Project ID: **60115**

Project Title: **Advanced High Resolution Seismic Imaging, Material Properties Estimation and Full Wavefield Inversion for the Shallow Subsurface**

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PROGRESS REPORT

RESEARCH OBJECTIVE: Develop and test advanced near vertical to wide-angle seismic methods for structural imaging and material properties estiamtion of the shallow subsurface for environmental characterization efforts.

RESEARCH PROGRESS AND IMPLICATIONS: As of the middle of the second year of this three year grant we have pursued a number of research themes relevant to this proposal, including further processing and analysis on existing high resolution data, new data acquistion at an environmental remediation site, and data processing algorithm development.

We continued work on a multi-source high-resolution dataset acquired at an open pit copper mine in 1997. The data were acquired near the face of the mine wall, in order to match high frequency seismic structures to geologic outcrop and known fluid pathways in fracture zones in the mine wall. The datasets included surface reflection, surface refraction, and transmission refraction (mine rim to mine base). A paper describing the results of the data analysis on one of the 4 lines we acquired was submitted to Geophysics this spring (Akerberg et al., 1999), and results were presented at the 1998 SEG and 1998 AGU meetings (. Processing continues on the additional 3 lines.

In the August 1998 we conducted a high resolution survey at Hill Air Force Base, Utah, at an environmental remediation site. We chose this site for investigation because

1) It is an active remediation site, with a very shallow target depth (10-15m).
2) It has been drilled extensively, so that a general knowledge of the target zone is available.
3) Rice chemical engineers have conducted a Surfactant/Foam flood remediation effort at this site, and therefore have a good working knowledge of the site characteristics. (It was they who interested us in this site, as the characterization based on wells alone was inadequate for their remediation program).
4) The target is a paleo-channel cut in a clay layer that has been covered with alluvium. DNAPLs (TCE) have collected in the low spots in the paleo-channel. Although the extensive well field has outlined the paleo-channel, the details of the structure are not known well enough for the remediation efforts to remove all of the DNAPL.

The experiment was paid for by the AATDF program (DoD) and this DOE grant. We used 180 seismic channels from the PASSCAL program of IRIS (Incorporated Research Institutions for Seismology) and from Rice. We tested three different sources: an 8 gauge shotgun, a 0.22 caliber rifle, and an accelerated weight drop, which provided signals with frequencies from about 30 Hz to about 300 Hz.

The data have been processed with conventional reflection processing and conventional refraction methods.

<u>Reflection Images</u>: Stacks of Lines 1 and 2 (Figures 1 and 2) with minimal velocity analysis show that the paleo-channel changes morphology rapidly (compare lines 1 and 2). At present there are some ambiguities in subsurface definition due to velocity uncertainties. For example, on Line 2 there is evidence for a deeper reflecting horizon which mimics the shape of the event we have tentatively identified as the paleo-channel. The deeper horizon may in fact be the water table, with the deeper horizon then being the top of the clay layer. Additional velocity analysis should clarify this point.

<u>Refraction Analysis</u>: The first arrival times from the Line 2 shotgun data have been picked and inverted for velocity and interface structure using a 2D travel-time inversion

program that solves for the flattest (most laterally constant) model. A set of 9 different 2-layer models were derived that about equally well fit the data to within estimated uncertainties (2.5 ms). The boundary between the 2 layers is interpreted to be either the top of the water table or that between the Provo and Alpine formations; more velocity analysis of the refraction and reflection data in the near future will likely resolve this ambiguity.

The 9 models correspond to different a priori assumptions about certain features of the models that are not well constrained by the travel-time data or that can vary according to the data's constraint. The velocity in the near surface is less than the speed of sound, being between ~200-300 m/s. The velocity at the base of the first layer is poorly constrained by the data, but is likely between ~350-900 m/s. We have therefore derived 3 sets of models such that the velocity at the base of the first layer is either 350, 700 or 900 m/s (fixed). In each set there were 3 models determined: (1) a laterally varying velocity at the top of layers 1 and 2 was allowed; (2) a laterally varying velocity at the top of layer 1 was allowed but a velocity of 1500 m/s at the top of layer 2 was assumed; and (3) the best constant velocity was determined for the top of layer 1 (the surface) and a velocity of 1500 m/s at the top of layer 2 was assumed. A velocity of 1500 m/s was assumed for the top of layer 2 in 6 of the 9 models because of its likelihood of being the top of the water table.

The results show that the depth to the boundary between the surface layer and the top of either the water table or the clay layer has a well defined maximum located between 10-15 m from the east end of the line, at 6-11 m depth depending on the assumptions made concerning the seismic velocities as described above. This location and the maximum estimated depth (11 m) correspond closely to the assumed location of the paleo-channel based on available well data.

<u>Model-Driven Waveform Inversion:</u> Most of the effort on this part of the project over the past year falls into the "infrastructure" category. We have made significant progress in two areas, and have:

1) Implemented and tested on small and large problems a new method for imposing bounds on weighted mean squares of model parameters during inversion. This is a regularization method for linear and nonlinear inverse problems, following ideas put forward by D. D. Jackson and other geophysicists. The paper reporting this work is titled "Extremal regularization", and is available through the TRIP web site (http://www.trip.caam.rice.edu). It has been submitted for publication. The code is written in C++, and will be part of the next release of the Hilbert Class Library (HCL).

2) Revised and improved the methodology, announced in last year's report, for generating inversion applications from finite-difference/element simulators. This methodology has several components:

A) An abstract class implementing the general finite difference loop: The user supplies an HCL operator class implementing the finite-difference step and sampling;

B) Software to assist the user in transforming Fortran subroutines embodying the finite-difference stencil into the class code mentioned in A), without writing any C++ at all;
C) An implementation of the adjoint state method, as part of the abstract class mentioned in A), which includes an essential checkpointing scheme due to Griewank rendering very large adjoint state computations feasible (10's of wavelengths for 3D viscoelastic finite-differences);
D) A method for using so called Automatic Differentiation tools (in particular Ralf Giering's TAMC) to automatically generate the remaining Fortran modules needed to complete the inversion code, and "wrapping" them in appropriate C++, again without need for the user to write C++.

The code generating tools (B and D) have been tested on "naive" (non-C++-literate) users with success.

In addition, we have completely rebuilt the "SEGY" class on which all of the applications envisioned in this report will rely for I/O and vector algebra services, to take advantage of the improved features of HCL1.0. This class implements the SEGY data structure as an HCL vector class. It accommodates several other seismic data formats, including SU and SEP, and is designed to permit straightforward extension to yet others. The "SEGY" class will be released along with the rest of HCL1.0 at the end of the summer.

PLANNED ACTIVITIES: We have a 3-D survey planned for Hill AFB in summer/fall 1999 as part of this project. Computer code integration and additional imagin software development are planned as well.

INFORMATION ACCESS:

Center for Computational Geophysics homepage:

http://terra.rice.edu/department/ccg/HAFB/

CCG members homepages:

http://terra.rice.edu/department/faculty/zelt
http://terra.rice.edu/department/faculty/levander
http://www.trip.caam.rice.edu/txt/bios/symes/william_symes.html
http://terra.rice.edu/department/staff/morozov
http://terra.rice.edu/department/students/dana

Papers

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<u>Abstracts</u>

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<u>Technical Reports</u>

A. Levander, C. Zelt, D. Dana, Interim Report: Hill AFB OU-2 High-Resolution Seismic Study, Rice University Geophysics Program, 11 March 1999, submitted to HAFB and DOE.

FIGURES

Figure 1: Map showing 1998 seismic lines at Hill AFB, the morphology of the channel from kriging well data, and the locations of the wells. The white box shows the 3D survey planned for 1999.

Figure 1: Map of Paleo-channel with 1998 2-D survey profiles show as black lines. The two white boxes show the minimum (top) and maximum (top+bottom) areas that will be surveyed in the 1999 3-D survey. The gray line shows the remediation pipeline.

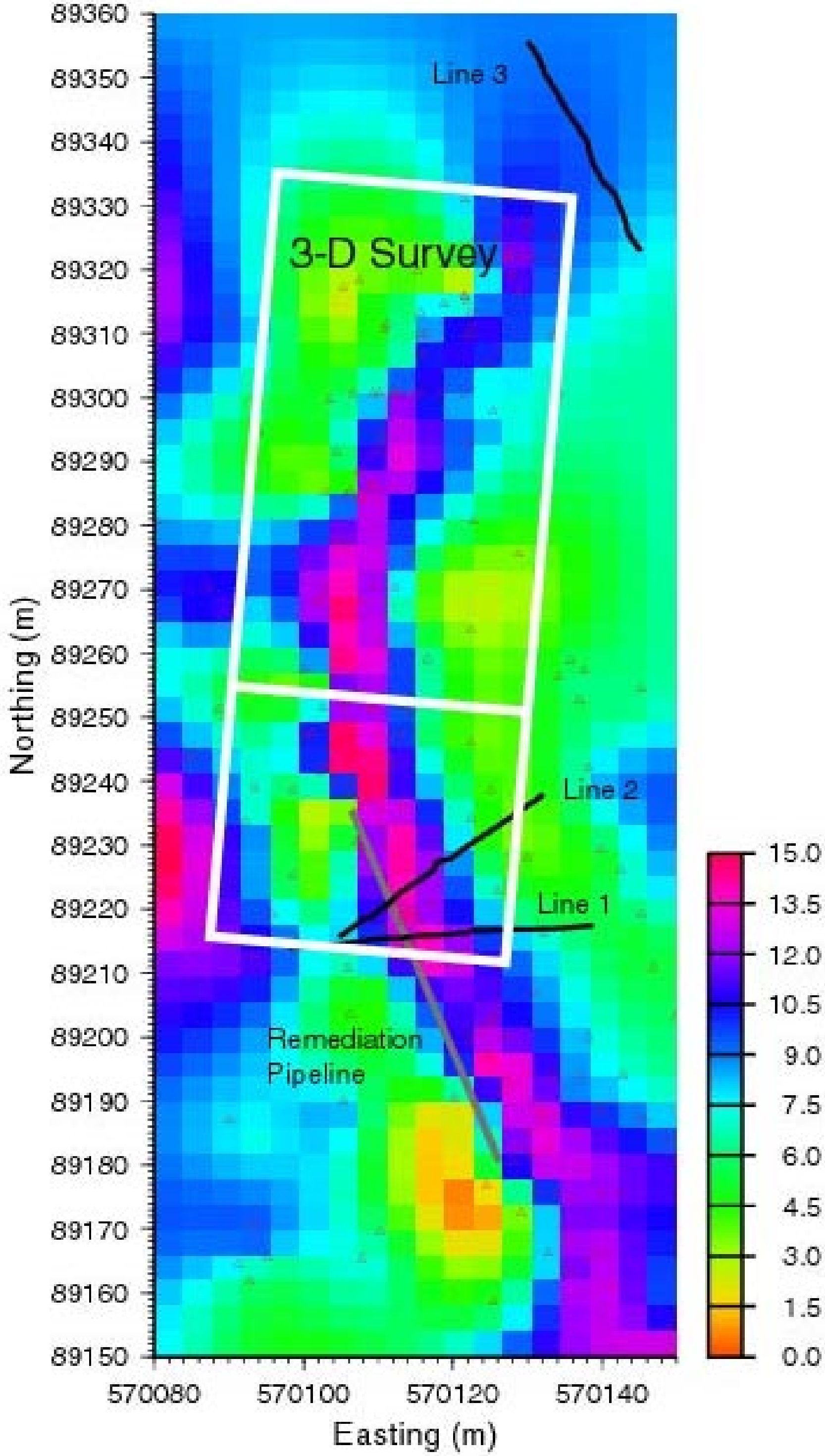

Figure 2: A) Preliminary stack and interpretation of Line 1 at Hill AFB (see Figure 1). B) Preliminary stack and interpretation of Line 2 at Hill AFB. Both lines show a clear channel structure, as well as deeper events. DNAPL's pool at the low spots in the channel. The two lines almost intersect at their western ends. The sections show a high degree of lateral variability in the channel structure.

Figure 2A: Line 1: Slide Hammer: Preliminary Stack

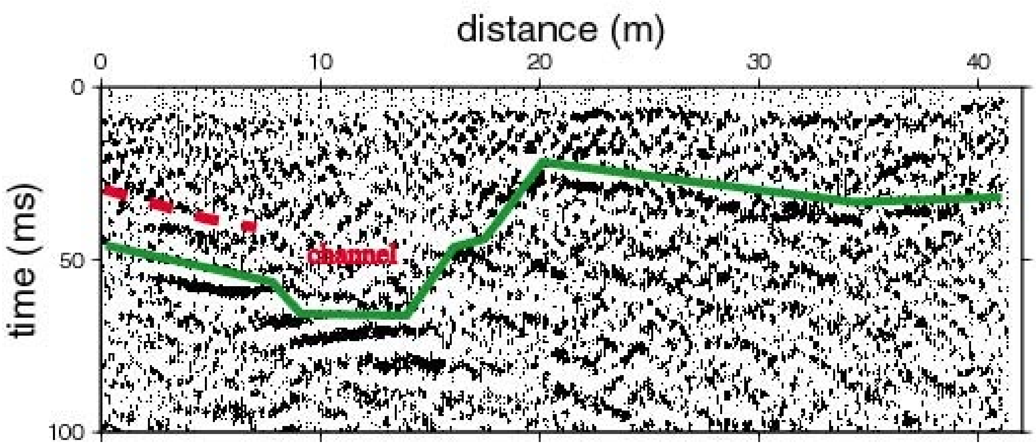

Figure 2B: Line 2: Slide Hammer: Preliminary Stack