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INSTRUMENTATION AND COMPUTATIONAL TECHNIQUES AND RESULTING GEOSTATISTICAL CHARACTERIZATION OF INEL VADOSE ZONE BASALT

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ABSTRACT

The geostatistical characterization of the Eastern Snake River Plains (ESRP) basalt found in the vadose zone at INEL depend heavily upon instrumentation and computer programs developed by the INEL Geoscience Unit personnel.

Individual flow lobes or fingers have an "ideal" four-element, vertical organization: (1) a substratum, (2) a bottom vesicular zone, (3) a central, largely nonvesicular zone, and (4) an upper vesicular zone.

Laboratory measurements of permeability, porosity, density, capillary pressure/pore-size distributions, and surface area were carried out with equipment developed and fabricated at INEL, and computation of the characterization parameters was carried out using personal computers, with computer programs specifically written for this purpose by the authors.

Median permeability (md), porosity (%), and grain density (g/cm^3) (respectively), are the following: for the lower vesicular zone 4, 21, and 3.04; for the central zone 8, 10, and 3.05; and for the upper vesicular zone 7, 22, and 3.04.

Core and outcrop studies at Box Canyon yield a median flow lobe thickness of approximately 4.6 m. The apparent length/maximum thickness geometric data analysis yields a general southwest-northeast flow lobe orientation at Box Canyon, and flow lobe length:width:thickness ratio of > 8.7:4.6:1.

Geostatistical analysis results from Hell's Half Acre were also used to develop distribution models for medial/distal length:width:thickness substrate elements. The median l/w/h is > 130:69:15 ft (> 40:21:4.6 m). The median substrate distribution is pahoehoe 51%, fracture/fissure 19%, rubble 17%, and bouldery/blocky/broken 13%.

INTRODUCTION

The characterization of the basalt beneath the Radioactive Waste Management Complex (RWMC) at the Idaho National Engineering Laboratory (INEL) (Figure 1) largely involved data acquisition for parameters that can be used to develop a conceptual model of the vadose zone basalt in and around the RWMC. This study was funded by the Waste Management Program, and the procedures and results were submitted to DOE as an FY-89 draft final report.

The RWMC has been subjected to emplacement of lava flows from both rift zones and to accumulation of alluvial sediments from the Big Lost River and loess deposits from sources to the southwest. The volcanism has been episodic, so that one or several lava flows are emplaced over a short period of time (a few hundred to a few thousand years) and no sediments accumulate between them. These volcanic episodes have been separated by long periods of time (10s to 100s of thousands of years) during which sedimentary interbeds

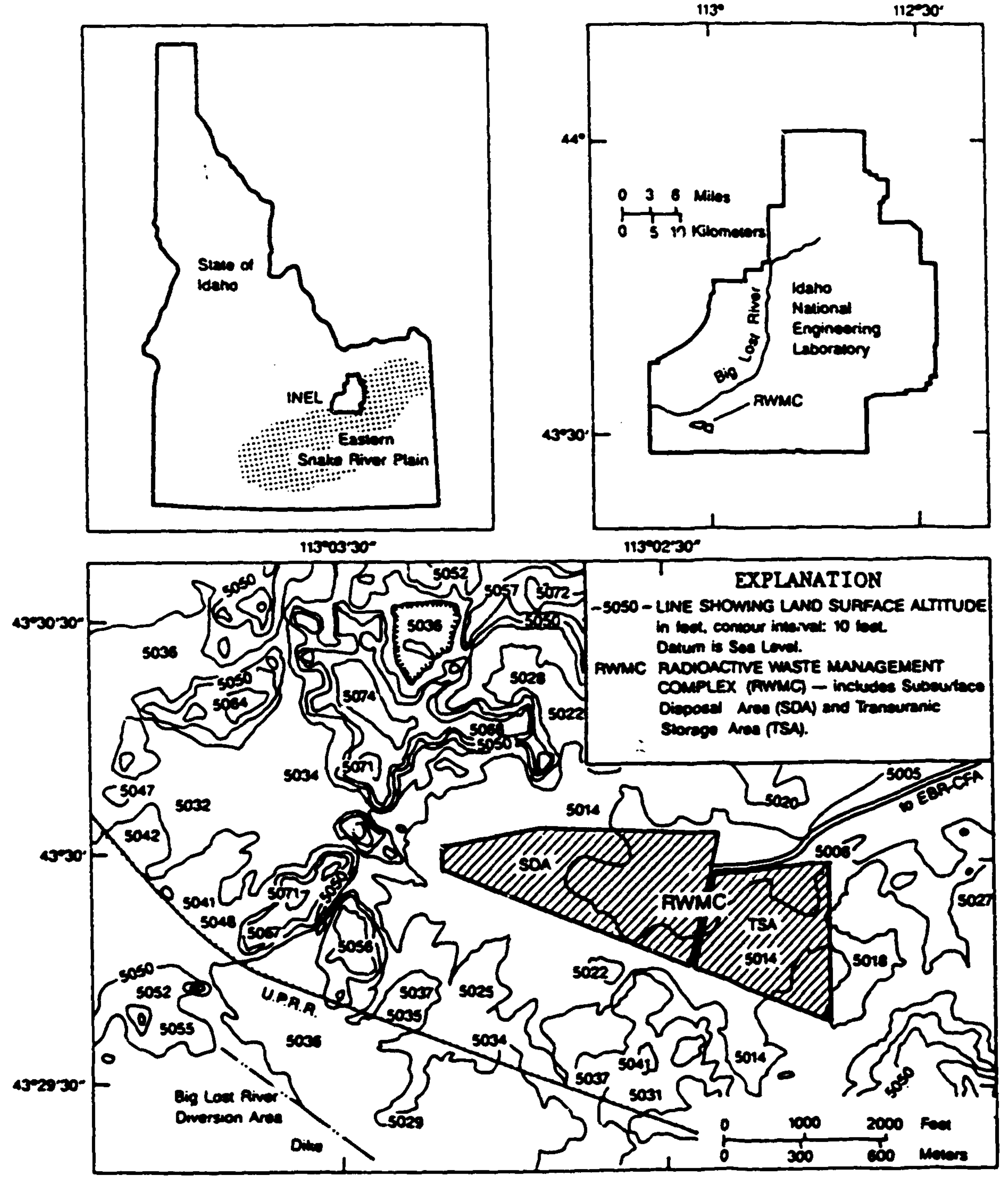

Figure 1. Location of the Radioactive Waste Management Complex at the INEL.

accumulate (Anderson and Lewis, 1989).

The individual lobes or fingers of these flows have an "ideal" four-element, vertical organization: (1) a substratum, (2) a bottom vesicular zone, (3) a central, largely nonvesicular zone (it can, however, contain an intermediate vesicular zone), and (4) an upper vesicular zone (Figure 2). Characterization of these elements were carried out by laboratory, core, and field studies.

The petrophysical and geostatistical characterization of these vadose zone basalts involve measurements of permeability, porosity, bulk density, capillary pressure/pore-size distribution, and surface area in the laboratory using basalt plugs, and the determination of flow lobe geometry, fracturing and substrate distribution from core and outcrop studies. The acquisition of these data depends heavily upon instrumentation and computer programs developed by INEL Geoscience Unit personnel.

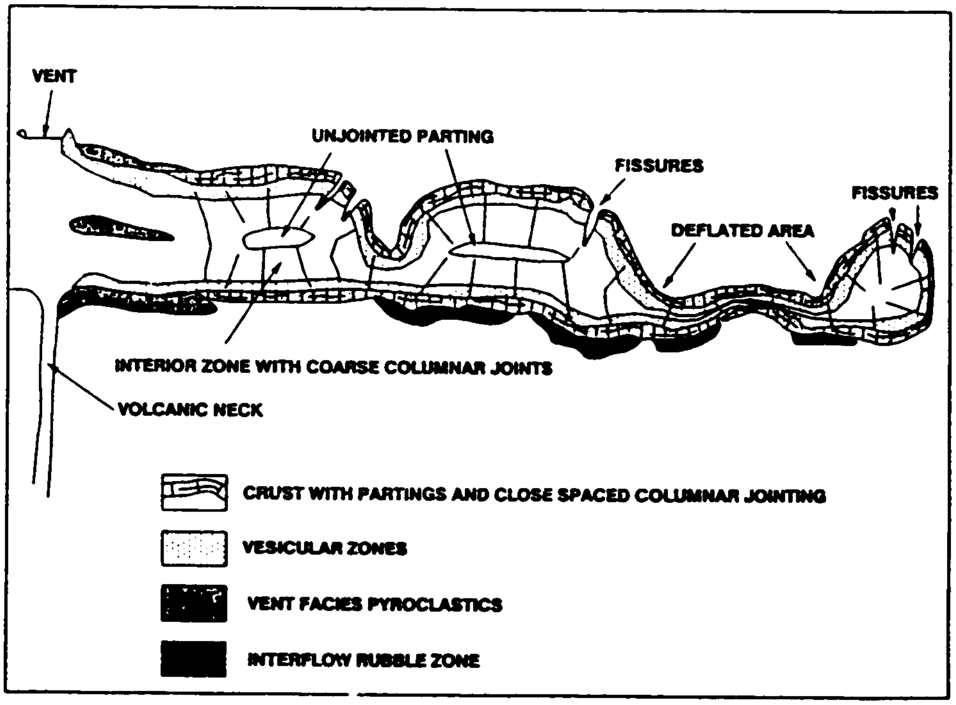

Figure 2. An idealized cross section showing flow geometries found at INEL sites.

EQUIPMENT

The following is a description of the equipment developed/used, principles of operation, limitations, and common problems associated with the operation of the equipment. More detailed information on the equipment or for operating procedures can be obtained from the authors.

Permeameter

The core and laboratory permeameters developed and fabricated at the INEL are essentially identical; both consists of a pressure or vacuum source flowing through a Drierite filter, a regulator, a bank of five flow gauges, a final pressure gauge (50 psi), and a sample holder (e.g., Figure 3). The difference between the two lies in the type of sample holder used. The sample holder for the core permeameter consists of a universal joint, a deformable rubber stopper shaped to the curvature of the core, and a clamp. The universal joint is glued to the stopper and is connected to the final pressure gauge. A clamp holds the sample holder firmly against the side of the core. The laboratory permeameter has a Hassler-type sample holder; i.e., a cylindrical 25 X 28 mm sample chamber that eliminates air flow around the sample by means of an inflatable rubber membrane.

The principle of operation of the laboratory air permeameter is as follows: The sample's diameter and length are measured and then the sample is placed in a Hassler holder. Gas is forced through the sample and the ambient temperature (used to calculate air viscosity), flowmeter number and reading (used to calculate air flow rate via a best fit curve calculated for each flowmeter), and differential pressure are measured. The measured data are recorded and subsequently used to calculate the gas and Klinkenberg (intrinsic) permeabilities of the sample, utilizing a BASIC computer program.

To determine the precision of the laboratory air permeameter, a series of repeat runs were made on a suite of plugs that range from < 0.01 to about

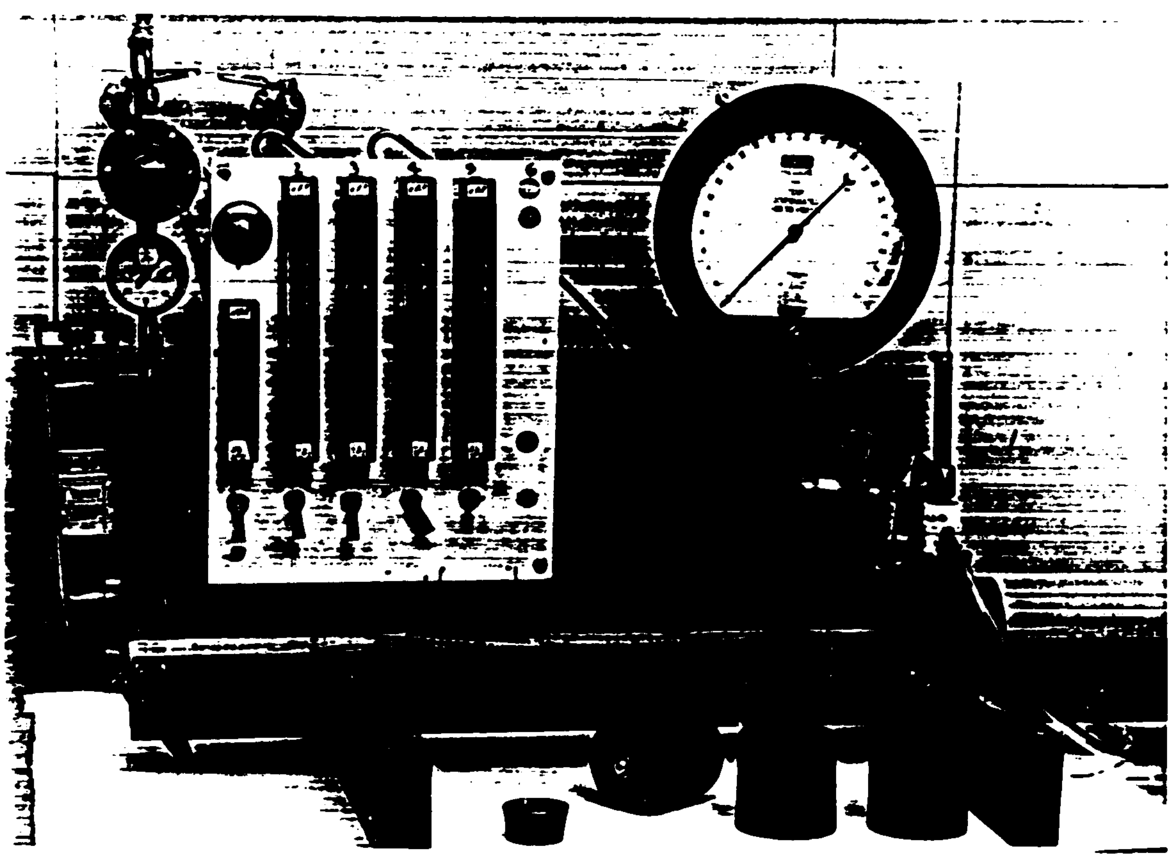

Figure 3. Permeameter used in the laboratory and core measurements. The sample holder here is set up to run core samples.

5000 md. The precision was found to be reasonably good; an average of +/- 8 %error can be expected for thi instrument.

To obtain accurate data, the permeameter has to be free of leaks, the flow meters clean and operating correctly, and the rotometers and gauges in calibration. In addition, the Hassler holder has to seal against the surface of the core as well as allow the gas to flow across the upper and lower faces of the sample.

Problems that are commonly found with this equipment are jerky movements of the flowmeter floats and leaking of the sample holder. Erratic movements of the flowmeter floats are due to dirty or damp flowmeter tubes, so the flowmeter tubes have to be cleaned and dried (pipe cleaners work well for this). Leaking of the sample holder is due to sleeve damage (scars, cracks, punctures, stiffness, etc.) and a new sleeve assemblage has to be installed. The sleeve should be checked after every ten measurements using a zero permeability aluminum plug to verify zero flow through the sample chamber.

Porosimeter/Bulk Density Measurements

A helium porosimeter was developed and fabricated at the INEL for laboratory measurements. This porosimeter consists of a pressure source (He), a regulator, a pressure gauge (300 psi), a valve separating the regulator from the pressure gauge, a sample chamber, and a three-way valve between the pressure gauge and the sample chamber (Figure 4).

The principle of operation of the helium porosimeter is as follows: Helium gas under pressure is introduced into a volume, V_1 in the porosimeter, and the pressure, P_1, is noted. This volume of gas is then allowed to expand into the sample chamber and the pressure, P_2, is noted. The volume of the sample chamber or sample (once the sample chamber volume is determined, the sample grain volume, V_s, can be calculated) is determined from the Boyle's Law relationship:

$$P_1 * V_1 = P_2 * (V_2 - V_s)$$

Sample diameter, length, and weight are also measured to determine bulk volume of the sample. If the bulk volume is carefully measured and the sample weights determined, the sample porosity, densities, and void volume can also be calculated.

To determine the precision of the helium porosimeter, a series of repeat runs were made on a suit of basalt plugs with measured porosities ranging from about 0.5 to 39 %. The standard deviation for porosity was about 0.305 % and for void volume about 0.038 cm^3.

To obtain accurate data, the porosimeter volumes have to remain constant and free of leaks, and the gauge has to be accurate. Also, the samples have to be of a regular shape so that the measured bulk volume can be accurately determined.

Problems that are found with this equipment are leaks in the sample cell and variations in the P_2/P_1 ratios from the gauge readings. A leaking sample cell indicates "O" ring damage so a new "O" ring has to be installed. Incorrect P_2/P_1 ratios may be due to leaks or the gauge (and system) being out of calibration. Leaks should be checked for first, but if none are found, the gauge and system has to be recalibrated.

The equipment that comprises the core porosimeter is a 5-kg scale, and a 10-cm scale or caliper. What is actually measured is the weight and dimensions of the core. The principle of operation is as follows: A dry piece of core with smooth ends, a relatively regular shape, and a weight less

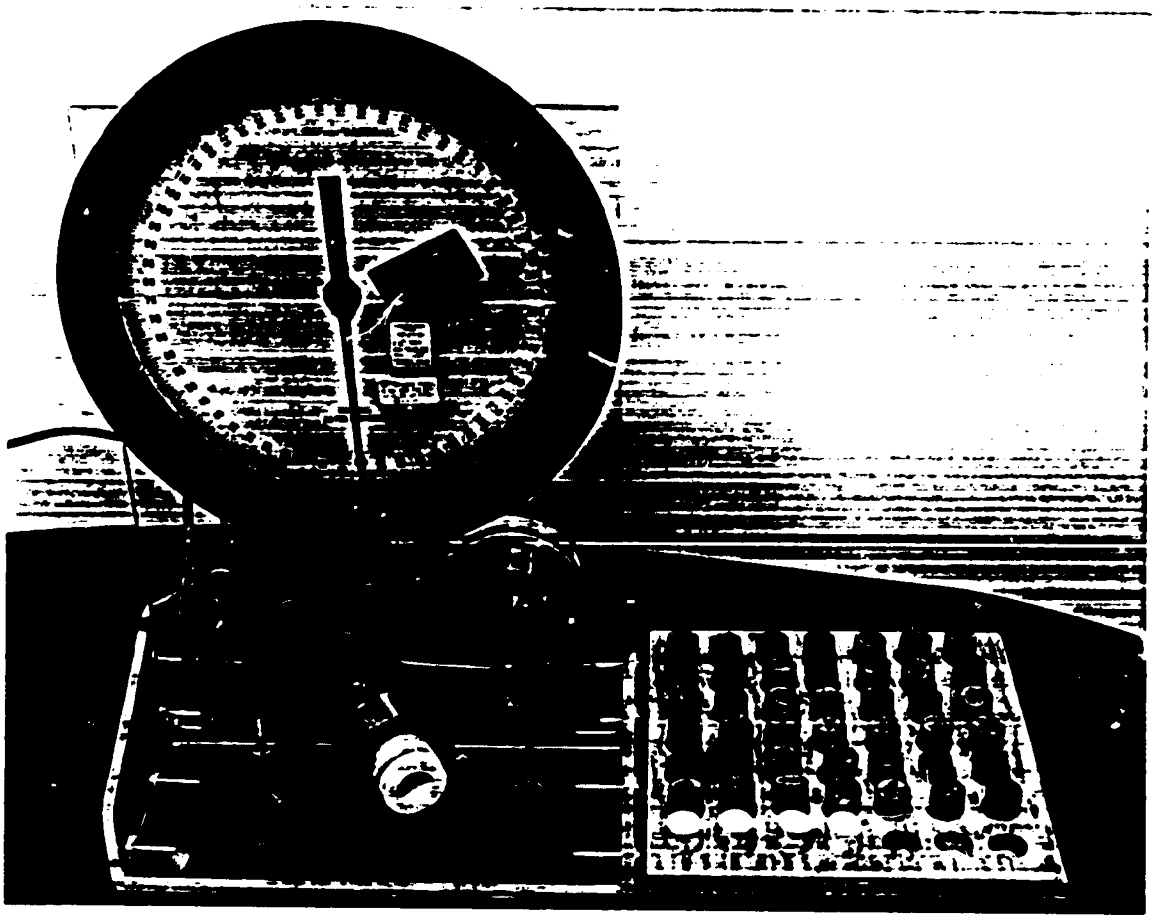

Figure 4. The laboratory helium porosimeter with some of the basalt plugs that were measured (at right).

then about 5 kg is selected for analysis. The weight, the average diameter, and the average length are determined. The bulk volume and bulk density are calculated from these data. Only by assuming a grain density value can the porosity be calculated. The median grain density of basalt core is generally 3.05 +/- 0.03 g/cm^3. The porosity can be calculated +/- 1 % using this median value and the calculated bulk density.

To obtain accurate data, each core sample has to be dry, clean, of regular dimensions, and less than 5 kg in weight. In addition the scale has to be in calibration, the sample cannot loose any fragments during the measurement procedures, and the scale pan has to remain clean and the scale zeroed before each measurement.

The problem that most commonly occurs during the measurements is that the scale does not return to zero after the measurement. This is usually due to rock fragments on the pan, so the pan has to be cleaned, the scale rezeroed, and the sample reweighed.

volume for a given capillary pressure is calculated for each individual plug using the void volume and the corresponding weight of water.

To assure the best possible data set, the humidity and the temperature inside the glove box has to remain constant. Prior to beginning the experiment, the glove box has to be checked for leaks (leaks can be sealed with silicon glue), and the box free of hygroscopic materials such as wood. Also, the type of salts used for the experiment have to be relatively temperature independent. The scale and the temperature probe have to be in calibration.

The problem commonly found in conducting this experiment the inability to maintain a constant relative humidity in the glove box. Changes in relative humidity are due to temperature fluctuations, significant leaks around the windows, gloves, and/or chamber door, or the opening of the chamber door. Temperature fluctuations can be minimized by one of two ways: (1) wrapping insulation around the glove box (Celotex or heavy blankets) or (2) installing a small heater with a fan and rheostat either inside the box or outside the box but within an enclosure. Leaks around the windows and gloves have to be sealed with silicon glue. If leaks occur around the door, the "O" ring has to be replaced. The chamber door has to remain closed during equilibration of the plugs to the humidity in the box.

<u>Box Canyon</u>

The Box Canyon outcrop study looked at the flow geometry in the X-Z or Y-Z sense. No specific equipment was developed for this study. Thirty-eight stations were established along the 2 1/2 mile section of the canyon. Each station location was plotted on a base map (with a scale of one inch equals one thousand feet) and all photo points and measurements were referenced to these locations. A Ranging Rangematic 610 was used to measure distances from photo locations to the outcrop, and the camera/lens/enlargement system was calibrated so that a measured distance on the photographic print could be related to a ground distance. From the angular relationships of the photos to the outcrop the maximum height, the normal to the outcrop, and the apparent length of each discernable flow were calculated.

<u>Hell's Half Acre Flow</u>

The Hell's Half Acre study looked at the flow properties in the X-Y sense. As at Box Canyon, no specific equipment was developed for this study. From four separate stations, one hundred-four grid point elevations were measured on the top of the flow ridges, in collapsed areas, and for a combined section of the flow using a lightweight transit and the Ranging Rangematic 610 range finder. The elevation and location data were used to generate variogram plots and kriged structure maps.

CALCULATIONS

Several BASIC computer programs were written to expedite the reduction of data from the laboratory and core analyses. Due to the length of these program listings, they are not presented here. However, copies of these programs are available from the authors.

<u>Permeability</u>

The laboratory air permeabilities were calculated using the BASIC

Equilibrium Water Saturation Experiment

The equipment used for this experiment are a 45.7 X 76.2 X 71.1 cm stainless steel glove box with top and side windows and a power outlet. Placed within the glove box are a digital readout scale; a 2 quart pyrex baking dish; two wire mesh racks stacked one above the other and suspended above the pyrex dish; a temperature probe; and a low-rpm fan (Figure 5).

The principle of operation is as follows: A number of basalt plugs (either oven-dried are completely saturated) are weighed and placed on-end on the wire mesh racks in the glove box. A salt solution of a specified concentration is poured into the pyrex dish at the bottom of the box. The glove box is sealed, and the basalt plugs are allowed to come to equilibrium with progressively higher or lower humidity values (the percent relative humidity being determined by the type and concentration of the salt solution used). The equilibrium saturation weight is measured and this weight, the salt type and concentration, and temperature are recorded. The weight of the water adsorbed by each plug is obtained by subtracting the initial dry weight of the sample from the corresponding equilibrium saturation weight. From a table, salt concentrations are converted to relative humidities, and from the humidity values, capillary pressures can be calculated. The percent of pore

Figure 5. This is the stainless steel glove box used for the equilibrium water saturation experiment. In the window, the top tier of basalt plugs can be seen.

computer program "PERMLAB.BAS". This program does the following: It asks for the well identification, then prompts for the sample depth and the corresponding data (temperature in °C, pressure in psi, flowmeter number, flowmeter reading, the diameter measurements in cm, and the length measurements in cm). Next, the program opens a file. It calculates air rate and permeability, prints these calculated values to the file and a line printer, and closes the file. The program reaches the branch point for additional samples (leaves the loop and closes the file when a depth of -99 is entered), then the branch point for additional wells, at which point the program either ends (no additional wells) or runs again.

The core permeabilities are calculated using the BASIC computer program "PERM82.BAS" for a 32 inch core and "PERM44.BAS" for a 1.77 inch core. (A generalized program applicable to any core diameter was not written because only two sizes of core have been used in the characterization program.) This program is structured essentially the same as the laboratory air permeability program; the difference being that "PERMLAB.BAS" requires diameter and length measurements.

Porosity/Bulk Density

The laboratory porosities and bulk densities were calculated using the BASIC computer program "POROHE.BAS". This program does the following: It asks for the well identification, then prompts for the sample depth and corresponding data (the diameter measurements in cm, the length measurements in cm, the sample weight, and the two pressure readings (P_1 and P_2) in psi). The program then opens a file. It calculates bulk density, grain density, porosity, and pore volume, prints these values to the file and the line printer, and closes the file. Next, the program loops to the next sample or leaves the loop (when "-99" is entered) and reaches the branch point for additional wells, at which point the program either ends or runs again.

Also available is a BASIC computer program named "LABCALC.BAS", which calculates laboratory density, permeability and porosity at the same time.

The core porosities and bulk densities are calculated using the BASIC program "PORO.BAS". This program is structured the same way as "POROHE.BAS", but the calculations differ. Only bulk density can be directly calculated from the data. To calculate other parameters, a grain density of 3.05 is assumed within the program. The porosity and void volume are then calculated based on this assumed value.

Equilibrium Water Saturation

Percent water saturation, pore-size distribution, and surface area are the values sought in this experiment. Two BASIC computer programs were written to calculate these values: "EQWSAT.BAS", which calculates the water volume and water saturation and converts capillary pressure to relative humidity and vice versa, and "PORSFC.BAS", which calculates pore-size distribution, pore volume, and surface area after the method of Dollimore and Heal (1970) and Gregg and Sing (1982).

The "EQWSAT.BAS" program does the following: It opens a file and asks for the well identification, sample label, and corresponding data (pore volume in cm^3, weight of the water adsorbed in grams, density of water in g/cm^3, and average temperature in °C). It then asks if capillary pressure and/or relative humidity are known. If one and not the other of these parameters are known, it will calculate the unknown parameter. If neither are known, and a

NaCl solution is used to set the humidity in the experiment, it will extrapolate capillary pressure from the solution concentration and calculate relative humidity. Next, the percent water saturation and water vapor pressure are calculated. These calculated values are printed to the file and line printer. A branch point for additional samples is reached (type "STOP" to exit loop), then the branch for additional wells, at which point the program either closes the file and ends or runs again.

The "PORSFC.BAS" program does the following: It opens a file and asks for the well identification, sample label and depth (ft), and data (initial dry weight of sample in grams, pore volume in cm^3, density of water in g/cm^3, chosen maximum and minimum pore radii used in the calculations in angstroms, and the set relative humidities (in fractions) and corresponding quantities of water adsorbed (in grams)). The values calculated and written to the file and the line printer are surface area, pore volume, cumulative surface area, cumulative pore volume, mean pore radius, and the change in pore volume divided by change in pore radius for the given pore radius. The branch point for additional samples, a new well, or to exit the loop (by typing "STOP") is reached. After exiting the loop, the program closes the file and ends.

Box Canyon and Hell's Half Acre Flow

The BASIC computer program "OTCLH.BAS" was written to calculate from the outcrop angle, camera incident angle, and distance data of Box Canyon the "true" heights (thicknesses), apparent lengths, and the apparent length to maximum height (La/Hmax) ratios.

The EPA GEO-EAS (Geostatistical Environmental Assessment Software) program, version 1.1, was used to generate the variograms and create kriged surficial structure maps of a flow lobe and large deflation structure at Hell's Half Acre Flow.

RESULTS

Porosity

The maximum and minimum and median porosity values (respectively) by element are the following: intermediate and lower vesicular zone 39, 12, and 21%; central zone 17, 3, and 10%; and the upper vesicular zone 43, 11, and 22%. In general, then, the maximum porosity for the nonvesicular elements is < 15% and the minimum porosity for the vesicular elements is > 15%. Thus, the vesicular and nonvesicular elements can be separated strictly on the basis of their porosity.

The porosity distribution for vesicular and nonvesicular zones is presented graphically in Figure 6. The generally-peaked distributions for the nonvesicular elements and the broader distributions for the vesicular elements can be noted in this figure.

Permeability

The maximum and minimum permeability values (respectively) by element are the following: intermediate and lower vesicular zone 1649 and < 0.05 md, central zone 253 and < 0.05 md, and upper vesicular zone 5000 and 0.1 md. The median permeability, by element, for all flows is: for the lower vesicular zone 4 md, the central zone 8 md, and the upper vesicular zone 7 md.

The permeability distribution for vesicular and nonvesicular zones is presented in Figure 7. The permeability distributions are generally broader

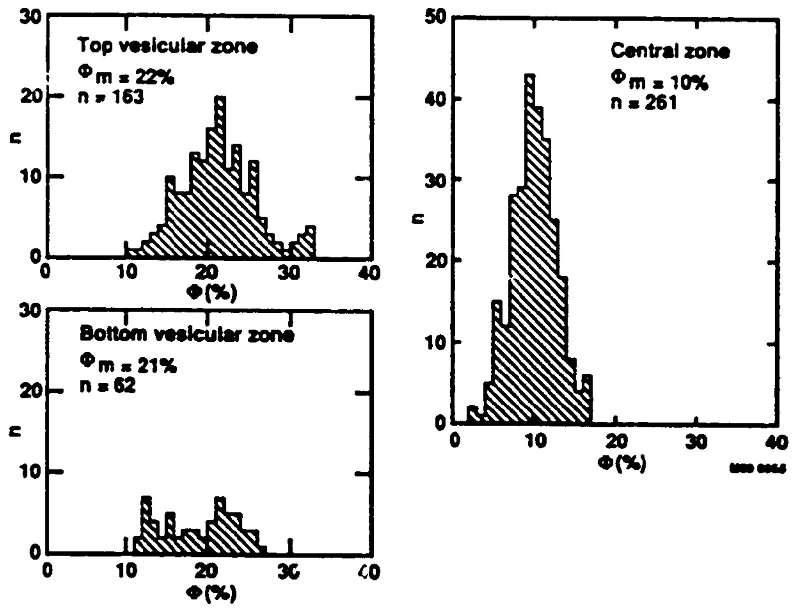

Figure 6. Porosity distributions for nonvesicular and vesicular portions of all flows.

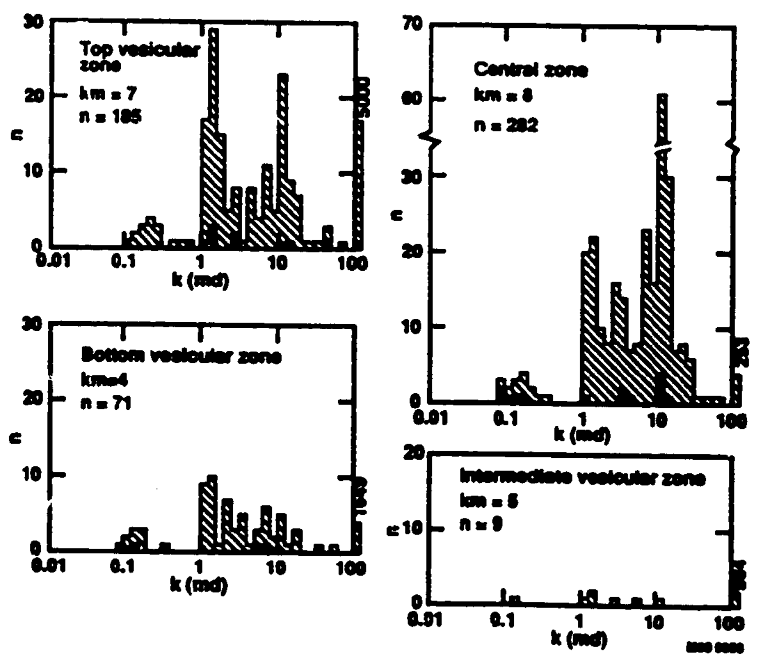

Figure 7. Permeability distributions for the nonvesicular and vesicular portions of all flows.

than the porosity distributions, with the lowest permeabilities typically occuring in very-tight, low-porosity, nonvesicular material. The highest maximum permeabilities occur in the vesicular zones in samples where good local connection between the vesicles occurs. However, in general, the median permeability of the vesicular elements is less than that of the central nonvesicular zone. The permeabilities, then, are generally controlled by the characteristics of the rock matrix. Because the vesicular zone has a lower glass and oxide content than the central zone, rock permeability must be a function, at least in part, of matrix crystallinity.

The permeability-porosity relation is quite complex, with scatter plots showing a true "shotgun" pattern. A permeability/porosity plot, for samples less than 100 md is presented as Figure 8. This figure illustrates the poor correlation between the two parameters; different rock characteristics control permeability and porosity. Whereas permeabilities are controlled by the rock matrix, porosities and bulk densities (see density section below) are controlled by the fraction of vesicles present in the sample.

Permeabilities were measured for a few fractured cores. The fractured material generally registered flow rates one or two magnitudes higher than that of the surrounding unfractured rock.

Density

Evaluating the grain density data by elements, reveals a small, consistent median density difference between the vesicular and nonvesicular zones. In general, the upper and lower vesicular elements have a median grain density of about 3.045 g/cm^3, and the nonvesicular elements have a median grain density of about 3.055 g/cm^3. The intermediate vesicular element has a median grain density of 3.05 g/cm^3. This affinity with the nonvesicular element median may be because the intermediate element is physically in the central nonvesicular area. However, the intermediate data set is so small (8

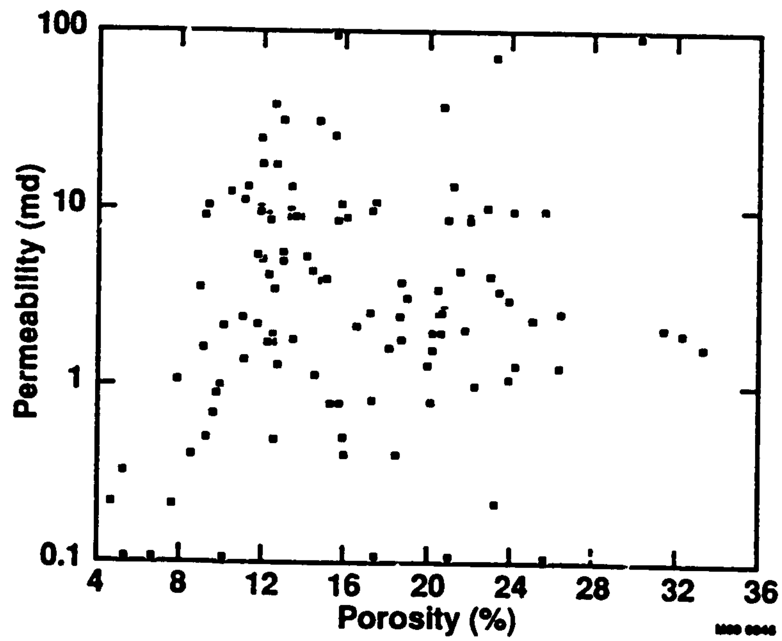

Figure 8. Plot of permeability vs. porosity for permeabilities < 100 millidarcys.

samples) that little statistical significance is involved with this observation.

The median grain density for all the samples is 3.05 g/cm^3. In general, the distributions are rather peaked and the non and vesicular elements have medians that are displaced only by 0.01 g/cm^3. The lower grain density of the vesicular element is probably a function of higher glass content.

With grain density and porosity known, bulk density can be obtained by the relationship: BD = (1-fractional porosity) X 3.05. In general, the bulk density distributions are similar to the porosity distributions, with vesicular median bulk densities near 2.40 g/cm^3 and nonvesicular median bulk densities near 2.70 g/cm^3. Generally, then, the bulk of the vesicular bulk densities are less than 2.60 g/cm^3 and the nonvesicular element bulk densities are greater than 2.60 g/cm^3.

<u>Equilibrium Water Saturation</u>

The equilibrium water saturation experiment is not, at present, completed. The wetting curve (adsorption curve) is still being obtained for the 45 basalt plugs in the glove box. In Figure 9, the range in water content of these plugs at increasing relative humidity is represented by samples C14, F10, and E38. The inverse relationship between permeability and percent water saturation (i.e., percent of pore volume) is readily apparent. C14 (Figure 9a) has a curve shape common for most of these basalt plugs and has a permeability of 1.67 md--slightly below the average for this sample group. F10 (Figure 9b) has a curve shape typical of those samples with the lowest percent water saturation, and has a permeability of 395.47 md. E38 (Figure 9c) has a curve shape typical of those samples with the highest percent water saturation, and has a permeability of < 0.01 md.

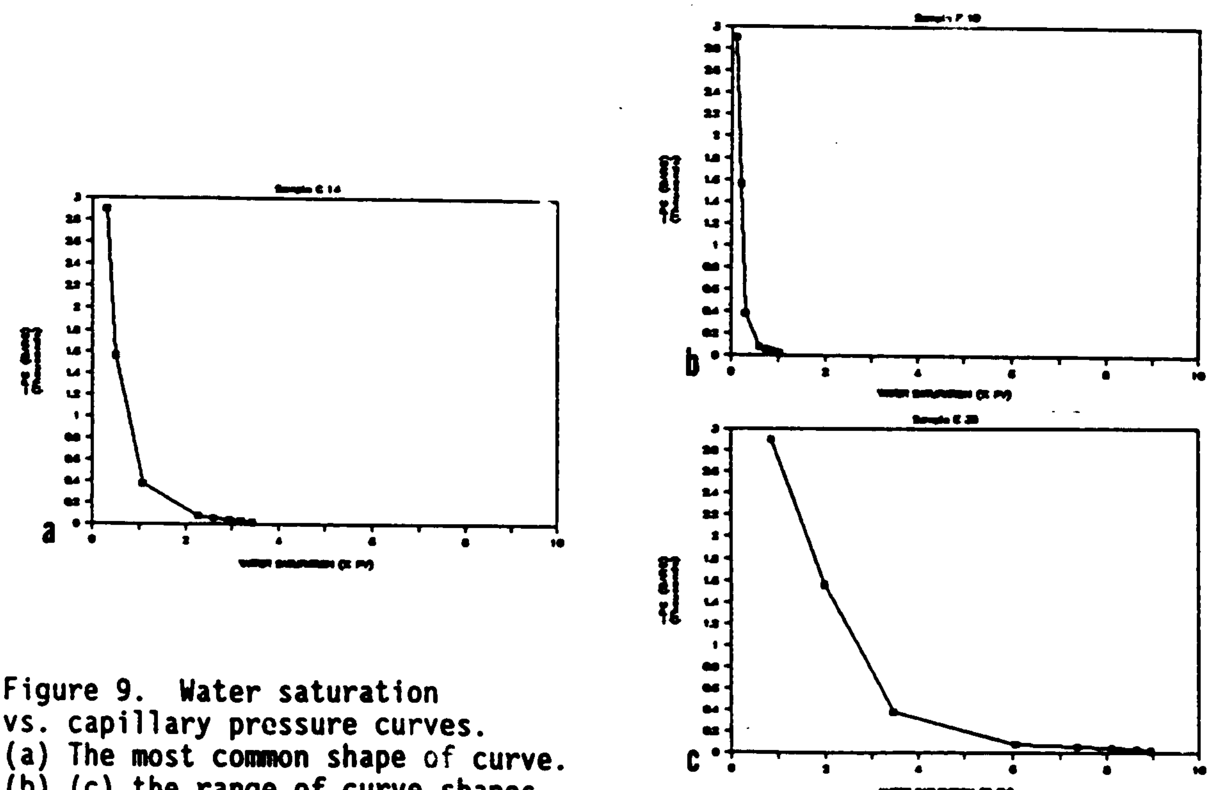

Figure 9. Water saturation vs. capillary pressure curves.
(a) The most common shape of curve.
(b),(c) the range of curve shapes.

Upon completion of the drying or desorption curve, the pore-size distribution and surface area will be calculated.

Box Canyon

The typical flow cross section is a complex shaped lens and the flow mechanism would appear to be a form of viscous fingering. Analysis of the two-dimensional geometry displayed by the 372 measured flows in Box Canyon yields a median flow height of about 12 ft. That compares with the 15-ft median flow height from RWMC core data. The maximum heights from the Box Canyon outcrop and RWMC core data are 60 and 76 ft, respectively. Thus, a reasonable analog exists at Box Canyon, although it may be a somewhat more distal flow geometry than is found for some of the RWMC flows.

For a complex series of viscous flow lobes generally oriented in the flow direction, a small apparent length to maximum height (La/Hmax) ratio will be apparent when looking head on at the flow lobes, and a large La/Hmax ratio when looking at cross sections cut roughly parallel to the lobes' flow directions. Plotting La/Hmax medians as a function of orientation in a rose diagram (Figure 10) yield generally a narrow lens when viewing in the northeast/southwest directions and an elongated lens when viewing in the northwest/southeast direction. To gather information on the plan view geometry, the study at Hell's Half Acre Flow was conducted.

Hell's Half Acre Flow

Variograms and kriged structure maps of the top of the flow lobe, the deflation structure or bowl, and the entire study area were generated. Also generated from this study were statistics on the type of surface that comprises a typical, relatively fresh basalt flow.

Four surfaces were identified at Hell's Half Acre: pahoehoe, fracture, rubble, and bouldery/blocky/broken. The texture of the pahoehoe surface is

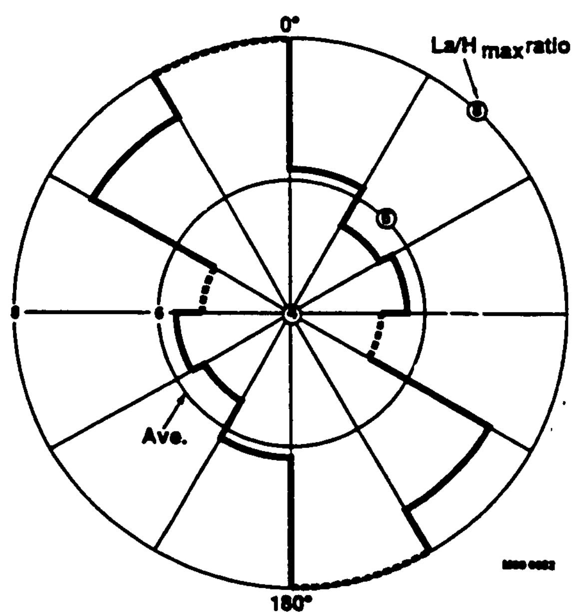

Figure 10. Median La/Hmax ratio as a function of the orientation of the normal to the apparent length direction.

not always well defined due to erosion; in some areas, little trace of the original texture is preserved. The fracture category is actually not a surface, but literally a fracture or fissure (generally > 2 ft in depth). The rubble surface consists of basalt fragments less than or equal to cobble-size, but most commonly pebble-size. The bouldery/blocky/broken surface typifies flow edges where the slope is steep and blocks of basalt are boulder size and larger.

The number and frequency of each surface type was calculated. The pahoehoe surface occurs with the greatest frequency (51% of the location points) followed by fracture (19%), rubble (17%), and bouldery/blocky/broken (13%).

Looking at a greatly-simplified model of a single lobe, insights can be gained into its three-dimensional configuration. The evaluation of the single lobe model with the orientation developed in Figure 11 yield a length:width:height ratio of around >8.7:4.6:1. So, if a wellbore encounters this median single lobe, more than half of the penetrations will be in a region near the edge of a flow (half the time within a distance less than 2.3 Hmax and one quarter of the time within a distance of less than 1.15 Hmax).

The generalized plan-view geometry and surface description data of the Hell's Half Acre study was used in conjunction with the Box Canyon data to construct a conceptual geologic model for the vadose zone under the RWMC. The median length/width/height is > 130:69:15 ft (> 40:21:2.6 m), and the median substrate distribution is pahoehoe 51 %, fracture/fissure 19%, rubble 17%, and bouldery/blocky/broken 13%. In real life, the flow lobe will have a complex geometry (as in Figure 2).

SUMMARY

The purpose of characterizing the ESRP basalts that underlie the RWMC at the INEL was largely to produce a geostatistical framework in which to build a three-dimensional model of the vadose zone basalts. The geostatistical characterization of these basalts involved measuring the following parameters: permeability, porosity, density, pore-size distribution/surface area, flow lobe geometry, fracturing, and substrate distributions.

Equipment designed and built at the INEL were used to measure permeability, porosity/density, pore-size distribution, and surface area. The permeameter measured core and laboratory permeabilities with a precision of about +/- 8% error. It consists of a pressure or vacuum source flowing through a Drierite filter, a regulator, a bank of five flow gauges, a final pressure gauge, and a sample holder. The laboratory helium porosimeter measured pore volume and porosity (to 0.038 cm^3 and 0.305% standard deviation, respectively) and density. It consists of a helium pressure source and regulator, a pressure gauge, and a sample chamber. The core porosimeter consists simply of a 5 kg scale and a 10 cm scale or caliper. Bulk volume and density were derived from the weight and dimension measurements, and porosity could be calculated by assuming a grain density of 3.05 g/cm^3.

Parameters directly measured by the equilibrium water saturation experiment were sample dry weight, the quantity of water adsorbed, temperature, and relative humidity. The equipment that comprises this experiment are a glove box within which is a temperature probe, a pyrex baking dish (for the salt solutions), a two-tiered wire mesh rack (to hold the samples), and a fan.

No equipment was developed for the Box Canyon and Hell's Half Acre Flow studies. A light-weight transit, a range finder, and a camera were used to measure distances, locations, and outcrop orientations and dimensions.

Several BASIC computer programs were written to reduce the data. Laboratory air permeabilities were calculated using the PC program "PERMLAB.BAS," and the core permeabilities were calculated using "PERM82.BAS" for a 32 inch core and "PERM44.BAS" for a 1.77 inch core. The laboratory porosities and densities were calculated using the PC program "POROHE.BAS," the core porosities and densities were calculated using the program "PORO.BAS," and "LABCALC.BAS" calculated laboratory densities, porosities and permeabilities at the same time. Water volume, water saturation, and the conversion of capillary pressure to relative humidity (and vice versa) for the water saturation experiment were calculated by the PC program "EQWSAT.BAS." The program "PORSFC.BAS" was written to calculate pore-size distribution, pore volume, and surface area. From the Box Canyon data, maximum heights, apparent lengths, and La/Hmax were calculated by the PC program "OTCLH.BAS." Variograms and kriged surface maps from the Hell's Half Acre data were generated using the EPA Geostatistical Environmental Assessment Software, GEO-EAS.

Permeabilities are generally matrix controlled. Although permeability values range from < 0.01 to 5000 md, in general, the median permeability of the vesicular elements is less than that of the more crystalline central nonvesicular zone.

Porosity values range from 3 to 43%, but in general, the maximum porosity for the nonvesicular elements is < 15% and the minimum porosity for the vesicular elements is > 15%. Median grain density for all samples is 3.05 g/cm^3, and the median bulk density for the vesicular zone is 2.40 g/cm^3 while that of the nonvesicular zone is 2.60 g/cm^3. Bulk density distributions are similar to porosity distributions in that either parameter can distinguish between the vesicular and nonvesicular zones. Both porosity and bulk density are controlled by the fraction of vesicles present in the sample.

The inverse relationship between permeability and equilibrium water saturation is illustrated by the water saturation data. In general, samples with the highest permeability have the lowest percent of the pore volume filled with adsorbed water, and those with the lowest permeability have a considerably higher percent of the pore volume filled.

From the Box Canyon and Hell's Half Acre Flow studies a single flow lobe model was developed in which the l/w/h ratio is > 130:69:15 ft (> 40:21:4.6 m), and the median substrate distribution is pahoehoe 51%, fracture/fissure 19%, rubble 17%, and bouldery/blocky/broken 13%.

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