DOE/ER/14079--T1

Final Report, DOE-FG-02-89ER14079
COMPUTATIONAL METHODS FOR IMPROVING THE RESOLUTION OF SUBSURFACE SEISMIC IMAGES

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This is the final report for Department of Energy Grant DOE-FG-02-89ER14079, initially covering the period September 15, 1990 through September 14, 1993, with an extension from January 1, 1994 through December 31, 1994. The specific areas of research evolved over the 4-year period of the grant, but always within the confines of the original goal: to devise computational methods for improving the resolution of subsurface seismic images.

Initially the research emphasis was primarily on developing methods for efficient ray-theoretic modeling of acoustic waves in triangulated representations of media and on efficient means of modeling waves that travel sub-horizontally in horizontally layered media. Subsequent directions included new efficient methods for imaging the Earth's subsurface (specifically, 3-D migration via the McClellan transformation, and squeezing dip moveout (DMO) for depth-variable velocity), demonstrations of the importance of taking *P*-wave anisotropy into account in migration and DMO, the development of algorithms for doing migration and DMO in heterogeneous, anisotropic media, and the development of a methodology for the all-important step of deriving the anisotropy parameters necessary for imaging of *P*-wave data.

Over the course of the grant, there have been two Principal Investigators (Professors David Hale and Ken Larner), and two co-investigators (Professors Norman Bleistein and Jack Cohen).

Enclosed are lists of publications and technical reports of research conducted under the grant. The list entitled "Technical Reports Sent to DOE" includes reports that were published in peer-review journals as well as those that appeared as reports of the Center for Wave Phenomena (CWP) at Colorado School of Mines, which were distributed to CWP's 25-30 industrial sponsors as well as to colleagues in universities, and subsequently were made available to the exploration geophysics community at large. As seen in the list, a total of 38 technical reports were sent to the DOE, all but seven of which directly reported on research supported by the subject grant (the asterisk * denotes those 31 reports covering research supported by the grant). Of those 31 reports, the 18 that denoted by a $\star$ were published in *Geophysics*, the peer-review journal of the Society of Exploration Geophysicists. Details of the publication issues are given in the enclosed list entitled "Center for Wave Phenomena." Those papers based on work funded under this grant are again indicated by the $\star$. In addition, each

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of the topics covered in the various publications resulted in a paper presented either orally or as a poster paper at various professional society meetings, most notably the Society of Exploration Geophysicists Annual International Meeting and various SEG workshops.

The research supported by this DOE granted benefitted from the fact that much of the research under the DOE grant dovetailed well with research of interest to sponsors of our industry-sponsored research project within the Center for Wave Phenomena (CWP) at Colorado School of Mines (CSM). Joint support by both the DOE and our many industry sponsors provided mutual leverage: On the one hand, most of the projects either may not have been initiated or would not have flourished so well without the DOE support. On the other, the input and supportive involvement of researchers from the seismic exploration industry was crucial to keeping the research well targeted on problems of practical interest.

Due in no small part to the grant support from the DOE, CWP's industry support has now grown to 36 sponsors, including oil companies, seismograph service companies, and hardware and software companies. CWP's current 36 sponsors constitute almost all of the companies in the industry that support research both in-house and outside. Therefore, each year when we presented results of our research under the DOE grant, we have, in the 2-1/2 day CWP Annual Project Review Meeting, been able to reach the vast majority of scientists in the seismic exploration industry who would benefit from the results of the research. As a result, many of the technological developments supported by the grant were implemented rapidly in industry. Examples include the 3-D depth migration via the McClellan transformation, triangulated modeling of the Earth's subsurface, dip-moveout processing for vertically heterogeneous media, migration via the method of Gaussian beams, efficient elastic-wave, finite-difference modeling and migration by flux-corrected transport, and dip-moveout in transversely isotropic media. Also, these developments, which were supported under the DOE grant, subsequently led to a much larger branching into parameter inversion and imaging in anisotropic media, currently supported by the DOE under the ACTI program.

Because the research done under Grant DE-FG-02-89ER14079 meshed so well with the interests of CWP sponsors, the research benefitted from various levels of involvement by all five of the academic leaders of CWP as well as the 15-20 graduate students in the project, although the DOE grant officially provided partial funding support to no more than two faculty members and full support to two students at any one time. Six graduate students whose research was supported by the DOE grant received degrees and produced theses based on the sponsored research (five M.S, and one Ph.D., with three of the M.S. students subsequently receiving the Ph.D. degree). In addition, one post-doc was partially supported during a portion of the grant period.

Another important offshoot from the research supported under the grant was that it allowed continued development of our seismic data processing system called SU (Seismic Unix), which provides a quite complete seismic data processing suite

freely available over the World Wide Web and Internet. The large number of seismic software programs developed under the grant have been incorporated into the SU system, making the new processing and analysis capabilities available to researchers in academia, industry, and national labs alike. Presently, the SU system is being used at over 1000 sites worldwide.

In summary, while the specific topics of investigations evolved considerably during the course of the grant period, the result of the research was a number of developments, subsequently implemented in the seismic exploration industry, for improving the quality and resolution of seismic imaging of the Earth's subsurface in areas of complex geologic structure. In particular, this has spawned an entirely new research area — development of practical methods for the processing and interpretation of *P*-wave data taking into account the reality of anisotropy in the Earth's subsurface — that is now a central focus of research within the Center for Wave Phenomena.

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Date July 1, 1997

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