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Glendora Seismic Experiment

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This is the data report submitted to IRIS-PASSCAL documenting data supplied to IRIS to fulfill requirements for experiments utilizing instrumentation borrowed from the IRIS-PASSCAL facilities. This document is in electronic form under the ./docs/data_report directory of the tar tape supplied with the printed form of this report. You can access this first page by pointing your browser at $base/docs/data_report/index.html where $base is the top level directory from which you run tar to extract the contents of the tape. Note that the first page of the report, of which this description is a part, utilizes frames that some older browser do not support. If you have a problem with this front page file (index.html) either view it as time to upgrade your browser message, or you will have to poke around the html files individual. With frames the table of contents on the left point to the main sections of this report. In addition, the tar tape contains a subdirectory called ./docs/navy_report containing a lengthy technical report I submitted to the U.S. Navy. This is an unpublished report on some aspects of the experiment that I don't expect to publish, but which may prove of interest to some readers. This report is cited in a few places in the text of this report.

Experiment Overview

The data described here were collected during a series of explosion tests conducted at the Glendora Lake Facility, of the Naval Surface Warfare Center Crane (NSWCC) on September 10-11, 1998. NSWCC is a U.S. Navy facility located in southern Indiana that maintains a stockpile of approximately 50% of military ordinance in the U.S. (The other 50% is mainly at China Lake in California). The Navy purchased an abandoned strip mine near Sullivan, Indiana (Figure 1) in the early 1990s before the open pit was filled. They allowed the pit to fill with water that forms the present landmark now called Glendora Lake. NSWCC has been developing facilities at Glendora for the past several years with the primary focus to date being testing of hydrophones. Due to increasing environmental regulation they have had problems testing underwater ordinance at sea. As a result, they were interested in the potential of utilizing Glendora Lake to test ordinance. The primary purpose of this experiment from the Navy's perspective was to develop empirical ground peak ground motion curves to evaluate potential seismic regulation limits on blasting in Glendora Lake. That is, they needed to know how large an explosive could be detonated in Glendora Lake before they exceeded peak ground motion limits defined in state and federal blasting regulation. This applied problem shaped the design of the experiment, but the availability of 100+ instruments gave us enough flexibility to also do some very small aperture array experiments.

The near surface geology strongly shapes these data in ways it is important to understand. Figure 2 shows an enlarged view of the area along with a cross-section of the known near-surface geology. The point to recognize is that all the area east of the main part of the lake (the part oriented north-south) is covered by approximately 30 m of mining spoil formed when the strip mined blasted and moved overburden rocks above the coals they were after. To the west of the lake and in the southernmost corner of the 200 line stations were located on the natural surface.

For the experiment we utilized 102 digital recorders equipped with 4.5 Hz natural period, triaxial seismometers. These instruments were deployed on a total of 174 points on the ground within a 3000 meter radius of the shot points (Figure 1) . 63 of these stations were operated in fixed, linear profiles directed radially away from the shot points in three different directions. These stations had a nominal station spacing of 75 m. Four additional instruments were equipped with strong-motion accelerometers. These were deployed near the foundations of buildings 8000, 8001, and 8002 and in the southwest corner of the floating building I will refer to in this report as the "Barge".

The remaining 105 points shown in Figure 1 form three small clusters of stations labeled "Array 1", "Array 2", and "Array 3". These arrays were formed by utilizing 35 instruments that were moved during the course of the experiment. The numbers indicate the deployment sequence. Array 1 recorded the first four shots, array 2 recorded the final two shots on September 10, and array 3 ran for all of September 11. These arrays were designed to examine wave propagation effects in the Glendora region in an attempt to better quantify the variability of seismic wave propagation in different directions at the site. Arrays 1 and 2 were designed to understand surface wave interactions with the edges of the mined out region and array 3 was designed to investigate possible site amplification at the top of the highwall pit on which building 8000 is situated and is shown in more detail in Figure 2

We had two different model REFTEK instruments: (a) newer units that were equipped with 24 bit digitizers, and (b) older units that used 16 bit digitizers. The 24 bit units were placed in the linear profiles at the points closest to the shot point. However, the more limited dynamic range of the 16 bit units (96 dB) led to clipping on some of the shots when they were located within 1000 m of the shot point. This could have been prevented by lowering the fixed gain on these instruments, but time constraints and access restrictions imposed for safety reasons allowed us to make a gain change only on units in the moving arrays during the second day of the experiment. For this reason potential users of this data need to beware of clipped data. Almost all the data from array 1 are clipped and several of the 100 line stations in the same area are clipped on almost every shot.

The location precision of these data is as good as is technologically feasible today. All station points were measured to a precision of approximately 1 cm using a Real-time Kinematic Global Positioning System owned by the Indiana University Department of Geological Sciences. We also used this equipment to precisely locate the shot point, the relative positions of survey points on most of the structures currently present at the Glendora Lake Facility, and a digital outline of the lake itself. The later was accomplished by putting the GPS system in a continuous acquisition mode and driving a boat around the shoreline and were used in preparing the maps in Figures 1 and 2.

Timing is not as good as would have been desirable for an experiment at this scale because we had only enough GPS units to equip about 1/4 of the stations. The rest had to utilize external clocks and a pulse test. The original log files are included in this tape under the directory data/logfiles to allow potential future users to evaluate the reliability of timing on any station. To correlate serial numbers of the log files with station names the best source is the stage table of the css3.0 database found in data/css3.0_format on the data tape for this experiment.

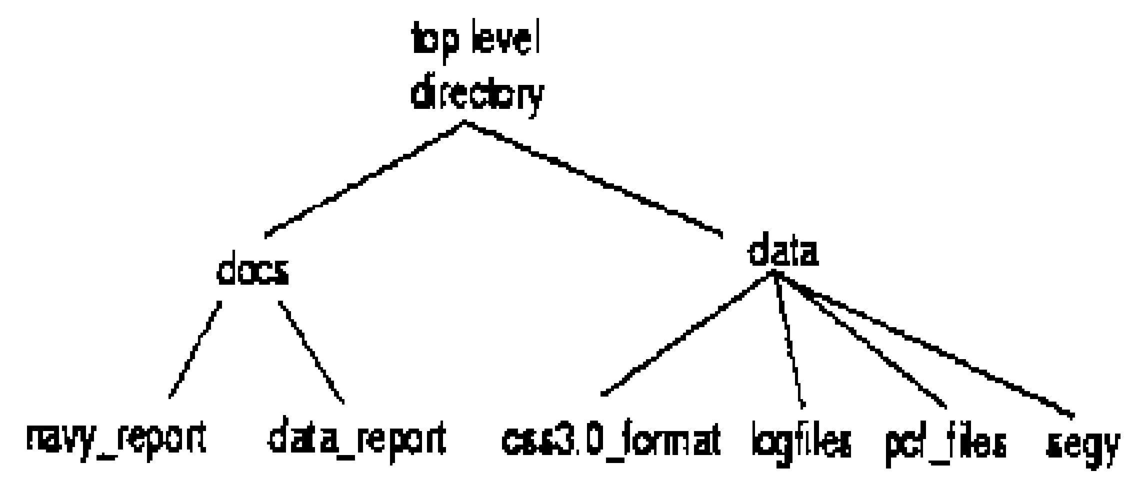
Data Tape Organization

Tape format

The data were originally written on 4 mm DAT tape using the UNIX tar command from a Sun workstation running Solaris 2.7. The specific command used to generate the tape was

tar cf /dev/rmt/0 .

The layout of directories under the "." directory from which this tape was produced is as follows:



navy_report contains files used to create an unpublished report on the results of these experiments to NSWCC

data_report is contains the electronic form of this report

css3.0_format contains database tables and waveform files in the css3.0 schema with some special extension tables.

logfiles contains Reftek logfiles produced when ref2segy was run on raw field tapes

pcf_files contains PASSCAL pcf_files used to make clock corrections on these data

segy contains segy disk images of these data importable into common reflection processing packages

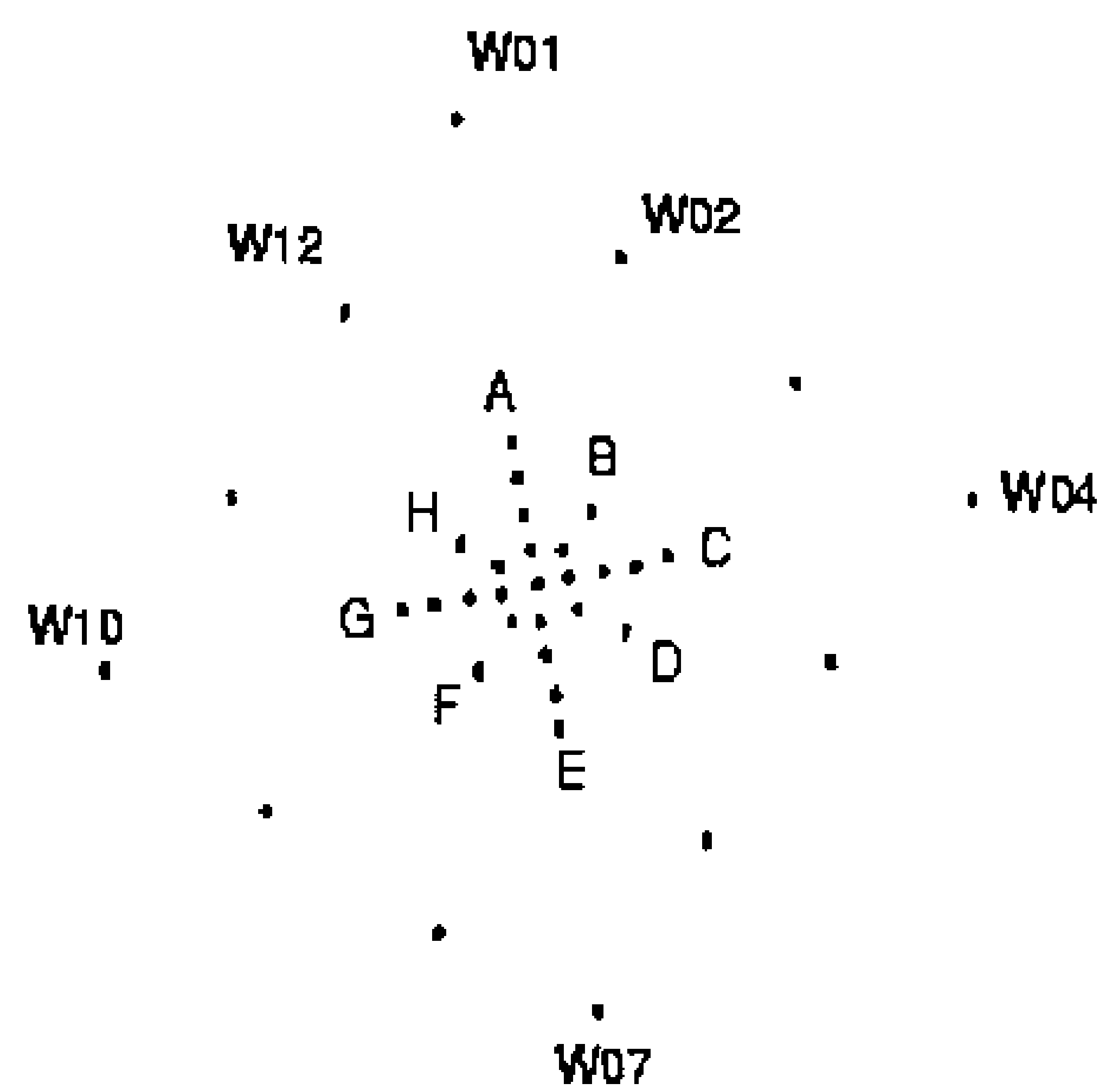
CSS format data

The data in this css3.0_format directory contain the most complete database of parameters from this experiment. The data in this directory can be immediately manipulated by software in the Antelope package from Boulder Real Time Technologies (http://www.brtt.com) and the older, public domain version of many of the same programs that was called Datascope which I believe is still available from IRIS.

The data in this directory have all the standard CSS3.0 tables. Note that all the 4.5 Hz sensor data use the Seed channel codes EHZ, EHN, and EHE. The accelerometer data are tagged GHZ, GHN, and GHE which DMC people told me was the correct code for strong motion accelerometer data. The response directory along with the associated CSS3.0 tables related to responses are correctly built so one could, in theory, build a SEED volume from these data. I considered this an absurd format for these data, however, and chose not to do so.

The station names have a pattern that is also important to know.

1. The "100" line stations (100, 101, 102, ..., 126) are stations on the linear profile running through array 1 shown in Figure 1. This line of stations radiates roughly east from the shot point with the lowest number closest to the shot point.
2. The "200" line stations (200, 201, ... , 216) are stations on the linear profile running roughly southward from the shot point. Station 200 is again the closest to the shot and 216 is the most distant station on this line.
3. The "300" line stations begin at a point approximately straight north of the shot point and run westward, across the lake, through array 3, and to the west outside of the mined area. Again 300 is the closest station to the shot point.
4. Arrays 1 and 2 used a common 24 element array geometry illustrated below. The naming conventions is nAm where n is the "array number" (1 or 2), A is the arm (i.e. A, B, C, ..., H), and m is the index position of that station relative to the center of the array. For example, 1B2 is the station just below and to the left of the "B" in this figure for array 1. Note that the actual geometries for arrays 1 and 2 are rotated relative to this figure.
5. Array 3 was a "grid array" with points located on an approximately uniform grid with 10 m between stations. Due to



a surveying error the actual geometry is a skewed rectangle. The naming convention is XnYm with n and m being index positions relative to an an grid origin, X0Y0, in the southwest corner of this array. Thus, for example, X1Y2 is 1 grid point east and 2 grid points north of X0Y0.

I've included the arrival table for picks on most of the seismograms in this database to aid future users of these data. I used some nonstandard tags on these phases that need to be explained:

1. The largest number of phase picks are P. P is the dominant P phase, but not necessarily the first arrival as would be the case by standard convention. P here is an intepretation by me. It is my best guess of a phase that propagates through the mined out area of Glendora as a head wave at the bedrock interface. Outside the mined out area it continues as a similar entity traveling through the bedrock, but the upper layer thins to the natural weathered layer.
2. In the mined area I pick a phase tagged "Pd" which is mnemonic for P direct. It is an interpretation that is not certain to be correct. In Poppeliers and Pavlis (2001) we argue this strong arrival is the direct wave traveling through the water saturated mining spoil. We originally interpretted this phase as a strong P to S conversion, but we became convinced it was a direct wave on the basis of two lines of evidence: (1) the polarization of this arrival is not consistent with a refracted S arrival, and (2) a noise test conducted independently (not included in this data set) found the velocity of water saturated mining spoil was consistent with that observed for this phase.
3. There are a few picks on the far end of the 100 line stations labelled Pr. These are what I interpret to be a secondary head wave generated at the contact between Pennsylvanian age sands and shales and Mississippian carbonates that conformably underly the Pennsylvanian rocks in this region.
4. There are a fair number of "A" picks for airwaves. Most of these are on the the G channels when I got interested in the strong air wave signals recorded on some buildings. (Look for example at the BARG on evid 5 and 9 which were large explosions shot very shallow. The Barge is a floating building in the middle of the lake that got hammered by the airwave from these shots. For example, the airwave generated accelerations were about twice the amplitude of the seismic wave amplitudes for evid 9.)
5. There are a few "R" and "L" picks lying around the database. These are mostly junk left from experimenting with pick schemes for portions of the surface wave train. They are what I interpretted as Rayleigh and Love modes respectively, but they should not be taken too seriously.

This database also contains a nonstandard table that is not part of CSS3.0. I defined an extension table to CSS3.0 I called "shot" (contained in the file "glendora.shot") that contains basic parameters of the shots that were recorded here. The schema descriptor for this table can be found in the same directory in the file named "shot_mods". The shot table documents shot size, shot depth, origin time, and shot location for each of the explosions that were recorded here. The user should note that the origin times are not accurate as they were constructed as a fixed time offset from the pick at the closest station. This table should be directly visible with the Datascope/antelope program called dbe. However, because it contains information not stored in the segy format files (see below) the contents are tabulated here for those unable to utilize the CSS3.0 files:

glendora.shot

File Edit View Options Graphics Help

evid	evname	lat	lon	elev	time	dnorth	deast	edepth	shotsize
1	shot1	39.1193	-87.3668	0.0562	9/10/1998 (253) 15:45:00.676	-0.0340	0.7501	6.1000	9.09
2	shot2	39.1193	-87.3668	0.0562	9/10/1998 (253) 16:00:00.994	-0.0340	0.7501	6.1000	18.18
3	shot3	39.1193	-87.3668	0.0562	9/10/1998 (253) 16:15:01.048	-0.0340	0.7501	6.1000	27.27
4	shot4	39.1193	-87.3668	0.0562	9/10/1998 (253) 16:30:00.833	-0.0340	0.7501	3.0500	9.09
5	shot5	39.1193	-87.3668	0.0562	9/10/1998 (253) 17:15:00.858	-0.0340	0.7501	3.0500	18.18
6	shot6	39.1193	-87.3668	0.0562	9/10/1998 (253) 17:30:00.920	-0.0340	0.7501	3.0500	27.27
7	shot7	39.1193	-87.3668	0.0562	9/10/1998 (253) 17:45:01.084	-0.0340	0.7501	1.5200	9.09
8	shot8	39.1193	-87.3668	0.0562	9/10/1998 (253) 18:00:00.959	-0.0340	0.7501	1.5200	18.18
9	shot9	39.1193	-87.3668	0.0562	9/10/1998 (253) 18:15:01.060	-0.0340	0.7501	6.1000	36.36
10	shot10	39.1193	-87.3668	0.0562	9/10/1998 (253) 18:30:01.609	-0.0340	0.7501	7.9200	45.45
11	shot11	39.1193	-87.3668	0.0562	9/10/1998 (253) 18:45:00.885	-0.0340	0.7501	6.1000	45.45
12	shot12	39.1193	-87.3668	0.0562	9/10/1998 (253) 20:15:01.422	-0.0340	0.7501	3.0500	45.45
13	shot13	39.1193	-87.3668	0.0562	9/11/1998 (254) 16:00:00.853	-0.0340	0.7501	15.2400	45.45
14	shot14	39.1193	-87.3668	0.0562	9/11/1998 (254) 16:32:05.692	-0.0340	0.7501	3.0500	45.45
15	shot15	39.1193	-87.3668	0.0562	9/11/1998 (254) 19:32:01.206	-0.0340	0.7501	15.2400	45.45
16	shot16	39.1193	-87.3668	0.0562	9/11/1998 (254) 19:45:14.686	-0.0340	0.7501	15.2400	45.45
17	shot17	39.1193	-87.3668	0.0562	9/11/1998 (254) 20:00:00.974	-0.0340	0.7501	15.2400	45.45
18	shot18	39.1193	-87.3668	0.0562	9/11/1998 (254) 20:15:01.110	-0.0340	0.7501	3.0500	45.45
19	shot19	39.1193	-87.3668	0.0562	9/11/1998 (254) 20:30:01.156	-0.0340	0.7501	3.0500	45.45
20	shot20	39.1193	-87.3668	0.0562	9/11/1998 (254) 20:45:00.695	-0.0340	0.7501	1.5200	18.18

Dismiss

Note that dnorth and deast in this and the similar site table are GPS measured offsets from the GPS reference station located near array 3. The absolute latitude and longitude of this origin is less reliable because it was not made from a differential measurement. It was, however, produced from an average estimated by the Trimble surveying software for the reference station. The actual accuracy of this measurement is not known, but the shot and station locations are known to a precision smaller than the size of the sensors we were using. The accelerometer locations are slightly less accurate. It is slightly worse in most cases because the GPS unit failed to lock near these metal buildings due, presumably, to strong multipaths induced by reflections from the buildings. We located points as close as possible and corrected the final locations with a simple tape and compass measurement. The nominal accuracy of this is probably about 20 cm, which is within the last significant figure of the tabulated data. Finally, the reader should recognize that the shot size here is kilograms of C4 (the explosive used for these tests by the Navy) and the edepth is the water depth in meters. Everything else is standard CSS3.0.

A final point about this component of the data is that we accidentally recorded a nearby mining explosion as we were pulling stations out on the morning of day 255. Data from this mining explosion are found only in the CSS database files. I did not write this event to a segy file.

SEGY disk image files

This is an active source data set that some may find useful to work with using one of several standard seismic reflection processing packages. For example, there is a fascinating problem here with surface wave propagation. I experimented briefly with f-k filtering in ProMAX and found a clear reflection of surface waves from the lake shore. There are probably a number of other similar bounce phases off the walls of the mined out region. Because this data set is not very large by modern standards I elected to also supply these data in what I will call segy disk image files. That is, these are bitstream versions of a segy tape stored on disk rather than individual seismogram files as used, for example, in PASSCAL segy. By "bitstream" I mean an image of a SEGY standard tape without the record marks. This means the file starts with the EBCDIC (this is actually filled with 3200 null bytes by the db2segy program used here) and binary reel headers followed by fixed length segy trace records. The distinction is that there are no record marks on a bitstream and position in the file can only be maintained by counting bytes from the beginning of the file. In addition, we violate the original SEGY standard by using IEEE four-byte floats in place of the defunct IBM floating point format that defined the original standard. This format is known to be readable in the Release 98 version of ProMAX using their SEG-Y Input module by selecting "Disk Image" and IEEE float in place of the defaults. I expect other packages to have similar capabilities.

Because of the geometry of this experiment the data don't really logically fit in a single multichannel framework. That is, I couldn't think of any rational way to assemble all the data into a single segy image that made much sense. Consequently, I created not one but five segy disk image files with the following contents:

1. The file *line100_300.sgy* contains data from the two linear profiles I referred to as the 100 and 300 line above. The order in the file is 319, 318, ..., 300, 100, 101, ..., 126. This was done because these two "lines" actually make a continuous profile with a minor bend at the 300 to 100 transition.
2. The file *line200.sgy* contains the 200 line data in order 200, 201, ..., 216.
3. The files *array1.sgy, array2.sgy,* and *array3.sgy* contain data from arrays 1, 2, and 3 respectively. Note that because these arrays did not record every shot, they contain only relevant data and are NOT filled with null shot records.

I chose to not put the accelerometer data into a segy format as I assumed no one would want these data in a multichannel format since the sensors have a drastically different response from the L28 data and are widely seperated from each other.

The five segy image files were produced from a program called db2segy which is a C program I wrote for this purpose. It is now being distributed by Boulder Real Time Technologies with their Antelope software as contributed software. db2segy creates a segy disk image according to a recipe defined by it's input "parameter file". The parameter file for db2segy for each of the five segy image file is important because it defines the way css3.0 station: channel codes should be mapped onto channel numbers, which is all that segy understands. In theory, one could get all they want out of the shot and receiver coordinates written in the trace headers by db2segy, but to make life a little easier for potential users I'm supplying two additional sets of files:

1. The data/segy/pf directory contains the parameter files used to drive db2segy for each of the five segy image files. They have names that have an obvious association (line200.pf, array1.pf, etc.)
2. The data/segy/db2segy_output directory contains the standard output stream when db2segy was created. The output of db2segy shows how each station, channel, and shot number are mapped onto the segy disk image file.

Note that for all these files I chose to effectively sort the data by channel first. Specifically, in every case if there are n stations in the given file then the east channels are the first n channels, the north components are the next n+1 to 2n channels, and the vertical are the last n channels.

Potential uses of these data

I believe it is worthwhile for the P.I. of any experimental project like this to describe potential uses of these data beyond those published or planned for publication by the P.I. and related individuals. That is the purpose of this section. The list below is surely not inclusive, but covers topics I considered interesting in the data for future study. The order is significant as it indicates my bias as the relative scientific merit, but since this is just an opinion it shouldn't be taken too seriously.

1. In a paper we plan to submit for publication roughly simultaneously with this report, Poppeliers and Pavlis [2001] used data primarily from array 3 to study topographic site effects. We found that topographic site effects seem to be one of those favored topics for people working on computer simulation of wave propagation, but there is almost no useful data on the subject. Every study we could find on topographic site effects used station spacing far too wide to do any type of wavefield processing and results were limited to relatively crude amplitude measurements. Array 3 provides some stunning results on topographic wave propagation effects. Until the paper is published look for a preprint under our anonymous ftp site .
2. These data have some very interesting applications to explosion source physics, particularly underwater explosives and seismic coupling questions. Anyone interested in this subject is encouraged to print out and read the unpublished report I wrote for the Navy (Pavlis, 1999) that is stored with these data. The report describes the spectral technique I used to isolate the source and propagation terms and average the results. The basic idea is that because we have a source whose location is essentially fixed relative to the profile stations spectral ratios between shots provided information on relative source spectral characteristics from shot to shot. The most remarkable result, I think, is found in Figure 3. That result shows that the high frequency output of these explosions is essentially independent of shot size. The primary variation in spectral amplitude is at frequencies below about 20 Hz. The literature on underwater explosions is enormous and perhaps this is a well known phenomenon, but I find it surprising. A working hypothesis is that it represents the fact that no material can maintain a shock front below a minimum scale length without being totally disrupted. In nuclear explosion physics this is the concept of a transient cavity within which all the material inside the cavity is first vaporized then permanently deformed. The effective source is a volume is related to when the expanding stress field around this cavity drops to near the elastic limit. At that critical size the source begins to radiate elastic waves at a characteristic period. In the case of water, this probably means that the initial transient bubble formed by the explosive gases initially has enough energy to vaporize water causing a critical shock front limit. This is different from the nuclear case because the explosive detonation time constant is much longer and there may be radiation effects that spread the pulse as the water bubble expands. That is, the pulse rise time is what presumably controls the high frequencies in the data, and the observations in figure 3 indicate some physical process that puts an upper limit on the pulse rise time. The point is that these data provide some potentially useful data to test theoretical models of seismic sources, particularly underwater explosions.
3. I mentioned earlier that these data have some very interesting potential for measuring wave propagation effects and particularly the scattering characteristics of surface waves. The mining spoil/bedrock interface is about as dramatic a real interface as could be conceived. It is unique it than it is an absolutely flat surface (Mining stopped at the base of the lowest coal unit the mining company was after -- they do not move extra rock for any reason as it costs them a lot of money to do so.) covered by a totally homogenous material (Fractured sandstone and shale fragment with scale lengths from about 1 m downward in size mixed up as if they had been run through a blender.). The Pennsylvanian rocks below the mined area are rather complex fluvial deposits at the outcrop scale, but at seismic wavelengths they are relatively homogeneous. In short, this is a pretty unique experimental measurement for wave propagation studies as it is not complicated greatly by potential anisotropic effects. It is complicated strongly by strong variations in the thickness of the near-surface waveguide formed by the mining spoil.

There are several 10s of meters of topography across the site. I apologize that I am unable to supply a topographic map of the area as I do not have one. A more dramatic features is that the waveguide abruptly terminates at the lake shore and at the boundaries of the mined area. As a result, there is strong observational evidence in these data that surface waves are strongly reflected from these essentially vertical discontinuities in the near-surface waveguide. The combination of the linear profiles with arrays 1 and 2 (I actually designed these arrays with this problem in mind.) make this a powerful tool to understand how surface wave interact with vertical boundaries. I'd love to work on this problem some day, but I don't see a window of time to do so for several years so have at it. I wish you luck.

4. In addition to source physics, a more complete study could be conducted on how different parts of the wavefield depend upon source depth. My report to the Navy used only simple spectral techniques because I used these as a way to better quantify an empirical size/depth relation for them. A more comprehensive study could be conducted to measure quantities like the relative excitation of surface waves, P, and what I called Pd in the data section. This could provide useful high-precision data to better understand empirical discriminates like Rg to P ratios being experimented with at this time in the nuclear monitoring world.
5. The air wave data interaction with buildings seen in the accelerometer data is amazing and indicates how strong the airwave generated by some of these shots was. (I note the personal experience of actually being able to feel a pulse of air with some of the large shallow shots, although clearly most of the energy was at frequencies below the limit of my hearing.) A good student project is to try to model the interaction of the airwave with a building to see if there is any consistency with independent measurements of air pressure made by Navy personnel. Unfortunately, I do not have the air pressure data available to me, but if I am still around when you read this and you want to pursue this I'll try to connect you with the right people.

References

Pavlis, G. L. (1999). Seismic monitoring measurements of nonfragmenting explosive tests at the Glendora Test Facility, NSWCC, unpublished report to Comarco Systems Inc., Bloomfield, Indiana, Subcontract 0002-3 of Navy Contract N00164-98-D-0008. (included with these data)

Poppeliers, C. and G. L. Pavlis (2000). The seismic response of a steep slope: an analysis from a dense, three-component seismic array, *Earth Interactions,* in review.