Annual Report DOE-EMSP Project DE-FG07-96ER14726

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In the first year of the project progress has been made in several areas which are central to the project.

Development of Joint Hydrogcological-Geophysical Co-Interpretation Procedure

A strong effort was invested in developing the concepts and the algorithm of our joint hydrogeological-geophysical co-interpretation approach. The reason for the concerted effort in that direction is the large amount of time we expect this task will take before completion, and also by the need to direct the data collection efforts. We are currently testing several ideas for co-interpretation, but we are at a quite advanced stage. We are testing these ideas using synthetic studies as well as some preliminary data that has been collected at the Lawrence Livermore National Lab site.

Part of our efforts is in developing methods for estimation of the semi-variograms of the logconductivity based on direct measurements as well as on seimsic velocity measurements as obtained from cross-well tomography. Preliminary tests show that these two sources of data complement each other quite well: the direct measurements supply the medium to small wave number portion of the logconductivity spectra, while a high resolution seismic survey supplies a good coverage of the large wave number part of the spectra.

We advanced significantly with formulating our approach for using Ground Penetrating Radar (GPR) imaging techniques in shallow subsurface surveys. Synthetic surveys show that GPR maybe very suitable for mapping spatial variations in saturations. We have access to field data and are analyzing it. Some additional issues that we investigated are listed below.

Development of The Synthetic Model

We are beginning to construct a synthetic medium to be used as a testing ground for the various geophysical surveying techniques. The earth cube we are constructing is made of pixels. We assigned porosity, velocity, and clay values to each pixels using the Marion and Yin binary mixture rock physics relations. The synthetic model will be used to simulated different hydrologic conditions, including fluid types and saturations, in order to determine the sensitivity of the different techniques and signals to changes in saturation, temperature, and ambient pressure. The model we construct attempts to mimic the geology of a contaminated site at Lawrence Livermore National Lab, in anticipation of the analysis of the data that has been and that will be collected there.

Resolution: Quantification of Spatial Response

We **have defined procedures** to quantify the resolution associated with various geophysical methods, such as 2-D surface seismic, vertical seismic profiling (VSP), logs, cross well, and ground penetrating radar (GPR).

The first procedure requires simulating the geophysical survey, collecting the synthetic data, and inverting . The reconstructed image is then compared with the **actual** one, and the spatial response and resolution are determined through spectral analysis. Through this procedure we can simulate different frequencies and acquisition parameters such as spacings of sources and receivers.

This procedure is quite tedious, and under some conditions can be simplified by employing the Born algorithm. The Born single scattering approximation allows to estimate the overall spatial imaging response in terms of simple filters in the spatial wavenumber domain, given the frequency and geometry of field geophysical measurements. The Born approximation has the potential to become a quick and efficient method for designing and checking the feasibility of field surveys.

Uniqueness of the Geophysical Response

We have developed techniques for combining statistical methods with deterministic rock physics relations from the lab and theory, that allows us to identify the *most likely* interpretation of geophysical anomalies, given calibration data for a site. The theoretical Gassman equation relating seismic velocity to pore fluid compressibility can be combined with the statistics of the calibration data to derive the probability distributions, and most likely interpretation of pore fluids, corresponding to observed velocities.

Upscaling analysis.

One of the key issues in integrating multiscale data is a thorough understanding of the various scales of measurements and their effects on the rock physical property being measured. Seismic waves propagating in heterogeneous media depend on the geologic scale, the seismic wavelength, and the propagation distance. Rock physical relations, established from cores at the laboratory scale can show a different behavior at log scale. It is necessary to properly upscale the laboratory relationships in order to integrate core and log measurements. The upscaling procedure should take into account the averaging characteristics of the logging tool, as well as the spatial correlation of the physical variable being measured. For example, the acoustic waves in a sonic tool measure a different average of the intrinsic rock velocities than does the ultrasonic transducer in the lab.

Averaging over a coarse scale can introduce scatter in an otherwise sharp, but non-linear, fine scale rock physics relation. The porosity-clay content bimodal relation has been established for sand-clay mixtures, based on a simple binary mixture model. This is a core-scale relation obtained in the laboratory. However, tools that make measurements over many core lengths may cause this sharp V-shaped curve to become a scatter cloud, just due to the spatial averaging effect. The nature of the scatter also depends on the spatial correlation at the fine scale. We show in Figure 1 synthetically generated porosity and clay depth series with **a** fractal spatial correlation. They are constructed so that the point-to-point fine scale porosity and clay values follow the non-linear V-relation exactly. We then do a simple running average over the depth series to simulate the effect of a logging tool that measures over a larger length than the lab core scale. Figure 2 plots both the fine scale velocity-clay and porosity-clay relations as well as the upscaled, smoothed values. We notice a surprising amount of scatter introduced by the simple averaging even though the underlying relation is a sharp V. The amount and nature of scatter depend on various factors such as the spatial correlation length of the intrinsic rock properties relative to the averaging length of the tool, and the spatial correlation structure of the porosity and clay. This therefore indicate that the relatively large scatter obtained from log measurements are not inconsistent with the much stronger correlations obtained in the laboratory, provided we realize that rock physics relations are not always simple, linear ones. Understanding how lab core scale measurements are affected by upscaling and averaging will provide strategies for inverting the scattered log measurements to arrive at the underlying physical relations.

EM **Crosswell and surface to borehole annual progress report:**

We have completed the crosswell and surface to borehole EM field work. The surveys were done in PVC cased wells at a DOE environmental site at Lawrence Liver-more National Labs from June 4 to June 25, 1997. Two surface to borehole profiles were measured with a surface transmitter loop (frequency 11.3 kH). and a vertical magnetic coil receiver placed in well 1250. The profiles were in the region between 1250 - 1251 and 1250 - 1252. For the crosswell EM survey seven data sets were collected at LLNL. **A** vertical magnetic coil transmitter (frequency of 9.6 kH) was placed in well 1250 and 1251. From well 1250 five data sets were collected with a vertical magnetic receiver placed successively in wells 1251 through 1255. The two last data sets were collected between wells 1251 - 1253 and wells 1251 - 1254. The data repeatability was very good (5 % difference in amplitude and less that +/- I degree in phase). 'This site, as any potential environmental site, presented quite a challenge in terms of' the data processing and acquisition. First of all, each well had metallic colIars every 2.3 meters which were securing electrodes from a previous survey .(Fig.3)
These collars caused detuning of our transmitter as it went through each collar. Thus, only the data between collars could be used which reduced the total number of measurements that could be taken. Part of the data processing includes the time consuming task of hand picking these points. This process takes weeks to complete for one data set. Aitionally, since the survey area is next to a helicopter landing pad, there are subsurface high voltage wires and communication lines. This caused surface noise that saturated the receiving coil forcing us to begin data acquisition at a depth of 27 meters or deeper depending on the well. Thus, we have much less coverage than we would ideally like. The data sets between 1250 - 1251 and 1250 -1252 have been processed.
One dimensional simulations of the data have been done. These simulations include various models that approximate the actual site and survey setup. The one dimensional simulations successfully give results that smoothly approximate the data except for some heterogeneities close to the wells. We have gone on to use 2 and 3 dimensional models which more closely resemble the sampling interval and the actual geology of the site. We have been using a new 3-dimensional code from Sandia National Laboratory. Considerable effort has gone into optimizing the finite difference meshes for the forward problem. We spent the beginning of the year doing simulations of a layered earth at frequencies in the range of that used in the actual field work. We ran many models and

compared the results to I-D model results in order to test the mesh and distance to boundaries. We also did some preliminary sensitivity analysis of the algorithm. **Now that the** field work is completed we can compare the data and model results. We find that the forward models give results with the same order of magnitude as the data. At the same time, we are just beginning to investigate the inverse problem using a 2-D dimensional inversion code from Sandia National Laboratory.

We have decided to use this new code rather that a well established 2 dimensional **Born** approximation cylindrical symmetry code for various reasons. First of ail, and most importantly, because of the previous investigations at this site, we know the geology is not cylindrically symmetric about the wells. Thus, the older code would be a poor representation to begin with. Secondly the SNL code is state of the art with 2-D which is the closest we can get to the actual 3-D geology without the problem of convergence that full 3-D codes present. Therefore, in the long run, we should get more reliable and more accurate results with this new algorithm from SNL. We have begun inverting the first data set (between wells 1250 -1251) . This algorithm is new and has very little body of experience behind it. The code is computationally intensive and requires run times of several days for model meshes complex enough to represent the LLNL field site. We are currently developing a set of meshing rules which will provide reliable and stable results for the LLNL field site.

Initial inverse runs of the LLNL data set #1 were unsuccessful. Since we need to understand the algorithm's response to changes in different parameters more clearly, we have backed up and are testing the inversion on a layered numerical model of LLNL. This model has a crosswell response which approximates the field data and thus a successful inversion of this numerical data should be able to guide us to a successful mesh design for the field data inversions.

3D VSP survey plans at Lawrence Livermore National Labs, and 3D VSP data imaging algorithm development

The proposed 3D VSP survey will utilize five pre-existing wells with VC casing down to depths of 60 m. The area occupied by this set of wells is approximately 91 m by 122 m., with minimum spacings of 21 m, and maximum spacings of about 46m. Shooting with our proposed circular shot point geometry around each well will result in an estimated maximum offset coverage of about 20 m from each well. This offset coverage will result in several overlapping imaged zones which will effectively extend the range of the imaged volume to allow structral interpretation over nearly 90 % of the survey site area of 91 m by 122 m.

We will utilize a 48 element hydrophone string as borehole receivers, and an accelerated weight-drop source (Bison EWG) at the surface. Data will be recorded with a 48 channel Geometrics Strataview machine. The hydrophone spacing on the string is at 0.5 m intervals, and will be baffled to suppress tube wave energy. The string will be deployed to cover depths of 13 m to 60 m.

The water table level at this site is at a depth of about 20 m., which t p-wave imaging at this site will be restricted to depths below 20 m., due to the unsaturated nature of the weathered layer. The thick weathered layer will also restrict useful imaging bandwidths to below about 220 Hz. resulting in an estimated sub-surface wavelength of about 10 m. The finest structuraimaging capability resulting from this 10 m wavelength limitation is about 2.5 m.

The sub-surface structures to be imaged at the LLNL site are expected to be laterally heterogeneous, with scale lengths of 6 m or less. The geology of interest at this site consists of unconsolidated fluvial deposits, mostly from meandering stream channels over a fan-out plain during the Quaternary era. The maximum depth of interest is about 100 m.

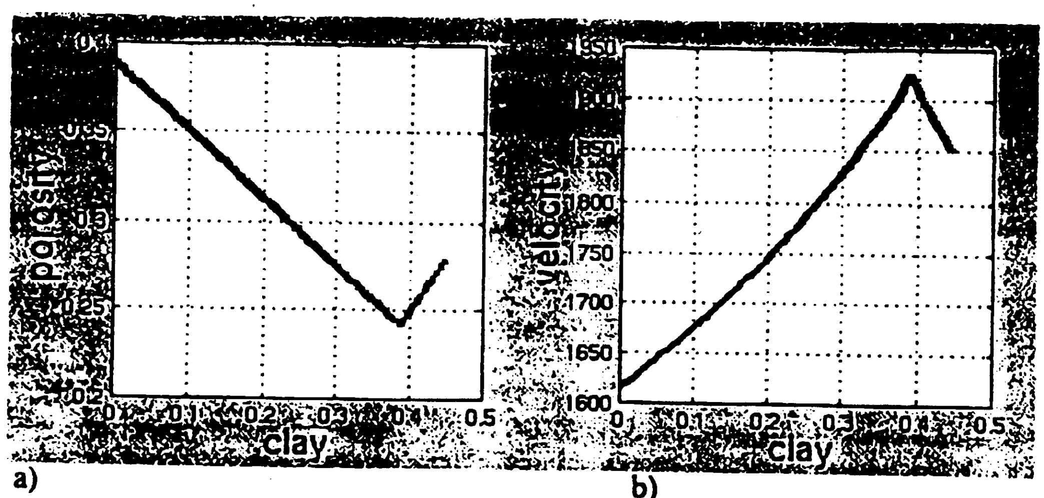
The lateral heterogeneity at this site makes it desirable to develop a more sophisticated imaging algorithm than the classic VSP - CDP mapping procedure designed to produce 2D depth sections of flat layer (non-dipping) structures. Our previous experience with the application of this classic mapping algorithm to VSP data gathered from a laterally inhomogeneous site similar to the LLNL site was the lateral smearing-out, or un-focusing, of sharply terminating structures like the edge of sand channels, sand lenses, etc. Also, the mapping of out-of-plane reflection events (3D) into a 2D plane could create undesirable imaging artifacts, and could lead to false structural interpretations.

The obvious solution to the above reflection/diffraction imaging problem' is to develop a 3D migration and imaging algorithm that works on the complete set of 3D VSP data at once. We are in the process of developing such an algorithm at present: After searching through many journal publications and making many enquiries, we came to the conclusion that no one else has (publicly) produced such a 3D VSP reflection/diffraction imaging algorithm. So we are starting from step one in the development of such an algorithm.

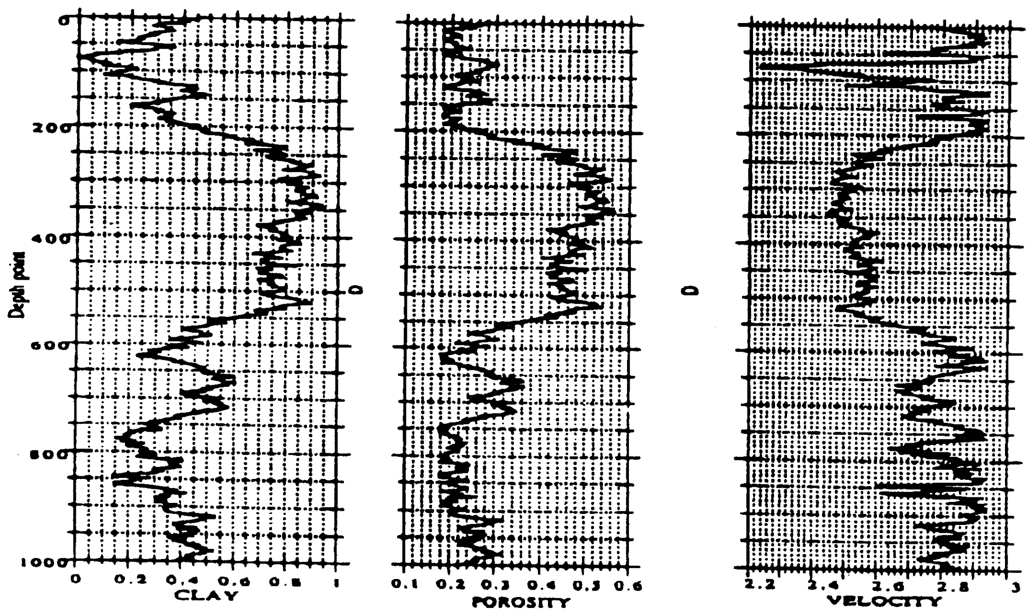
The first step in developing this 3D VSP migration and imaging algorithm was to look back at the history and development of surface seismic data migration techniques, and decide what methods were suitable, and what methods were not. Due to the complex 3D geometry of source and receiver locations in our acquisition setup, trace data from which have to be simultaneously processed, we came to the conclusion that full wavefield migration techniques would be far too complex and difficult to compute in a 3D wavefield domain. Finite differencing in a 3D space - time domain was also deemed too expensive in computer time and memory. This led us back to the more conceptually simple theory of the trace (time domain) data being a series of generalized radon transforms (GRT). With a suitable velocity function in 3D space, one can create an inverse GRT operator that can sum from the multitude of source - receiver pairs, of any arbitrary geometry, into any point in 3D space, with suitable amplitude weighting functions.

The 3D VSP migration and imaging algorithm we are presently developing is based on such an inverse GRT operation. A suitable velocity function for such an operator is initially created from direct wave first break time arrivals, that are then inverted into a depth dependant velocity profile. Raytracing is then performed through this variable velocity media to compute predicted arrival times for reflection/diffraction events from any point in the 3D image space. Arrival event amplitudes will also be taken into account for suitable weighting prior to summation into image space by the inverse GRT operator At present, work is progressing on development of the 3D raytracing routines. This is the most important and labor (brain) intensive part of the migration and imaging algorithm. Computationally, raytracing is a lot faster than wavefield processing, but an implicit assumption about the relation between the imaging wavelength and the dominant length of the structure to be imaged is being made: Typically one would like the minimum structure length to be at least three times the dominant wavelength of the recorded seismic wave. But this rule-of-thumb is not absolutely strict, and it has been shown that optic ray theory can even be quite effective when structural scale lengths are about equal to one wavelength.

We expect to have an alpha version of this 3D VSP migration & imaging algorithm ready for testing in early January 1998.

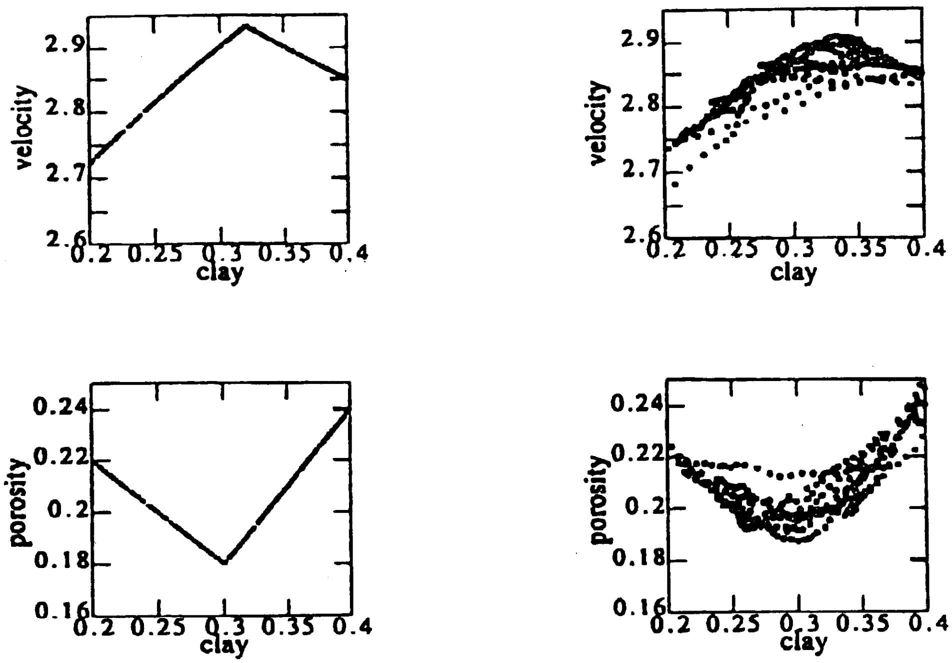


Rock physics relations assigned at the pixel scale of the earth model.



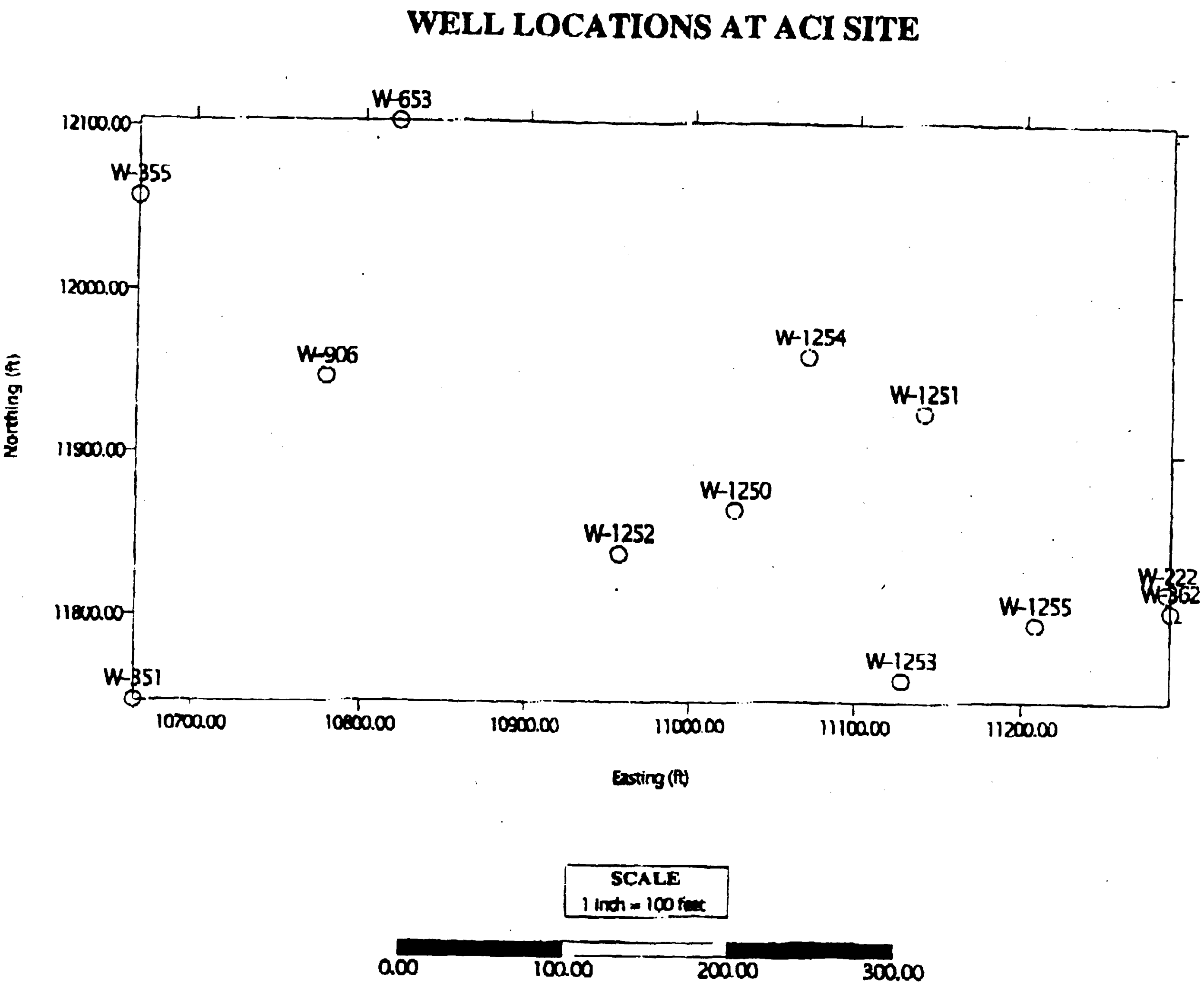
Synthetic clay, porosity, and velocity logs generated from Marion-Yin binary mixture model.

Figure 1



Scatter introduced by upscaling non-linear relations.

Figure 2



WELL LOCATIONS AT ACI SITE
W-653
W-355
W-906
W-1254
W-1251
W-1250
W-1252
W-222
W-362
W-1255
W-1253
W-351
12100.00
12000.00
11900.00
11800.00
Northing (ft)
10700.00
10800.00
10900.00
11000.00
11100.00
11200.00
Easting (ft)
SCALE
1 Inch = 100 feet
0.00
100.00
200.00
300.00

Figure 3