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Pilot Geophysical Studies in Mortandad Canyon - Los Alamos National Laboratory Los Alamos County, NM

Geophex Job No. 1171

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Executive Summary

Geophex was directed by the Department of Energy, through a contract with Pacific Western Technologies, Ltd., to conduct two pilot geophysical studies in Mortandad Canyon at the Los Alamos National Laboratory. Specifically, Geophex was asked to evaluate the applicability of two geophysical methods, DC resistivity and seismic reflection, at the Los Alamos National Laboratory. These studies were carried out during May and June of 2002. Both methods proved to be extremely successful at providing detail geologic information to depth (200 feet for resistivity and 13,000 feet for the seismic reflection) at this site. The detail provided by both methods can be used to refine the stratigraphic and groundwater models for Los Alamos National Laboratory.

Nine DC resistivity profiles were acquired throughout the canyon using a dipole-dipole configuration. Of these nine profiles, one profile (Line 1) was collected continuously for 9,290 ft. Resistivity data provides a method to detect "moist" zones in the alluvium and upper Bandelier Tuff of Mortandad Canyon. In the upper Bandelier Tuff, low resistivity zones are interpreted to be "wet" or clay-rich fracture zones. These fractures zones are supported by the fracture zone interpretations in the CMP reflection section. The largest spatial area of "moist" alluvium and bedrock occur in the vicinity of R-15.

Seismic pilot studies in Mortandad Canyon consisted of Vertical Seismic Profiles (VSPs) in R-15 & R-13 and a two-mile Common Midpoint (CMP) reflection profile along the axis of the canyon. VSP data provided an opportunity to:

1) Test surface impact sources to vibratory sources for generating seismic energy at LANL
2) Determine in situ velocity structure for the upper 1000 ft. of the stratigraphic section
3) Track the exact depth and nature of reflectivity in the stratigraphic section and incorporate it in the interpreted Mortandad Canyon CMP reflection section.

CMP data provide a view of structure along the axis of the canyon. Fracture zones and variations in thickness and elevation are present in the section. CMP data provide the ability to track these horizons more accurately than by simply extrapolating well information alone.

1.0 Introduction

Geophex was contracted by the Department of Energy to conduct two pilot geophysical studies in Mortandad Canyon at the Los Alamos National Laboratory. The purpose of these two studies was to evaluate the applicability of geophysical methods at the Los Alamos National Laboratory, specifically, DC resistivity and seismic reflection. These studies were carried out during May and June of 2002. The locations of all data types collected are shown on Plate 1.

Nine DC resistivity profiles were acquired throughout the canyon using a dipole-dipole configuration. Of these nine profiles, one profile (Line 1) was collected continuously for 9,290 ft. down the canyon starting near MCO-4. The remaining eight profiles (Lines 3-10) transect the canyon and intersect Line 1 at various locations. Profile depths varied based on the total length of line available. In the upper stretches of the canyon, the shortest profile (Line 3) penetrated approximately 20-30 ft. below surface level (bsl). The longest profiles (Line 1 & Line 10) imaged to 200 ft. bsl.

Seismic pilot studies in Mortandad Canyon consisted of Vertical Seismic Profiles (VSPs) in R-15 & R-13 and a two-mile Common Midpoint (CMP) reflection profile along the axis of the canyon.

This report discusses the acquisition parameters, processing steps and results for each of the two geophysical methods evaluated during these studies. This report also has an accompanying binder that contains eight plates (Plate 1, Plate 2, Plate 3, Plate 4, Plate 5A, Plate 5B, Plate 6A and Plate 6B).

2.0 DC Resistivity (DCRES) Data Acquisition

Geophysics acquired 9 dipole-dipole resistivity lines (see Plate 1 for locations). Resistivity data were collected using an AGI SuperSting Eight-Channel Earth Resistivity IP meter with a 56 electrode cable (Figure 1). Electrodes are connected to a stainless steel stake with a rubber band and planted in the ground (Figure 2). Prior to data acquisition, a contact resistance checks are conducted to verify each electrode is ready to acquire data. To reduce surface contact resistances, electrodes are treated with salt water prior to the test and data acquisition.

After checking the line, the dipole-dipole command file is imported in the SuperSting. The data acquisition for a particular command file takes approximately 35 minutes. As data collection progressed, stakes for the next deployment of line were emplaced. Five days were needed to acquire these nine lines of resistivity data. At the same time, the active profile locations were surveyed with a Trimble Differential Global Positioning System (DGPS) primarily for X-Y location. Since elevation data from DGPS tend to be less reliable, electrode elevations were surveyed by optical level techniques to 0.1 ft. accuracy.

Figure 1. AGI Supersting resistivity meter

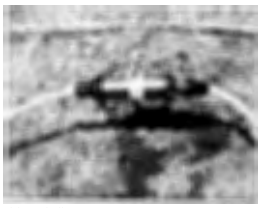


Figure 2. Supersting electrode during acquisition

Electrode spacing and total line length recorded for each profile during this study are listed in Table 1.

Table 1. Electrode spacing and profile length for Mortandad Canyon resistivity data

Profile Line	Electrode Spacing (ft)	Total Profile Length (ft)
Line 1	18.0	9,290.6
Line 3	7.4	134.6
Line 4	9.8	901.8
Line 5	7.0	125.0
Line 6	6.6	114.6
Line 7	9.8	901.8
Line 8	8.2	458.1
Line 9	13.1	695.4
Line 10	18.7	1003.7
	Total Recorded Length:	13,198.7

2.1 Vertical Seismic Profiles (VSP) Data Acquisition

Vertical Seismic Profile data were recorded in R-15 and R-15 to record the seismic wavefield in situ (Figure 3). This information is used to determine a precise velocity vs. depth curve and investigate which depths of the section produce observable reflections. A truck-mounted spring actuated impact hammer (SAH) source and a Minivib II (Industrial Vehicles Inc.) swept source were used during the VSP data collection to compare source effectiveness in the strata of Mortandad Canyon (Figure 4). At each depth level, the tool was locked to the sidewall via a control box sitting next to the operator, the winch cable stacked to reduce any cable induced vibration in the elements and the sources were fired sequentially. All field data depths were measured from surface elevation. Impact field records were stacked prior to writing to disk. Vibrowed sweep records were saved individually to allow for the application of pre-correlation signal enhancement techniques (discussed further in section 3.2).

After a day of system testing, one day was needed to record R-13 and R-15 from 50-1020 ft below surface level (bsl).

Figure 3. VSP acquisition in R-13 Mortandad Canyon

Figure 6. Minivib II (left) and VSP support truck (right) VSP survey at R-13

VSP acquisition details are shown in Table 2.

Table 2. Acquisition Parameters for Mortandad Canyon VSPs

	R-13	R-15
Geophone Type	Analog, Triaxial Sidewall Sondes	Analog, Triaxial Sidewall Sondes
Seismograph	Seismaxis RAS-24	Seismaxis RAS-24
Sample Rate	1 ms	1 ms
Recording orientation	Vertical	Vertical
Depth increment (Meters)	20 ft	10 ft
Number of sweeps taken	4	4
Source Triggering Mode	Operator Controlled	Operator Controlled
Sweep frequency	15-300 Hz, Linear Upsweep	15-300 Hz, Linear Upsweep
Sweep length	8 sec	8 sec
Pilot Trace Channel Number	12	12
Field Record Length (Seconds)	12 sec	12 sec
Corrected Record Length	4 sec	4 sec
Depth Increment (SAH)	50-1020 - 20 ft	20 ft
	20 ft (700 - 800)	
Number of receivers deployed	8-15	16
VSI Record Length	4 sec	4 sec
Source Triggering (SAH)	Seismaxis Harness, 0 ft	Seismaxis Harness 0 ft
Source offset to well	50 ft N of well	50 ft east of well
Depths Recorded	50 ft (bgl) - 1020 ft (bgl)	50 ft (bgl) - 1020 ft (bgl)
Raw Data Format	SEG-2	SEG-2

2.2 Common Midpoint Seismic Reflection (CMP) Data Acquisition

Seismic Reflection data were recorded for two miles in Mortandad Canyon along the south side of the canyon access road (see Plate 1). Acquisition parameters were determined after a day of testing (known as a "Walkaway" test). The "Walkaway" test consists of deploying all 192 channels and recording two source offsets into the entire spread. The resulting shot gather provides an opportunity to study a larger sampling of the seismic wavefield than usually seen during production recording. For Mortandad Canyon, the "Walkaway" test resulted in modifications at the sweep length, near source offset (240 ft.), and the number of active recording channels from initial plans.

For production acquisition, twelve days were needed to record 2160 stations over two miles. With the considered "end on" and "in-line" shooting strategy, 1421 shots were recorded over the entire line. As the monsoon season approached towards the end of the study, we were necessarily forced to shut down daily production early due to afternoon electrical storms. The detailed acquisition parameters for Mortandad Canyon are listed in Table 3.

Table 3. Seismic Reflection acquisition parameters for Mortandad Canyon

Geophones	Mark Products SM-4 (4.5 Hz Corn series)
Geophone Station Interval	5 feet
Seismograph	6 - Seismaxis RAS-24 seismographs
Sample Rate	1 ms
Number of Active Recording Channels	120 channels
Recording Geometry	End-on (240 ft offset) & In-line (every third station for refraction statics)
Source	1 - IVI Minivib II
Number of Sweeps per shot point	2
Shot Point Interval	10 feet
Source Triggering	Radio Controlled
Sweep frequency	15-300 Hz, Linear Upsweep
Sweep length	8 sec
Pilot Trace Channel Number	6
Field Seismic Record Length	12 sec
Corrected Record Length	4 sec
Field Data Format	SEG-2

A Minivib II (Industrial Vibrator, Inc.) was used as the source (Figure 5). A Seismaxis RAS-24 system was used to record the data (Figure 6). The RAS-24 is a distributed 24-bit, 24-channel system. Four RAS-24 units were needed to expand the active spread (i.e. 120 channels) and three units were used to roll the line forward during production (Figure 7). In total, forty gigabytes of 100% uncorrelated field data were recorded for Mortandad Canyon Line 1.

Figure 5. Midwift II during CMP acquisition in Mortandad Canyon

Figure 6. A single RAS-24 Seismometer seismograph

Figure 7. "Rolling" Mortandad Canyon Line 1 forward

3.6 DC Resistivity (DCRES) Data Processing

Data were transferred from the Superdrag to a laptop DC in the office. Each profile was inverted by RES2DINV® software (Geoelectric Imaging, Inc.).

Data processing consists of: 1) entering the elevations, 2) editing of any outlying data points, 3) combining individual acquisition deployments for long profile lines, 4) a final inversion with RES2DINV®, 5) inversion results are transferred to ASCII "XYZ" files, and 6) these files are imported into Claris Montaj® software (Geosoft, Inc.) for gridding and display.

The data files are gridded using a minimum curvature algorithm. Gridding determines how values are predicted between data points, or in areas without data. The minimum curvature method assumes a simple linear variation between data points. Data values are then contoured in a similar manner as elevations are contoured for a topography map. Contour values are then assigned a color as depicted by the color bar adjacent to each resistivity profile. The result is a color contour image of the data values (Figures 8).

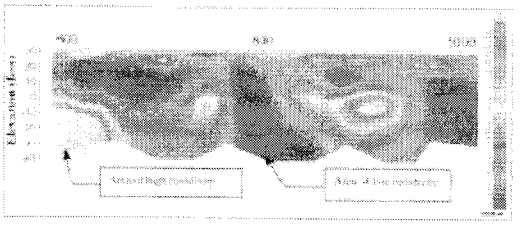
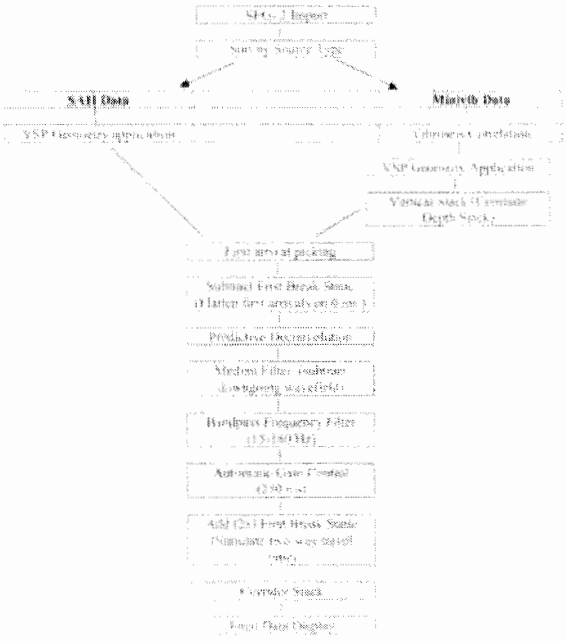


Figure 8. Example of resistivity profile

3.1 Vertical Seismic Profiles (VSP) Data Processing

VSP data processing begins with importing the SEG-2 filed data into Vista (Seismic Image Software) seismic processing software. Vista is a Windows based seismic reflection processing package designed for the Oil & Gas industry. Currently, Geophex owns a license for VSP and one license for 2-D reflection processing.

The following processing steps were implemented for both the SAH and Minivib VSP data:



3.2 Common Midpoint Seismic Reflection (CMP) Data Processing

The following flow chart describes the processing steps implemented with Vista (Seismic Image Software) for the Mortandad Canyon reflection data. The processing scheme here is commonly used in the reflection data processing. However, the testing and implementation of processes like vibroseis predeterming, refraction statics, F-X predictive decorrelation and spectral balancing are tools that have recently proved invaluable in processing of near surface data. Specifically with these data, the acquisition was designed to take advantage of refraction statics algorithms for determining the corrections needed in the allocation (due to it's varying depths) and F-X predictive decorrelation operators are more effective removing of the surface waves (a.k.a. groundroll) given the close (5-9) geophone spacing utilized. One hundred gigabyte of data was generated during the processing of this profile line.

The following processing steps were implemented for the Mortandad Canyon CMP data:

1. SEG-2 Data Import
2. Vibroseis Prewhitening
3. (T-X AGC-500 ms) Note: This process was tested and found to boost the background noise on shot gathers to an unacceptable level and was then removed)
4. Vibroseis Correlation (Pilot recorded on either Channel 1, 2, or 3)
5. Vibroseis Correlation (Pilot recorded on either Channel 1, 2, or 3)
6. Geometry Input & Application (Shot & Receiver Locations in NM State Plane Coord.)
7. Vertical Stack (Sum together the 2 sweeps recorded at each shot point)
8. First Arrival Picking
9. Refraction Statics Application (A dataset with a fixed and another with floating datum corrections were generated and processed)
10. F-K filtering (Pie slice reject to reduce surface waves)
11. Spectral Balancing (20 Hz window)
12. Predictive Decorrelation (with a Time & Space operator to further reduce surface waves and multiples from the first arrival)
13. Bandpass Filter (Ormsby 15-150 Hz)
14. AGC (1.5 - 500ms window)
15. CMP Sorting
16. Velocity Analysis (Semblance, and Constant velocity stacking based)
17. Muting (designed to eliminate the first arrival and higher frequency artifacts in the later parts of the data (> 2.0 sec.)
18. Normal Moveout Correction
19. CMP Stacking
20. Brute Stack
21. Velocity Analysis (refined to improve the NMO velocity function)
22. Normal Moveout Correction (w/ refined NMO velocities)
23. CMP Muting (to reduce NMO stretch artifacts in the near surface)
24. F-X Filtering
25. CMP Stacking
26. Final CMP Stack
27. Post Stack Kirchoff Migration (was tested but did not improve the image & is not shown)
28. Integration and Interpretation with VSP data
29. Input into montage for final display plots

4.0 DC Resistivity (DCRES) Results

DCRES data is displayed in Appendix A as individual profile lines and Plate 2 as a montage of the entire data set. Also, Line 1 resistivity data is shown with the CMP data in Plate 4 but will be discussed further in the CMP section. The following discussion consists of observations and interpretations of these data.

- Various zones are inferred to be "moist". It is interpreted that these zones are partially saturated and appear as low resistivity (blue colors) in Appendix A, and Plates 2 and 4.
- These "moist" zones (i.e., low resistivity) correspond to moisture weight percent data that is superimposed on the profile. Therefore, DC resistivity is interpreted to be mapping current sediment moisture. However, it is assumed that these zones would indicate the preferential groundwater flow pathways during any recharge event.
- High resistivities (red/pink colors) are inferred to be either "dry" unconsolidated sediments or "dry" bedrock (i.e., upper portions of the Tshirege Member of the Bandelier Tuff). Gamma logs were placed on the resistivity data to aid in the determination between the two. It is presumed that high resistivity zones in the deeper parts of the profiles (> 50 ft. bsl) represent bedrock. The transition from red to pink colors indicates zones decreasing moisture content (i.e. "dry" zones) within that volume of bedrock.
- "Dry" bedrock is not uniform in elevation or across the deeper parts of the profiles. Vertical zones of low resistivity extend to depth in certain areas. These are interpreted to be either "moist" or clay-rich fracture zones within the bedrock or effects of the resistivity line being too close (< 30 ft.) from a cased monitoring well with bentonite grout. The later can be eliminated in many cases by referring to an attached spreadsheet listing Mortandad Canyon wells and their offsets from the resistivity profiles (Appendix D).
- On Line 1, the majority of low resistivity zones at depth occur between the intersections of Line 4 and 8.
- Cross Canyon profiles (Lines 3-9) highlight low resistivity on the southern edge of the canyon. The "moist" zone tends to begin shallow and progressively go deeper towards the center of the canyon.

4.2 Vertical Seismic Profiles (VSP) Results

Vertical Seismic Profile data were acquired to investigate a number of different issues including:

1) A comparison of a surface impact sources versus a swept sources for producing usable seismic energy in this environment,
2) Measuring and analyzing *in situ* seismic velocity in the upper 1000 ft. to be used with subsequent CMP data reduction,
3) Correlating seismic reflection energy observed within the upper 1000 ft. with the known geology, and
4) Observing reflections from both the upper 1000 ft. and below the recorded borehole interval to correlate with CMP sections.

The remainder of this section lists observations and interpretations relevant to these points. The VSP data are displayed in Appendix B and the subsequent velocity analyses are in Appendix C.

- The Spring Actuated Hammer (SAH) impact source produced results that were comparable and of equal quality to the Minivib for the VSPs in R-13 and R15. However, these data only extended to 1020 ft. bsl and upon analysis of "deeper" data (see B7-B8 or B15-B16 in Appendix B) the Minivib produced data with more power at these later times.
- The observed average velocities (and similarly the observed arrival times) range from lows of 1500 ft/s near the surface to 6000 ft/s at 1020 ft. bsl in these data (Appendix C). Three distinct depth zones appear to separate the seismic velocities: 0-480 ft. bsl, 480-800 ft. bsl, and > 800 ft. bsl. It is interpreted that these zones infer the changes in bulk lithology present in the section (i.e. "dry" tuff, "dry" to "wet" basalt, and "wet" tuff, respectively). In the upper zone, R-15 velocities are higher than R-13 inferring the Bandelier Tuff is better consolidated in this locale. In the intermediate zone, the Cerros del Rio Basalts show less variation in velocity, but subtle differences are present. The velocity in R-15 is faster than R-13 until ~ 600 ft. bsl where they switch. This depth range is close to where a perched water table is found in R-15 (~630 ft. bsl). The reduction in velocity near this zone is interpreted to indicate the increased fracturing or void presence of the basalts at this depth. It is this fracturing or void presence in the basalts that accommodates the presence of groundwater and higher porosities. Finally, the deepest interval (> 800 ft. bsl) is typically saturated Puye Formation where the velocities are nearly identical for both wells. We interpret this to infer that these units of the Puye Formation have similar physical properties and exist in a similar physical state at both sites.
- Since the VSPs measure *in situ* velocity, it is possible to determine Two-way travel time (TWT) in the recorded interval directly and predict the Two-way times for depths below the borehole. TWT is what is observed in surface reflection seismic profiles (as discussed in the next section). The Two-way time is the Time to Depth function required to correlate known geology from boreholes to reflection events observed on CMP sections. Appendix C contains the graphs of the Two-way time vs. depth for the borehole interval and projected depths. The data for the projected TWT was taken from refraction profile velocity estimates published by Biehler, et al., 1991 (Geophysics, vol. 3, p. 340-353). The resulting Time to Depth can be seen on the subsequent CMP section plots shown in Plates 3-6.

- Finally, VSP data observe the reflected wavefield directly and allow one to determine the precise geologic causes of those reflections (provided the lithologies within the borehole are known). In combination with a known Time-depth function, these lithologies can be mapped on a coincident CMP reflection section and traced away from the borehole. In the Mortandad Canyon VSPs, the following tables describes the observed *in situ* reflectivity in R-13 and R-15 respectively:

Table 4. Summary of Reflectivity observed in R-13 from VSP data

Borehole Lithologies	~ TWT time (ms)	Depth (ft)	Nature of Reflection
Top of the Otowi Mbr-Bandelier Tuff	140	248	Lithologic contact
Top of the Cerros del Rio Basalt	180	303	Lithologic contact
Internal events to the Cerros del Rio Basalt	220, 250	~525, ~ 650	unknown
Bottom of the Cerros del Rio Basalt	260	730	Lithologic contact
Internal Puye Fm (fanglomerate/pumiceous	988	325	Lithologic contact
Weak Internal Puye Fm.	280	~ 830	Regional Groundwater??

Note: The bottom of the recorded VSP interval is 360 ms TWT.

Table 5. Summary of Reflectivity observed in R-15 from VSP data

Borehole Lithologies	~ TWT time (ms)	Depth (ft)	Nature of Reflection
Top of the Otowi Mbr-Bandelier Tuff	100	120	Lithologic contact
Top of the Cerros del Rio Basalt	225	494	Lithologic contact
Bottom of the Cerros del Rio Basalt	290	750	Lithologic contact
Internal Puye Fm (fanglomerate/pumiceous	~340	~ 1000	Lithologic contact
Weak Internal Cerros del Rio Basalt.	280	~ 650	PerchedGroundwater?
Nothing from Regional Groundwater table			

Note: The bottom of the recorded VSP interval is 360 ms TWT.

Appendix B contains figures showing the information in these tables. These are the Corridor stacks on pages B7, B8, B15, and B16.

4.3 Common Midpoint Seismic Reflection (CMP) Results

Surface CMP sections are presented in plates 3-6. Plates 3 and 4 focus on shallow depths (< 2800 ft.), some of which can be correlated directly with the VSP results. Plate 4 presents resistivity data overlain on the interpreted section. Plates 5 and 6 present the deeper section that was recorded down to 2.5 sec (or approximately 13, 000 ft. bsl).

The remaining discussion summarizes the results of these data:

- The four largest amplitude reflection horizons have been traced to provide the interpreted section displayed on Plates 3 and 4. This is done by tracing the horizons (shown in the previous tables) between the wells on the raw CMP section. Variations in elevation and thickness, and interpreted fracture zones are visible. Overall the shallow interval surrounding R-15 is slightly deeper than further east.
- Perched water zones and the regional groundwater produced very weak (if any) reflection according to the VSP data. However, internal reflections in the Cerros del Rio basalt near R-15 are possibly from this interface. However, there is no unique way to determine whether reflections internal to any unit are distinctly lithologic or potential perched water tables from surface data alone.
- The resistivity overlay in Plate 4 highlights that many of the deep low resistivity zones correlate to fracture zones mapped in the upper 1000 ft. of the seismic data. Again, it is interpreted that these areas represent either "moist" or clay rich fracture zones. Additionally, the "bowl" shaped structure seen in the seismic data is mimicked by the high resistivity anomalies that were discussed as bedrock earlier.
- Deep seismic sections are unconstrained (i.e. no geologic/lithologic information is available) to precisely interpret the mapped horizons. However, tracing laterally coherent events reveals some wedge-like features under the eastern edge of the profile. Again, a "bowl"-like structure exists with the deepest part lying near R-15. Additionally, fracture zones and faulting are prevalent in this region.