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by

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**A COMPUTER-BASED SYSTEM FOR PROCESSING GEOPHYSICAL DATA
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ABSTRACT

A diverse set of computer programs has been developed at the Lawrence Livermore National Laboratory (LLNL) to process geophysical data obtained from boreholes. These programs support such services as digitizing analog records, reading and processing raw data, cataloging and storing processed data, retrieving selected data for analysis, and generating data plots on several different devices. A variety of geophysical data types are accommodated, including both wireline logs and laboratory analyses of downhole samples. Many processing tasks are handled by means of a single, flexible, general-purpose data-manipulation program. Separate programs are available for processing data from density, gravity, velocity, and epithermal neutron logs.

The computer-based storage and retrieval system, which has been in operation since 1973, currently contains over 4400 data files. Most of this data was obtained from the Nevada Test Site (NTS) in conjunction with

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the nuclear test program. Each data file contains a single geophysical parameter as a function of depth. Automatic storage and retrieval are facilitated by the assignment of unique file names which define the storage location of each data file. Files of interest to the user may be located and retrieved by means of a search program which examines the catalog.

A convention recognized by all programs in the system is that of a zero ordinate denoting a gap in an otherwise continuous data trace. This convention provides a simple mechanism for editing and displaying data files in an automated and consistent manner.

Key Words: Geophysical logging, data processing, data management, computer graphics.

INTRODUCTION

Geophysical data obtained from boreholes are processed at the LLNL in Livermore, California, in support of the nuclear test program. The data are used to evaluate the geological and geophysical setting for proposed underground test sites. The goal of the containment program is to assure that the radiation produced by the detonation of a buried nuclear device will be successfully contained. Special attention is given to those parameters which might adversely affect containment.

This paper will describe the computer-based system which has been developed to process geophysical data in support of the containment program. Several very successful processing techniques which might be adapted to any processing environment will be discussed. These techniques include a method for denoting gaps in data, the implementation of a flexible, general-purpose data-manipulation program, and a storage and retrieval system based on a catalog file and unique file names. Examples will be given of several standard graphical and tabular displays prepared for the containment program.

DATA TYPES

The data are obtained primarily from the Nevada Test Site (NTS) which is located in southern Nevada approximately 110 km northwest of Las Vegas. Boreholes at NTS generally penetrate alluvium, tuff, and basalt. A typical borehole is 300 to 800 meters in depth. Instrument and exploratory holes are generally 0.23 to 0.33 meters in diameter, while emplacement holes range from 2.1 to 2.5 meters in diameter. The holes are normally uncased except for a surface liner which extends to a depth of 35 meters. The NTS water table is at a depth of approximately 550 meters.

Because the boreholes are large in diameter and generally not fluid-filled, special logging tools are required to obtain the geophysical data. Over 4400 data files have been stored and cataloged since 1973, when the storage and retrieval system (Richter, 1973) became operational. The

distribution, as of January 1982, of these data files by log-type is presented in Figure 1. Note that gamma-gamma density logs are the dominant data type with some 1200 files. Most other data types are represented by 100 to 300 files each.

A brief description of the log types may be in order. The caliper tools generally measure the borehole diameter along three horizontal axes. A variety of gamma-gamma density tools are used to obtain the bulk density of the formation. Single-receiver tools are equipped with one or two proximity wheels to measure the gap between the tool and the borehole wall. A two-receiver, borehole-compensated density tool is also available, but only for the small diameter holes. A gravity meter is used in the large-diameter holes to obtain bulk densities between measurement stations.

The Dry Hole Acoustic Log (DHAL) is a clamp-in device with a piezoelectric transmitter and one or two receivers (Hearst and Carlson, 1970). A standard 3-D acoustic tool is used to obtain acoustic velocities in small-diameter, fluid-filled holes. Vibroseis surveys measure acoustic velocity by means of a surface vibrator and a downhole, lock-in geophone.

Resistivity measurements in small-diameter holes are made via the standard induction and wet-hole electric tools. A special tool using four rolling contacts arranged in a Wenner configuration is used in large, dry holes.

A digital magnetometer (Douglas and Millett, 1978) measures the total magnetic intensity. Several epithermal neutron tools have been calibrated to provide measures of water content in both saturated and unsaturated media (Hearst, et al, 1981). The computed category generally represents acoustic impedance values calculated from bulk density and velocity measurements.

The last four categories in Figure 1 (grain density, water content, CO₂ content, and clay content) represent not logs but laboratory measurements made on material samples. Since core samples are generally not available, most laboratory analyses are performed on material obtained from the borehole wall by means of a special sidewall sampler.

It should be noted that both continuous and discrete data are collected and stored. Continuous data are obtained from continuously recording downhole tools. Discrete data are obtained from sample data and from station tools which must be stationary while making the geophysical measurement.

Of the data files currently in storage, approximately 73 percent were obtained from logs run by the Birdwell Division of Seismograph Services Corporation. Another 25 percent were obtained from logs or samples collected by the LLNL. The balance of the data (some 2 percent) was obtained from small-hole logs run by a variety of contractors.

GAP CONVENTION

Gaps may, and frequently do, occur in geophysical data for a variety of reasons. Those tools which must maintain contact with, or proximity to, the borehole wall cannot make a proper measurement when the wall is rough and irregular. Deep breakouts in the borehole wall often exceed the range of mechanical measurement devices such as those used on caliper logs and those used to measure the gap between the sonde and the borehole wall. Mud on the borehole wall will often render the proximity-measuring devices inoperative. Large variations in the measured parameter occasionally exceed the operating range of either the tool or the recording system. Separate logging runs made in the same hole do not always overlap. When these nonoverlapping logs are combined, a method should be available to denote the gap where no measurements were made.

Many processing procedures are affected by gaps in the data. Calculations involving several input parameters should not generate output in regions where any one of the input parameters is missing. Graphical displays should be able to depict those regions where no measurements have been made. Gaps must be properly handled to perform such mathematical procedures as averaging or integrating over depth.

The convention we have chosen to use denotes gaps by means of zero ordinates embedded in the data. All programs in the geophysical processing system recognize this convention. Any process which requires special treatment at gap locations must test every data point for the flag

value of zero. Since a zero ordinate means that no data exists at that point, legitimate measured values of zero must be offset slightly lest they be interpreted as gaps. The offset is obtained simply by adding a very small constant to the measured value. On our computer system, we have chosen an offset value of 10^{-50} .

The gap convention allows us to depict gaps in data traces graphically as illustrated in Figure 2. The upper plot shows a proximity trace which has a number of flat-topped regions where the range of the proximity device has been exceeded. We have chosen to denote the flat-topped regions as gaps since we do not know the actual proximity value there. The lower plot shows the same data trace with the gap flags inserted. Note that plotting is inhibited whenever a gap flag (zero ordinate value) is detected. Plotting resumes when the next non-zero ordinate value is encountered.

This plotting convention is also well-suited to displaying maps or contour lines which consist of many disjointed line segments. Any number of line segments can be stored in a single data file by delimiting each line segment with a gap flag. This capability is illustrated in Figure 3 where the EG&G corporate logo has been plotted. Note that the logo consists of seven closed line segments. As the logo was being digitized, the operator delimited each closed line segment with a gap flag simply by pointing to a region on the digitizer which causes a zero ordinate to be inserted.

The gap convention also applies to any mathematical operation involving one or more parameters. To illustrate that no output is generated whenever a gap occurs in any one of the input parameters, we have shown the result of an acoustic impedance calculation in Figure 4. The acoustic impedance trace on the bottom is the product of the velocity trace at the top with the density trace in the middle. Note that a gap in either the velocity or the density results in a gap in the acoustic impedance. In general, a gap in any input parameter will result in a gap in the output.

DATA PROCESSING

The data processing system consists of a diverse set of programs operating on several different computer systems. The bulk of the processing is performed on the large, time-shared computing facility at the LLNL. The facility is also used for long-term storage of the data. All of the programs utilizing that facility are written in FORTRAN for the CDC-7600 computers manufactured by Control Data Corporation. A PRIME-750 minicomputer is used to read digital tapes from the logging contractor. A local LSI-11/23 microcomputer manufactured by Digital Equipment Corporation is used to transfer data files from the PRIME to the CDC-7600. A Tektronix-4051 microcomputer is used for some specialized digitizing and color graphics applications. The bulk of the digitizing and graphics functions are handled directly on the central computing facility.

The data processing software consists of some 44 programs and 23 macros. The macros are special instruction sets for the general-purpose data manipulator to be described later. Of the 44 programs, 9 are involved in the file transfer function and 12 in the catalog and storage function. Twenty-three programs are involved in various data processing functions such as data acquisition, verification, conversion to engineering units, zonal averaging, and graphical output.

The bulk of the data currently in storage was obtained by digitizing analog records via a digitizer tablet linked directly to the central computing facility. This manual digitizing process is in large part being replaced by the reading of digitally-recorded magnetic tapes which have recently become available from the logging contractor. Small data sets such as those obtained from samples and from station tools are generally keypunched.

Many separate programs have been written to accommodate the various geophysical logging tools. The bulk density program will accept raw data from three different models of the gamma-gamma density tool. This program considers both hole-size effects, and the gap between the tool and the borehole wall. The proximity trace is smoothed to approximate the time-constant on the gamma-ray count-rate meter.

Another program processes the data from the borehole gravimeter to obtain the mean bulk density between each pair of measurement stations. This data is corrected for the effects of tide and terrain. A separate

program is available to calculate the effects of subsurface structure on the gravimetric density (Hearst, 1981).

Several epithermal neutron tools have been calibrated to measure water content in partially saturated media (Hearst, et al, 1981). The neutron program combines neutron count rate, neutron proximity, and bulk density data to obtain the water content.

Five separate programs are available for processing the raw data obtained from the DHAL and vibroseis velocity tools and from laboratory analyses of grain density and water content from downhole samples.

GENERAL-PURPOSE DATA-MANIPULATOR

Many different tasks are handled by a single, general-purpose data manipulation program. This program is specifically designed to operate on up to 14 separate arrays. It contains a variety of mathematical and statistical routines to perform such functions as calculating integrals and frequency distributions. It can interpolate on depth to generate an equally-spaced array which can then be easily depth-aligned with another interpolated data array. It can be used to insert gaps at all locations where the data exceeds a specified threshold value. English to metric conversions are performed routinely since most data are collected and stored in English units.

This same program provides graphical output on several different devices. Overplots of several data types or of different smoothing intervals are possible. Crossplots of two separate arrays can also be generated.

Flexible input and output formats provide a convenient mechanism for reformatting nonstandard data files. It should be noted that all of the data processing routines generate output files in a single, standard format which will accommodate up to six data arrays. The storage system, to be discussed later, generates binary files containing two arrays.

The general-purpose data manipulator operates from an instruction file. To simplify the generation of instruction files for operations which are performed repeatedly, a series of 23 macro files has been written. Each macro is designed to perform one particular task. A macro file is a skeleton instruction file which can be executed only after several variables within the macro have been defined. These variables typically include the input and output file names and several numeric processing constants. Thus, the generation of instruction files has been reduced to the relatively simple process of modifying several variables in an existing macro file.

The macros for the general-purpose processor provide a mechanism for handling many processing tasks which would otherwise require separate stand-alone programs. For example, macros are available for computing velocities from the two-receiver DHAL, for calculating acoustic impedance,

for correcting gamma-gamma density values for water content, and for correcting dry-hole resistivity measurements for variations in the bridge current. New tasks can be handled quite simply by either modifying existing macros or by writing new macros.

DATA STORAGE SYSTEM

All processed data is cataloged and stored via the Geophysical Data System (GDS). GDS consists of a single catalog file and over 4400 data files. The system is implemented via twelve separate programs. Eight programs are involved with the generation and maintenance of the catalog file and the data files. The remaining four programs allow the user to search the catalog and retrieve data for printing or plotting.

The catalog file contains 35 descriptors for each data file. Each descriptor is a ten-character word on the CDC-7600 computer. The descriptors are clear ASCII text to allow for simple direct searches and readable listings. All catalog entries are sequential. New entries are simply added to the end of the catalog. For user convenience, a catalog listing sorted by holename, log-type, and run number can be generated. The contents of the descriptor words are given in Table I. Note that each of the 35 descriptors contains one particular type of information. The catalog can be searched for any combination of the 35 descriptors. Any subset of the files selected by the search program may be requested for retrieval and display.

Each GDS data file contains a single geophysical parameter as a function of depth. Individual files contain a maximum of 5000 points in binary format with depth as the abscissa and a geophysical parameter as the ordinate. A header block consisting of selected catalog descriptors plus up to 1600 characters of free-field text precedes the data in each file. The header block is used by several programs to identify the data contained in the file and to provide automatic labeling of plot axes.

UNIQUE FILE NAMES

A very important feature of GDS is that each data file is assigned a unique file name. No changes can be made to any GDS data file without the assignment of a new file name. Moreover, each nine-character file name uniquely identifies that file's location in the storage system as depicted in Figure 5.

Note that the storage system is arranged in a tree structure. Only three levels are required for the storage of GDS files. The upper level consists of a series of up to 50 directories, each of which point to a series of up to 48 middle-level directories. Each of the mid-level directories in turn points to up to 50 data files. This simple, three-level structure will accommodate up to 120,000 data files. It should be noted that the structure could be easily expanded to accommodate more files.

The general format of a GDS file name is GnnDmmFnn where nn may range from 01 to 50 and mm may range from 01 to 48. Referring to Figure 5, note that Gnn refers to the upper level directory and Dmm to the middle-level directory. Thus, by disassembling the file name G02D01F01, we obtain the storage address G02:D01:G02D01F01.

The unique relationship between the GDS file name and the storage location makes automatic storage and retrieval possible. Given a file name, the storage address for that data file can be constructed and a read or write command can be issued automatically without any user intervention.

OUTPUT FORMATS

A variety of devices are available at the LLNL for the output of text or graphics. A Television Monitor Display System (TMDS) is available for text editing and for previewing graphical displays. UX80 graphics files may be printed on local electrostatic printers at sizes up to 0.6 meters in width and 3.6 meters in length. An FR80 camera system can print graphics files on 16-, 35-, or 310-mm film. The 310-mm size is also available as a photographic positive print. Both text and graphics files can be printed on a non-impact printer located at the computer center. Multicolor pen plots may be generated on a local microcomputer.

A typical summary plot generated for the containment program is presented in Figure 6. This plot presents a number of different geophysical parameters for a particular borehole. Note that symbols are plotted at the measurement stations on the sound-speed plot. A number of plots contain several data traces with different line widths. The broader lines are used for those traces which have been smoothed over a larger depth interval. The density plot contains two gamma-gamma density traces, as well as a gravimetric density trace which is composed of a series of horizontal and vertical line segments.

It should be noted that only the data traces and the plot grid are computer generated. These data traces are glued onto a master sheet which contains all of the textual information. This procedure allows individual data traces to be added or replaced without needing to regenerate all of the data plots. The plots in Figure 6 were generated with a single macro on the data manipulation program.

A separate program is available to generate zonal averages of several parameters with either linear or spherical weighting by depth. Spherical weighting considers a sphere of a given radius about a designated point in the borehole. If the sphere is then divided into a series of horizontal slabs, with each slab centered on a data point, the datum within each slab is weighted according to the volumetric fraction represented by that slab. Linear weighting is accomplished either by integration or by numeric averaging, depending on the data type.

A typical example of computer-generated zonal averages is presented in Figure 7. The upper table presents the mean values for a number of different parameters. The mean values were obtained over an averaging radius of 12 meters centered on a reference depth of 335 meters. The depth interval covered by each of the measured parameters is noted at the bottom of the figure. Several of the parameters reported in the upper table were derived from the measured parameters. The calculated parameters are noted as such in the column labeled "Log-Type." The estimated error is either the standard error of the mean or some other error measure related to the measurement process for that particular parameter. The data range within the averaging interval as well as the source of each data type is noted in the upper table. The overburden values listed in the middle of Figure 7 represent the mean values of those parameters from the reference depth of 335 meters to the surface. Since none of the measurements extend to the surface, an assumed or an extrapolated value must be used for the near surface.

CONCLUSION

Geophysical data processing at the LLNL involves a diverse set of computer programs operating on several different computer systems. Several factors have contributed to the success of the entire processing system, namely:

- 1) A convention for handling gaps in the data.
- 2) A general-purpose program for manipulating data.

- 3) A catalog file for locating processed data.
- 4) Unique file names which define the storage location of data files.
- 5) Flexible programs for generating plots and zonal averages of *many* separate parameters.

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Table 1. Catalog descriptors.

DESCRIPTOR NUMBER	TYPE OF INFORMATION	FORMAT
1	Name of data file	GnnDmmFnn
2	Number of points in file	
3	Tape storage addresses	CHnnn-nnn
4	Hole identification	
5	Hole type	
6	Log type	
7	Log run number	
8	Date of logging run	YR-MO-DY
9	Time of logging run	START-STOP
10-11	Ordinate data type	
12	Ordinate data units	
13-14	Abscissa data type (depth)	
15	Abscissa data units	
16	North coordinate of borehole	
17	East coordinate of borehole	
18	Surface elevation at borehole	
19	Drilled depth of borehole	
20	Minimum abscissa value (depth)	
21	Maximum abscissa value (depth)	
22	Logging agency	
23	Processing agency	
24	Processing date	YR-MO-DY
25	Primary data analyst	
26	Digitizing method	
27-28	Processing programs	
29-32	Data quality by depth zones	G START-STOP
33-35	Common hole name and comments

Figure 1. The distribution according to log type of the 4400 geophysical data files in storage as of January 1982.

Figure 2. An illustration of how gap flags inhibit plotting. The data set for the upper plot does not contain any gap flags. The data set for the lower plot is identical to that of the upper one except that gap flags have been inserted in the flat-topped regions where the range of the measuring device was exceeded.

Figure 3. An example of how the gap convention allows a series of discontinuous line segments to be plotted. The figure shown here, the EG&G corporate logo, consists of a series of seven closed line segments. The data to generate this figure resides in a single data file. Gap flags delimit each line segment.

Figure 4. An example of how gaps are handled in mathematical operations. The acoustic impedance trace on the bottom is the product of the velocity and density traces above it. Note that a gap in either of the two input operands produces a gap in the resultant acoustic impedance.

**EACH FILE NAME UNIQUELY IDENTIFIES
A LOCATION IN STORAGE E.G., G02D01F01**

Figure 5. Each GDS file name uniquely identifies a location in storage. The GDS storage system consists of a three-level tree structure where each G-level directory points to a series of D-level directories, each of which points to a series of data files. The location and storage address for the file named G02D01F01 is illustrated.

Figure 6. A typical summary plot generated for the containment program. Symbols on the sound-speed plot indicate the measurement locations. Heavier line widths indicate larger smoothing intervals. Text was not computer generated.

DATA SUMMARY FOR 335.0 M

AVERAGING RADIUS = 12.03 M (11.89 UP, 12.18 DOWN) MEDIUM IS TUFF
 AVERAGING INTERVAL = 323.1 T 347.2 M

PARAMETER	MEAN VALUE	UNITS	NO. POINTS	STD DEV	ESTIMATED ERROR	DATA-RANGE	DEPTH-RANGE	AVERAGING METHOD	LOG-TYPE	RUN NO.
BULK DENSITY	1.70	MG/M3	130	0.13	0.09	1.44 TO 1.96	323.2 TO 347.0	SPH	DENSITY BC	1,2
GRAIN DENSITY	2.41	MG/M3	9	0.04	0.01	2.37 TO 2.50	326.1 TO 344.4	SPH	SAMPLE	1,1
WATER CONTENT	12.3	WT%	9	2.7	0.9	9.6 TO 16.1	326.1 TO 344.4	SPH	SAMPLE	1,1
POROSITY	38.1	VOL%	9	5.1	1.7	32.7 TO 44.3	326.1 TO 344.4	SPH	CALCULATED	
SATURATION	55.0	VOL%	9	5.1	1.7	46.2 TO 62.0	326.1 TO 344.4	CALC	CALCULATED	
GAS POROSITY	17.2	VOL%	9	2.9	1.0	12.6 TO 21.3	326.1 TO 344.4	SPH	CALCULATED	
CO2 CONTENT	0.7	WT%	1	0.	0.	0.1 TO 0.1	329.2 TO 329.2	INT	SAMPLE HNT	1,1
COMPOSITE VELOCITY	2253.	M/S	125	232.	113.	1449. TO 2910.	324.1 TO 347.2	INT	COMPOSITE	1,2,1
SEISMIC VELOCITY	2437.	M/S	2	.	390.	. TO .	289.6 TO 365.8	INT	VIBROSEIS	1

OVERBURDEN PARAMETERS

BULK DENSITY = 1.90 MG/M3 + - 0.10
 COMPOSITE VELOCITY = 1523. M/S + - .
 SEISMIC VELOCITY = 1745. M/S + - 87.
 GAS POROSITY = 14.8 VOL%

BULK DENSITY IS WATER-CORRECTED

VOLUMETRIC AVERAGING

DATA TYPE	STARTING DEPTH	ENDING DEPTH
DENSITY	24.3	580.8
DENSITY GR	30.5	585.1
WATER CONT	30.5	585.1
CO2 CONTEN	30.5	469.4
VELOCITY	27.4	578.7
TRAVEL TIM	30.5	518.2

Figure 7. A typical set of computer-generated zonal averages for several measured and calculated parameters. The depth interval of each measured parameter is listed at the bottom of the figure. Note that error estimates, data ranges, averaging method, and data source are given for each mean value presented in the upper table.