Jointly developed Code**
   Jointly developed code consist of a snapshot of LLNL's E3D at the beginning of this CRADA, with additional functionality added as a result of Schlumberger's contribution in the form of technical expertise, algorithms, and code fragments. Schlumberger received a copy of jointly developed code during the task development cycle described above. Schlumberger has the right to install and run the jointly developed code in-house for the duration of the project and for three years thereafter. The code will be run for purposes of research and development, not for commercial services. For the duration of the project and for three years thereafter, LLNL shall not, without the prior written approval of Schlumberger, use jointly developed code for projects that include partners having a commercial interest in seismic exploration, or in acquisition or processing of seismic data. For the same period, LLNL will inform Schlumberger of any other project with outside partners using jointly developed code. In the event that LLNL offers jointly developed code for commercial uses under a license, Schlumberger shall have the right to participate in the offer under terms that are no less favorable than those offered to any other licensee.

4. Final Report and Abstract due within thirty (30) days of completion or termination of the project, as required under Article XI of the CRADA. (LLNL/SCR)

This CRADA was originally designated as a ten (10) month project. Four (4) no-cost time extension (NCTE) requests were executed for this CRADA, with the last one extending the project to April 13, 2009. The NCTEs were needed to allow enough time to complete and evaluate the final tasks and deliverables for the project, and to allow time to negotiate a possible amendment for potential follow-on tasks and deliverables. All of the tasks and deliverables for this project were successfully completed.

C. Technical Accomplishments

The primary technical accomplishment of this project was the development of two synthetic seismic datasets representative of the data acquired for hydrocarbon exploration and reservoir characterization activities. Specifically, 3-D pressure and multi-component acoustic datasets were developed for a 2.5D (slab) model of the normal-faulted Gullfaks field in the North Sea and a 3D model of a subsalt field in the Barents Sea. These datasets were obtained using the E3D finite-difference seismic wave propagation code and high performance computing resources at LLNL. For each model dataset, two subsets of data were generated. The first subset incorporated a reflecting (free-surface) boundary along the top boundary of the numerical grid. The second subset incorporated an absorbing boundary along the top boundary of the numerical grid. Data with and without free-surface effects are important for implementing algorithms for wavefield separation and multiple attenuation. The details of these models, the simulation characteristics, and the datasets are described in Musil et al. [2007]. A summary is given below.

For the first dataset, a reservoir model based on the North Sea Gullfaks oil field (Figure 1) was employed. The 3-D grid was constructed by replicating a 2-D section in the cross-line direction resulting in a so-called 2.5D model. The model grid had approximately 250 million grid points. A total of 562 source gathers were computed using free-surface and absorbing boundary conditions along the top surface (281 source gathers for each case). The sail direction was parallel to the 2D generating section. The required storage for the computed synthetic data was 1.2 TB. The computational runtime for each simulation was approximately 3-hours using 24 cpu's of a 64-bit Itanium 2 parallel Linux cluster (1024 node system, 4 cpu's/node, 8 GB memory/node). This runtime was later reduced to well under 2 hours.

For the second dataset, a salt model originating from the Barents Sea area (Figure 2) was adapted. The 3-D model had a dominant direction with a significant model variation while the perpendicular direction had a mild model variation. This model contained approximately 1.5 billion grid points. A total of 450 source gathers were computed using reflecting and absorbing boundary conditions along the top surface (225 source gathers for each case). The sail direction was parallel to the dominant direction of model variation. The required storage for the computed synthetic data was 2.4 TB. The computational runtime for each simulation was approximately 3-hours, using 120 cpu's of the high performance computing system described above.

The simulation parameters used to create both model datasets are given in Table 1.

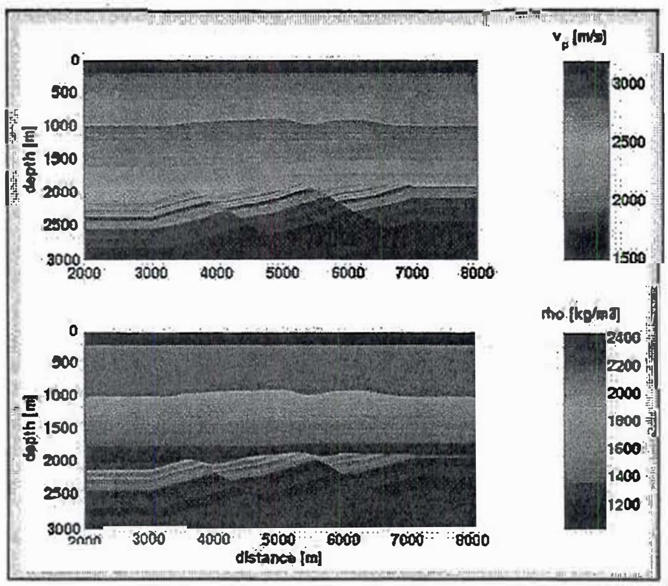

Figure 1: North Sea Gullfaks model (2.5D)

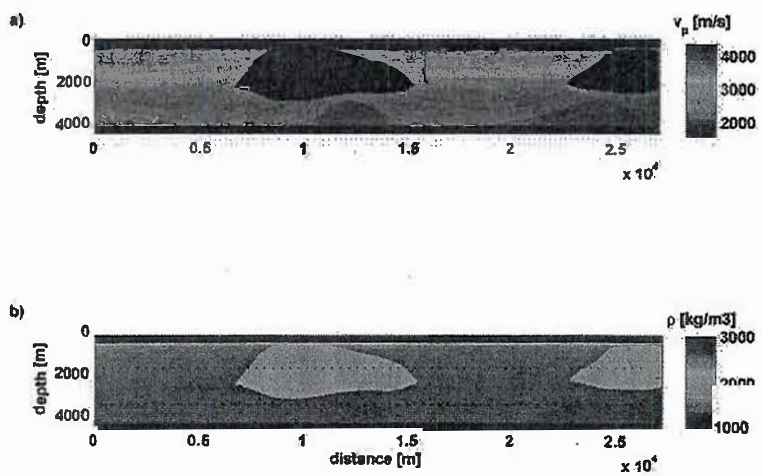

Figure 2: Barents Sea subsalt model (3D)

Parameters	Gullfaks	Barents Sea
FD spatial sampling	5 m	10 m
Grid xyz dimensions	2101 x 201 x 601	2701 x 1201 x 451
FD temporal sampling	0.75 ms	1 ms
Number of time steps	8000	10800
Seismogram sampling	6 ms	12 ms
Number of samples	1000	900
Frequency bandwidth	Ricker 0-60 Hz	Box 0-30 Hz
Source spacing	25 m	50 m
Receiver spacing	12.5 m	25 m
Source depth	5 m	10 m
Receiver depths	10, 15, 20, 200 m	15, 30, 50 m

Table 1: Modeling parameters for Gullfaks and Barents sea datasets

Prior to launching the large-scale simulation effort, the E3D code was thoroughly tested against the Schlumberger FDAV3D code. Initially, a significant difference between the codes was determined to be caused by the boundary condition implementation within each code. Boundary conditions within E3D were being handled using the Clayton-Engquist formulation (among other techniques). However, this formulation does not fully attenuate artificial boundary reflections. As part of this collaboration, the more effective Perfectly Matched Layer (PML) boundary conditions were implemented. Following this implementation, the agreement between the two codes became quite good (Figure 3).

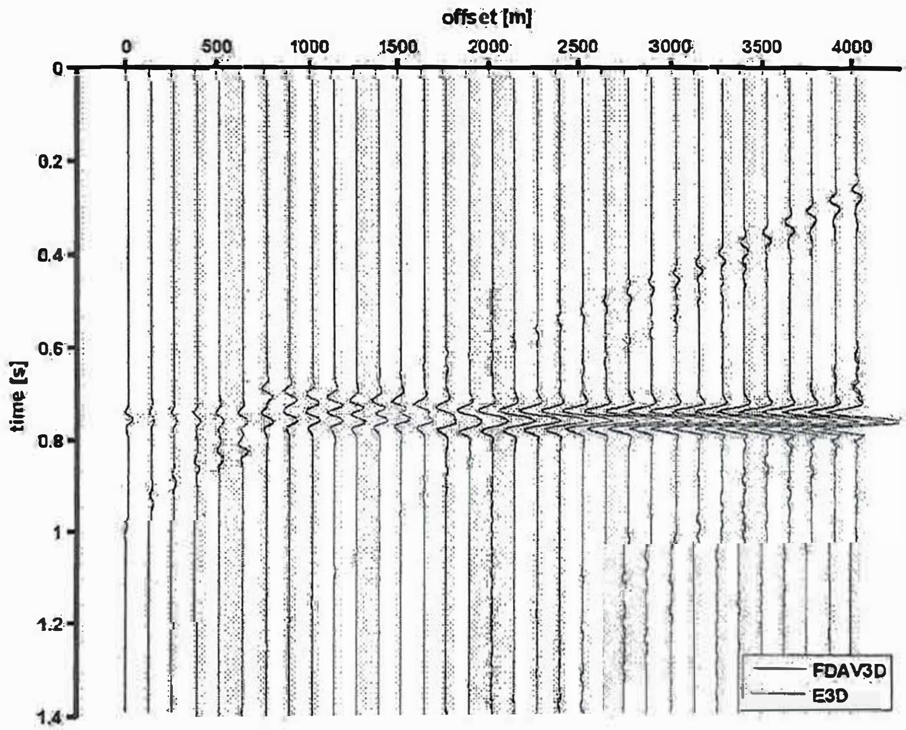

Figure 3: Sample source gathers from the Gullfaks model using FDAV3D and E3D

As a research component of this project, test elastic simulations were performed using the Gullfaks model. Elastic modeling is less common than acoustic modeling because of its higher computational cost. In addition to other needs, the elastic simulations were performed to evaluate computational performance and to compare elastic synthetics computed using E3D with those computed using FDAV3D. As with the acoustic case, the agreement between the two codes was good.

E3D was ported to a BlueGene/L (BGL) system at the IBM Rochester Research Center to evaluate the performance and scalability of E3D on this system, and to generate large data volumes that could be interrogated using 3-D visualization software. Simulations were performed using the Gullfaks model, except that the cross-line aperture was increased to be three times larger than the model used for Task 1. The simulation required 75 minutes using 256 cpu's of the BGL system. This compares favorably with the Task 1 simulations (the processor speed per BGL cpu is slower than the Linux processors used for Task 1).

D. Expected Economic Impact

The synthetic seismic datasets developed for this CRADA are being used to evaluate and improve seismic processing algorithms and to investigate strategies that optimize the value of the multi-component seismic data collected in the field. Because the CRADA output is currently being used for research purposes, it is difficult to quantify the economic impact. However, the collection and processing of multi-component seismic data for large 3-D exploration surveys can be multi-million dollar ventures. Conversely, the potential payback from a successful exploration operation can be in the billions. Hence, any improvement to the algorithms and tools currently used by the exploration industry will significantly reduce data acquisition and analysis costs, and increase the likelihood of successful exploration efforts.

D.1 Specific Benefits

Benefits to DOE

The benefits to DOE/LLNL include: 1) the development and integration of new capabilities into existing seismic modeling tools (e.g., E3D); and 2) the establishment of synergistic cooperation between LLNL and Schlumberger (including affiliated organizations). The benefits enhance both national and energy security activities at DOE/LLNL.

New algorithms were implemented into the E3D finite-difference wave propagation code. For example, enhanced boundary conditions using the Perfectly Matched Layer (PML) technique were developed and integrated into the LLNL tools. These boundary conditions reduce undesired artificial reflections from the boundaries of the numerical grid. In addition, capabilities were developed that substantially improved computational performance. Changes were made to the I/O stream to reconfigure the synthetic data so that it was in a format compatible with that used by the exploration industry. These improved capabilities can now be utilized in DOE mission areas that require seismic modeling expertise.

A cooperative working relationship was established with Schlumberger. This relationship has led to potential follow-on activities with the exploration industry.

Benefits to Industry

Schlumberger and its affiliates (e.g., WesternGeco) are utilizing the synthetic seismic datasets to: 1) improve seismic data processing capabilities; and 2) investigate strategies for optimizing field acquisitions. For example, the synthetic data have been used to evaluate multiple attenuation methods and to investigate ray-based Born techniques [Musil and Kostov, 2007; Musil et al., 2007]. In addition, CRADA results were presented to the broader community at the November 2007 meeting of the Oslo Society of Exploration Geophysicists (OSEG) [Kostov et al., 2007].

Results from this CRADA are allowing our industry partners to more cost-effectively detect subsurface hydrocarbons. This is particularly applicable to marine environments that require large/expensive 3-D data collection efforts and to geological regimes where oil and gas deposits remain elusive due to complex earth structures (e.g., salt domes).

E. Partner Contribution

Schlumberger provided LLNL with gridded geological representations of the material properties for the two models used in Tasks 1 and 2. In addition, Schlumberger provided seismic source parameterizations (e.g., source frequency and source time history) and the criteria used to define the seismic survey configuration represented by the simulations (e.g., the location of each seismic source and the geometry and location of the pressure and multi-component sensors).

No subject inventions were created during the CRADA project.

F. Documents/Reference List

* Protected CRADA Information

Musil, M, and C. Kostov, Multiple attenuation methods for 3D data and 2.5D earth: further numerical examples, Schlumberger OFSR Report (draft), 2007. *

Musil, M., H. Bernth, C. Chapman, C. Kostov, Examples of ray-based Born seismograms for a complex north sea model, Schlumberger OFSR/RN/2007/053/GEP/C, 2007. *

Reports

Kostov, C., M. Musil, H. Bernth, S. Larsen, Computing seismic waves in a model of Gullfaks: examples from a recent seismic simulations project, Oslo Society of Exploration Geophysicists (OSEG) meeting, November 2007.

Larsen, S., C. Kostov, M. Musil, Numerical simulations of 3-D seismic data: synthetic seismic dataset for CRADA TC02095.0, UCRL-MI-223591, 2006. *

Musil, M. S. Larsen, B. Arntsen, H. Bernth, C. Kostov, 3D acoustic finite-difference modeling, Schlumberger OFSR Report (draft), 2007. *

Copyright Activity
Software modifications were made to the E3D, Version 2 software (see Background Intellectual Property section below).

Subject Inventions
None

Background Intellectual Property
LLNL disclosed the following Background Intellectual Property (BIP) for this project:

E3D, Version 2 software, Author: Shawn Larsen; LLNL No. UCRL-2000053, CP00646

Schlumberger Cambridge Research executed a license for the LLNL BIP in December 2005; LLNL Case No. TL02035-0.0.

SCR disclosed the following BIP for this project:

- FDAV3D software (copyright protected) described in internal Schlumberger research report, OFSR/RN/1999/001/RDI/C, Concept summary: Finite-difference modeling of three dimensional wave propagation in anisotropic viscoelastic media, by Johan O. A. Robertsson and Richard T. Coates.
- Material property grids to be used for the finite-difference numerical simulations.
- Wavefield sampling specifications for the numerical simulations.
- Research report OFSR/RN/2000/073/RDE/U, Extension of PML ABC to Elastic Wave Problems in General Anisotropic and Viscoelastic Media, Yong-Hua Chen, Richard T. Coates, Johan O. A. Robertsson

G. Acknowledgement

Industrial Participant's signature of the final report indicates the following:

1) The Participant has reviewed the final report and concurs with the statements made therein.
2) The Participant agrees that any modifications or changes from the initial proposal were discussed and agreed to during the term of the project.
3) The Participant certifies that all reports either completed or in process are listed and all subject inventions and the associated intellectual property protection measures generated by his/her respective company and attributable to the project have been disclosed and included in Section E or are included on a list attached to this report.
4) The Participant certifies that if tangible personal property was exchanged during the agreement, all has either been returned to the initial custodian or transferred permanently.
5) The Participant certifies that proprietary information has been returned or destroyed by LLNL.

Kostov July 1, 2009

Clement Kostov, Program Manager, Modeling and Inversion, Geophysics Department Date
Schlumberger Cambridge Research

July 8, 2009

Julio Friedmann, LLNL Principal Investigator Date
Lawrence Livermore National Laboratory

7/13/09

Erik J. Stenehjem, Industrial Partnerships Director Date
Lawrence Livermore National Laboratory

Attachment I – Final Abstract

Numerical Simulations of 3D Seismic Data

Final Abstract (Attachment I)
CRADA No. TC02095.0
Date Technical Work Ended: April 13, 2009

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A. Parties

This project was a relationship between Lawrence Livermore National Laboratory (LLNL) and Schlumberger Cambridge Research (SCR).

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B. Purpose and Description

The primary objective of this effort was to develop synthetic seismic datasets similar to the datasets acquired for hydrocarbon exploration and reservoir characterization. Synthetic datasets can be used to develop and improve the data acquisition and processing technologies used by the oil and gas industry to discover and recover subsurface hydrocarbons.

Specifically, Schlumberger and LLNL developed synthetic datasets for two acoustic models of exploration interest: a 2.5-D (slab) model and a 3-D model. Schlumberger provided LLNL with gridded geological representations of both models, as well as appropriate simulation parameters. LLNL enhanced its seismic simulation capabilities, and generated the synthetic data using high performance computing resources available at the Livermore Computing facility. These datasets were delivered to Schlumberger. In addition, Schlumberger and LLNL worked together to define simulation parameters for an elastic model, and explored strategies to utilize high performance computing for seismic exploration and data processing.

The deliverables from the original project proposal were slightly modified to best meet the needs of the industry partner. These revisions were discussed and agreed to by project participants. This CRADA was originally designated as a ten (10) month project. Four (4) no-cost time extension (NCTE) requests were executed for this CRADA, with the last one extending the project to April 13, 2009. The NCTEs were needed to allow enough time to complete and evaluate the final tasks and deliverables for the project, and to allow time to negotiate a possible amendment for potential follow-on tasks and deliverables. All of the task and deliverables for this project were successfully completed.

C. Benefit to Industry

Schlumberger and its affiliates (e.g., WesternGeco) are using the synthetic seismic datasets to: 1) develop and improve seismic data processing capabilities; and 2) investigate methods to optimize field acquisition strategies. Internal reports describing selected advances have been generated by Schlumberger. In part, seismic modeling results from this CRADA were presented to a larger industry audience at the November 2007 meeting of the Oslo Society of Exploration Geophysicists (OSEG).

D. Benefit to DOE/LLNL

The benefits to DOE/LLNL include: 1) the development and integration of new capabilities into existing seismic modeling tools (e.g., E3D); and 2) the establishment of synergistic cooperation between LLNL and Schlumberger (including affiliated organizations). The benefits enhance both national and energy security activities at DOE/LLNL.

The development of robust synthetic seismic datasets required modifications to the E3D finite-difference wave propagation code. For example, enhanced boundary conditions using the Perfectly Matched Layer (PML) technique were implemented. These boundary conditions significantly reduced undesired artificial reflections from the boundaries of the numerical grid. In addition, capabilities were developed to substantially improve computational performance and to reconfigure the generated synthetic data to be in a format consistent with that used by the exploration industry. These improved capabilities can now be utilized in DOE mission areas that require seismic modeling expertise.

A cooperative working relationship was established with Schlumberger. This relationship has led to potential follow-on activities with the exploration industry.

E. Project Dates

June 13, 2006 through April 13, 2009