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Project/Task WAG-7 Pits and Trenches RI/FS
Subtask Hydraulic Characterization Data: Basalts

EDF Page 1 of 35

TITLE: SDA Hydraulic Characterization Data Compilation: Basalts

SUMMARY

The summary briefly defines the problem or activity to be addressed in the EDF, gives a summary of activities performed in addressing the problem and states the conclusions, recommendations, or results arrived at from this task.

This report is a compilation of basalt hydraulic characteristic data for the Subsurface Disposal Area (SDA) at the Radioactive Waste Management Complex (RWMC). The major objective of the report is to generate one document that contains the basalt hydraulic characteristics information needed by the modelers to simulate flow and contaminant transport beneath the RWMC. Not all the information in the references could be put into this document; therefore, a section on the abstracts of key references is included to help lead the modelers to more detailed information when needed. The report is primarily tables recreated from tables in related references. Many of the details explaining the information in the tables must be found in the references; however, there is some explanation included that was prepared in a previous RWMC physical characteristics study that has not been published.

The report is divided into the following four sections;

1. Introduction
2. Abstracts of key references
3. Hydraulic characteristic data
4. References

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SDA Hydraulic Characterization Data Compilation: Basalts

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1.0 INTRODUCTION

This report is a compilation of basalt hydraulic characteristic data for the Subsurface Disposal Area (SDA) at the Radioactive Waste Management Complex (RWMC). The major objective of the report is to generate one document that contains the basalt hydraulic characteristics information needed by the modelers to simulate flow and contaminant transport beneath the RWMC. Not all the information in the references could be put into this document; therefore, a section on the abstracts of key references is included to help lead the modelers to more detailed information when needed. The report is primarily tables recreated from tables in related references. Many of the details explaining the information in the tables must be found in the references; however, there is some explanation included that was prepared in a previous RWMC physical characteristics study that has not been published, as well as text from some references where electronic copies are available.

The report is divided into the following four sections;

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2.0 ABSTRACTS OF KEY REFERENCES

A lot of data has been collected to characterize the hydraulics of the basalts. However, the information is distributed over many documents. This section is primarily the abstracts for the important documents. It also includes some minor notes. The abstracts have been lifted directly from the reports with only minor modifications.

The information is provided here as an easy reference location both for people currently working on the SDA modeling and those who in the future will need a summary of the work completed. Not all the information in the references could be put into this document; therefore, this section can help lead those interested to more detailed information when needed.

Bishop, C. W., 1991, *Hydraulic Properties of Vesicular Basalt*, Masters Thesis, The University of Arizona, Tucson, Arizona.

Laboratory experiments were conducted on vesicular basalt cores to determine hydraulic properties including dry bulk density, effective porosity, skeletal density, saturated hydraulic conductivity, and moisture characteristic curves. Unsaturated hydraulic conductivity and diffusivity as a function of matrix suction were also estimated.

A large vesicular basalt block taken from the Radioactive Waste Management Complex at the Idaho National Engineering Laboratory was used to run infiltration tests. Infiltration curves were developed for the large basalt block. Saturated hydraulic conductivity was estimated for the block.

The major conclusion drawn from the above research is that a saturated wetting front will move fairly rapidly through the basalt, but as matrix suctions increase above one bar, the moisture is bound in the small pore spaces and moves very slowly.

All the data obtained in the above study are measurements of the vesicular basalt matrix. The controls in the matrix are the fine microfractures that connect the vesicles. Thus, these measured values are low. Since these measurements are scale dependent, hydraulic properties measured on a field scale will be different. On this scale under "wet" conditions resulting from snow melt or flood water infiltration, controls are expected to be fractures, void spaces, rubble zones and the like. At low matrix tensions, these should prove to be fairly rapid conduits of water. Therefore, one recommendation forthcoming from the above research is that calibration of a model for this basalt must consider actual field conditions especially when appraising "wet" conditions. These saturated front conditions appear to be the predominate hydraulic controls on the movement of contaminants beneath the RWMC.

Chaves, A., 1988, *Special Core Analysis of Basalt Samples*, TR 89-27, Submitted to EG&G Idaho, Inc., Mr. Dick Smith from Terra Tek Core Services, Univ. Research Park, 420 Wakara Way, Salt Lake City, Utah 84108.

Four basalt samples were sent to Terra Tek by EG&G Idaho for tests. Requested measurements included effective and total porosity, gas and liquid permeability, and capillary pressure by mercury injection.

Knutson, C. F., K. A. McCormick, J. C. Crocker, M. A. Glenn, and M. L. Fishel, 1992, *3D RWMC Vadose Zone Modeling (Including FY-89 to FY-90 Basalt Characterization Results)*, EGG-ERD-10246.

The modeling and geostatistical studies discussed in this report were conducted for the Department of Energy Field Office, Idaho, at the Idaho National Engineering Laboratory. This document provides (a) a summary of the Radioactive Waste Management Office (RWMC) vadose zone basalt characterization studies carried out during FY-89 to FY-90, (b) a view of a prototype 3D stochastic geological model of the subsurface interval from the base of the surficial layer to the top of the aquifer under the RWMC (developed by members of the EG&G Idaho, Inc., Geosciences Department for the Environmental Restoration Department utilizing the geostatistical data developed from the FY-89 to FY-90 basalt characterization study field work), and (c) suggestions for additional tasks that if completed would substantially increase the understanding of the subsurface hydrology and geology in the RWMC area.

Knutson, C. F., K. A. McCormick, R. P. Smith, W. R. Hackett, J. P. O'Brien, and J. C. Crocker, 1990, *FY 89 Report, RWMC Vadose Zone Basalt Characterization*, Informal Report, EGG-WM-8949.

The studies discussed in this report were conducted for the Department of Energy (DOE) at the Idaho National Engineering Laboratory (INEL). This report summarizes the petrological information developed as an initial step in the characterization of basalt in the vadose zone beneath the Radioactive Waste Management Complex (RWMC). The study was based on the concept of modified plains volcanism, which explains the emplacement of basalt lave flows on the Eastern Snake River Plain. A petrologic study, including lithologic logging of the core and representative samples of basalt, was performed. Subsequent studies of the core samples were also conducted. Petrophysical studies were performed measuring porosity, permeability, grain density, equilibrium water saturation, and pore-size distribution of flow groups. Thin cylindrical slices were cut from the petrophysical plugs, and petrographic studies analyzing texture and mineralogy were accomplished using a petrographic microscope. These studies, along with geostatistical studies of Box Canyon of the Big Lost River and Hell's Half Acre, resulted in a conceptual geologic model of the basalt of the vadose zone under the RWMC. The evaluation of this preliminary model was used as a basis for recommendations of subsequent data acquisition efforts.

3.0 HYDRAULIC CHARACTERISTIC DATA

A Remedial Feasibility Investigation (RFI) was terminated when the RWMC was designated a CERCLA site. A fairly comprehensive report on the physical characteristics of the RWMC was almost complete at the time but was never published. The report summarized much of the work done at the RWMC before 1989. The tables and some of the text from the unpublished report are presented in Section 3.1 (Summary of Data from EG&G Idaho, Inc. Studies). The data presented in Section 3.1 is summarized primarily from Knutson, et al., 1990 and Knutson, et al., 1992. The tables from Bishop 1991 and Chaves 1988 are presented in Sections 3.2 and 3.3, respectively. Section 3.4 is a summary of some of the basalt parameter values used in past modeling studies.

3.1 Summary of Data from EG&G Idaho, Inc. Studies

The RWMC is located near the southwestern margin of the interrift basin near the Arco Rift zone and Plain Axis Rift zone. The area has been subjected to (a) emplacement of lava flows from both rift zones and (b) accumulation of lacustrine, fluvial, and alluvial sediments from the Big Lost River and loess deposits from sources to the southwest.

The collapse/rubble zone is the nomenclature given to a single complex vesicular zone, often rubblized, that occurs between two flow breaks. These elements may be one of the most transmissive portions of the basalt sequence. They occur relatively frequently, about 13% of the basalt-basalt contacts are of this type (119 flows were used in the analysis; 20 basal flow contacts were with sediments and 13 were with a collapse/rubble element). It was not possible to make any quantitative measurements of the transmissivity, porosity, or bulk density of these collapse/rubble zones from either the core or the available logs. This represents an important area in which more work should be done.

3.1.1 Permeability. The permeability data from Knutson et al. 1990 are summarized in Table 3.1-1. This data set includes both lab and field values. The median permeabilities for the upper, central, and lower elements for Flow Group A were 16, 22, and 8 mD; for Flow Group B were 6, 9, and 4 mD; and for the Flow Group C were 7, 9, and 4 mD (the intermediate vesicular element in Group C had a median permeability of 5 mD).

The permeability data from Knutson et al. 1992 are summarized in Table 3.1-2. Stochastic distribution equations (SDEs) were calculated for the permeability distributions for each of the elements and data sets. The coefficients for all the permeability SDEs are presented in Table C-2 of Knutson et al. 1992.

The permeability information can be summarized as a distribution characteristic of the flow elements. The flow elements used were (a) the upper vesicular zone; (b) the central; (c) infrequent intermediate vesicular intervals, which represent bubble trains incorporated into vesicular intervals by the viscous flow of the cooling but still plastic basalt and bubble plumes rising via gravity and density differentials; and (d) the lower vesicular zone.

The permeabilities are generally controlled by the characteristics of the rock matrix. Although the highest maximum permeabilities occurred in the vesicular elements in samples where good local connection between the vesicles occurred, generally the median permeability of the vesicular elements was less than that of the central nonvesicular element.

Fractures are prevalent throughout the basalts that underlie the INEL Site. Information on fracture location, morphology, orientation, and filling within flow units is derived from the Box Canyon and Hell's Half Acre Flow field studies and core from the 15 RWMC wells.

Knutson et al. 1992 (page 3-12) reports the results of fracture/joint permeabilities determined on a few fracture sets in both core samples and outcrops. The core fractures were classified as hairline, and permeabilities were measured on unconfined samples. The measured permeabilities ranged from 400 to 800 milliDarcy (mD), one to two orders of magnitude higher than the permeabilities of the core matrix surrounding the fractures. Permeability was measured on five fractures occurring in outcrops located near the west end of Box Canyon. Permeabilities ranged from 1 to 150 Darcy (D), while apertures ranged from 0.5 to 2.5 mm (0.02 to 0.1 in.).

Table 3.1-1. Permeability distributions by zones for flow units, flow groups, and all samples (values are in millidarcy) (Knutson et al. 1990, Table 2).

	Flow Units				Flow Groups			
Element	Minimum	Median	Maximum	Number	Minimum	Median	Maximum	Number
1TV	1	3	16	8	1	3	16	8
C	<0.05	5	22	12	<0.05	5	22	12
BV	0.20	7	8	3	0.20	7	8	3
2-1TV	1	3	415	14				
C	0.30	5	48	22				
BV	1	3	7	9				
2-2TV	0.7	8	5000	44	0.3	55	5000	86
C	0.1	5	253	71	0.3	9	253	148
BV	0.36	4	873	17	0.3	4	1649	33
2-3TV	0.3	8	395	28				
C	0.3	15	112	53				
BV	0.1	6	no data	1649				
3-1TV	0.4	7	437	38				
C	1	10	31	28				
BV	1	5	36	9				
3-2TV	0.1	5	1574	24	0.1	7	4824	91
C	2	10	47	27	<0.05	9	175	122
VI	117	117	117	1	0.2	5	984	9
BV	0.3	15	241	10	<0.05	4	241	35
3-3TV	0.3	4	4824	29				
C	<0.05	9	175	67				
VI	0.2	3.5	984	8				
BV	<0.05	4.5	81	16				
	All Samples							
ALLTV	0.1	7	5000	185				
C	<0.05	8	253	282				
VI	0.2	5	984	9				
BV	<0.05	4	1649	71				

Table 3.1-2. Permeability distributions by zones for flow units, flow groups, and all samples (values are in millidarcy) (Knutson et al. 1992, page 4-4 to 4-10).

	Flow Units				Flow Groups			
Element	Minimum	Median	Maximum	Number	Minimum	Median	Maximum	Number
1TV	1	4	16	47	1	4	16	47
C	0.002	9	75	47	0.002	9	75	47
BV	0.20	7	16	47	0.20	7	16	47
2-1TV	0.9	5	1040	163				
C	0.06	4	444	163				
BV	0.08	3	772	163				
2-2TV	0.7	8	5000	324	0.9	6	5000	768
C	0.002	6	253	324	0.002	8	444	768
BV	0.002	3	105	324	0.002	5	1712	768
2-3TV	0.1	6	873	276				
C	0.3	12	106	276				
BV	0.08	6	1712	276				
3-1TV	0.004	4	437					
C	0.1	9	138					
BV	0.4	3	51					
3-2TV	0.002	3	5403		0.002	5	5402	711
C	0.1	9	309		0.002	9	444	711
VI					1	5	984	711
BV	0.3	4	57		0.002	4	1712	711
3-3TV	0.1	4	4824					
C	0.002	9	330					
VI								
BV	0.002	5	1575					
	All Samples							
ALLTV	0.002	5	5402					
C	0.002	9	444					
VI	1	5	984					
BV	0.002	4	1712					

3.1.2 Porosity. The porosity distributions by elements for flow units, flow groups, and all samples from Knutson et al. 1990, Table 1 are shown in Table 3.1-3. Both the field and laboratory values are integrated into this data set. The median porosities for the upper, central, and lower elements or zones for the Flow Group A were 19, 8, and 23%; for the Flow Group B were 22, 10, and 21%; and for the Flow Group C were 21, 11, and 18%. The medians for all samples were 22, 10, and 21%.

The porosity distributions by elements for flow units, flow groups, and all samples from Knutson et al. 1992 are shown in Table 3.1-4.

A comparison of the permeability and porosity distributions reveal that the permeability distributions, even plotted as a logarithmic function, are generally broader than the porosity distributions. The lowest permeabilities generally occurred in very-tight, low-porosity, nonvesicular material.

Table 3.1-3. Porosity distributions by elements for flow units, flow groups, and all samples (values are in percent) (Knutson et al. 1990, Table 1).

Element	Flow Units				Flow Groups			
	Minimum	Median	Maximum	Number	Minimum	Median	Maximum	Number
1TV	14	19	27	9	14	19	27	9
C	3	8	8	13	3	8	14	13
BV	14	23	33	5	14	23	33	5
2-1TV	14	22	26	13				
C	5	10	14	16				
BV	15	20	24	9				
2-2TV	16	23.5	38	38	12	22	38	86
C	3	10	17	70	3	10	17	144
BV	13	22	33	16	12	21	39	32
2-3TV	12	21	29	35				
C	4	11	16	58				
BV	12	14	40	7				
3-1TV	15	21	29	28				
C	6	12	14	34				
BV	13	18	26	5				
3-2TV	11	20.5	33	18	11	21	43	68
C	6	11	17	17	6	11	17	109
VI								
BV	14	21.5	34	8	12	18	35	25
3-3TV	15	23	43	22				
C	6	10.5	17	58				
VI								
BV	12	17.5	26	12				
	All Samples							
ALLTV	11	22	43	163				
C	3	10	17	261				
VI								
BV	12	21	39	62				

Table 3.1-4. Porosity distributions by elements for flow units, flow groups, and all samples (values are in percent) (Knutson et al. 1992, pages 4-13 to 4-21).

Element	Flow Units				Flow Groups			
	Minimum	Median	Maximum	Number	Minimum	Median	Maximum	Number
1TV	14	21	29	41	14	21	29	41
C	3	10	15	41	3	10	15	41
BV	14	23	29	41	14	23	29	41
All	3	14	29	41	3	14	29	41
2-1TV	9	22	36	146				
C	3	10	22	146				
BV	5	22	30	146				
All	3	14	36	146				
2-2TV	7	22	40	306	7	22	40	718
C	1	10	22	306	1	11	23	718
BV	6	21	33	306	5	22	33	718
All	1	15	40	306	1	14	40	718
2-3TV	8	21	32	266				
C	4	11	23	266				
BV	10	22	32	266				
All	4	13	32	266				
3-1TV	8	21	30	185				
C	7	12	27	185				
BV	11	21	29	185				
All	7	15	30	185				
3-2TV	6	22	34	207	6	22	43	701
C	4	12	36	207	1	12	32	701
BV	12	22	33	207	6	21	35	701
All	3	15	35	207	1	15	43	701
3-3TV	10	23	43	309				
C	1	12	32	309				
BV	6	20	35	309				
All	1	15	43	309				
	All Samples							
ALLTV	6	22	43	1460				
C	1	11	32	1460				
BV	5	22	35	1460				
IV	15	22	31	1460				
All	1	14	43	1460				

3.1.3 Density. From Knutson et al. 1990, the median grain density for all the samples is 3.05 g/cm^3, and the grain density distribution is relatively peaked. However, when the data are evaluated by elements, there is a small, consistent median density difference between the vesicular and nonvesicular elements (Table 3.1-5). In general, the nonvesicular elements have a median grain density of 3.05 g/cm^3, and the vesicular elements a median grain density of 3.04 g/cm^3. The intermediate nonvesicular element has a median grain density of 3.04 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 element sample set is so small (8 samples) that little statistical significance can be placed on this observation.

The grain density distributions for Flow Groups A, B, and C are rather peaked and the nonvesicular and vesicular elements have medians that are displaced only by about 0.01 g/cm^3.

In general, the bulk density distributions are similar to the porosity distribution, with vesicular median bulk densities near 2.40 g/cm^3 and nonvesicular median bulk densities near 2.70 g/cm^3. In general, the bulk density of the vesicular elements are less than 2.60 g/cm^3, and the nonvesicular element bulk densities are more than 2.60 g/cm^3.

The data ranges for the grain density distribution curves from Knutson et al. 1992 are shown in Table 3.1-6.

Table 3.1-5. Grain density distributions by elements for flow units, flow groups, and all samples (values are g/cm^3) (Knutson et al. 1990, Table 3).

	Flow Units				Flow Groups			
Element	Minimum	Median	Maximum	Number	Minimum	Median	Maximum	Number
1TV	3.02	3.04	3.06	5	3.02	3.04	3.06	5
C	3.03	3.05	3.07	8	3.03	3.05	3.07	8
BV	2.99	3.04	3.05	4	2.99	3.04	3.05	4
2-1TV	3.02	3.05	3.07	12				
C	3.02	3.05	3.09	12				
BV	2.98	3.05	3.09	7				
2-2TV	2.99	3.04	3.19	40	2.98	3.04	3.09	72
C	3.00	3.05	3.08	51	3.00	3.05	3.11	109
BV	3.00	3.04	3.09	15	2.96	3.04	3.09	27
2-3TV	2.94	3.04	3.08	20				
C	3.00	3.06	3.11	46				
BV	3.00	3.05	3.08	5				
3-1TV	2.94	3.02	3.05	21				
C	3.00	3.04	3.11	24				
BV	2.98	3.03	3.07	6				
3-2TV	2.97	3.04	3.19	29	2.94	3.04	3.21	78
C	3.00	3.04	3.07	20	3.00	3.05	3.11	79
VI	no data	3.05	no data	1	2.99	3.05	3.10	6
BV	2.99	3.02	3.07	13	2.98	3.04	3.08	30
3-3TV	2.99	3.05	3.19	28				
C	3.01	3.07	3.11	35				
VI	2.99	3.05	3.10	51				
BV	3.00	3.06	3.08	11				
	All Samples							
ALLTV	2.94	3.04	3.21	155				
C	3.00	3.05	3.11	196				
VI	2.99	3.05	3.10	8				
BV	2.96	3.04	3.09	61				

Table 3.1-6. Data ranges for the grain density distribution curves (values are g/cm^3) (Knutson et al. 1992, page 4-31).

Element	Data Range			
	Minimum	Median	Maximum	Number
TV	2.95	3.04	3.24	no data
C	2.72	3.05	3.13	no data
BV	2.98	3.05	3.10	no data
All data	2.72	3.05	3.24	no data

The bulk density distributions by elements for flow units, flow groups, and all samples from Knutson et al. 1990 are shown in Table 3.1-7. The bulk density distributions by elements for flow units, flow groups, and all samples from Knutson et al. 1992 are shown in Table 3.1-8. The SDE coefficients for elements of the sample sets are presented in Table C-4 of Knutson et al. 1992.

Table 3.1-7. Bulk density distributions by elements for flow units, flow groups, and all samples (values are g/cm^3) (Knutson et al. 1990, Table 4).

Element	Flow Units				Flow Groups			
	Minimum	Median	Maximum	Number	Minimum	Median	Maximum	Number
1TV	<2.20	2.40	2.61	11	<2.20	2.40	2.61	11
C	2.54	2.73	2.97	20	2.54	2.73	2.97	20
BV	<2.20	2.30	2.45	6	<2.20	2.30	2.45	6
2-1TV	<2.20	2.42	2.61	21				
C	2.57	2.76	2.95	30				
BV	2.29	2.37	2.61	12				
2-2TV	<2.20	2.38	2.61	71	<2.20	2.38	2.65	140
C	2.51	2.75	>3.00	87	2.43	2.73	>3.00	220
BV	<2.20	2.42	2.65	22	2.33	2.45	2.57	2
2-3TV	<2.20	2.39	2.65	48				
C	2.43	2.72	2.93	103				
BV	<2.20	2.39	2.65	6				
3-1TV	<2.20	2.38	2.67	49				
C	2.51	2.69	2.87	56				
BV	<2.20	2.24	2.65	9				
3-2TV	<2.20	2.39	2.65	40	<2.20	2.38	2.67	142
C	2.53	2.72	2.87	39	2.51	2.71	2.93	194
VI	no data	no data	no data	no data	<2.20	2.29	2.59	8
BV	<2.20	2.30	2.59	13	<2.20	2.36	2.65	35
3-3TV	<2.20	2.40	2.65	53				
C	2.51	2.73	2.93	99				
VI	<2.20	2.27	2.59	7				
BV	2.23	2.45	2.59	13				
	All Samples							
ALLTV	<2.20	2.39	2.67	293				
C		2.72	>3.30	434				
VI	<2.20	2.34	2.58	100				
BV	<2.20	2.39	2.65	81				

Table 3.1-8. Bulk density distributions by elements for flow units, flow groups, and all samples (values are g/cm^3) (Knutson et al. 1992, pages 4-22 to 4-30).

Element	Flow Units				Flow Groups			
	Minimum	Median	Maximum	Number	Minimum	Median	Maximum	Number
1TV	2.18	2.41	2.61	38				
C	2.32	2.73	2.90	38				
BV	2.19	2.34	2.49	38				
All	2.18	2.60	2.90	38				
2-1TV	1.96	2.39	2.78	146				
C	2.39	2.73	2.97	146				
BV	2.12	2.39	2.90	146				
All	1.96	2.71	2.97	146				
2-2TV	1.83	2.36	2.84	304	1.83	2.39	2.84	715
C	2.34	2.74	3.03	304	2.34	2.73	3.03	715
BV	2.00	2.39	2.86	304	2.00	2.39	2.90	715
All	1.83	2.58	3.03	304	1.83	2.63	3.03	715
2-3TV	2.06	2.40	2.80	265				
C	2.35	2.72	2.93	265				
BV	2.05	2.39	2.80	265				
All	2.05	2.65	2.93	265				
3-1TV	2.11	2.39	2.80	184				
C	2.26	2.68	2.84	184				
BV	2.18	2.33	2.733	184				
All	2.11	2.60	2.84	184				
3-2TV	1.94	2.37	2.87	207	1.70	2.37	2.87	704
C	2.22	2.69	2.96	207	2.08	2.69	3.01	704
BV	2.04	2.36	2.69	207	1.96	2.37	2.88	704
IV					2.09	2.39	2.58	704
All	1.94	2.59	2.96	207	1.70	2.61*	3.01	704
3-3TV	1.70	2.36	2.74	313				
C	2.08	2.71	3.01	313				
BV	1.96	2.46	2.88	313				
All	1.70	2.60	3.01	313				
	All Samples							
ALLTV	1.70	2.39	2.87	1457				
C	2.08	2.71	3.03	1457				
BV	1.96	2.39	2.90	1457				
IV	2.09	2.38	2.61	1457				
All	1.70	2.61	3.03	1457				

3.1.4 Equilibrium Saturation. Table 3.1-9 is the equilibrium water saturation adsorption data from each of the 45 basalt plugs in the equilibrium water saturation experiment from Knutson et al. 1990.

Table 3.1-9. Equilibrium water saturation adsorption data (Knutson et al. 1990, Table 5).

Well	Sample	Laboratory Por. (%)	Laboratory Perm. (mD)	Rh: 12.20	32.00	75.70	94.30	95.70	96.60	97.70	98.40	99.30	99.80	100.0
				% Water Saturation Given Relative Humidity (Rh in %)										
79-1	A 2	23.48	3.50	0.16	0.53	0.46	0.89	1.02	1.18	1.31	1.35	1.38	1.22	75.01
79-2	B 2	23.60	1.10	0.13	0.29	0.58	1.26	1.48	1.64	1.71	1.81	1.87	1.71	65.69
	B 4	13.04	10.55	0.58	0.58	1.40	2.45	2.74	2.97	3.20	3.32	3.32	3.26	82.33
	B 9	26.63	2.63	0.09	0.32	0.43	0.84	0.92	1.01	1.15	1.21	1.21	1.27	49.57
79-3	C 1	24.98	3.38	0.06	0.18	0.20	0.58	0.68	0.86	0.92	0.95	0.92	0.73	47.27
	C 5	14.78	1.07	0.20	0.36	0.72	1.48	1.74	1.99	2.25	2.35	2.35	2.10	73.79
	C 9	8.85	0.21	0.60	1.12	2.07	4.15	5.01	5.61	5.96	6.22	6.48	5.88	72.19
	C 11	21.64	1.79	0.10	0.24	0.38	0.73	0.80	0.91	1.05	1.12	1.12	1.26	55.28
	C 14	15.59	1.67	0.29	0.48	1.07	2.28	2.61	2.95	3.19	3.44	3.39	3.29	71.76
76-2	D 3	26.90	11.21	0.00	0.11	0.25	0.56	0.62	0.68	0.73	0.76	0.76	0.62	60.46
	D 7	22.93	2.73	0.13	0.20	0.30	0.63	0.76	0.86	0.96	1.03	1.03	1.00	68.71
	D 10	10.56	1.20	0.29	0.51	0.94	1.89	1.96	2.18	2.25	2.40	2.47	2.47	70.93
	D 15	16.53	2.22	0.14	0.32	0.46	1.05	1.14	1.32	1.46	1.55	1.50	1.41	86.34
	D 17	26.29	873.74	0.20	0.93	1.45	3.77	4.98	5.70	1.72	–	–	–	–
78-3	E 2	12.82	33.59	0.18	0.24	0.59	1.25	1.30	1.48	1.72	1.90	2.02	1.96	88.37
	E 5	22.07	2.56	0.14	0.20	0.31	0.61	0.68	0.78	0.82	0.89	0.92	0.89	57.38
	E 7	22.26	4.07	0.10	0.17	0.37	0.78	0.91	1.08	1.18	1.22	1.28	1.15	58.15
	E 11	17.07	4.77	0.22	0.44	0.71	1.55	1.72	2.03	2.16	2.30	2.34	2.43	78.25
	E 17	11.01	12.33	0.34	0.76	1.58	3.50	3.64	3.98	4.25	4.88	4.87	5.15	81.40
	E 18	12.06	9.36	0.31	0.50	0.81	1.56	1.80	1.99	2.18	2.30	2.37	2.12	84.16
	E 20	12.21	8.92	0.19	0.31	0.74	1.49	1.73	1.92	2.10	2.23	2.35	1.73	90.39
	E 24	21.25	0.42	0.11	0.18	0.53	1.10	1.24	1.45	1.49	1.56	1.63	1.56	68.86
	E 26	6.48	0.18	0.47	0.82	1.86	3.85	4.19	5.01	5.47	5.83	5.94	5.83	82.10
	E 27	10.89	46.79	0.21	0.28	0.90	1.80	1.93	2.14	2.49	2.63	2.63	2.83	93.45
	E 30	43.24	4824.28	0.04	0.44	0.91	1.65	1.77	1.96	2.05	2.28	2.31	2.45	64.09
	E 32	20.94	19.75	0.21	0.43	1.04	1.97	2.47	2.72	2.86	3.12	3.15	3.04	69.56
	E 34	23.44	0.16	0.26	0.58	1.19	2.18	2.51	2.79	2.89	3.18	3.24	3.98	67.54
	E 38	12.55	0.00	0.84	1.98	3.48	6.06	7.38	8.10	8.64	8.95	8.94	9.31	68.52
78-5	F 1	19.43	3.35	0.12	0.31	0.43	0.78	0.89	1.09	1.16	1.20	1.09	1.17	71.92
	F 2	11.76	4.05	0.26	0.64	1.09	1.85	2.04	2.30	2.42	2.55	2.55	2.62	83.49
	F 3	22.51	1.04	0.13	0.30	0.53	1.10	1.24	1.40	1.47	1.50	1.54	1.54	65.71
	F 6	16.07	8.77	0.19	0.42	0.66	1.36	1.55	1.74	1.88	2.02	2.02	1.93	71.95
	F 10	25.87	395.47	0.09	0.20	0.29	0.58	0.73	0.84	0.93	1.02	0.99	0.87	63.59
	F 13	11.68	29.22	0.19	0.39	0.84	1.75	1.87	2.13	2.33	2.46	2.52	2.33	81.21
	F 17	25.15	2.42	0.18	0.42	0.72	1.26	1.35	1.44	1.59	1.71	1.74	1.89	51.98
	F 22	12.80	19.92	0.29	0.47	1.00	1.95	2.24	2.47	2.59	2.65	2.77	2.36	81.71
	F 23	10.82	5.54	0.28	0.77	1.53	3.06	3.48	3.90	4.24	4.39	4.45	4.18	91.17
	F 24	21.42	123.82	0.14	0.32	0.71	1.34	1.55	1.73	1.83	1.98	2.01	2.05	65.72
	F 27	31.56	2.17	0.12	0.38	0.84	1.44	1.63	1.82	1.92	2.09	2.01	2.28	67.81
	F 28	17.94	11.22	0.55	1.10	2.19	3.62	4.08	4.50	4.92	5.31	5.31	6.23	74.29
	F 32	13.73	9.47	0.77	1.48	2.68	4.77	5.58	6.08	6.46	6.96	7.01	7.94	82.04
93-A	G 2	11.26	1.37	0.40	0.67	1.28	2.22	2.35	2.55	2.69	2.83	3.03	3.03	82.99
	G 5	16.68	0.53	0.27	0.59	1.04	1.85	2.03	2.17	2.35	2.48	2.53	2.48	75.04
96-A	H 2	12.50	9.58	0.24	0.36	0.79	1.63	1.75	1.93	2.23	2.36	2.35	2.42	77.76
76-3	I 2	13.19	32.46	0.29	0.63	1.15	2.65	2.94	3.28	3.40	3.57	3.69	3.80	83.81

3.2 Bishop 1991

The data and text in this section are summarized from Bishop 1991.

3.2.1 Porosity and Dry Bulk Density. Table 3.2-1 is a tabulation of the porosity, dry bulk density, saturated bulk density, and skeletal density found in 71 cores. Table 3.2-2 is a summary of the statistical properties of the basalt core bulk density and porosity. Table 3.2-3 is a summary of the statistical properties of the skeletal density.

Dry bulk density was determined for 71 cores. Obtaining an accurate saturated weight was difficult as immediately upon removal from the solution, water drained out of the larger vesicles and, thus the core was no longer fully saturated. This problem was resolved by using a tared weighing dish. Water that drained out of the vesicles was included in the saturated weight.

Dry weights ranged from 310.49 to 349.92 gm, while saturated weights ranged from 345.17 to 380.00 gm. Statistics for dry bulk density indicate a mean of 2.40 gm/cm^3 and a range of 2.14 to 2.58 gm/cm^3 with standard deviation of 0.09. Considerably more variation was evident in the porosity values.

Three of the samples were apparently slightly more dense (4-2B, 17.92%; 6-1C, 17.13%; AND E5-1B, 18.53% porosity). Samples VC-E2, VA4 and 2-1A (35.97, 27.08, and 27.81% porosity) were the most porous of the cores. Variations in porosity were not obvious from physical inspection. Mean porosity was about 23%.

Table 3.2-1. Porosity and density values (from Bishop 1991, Table 2).

ID No	POROSITY (%)	DRY B.D (gm/cm^3)	SAT.B.D (gm/cm^3)	SK. D. (gm/cm^3)
1-1A	23.13	2.417	2.648	3.14
1-2A	25.18	2.323	2.575	3.11
2-1A	27.81	2.251	2.529	3.12
4-1B	22.52	2.361	2.586	3.05
4-1C	25.13	2.368	2.619	3.16
4-2A	23.33	2.277	2.510	2.97
4-2B	17.92	2.396	2.575	2.92
4-2C	23.50	2.313	2.548	3.02
6-1A	21.88	2.467	2.686	3.16
6-1B	26.65	2.141	2.407	2.92
6-1C	17.13	2.358	2.529	2.85
6-2A	21.66	2.472	2.688	3.16
6-2B	21.94	2.363	2.582	3.03
6-2C	22.24	2.484	2.707	3.19
7-1C	21.90	2.215	2.434	2.84
7-2A	22.64	2.265	2.491	2.93
7-4B	22.23	2.223	2.445	2.86
7-5A	21.09	2.221	2.432	2.81
8-1A	23.24	2.348	2.580	3.06
8-1B	22.42	2.387	2.612	3.08
8-2A	23.48	2.325	2.560	3.04
8-2B	24.37	2.427	2.671	3.21
8-2C	20.37	2.395	2.598	3.01
V9-A	21.05	2.533	2.743	3.21
V9-B	22.28	2.426	2.649	3.12
V9-C	20.31	2.500	2.703	3.14
V-8B	24.67	2.353	2.600	3.12
10-1 B	23.32	2.442	2.675	3.18
10-1 C	21.12	2.493	2.704	3.16
10-2 A	22.63	2.497	2.723	3.23
10-2 B	24.24	2.473	2.715	3.26
12-1 A	22.62	2.449	2.675	3.17
12-1 B	20.19	2.508	2.710	3.14
12-2 A	20.79	2.488	2.696	3.14
12-2 B	24.24	2.486	2.728	3.28
12-2 C	22.12	2.455	2.676	3.15
14-3 A	22.78	2.430	2.658	3.15
14-4 B	24.86	2.364	2.613	3.15
17-1 A	24.52	2.343	2.588	3.10
17-1 C	23.73	2.357	2.594	3.09
17-2 A	25.35	2.361	2.615	3.16
E4-2 A	23.90	2.431	2.670	3.19
E4-2 B	20.48	2.357	2.561	2.96
E4-3 A	21.94	2.377	2.596	3.04
E4-4 A	23.03	2.404	2.635	3.12
E4-4 B	24.27	2.407	2.650	3.18
E4-4 C	23.60	2.460	2.696	3.22
E5-1 A	21.13	2.449	2.660	3.10
E5-1 B	18.53	2.441	2.626	3.00
E5-2 A	21.78	2.463	2.680	3.15
E5-2 B	22.09	2.486	2.707	3.19
E5-2 C	20.41	2.493	2.697	3.13
H10- B	21.23	2.447	2.659	3.11

Table 3.2-1 (continued). Porosity and density values (from Bishop 1991, Table 2).

ID No	POROSITY (%)	DRY B.D (gm/cm^3)	SAT.B.D (gm/cm^3)	SK. D. (gm/cm^3)
H13- B	20.44	2.520	2.724	3.17
H4B	23.21	2.325	2.557	3.03
H4-C	24.23	2.423	2.666	3.20
V10- C	21.75	2.533	2.750	3.24
V6E2	24.55	2.217	2.462	2.94
V8B	24.42	2.312	2.556	3.06
V9A	21.05	2.533	2.743	3.21
V9B	22.48	2.403	2.628	3.10
V9C	20.59	2.498	2.704	3.15
V9'- B	21.61	2.458	2.674	3.14
VA	25.02	2.373	2.623	3.16
VA3	22.60	2.378	2.604	3.07
VA4	27.08	2.282	2.553	3.13
VC-2 E	35.97	2.350	2.710	3.67
V'9C	22.29	2.481	2.704	3.19
V'9- A	25.24	2.454	2.706	3.28
WC4	24.47	2.336	2.581	3.09
W-13 A	20.85	2.583	2.792	3.26

Table 3.2-2. Summary of dry bulk density and effective porosity values obtained from vesicular basalt cores (from Bishop 1991, Table 3).

Statistical Parameter	Dry Bulk Density (gm/cm^3)	Effective Porosity (%)
Mean	2.40	22.86
Coef. Var.	0.038%	10.94
Minimum	2.14	17.13
Median	2.41	22.60
Maximum	2.58	35.97

Table 3.2-3. Summary of skeletal density statistical properties (from Bishop 1991, Table 4).

Statistical Property	Skeletal Density mg/cm^3
Mean	3.11
Coefficient of Variation	4.18%
Minimum	2.81
Median	3.14
Maximum	3.67

3.2.2 Pneumatic Permeability. Six samples that were subcored and tested for pneumatic permeability are listed in Table 3.2-4. The porosity is a total porosity, therefore it is higher than the effective porosities listed above.

Table 3.2-4. Summary of pneumatic permeability data (from Bishop 1991, Table 5).

Sample	Total Porosity	Void Vol. cm^3	Air Perm. cm^2
P-1	30.58%	4.09	4.67E-11
P-2	26.73%	3.57	3.66E-11
P-4	28.53%	3.80	4.92E-11
P-5	29.44%	3.93	4.82E-10
P-6	37.48%	5.01	3.68E-11
P-7	24.86%	3.32	5.18E-11

3.2.3 Saturated Hydraulic Conductivity. In the studies performed by Bishop 1991, at least two saturated hydraulic conductivity (K_s) tests were run for each core sample. If the second value was significantly different than the first value, the test was repeated at least twice again at a later time. This limited the possibility of experimental error. Values for K_s are listed in Tables 3.2-5 and 3.2-6. The samples have been separated into the cores drilled vertically (Table 3.2-5) and those cored drilled horizontally (Table 3.2-6). Twenty-nine vertical and seventeen horizontal cores were tested for K_s. Mean K_s measured were an order of magnitude higher in the vertical direction than the horizontal (vertical, 9.81×10^{-7} m/s; horizontal, 8.42×10^{-8} m/s). This apparent K_s anisotropy resulted principally from three samples whose measured K_s values were approximately 8.80×10^{-6} m/s. When these samples along with all whose measured time was less than one minute were deleted, the mean K_s values for both directions were virtually indistinguishable. Bishop 1991 does not expect the apparent vertical anisotropy to persist to the field scale. There it is expected that a saturated wetting front with relativity little matrix suction should flow fairly readily through the horizontal flow channels and along flow tops and bottoms.

A statistical summary of the Ks and air permeability values for both the vertically and horizontally drilled wells is shown in Table 3.2-7.

Table 3.2-5. Ks and air permeability values for cores drilled vertically (from Bishop 1991, Table 6).

Sample Name	K_s (m/s)	air permeabilities (m^2)
10-2A	$1.2090 X 10^{-8}$	$1.1025 x 10^{-14}$
10-2B	$1.4710 X 10^{-7}$	$1.3414 x 10^{-14}$
10-2C	$8.8260 X 10^{-8}$	$8.0486 x 10^{-15}$
12-2A	$1.2791 X 10^{-7}$	$1.1665 x 10^{-14}$
12-2C	$2.3854 X 10^{-7}$	$2.1753 x 10^{-14}$
14-4B	$1.6466 X 10^{-8}$	$1.5016 x 10^{-15}$
17-2A	$4.7452 X 10^{-8}$	$4.3272 x 10^{-15}$
1-2A	$4.4352 X 10^{-8}$	$4.0445 x 10^{-15}$
4-2A	$3.0860 X 10^{-8}$	$2.8142 x 10^{-15}$
4-2B	$9.2905 X 10^{-8}$	$8.4722 x 10^{-15}$
6-2B	$4.2433 X 10^{-8}$	$3.8695 x 10^{-15}$
6-2C	$4.7198 X 10^{-8}$	$4.3041 x 10^{-15}$
7-2A	$2.8198 X 10^{-8}$	$2.5714 x 10^{-15}$
8-2A	$9.0061 X 10^{-8}$	$8.2129 x 10^{-15}$
8-2B	$8.8260 X 10^{-6}$	$8.0486 x 10^{-13}$
8-2C	$8.8260 X 10^{-6}$	$8.0486 x 10^{-13}$
104-2A	$2.9818 X 10^{-8}$	$2.7191 x 10^{-15}$
104-2B	$1.1172 X 10^{-7}$	$1.0188 x 10^{-15}$
104-4A	$3.0330 X 10^{-8}$	$2.7658 x 10^{-15}$
104-4B	$5.3491 X 10^{-8}$	$4.8779 x 10^{-15}$
104-4C	$6.3957 X 10^{-8}$	$5.8323 x 10^{-15}$
105-2A	$7.5436 X 10^{-8}$	$6.8791 x 10^{-15}$
105-2B	$8.8260 X 10^{-6}$	$8.0486 x 10^{-13}$
V8B	$7.1756 X 10^{-8}$	$6.5436 x 10^{-15}$
V9C	$9.1938 X 10^{-8}$	$8.3840 x 10^{-15}$
VA	$6.9496 X 10^{-8}$	$6.3375 x 10^{-15}$
VC10	$8.2486 X 10^{-8}$	$7.5221 x 10^{-15}$
VCE2	$6.2596 X 10^{-8}$	$5.7082 x 10^{-15}$
WB10	$5.9635 X 10^{-8}$	$5.4382 x 10^{-15}$

Table 3.2-6. Ks and air permeability values for cores drilled horizontally (from Bishop 1991, Table 7).

Sample Name	K_s (m/s)	Air Permeability (m^2)
8-1A	5.8450×10^{-8}	5.3302×10^{-15}
10-1B	6.3043×10^{-7}	5.7490×10^{-14}
12-1A	3.8541×10^{-8}	3.5147×10^{-15}
17-1C	1.7306×10^{-8}	1.5782×10^{-15}
4-1B	1.5191×10^{-8}	1.3853×10^{-15}
10-1C	5.2850×10^{-8}	4.8195×10^{-15}
12-1B	4.5031×10^{-8}	4.1064×10^{-15}
2-1A	1.5789×10^{-8}	1.4398×10^{-15}
4-1C	1.5217×10^{-7}	1.3877×10^{-14}
17-1A	3.0860×10^{-8}	2.8142×10^{-15}
2-1D	1.5191×10^{-8}	1.3853×10^{-15}
7-1C	3.7557×10^{-8}	3.4249×10^{-15}
E5-1B	5.2850×10^{-8}	4.8195×10^{-15}
8-1B	5.8450×10^{-8}	5.3302×10^{-15}
1-1A	1.0263×10^{-7}	9.3588×10^{-15}
6-1C	5.8450×10^{-8}	5.3302×10^{-15}
E4-3A	5.0434×10^{-8}	4.5992×10^{-15}

Table 3.2-7. Summary of hydraulic conductivity values obtained from 29 vertically and 17 horizontally cored basalt samples (from Bishop 1991, Table 8).

Statistical Parameter	Horizontal Basalt Cores	Vertical Basalt Cores
Mean	8.42×10^{-8} m/s	9.81×10^{-7} m/s
Coef. Var.	166.77%	271.21%
Minimum	1.52×10^{-8} m/s	1.65×10^{-8} m/s
Median	5.04×10^{-8} m/s	7.18×10^{-8} m/s
Maximum	6.30×10^{-7} m/s	8.83×10^{-6} m/s

The cores with the high hydraulic conductivity values were visually inspected to determine if any evidence for the high K_s values was present. Secondary mineralization was evident throughout the cores, indicating that they had indeed been conduits for water in the past. However, fractures or connected vesicles were not evident.

Positions of these cores within the large original block were checked. A majority of the K_s values less than 1.47×10^{-7} m/s (corresponding to a measured time of 60 seconds or less) were located in the center of the block.

3.2.4 Moisture Characteristic Curves. Bishop 1991 notes that the slopes of moisture characteristic curves in soils traditionally show considerable variation between the sorption and desorption limb of the curve. This hysteresis results in equilibrium soil wetness at a given matrix tension being greater in desorption than in sorption. Although this research concentrated on the desorption limb of the moisture characteristic curve, the sorption limb was investigated on limited scale.

Moisture characteristic curves were developed from equilibrium data derived from both the pressure plate extractors and Tempe pressure cells techniques. Table 3.2-8 is a listing of equilibrium points corresponding to matrix suctions for the desorption limb.

Although there is some variability among the individual samples, the data indicate that moisture readily moves through the basalt at low matrix suctions while at higher suctions water is tightly bound in the small pores by capillary forces. Capillarity in the large vesicles is low and is easily overcome by gravity and slight applied suctions.

The sorption limb of the moisture characteristic curve occurs when a core at residual water content is gradually wetted up while reducing pressure. Table 3.2-9 is a summary of the statistical parameters obtained from this experiment.

Due to its structure, the vesicular basalt absorbed very little water at any of the pressure steps. At zero pressure weights of the cores increased a few tenths of a gram at each weighing. The minuscule weight increases continued for months. This indicates that only the smallest pore spaces filled since the capillary forces in these pores were sufficiently high to draw water. Large vesicles with low capillarity never filled. There was also the probability of entrapped air not allowing some of the vesicles to fill. During the months that the experiment was run, the cores remained in the humid environment within the pressure plate extractor. What appeared to be a biological growth developed on three core surfaces which could have further inhibited the core's ability to sorb water.

Table 3.2-8. Moisture characteristic (desorption) curve equilibrium points (from Bishop 1991, Table 9).

Vesicular basalt moisture characteristic curve data (kPa units)								
Sample	Water	10.00	25.00	50.00	90.00	200.00	300.00	500.00
12-1b	26.90	14.58	2.50	3.30	4.10	0.26	0.06	0.13
wp-13	24.29	22.19	0.00	0.00	0.00	0.22	0.22	-0.02
10-1b	26.81	16.41	2.90	2.90	1.80	0.58	0.06	0.01
8-2b	28.28	18.53	2.60	2.70	2.50	0.32	0.17	0.07
e4-3a	30.26	20.74	2.30	3.20	1.60	0.47	0.03	0.12
2-1d	31.85	20.03	3.20	3.80	2.00	0.54	0.12	0.12
10-1c	28.24	16.05	3.50	5.00	1.40	0.31	0.24	0.01
10-2c	29.61	18.44	2.30	3.10	3.50	0.25	0.01	0.07
14-2a	32.93	23.09	1.40	1.80	3.80	0.70	0.27	-0.02
e4-2a	30.47	28.53	0.00	0.00	0.00	0.24	0.02	0.01
e5-1b	26.01	15.69	1.20	1.80	4.80	0.32	0.18	0.02
6-2c	25.23	16.15	1.90	2.30	2.00	0.76	0.33	0.07
14-2b	32.47	24.42	0.00	0.00	0.00	0.42	1.04	2.51
2-1a	38.03	22.15	2.20	2.90	3.60	0.90	1.25	1.30
10-2a	32.64	17.30	2.30	2.80	2.90	0.64	2.92	0.66
17-2a	37.90	12.73	3.50	5.10	6.60	0.62	0.46	1.01
14-1c	37.46	18.89	3.00	0.30	3.70	0.77	0.16	2.39
12-2a	31.11	12.74	2.00	3.50	3.80	1.38	2.05	2.27
14-2c	42.38	30.44	0.00	0.00	0.00	0.69	5.84	1.83
14-4b	33.98	17.62	2.50	1.00	2.50	0.46	1.02	3.42
8-1c	30.43	20.47	0.00	0.00	0.00	1.15	4.83	0.42
e5-2a	29.93	12.52	4.00	3.50	2.20	0.83	1.78	1.36
4-1c	37.49	24.35	0.00	0.00	0.00	0.10	1.67	5.42
14-3a	41.36	22.69	2.50	3.40	3.00	1.34	1.60	2.06
8-1b	33.56	17.42	2.02	2.50	2.60	0.88	2.60	1.46
va4	37.63	26.18	0.00	0.00	0.00	1.07	0.95	1.34
12-2b	33.44	24.58	0.00	0.00	0.00	3.19	0.44	1.38
12-1a	34.07	16.06	2.30	3.50	4.40	1.11	0.96	2.06
hb10	34.79	24.19	0.00	0.00	0.00	3.01	1.45	1.18
v6e2	34.47	15.21	1.60	2.40	5.60	2.43	0.78	1.31
4-1a	43.08	32.73	0.00	0.00	0.00	3.03	0.49	1.08
14-x	32.60	20.38	0.00	0.00	0.00	0.82	1.20	2.71
6-2a	33.60	22.84	0.00	0.00	0.00	1.05	1.13	0.66
17-1b	33.02	25.28	0.00	0.00	0.00	1.89	0.94	1.20
17-1a	37.27	16.99	3.00	3.40	4.20	0.94	1.79	1.31
14-1a	37.60	24.16	0.00	0.00	0.00	1.00	1.35	1.19
e4-2c	37.59	22.12	3.20	3.50	0.00	1.14	1.58	1.53
6-2a	30.43	15.74	0.00	3.70	2.80	2.05	1.40	0.15
e4-4c	33.38	17.41	2.70	3.30	3.10	2.08	1.48	-0.04
e4-2a	33.54	15.63	2.70	4.60	3.70	1.19	1.90	-0.09
17-1c	40.30	19.81	3.00	4.30	0.00	1.59	0.74	0.33
17-1a	37.27	24.79	2.50	2.50	1.20	2.13	1.45	-0.28
e4-2a*	32.63	14.23	3.30	3.20	3.70	2.82	2.04	-0.05
4-2b	32.67	15.11	2.80	3.50	0.00	0.63	1.56	1.56
hb10	28.17	18.98	0.00	0.00	0.00	1.00	1.43	1.37
e4-2b	28.25	10.80	2.50	2.80	3.10	0.93	0.63	1.01
4-1b	30.26	8.10	3.20	3.70	3.80	1.32	1.02	1.61
17-2a	34.56	25.29	0.00	0.00	0.00	0.97	0.98	1.49
va3	31.17	26.29	0.00	0.00	0.00	1.11	0.26	0.66
8-2a	30.07	10.78	2.80	4.00	3.30	1.07	0.52	1.73
vce2	34.62	14.24	1.60	2.40	5.60	0.31	0.69	0.98
wa13	30.05	15.65	2.30	3.00	0.90	1.79	0.80	0.76

Table 3.2-8 (continued). Moisture characteristic (desorption) curve equilibrium points (from Bishop 1991, Table 9).

Vesicular basalt moisture characteristic curve data (kPa units)								
Sample	Water	10.00	25.00	50.00	90.00	200.00	300.00	500.00
10-2b	32.99	16.35	0.00	4.30	4.90	0.56	0.37	1.19
1-1a	32.43	13.73	2.80	5.30	no data	0.54	0.78	0.88
6-1a	32.34	10.75	4.00	2.50	3.10	0.11	0.44	0.97
8-2c	33.92	16.45	2.60	2.70	1.60	2.05	0.27	1.50
va	33.28	15.18	0.00	2.40	5.40	3.63	0.78	0.38
va4	32.36	13.98	2.50	3.20	2.30	0.81	0.91	0.58
v'9b	32.08	10.83	3.30	3.70	3.70	2.71	0.04	0.67
12-2b	28.87	17.29	0.00	1.60	4.80	0.51	0.20	0.84
v9b	30.45	17.00	1.40	0.00	4.30	2.84	0.35	0.84
e5-2b	28.80	9.38	3.10	2.80	2.30	2.66	0.17	1.04
v'9c	31.29	22.97	0.00	0.00	0.00	1.95	0.36	0.73
4-1c	34.71	9.39	4.10	4.70	5.10	1.50	0.21	1.31
vc10	29.11	14.96	2.30	3.00	0.40	2.09	0.53	0.79
6-1c	35.07	16.19	2.30	4.00	2.70	1.95	0.40	0.86
v8b	34.28	16.78	1.50	2.40	2.30	3.54	0.03	0.93
v9c	28.40	12.79	2.90	2.70	2.50	1.18	0.58	0.95
10-2a	32.64	27.10	0.00	0.00	0.00	1.65	0.57	-0.28
e5-1b	31.10	24.93	0.00	0.00	0.00	1.24	1.18	-0.01
14-1c	38.33	28.82	0.00	0.00	0.00	2.69	1.95	-0.19
vb10	31.91	26.55	0.00	0.00	0.00	1.41	0.90	-0.07
12-1b	32.55	27.57	0.00	0.00	0.00	0.91	0.70	-0.04
12-2a	34.64	28.66	0.00	0.00	0.00	2.02	0.40	-0.04

Table 3.2-9. Summary of statistical parameters for sorption limb of moisture characteristic curve (volumetric water contents) (from Bishop 1991, Table 10).

Statistical Property	500 kPa	300 kPa	100 kPa	50 kPa	0 kPa
Mean	1.15%	1.25%	1.40%	1.56%	3.99%
Coef. Var.	11.67%	10.87%	9.73%	10.57%	4.69%
Minimum	0.914%	0.928%	1.047%	1.175%	3.538%
Median	1.115%	1.145%	1.365%	1.435%	3.780%
Maximum	1.378%	1.363%	1.436%	1.610%	4.046%

3.2.5 Unsaturated Hydraulic Conductivity Parameters. The moisture characteristic curves were fit with a cubic spline generated curve and one hundred twenty-one points were taken from the curve and input into Van Genuchten's RETC program. RETC was then run, and the fitting parameters n and a were obtained. Previous research by Guzman (unpublished text) has suggested that RETC yielded more accurate fitting parameters by using the cubic spline curve and extracting numerous points from it.

Using the above technique, van Genuchten fitting parameters were obtained for 60 basalt samples. Table 3.2-10 is a summary of the statistical properties for the fitting parameters α and n. Saturated hydraulic conductivity and saturated water content, known from previous experiments, were set in the program. Residual water content, α and n were analyzed.

Table 3.2-10. Summary of statistical properties of fitting parameters for 60 vesicular basalt samples using RETC (from Bishop 1991, Table 11).

Statistical Properties	n	α (cm^{-1})
Mean	1.4741	0.0384
Coef. Var.	8.37%	33.85%
Minimum	1.222	0.0101
Median	1.3980	0.0377
Maximum	1.8255	0.0690

Seven core samples were processed in the Tempe pressure cells with one large pressure step--70 kPa. This data along with several equilibrium points were supplied to the SFIT program for the purposes of comparing estimated relative hydraulic conductivities yielded by SFIT with those from RETC. Table 3.2-11 is a summary of statistical properties of the RETC fitting parameters for the seven cores in this comparison, and Table 3.2-12 lists those developed from SFIT.

Table 3.2-11. Summary of statistical properties for RETC fitting parameters for seven core samples (from Bishop 1991, Table 12).

Statistical Parameters	n	α (cm^{-1})
Mean	1.5613	0.0359
Coef. Variation	9.437%	16.239%
Minimum	1.3896	0.0278
Median	1.5755	0.0349
Maximum	1.8254	0.0448

Table 3.2-12. Summary of statistical properties for SFIT fitting parameters for seven core samples (from Bishop 1991, Table 13).

Statistical Properties	n	α (cm^{-1})
Mean	0.327	3.72
Coef. Var.	56.58%	46.40%
Minimum	0.057	2.08
Median	0.411	2.83
Maximum	0.537	7.04

3.2.6 Infiltration Curves. Infiltration curves were constructed for each of three porous plates (A, B and C. Total solution infiltrated into the block was 6.6 liters. It is believed that excess solution evaporated from the bottom of the block. At approximately 42,000 minutes there is a distinct change in the slope. This occurs on the same day as the block was totally wrapped in duct tape.

Saturated hydraulic conductivity for the block was estimated by analyzing the slope of the infiltration curves. Table 3.2-13 lists the K values obtained from each infiltration curve and the average of the three which was assumed to be the K for the block.

Table 3.2-13. Summary of K values obtained from the infiltration curves (from Bishop 1991, Table 14).

Plates Parameter	A (m/s)	B (m/s)	C (m/s)	Average Value
K	1.32E-08	2.12E-08	1.56E-08	1.67E-08

When the 50 cm x 20 cm x 20 cm block experiment had first been proposed, it had been hoped that comparing hydraulic properties of the block with those of the cores would yield some information on the effect scale has on these properties. However, properties measured on the block also represent the matrix. This is because the microfractures on this scale are still the primary means of connecting the vesicles. A considerably larger scale is necessary to evaluate flow paths within the basalt other than the microfractures. Nevertheless, the saturated hydraulic conductivity information is valuable because it appears to validate the accuracy of K values measured on the core.

Table 3.2-14 is a summary of the physical properties of basalt from Bishop 1991.

Table 3.2-14. Summary of the physical properties of basalt (from Bishop 1991, Appendix).

ID No.	Length (cm)	Dia. (cm)	Dry wt (gm)	Sat. wt (gm)	Porosity (%age)	Dry B.D (gm/cm^3)	Sat. B.D (gm/cm^3)
1-1A	5.60	5.60	333.35	365.25	23.13	2.417	2.648
1-2A	5.60	5.60	320.44	355.17	25.18	2.323	2.575
2-1A	5.60	5.60	310.49	348.85	27.81	2.251	2.529
4-1B	5.60	5.60	325.66	356.72	22.52	2.361	2.586
4-1C	5.60	5.60	326.55	361.21	25.13	2.368	2.619
4-2A	5.60	5.60	314.04	346.22	23.33	2.277	2.510
4-2B	5.50	5.60	324.58	348.85	17.92	2.396	2.575
4-2C	5.50	5.60	313.34	345.17	23.50	2.313	2.548
6-1A	5.60	5.60	340.23	370.41	21.88	2.467	2.686
6-1B	5.70	5.60	311.41	350.17	26.65	2.141	2.407
6-1C	5.60	5.60	325.22	348.85	17.13	2.358	2.529
6-2A	5.60	5.60	340.94	370.81	21.66	2.472	2.688
6-2B	5.70	5.60	343.67	375.58	21.94	2.363	2.582
6-2C	5.70	5.60	348.77	380.00	22.24	2.484	2.707
7-1C	5.70	5.60	322.21	354.07	21.90	2.215	2.434
7-2A	5.70	5.60	329.43	362.36	22.64	2.265	2.491
7-4B	5.70	5.60	323.36	355.69	22.23	2.223	2.445
7-5A	5.80	5.60	340.30	372.62	21.09	2.221	2.432
8-1A	5.70	5.60	329.61	362.23	23.24	2.348	2.580
8-1B	5.70	5.60	335.18	366.65	22.42	2.387	2.612
8-2A	5.50	5.60	325.89	355.96	23.48	2.325	2.560
8-2B	5.60	5.60	334.74	368.35	24.37	2.427	2.671
8-2C	5.60	5.60	336.25	370.17	20.37	2.395	2.598
V9-A	5.50	5.60	343.09	371.60	21.05	2.533	2.743
V9-B	5.45	5.60	325.66	355.57	22.28	2.426	2.649
V9-C	5.60	5.60	344.78	372.80	20.31	2.500	2.703
V-8B	5.60	5.60	324.57	358.60	24.67	2.353	2.600
10-1B	5.60	5.60	336.83	369.00	23.32	2.442	2.675
10-1C	5.60	5.60	343.87	373.00	21.12	2.493	2.704
10-2A	5.60	5.60	344.40	375.62	22.63	2.497	2.723
10-2B	5.55	5.60	338.00	348.85	7.94	2.473	2.552
12-1A	5.60	5.60	337.80	369.00	22.62	2.449	2.675
12-1B	5.60	5.60	345.98	373.83	20.19	2.508	2.710
12-2A	5.60	5.60	343.18	371.86	20.79	2.488	2.696
12-2B	5.60	5.60	343.00	348.85	4.24	2.487	2.529
12-2C	5.60	5.60	338.60	369.11	22.12	2.455	2.676
14-3A	5.50	5.60	329.00	361.57	24.04	2.429	2.669
14-4B	5.55	5.60	323.20	357.18	24.86	2.364	2.613
17-1A	5.50	5.60	317.42	350.64	24.52	2.343	2.588
17-1C	5.60	5.60	325.08	357.81	23.73	2.357	2.594
17-2A	5.60	5.60	325.71	360.68	25.35	2.361	2.615
E4-2A	5.60	5.60	335.30	368.27	23.90	2.431	2.670
E4-2B	5.60	5.60	325.04	353.29	20.48	2.357	2.561
E4-3A	5.60	5.60	327.79	358.05	21.94	2.377	2.596
E4-4A	5.60	5.60	331.62	363.39	23.03	2.404	2.635
E4-4B	5.60	5.60	332.02	365.50	24.27	2.407	2.650
E4-4C	5.60	5.60	333.54	366.39	23.82	2.418	2.656
E5-1A	5.60	5.60	337.73	366.87	21.13	2.449	2.660
E5-1B	5.70	5.60	342.67	368.68	18.53	2.441	2.626
E5-2A	5.60	5.60	339.65	369.69	21.78	2.463	2.680
E5-2B	5.55	5.60	336.90	366.44	21.61	2.465	2.681
E5-2C	5.60	5.60	343.88	372.03	20.41	2.493	2.697

Table 3.2-14 (continue). Summary of the physical properties of basalt (from Bishop 1991, Appendix).

ID No.	Length (cm)	Dia. (cm)	Dry wt (gm)	Sat. wt (gm)	Porosity (%age)	Dry B.D (gm/cm^3)	Sat. B.D (gm/cm^3)
H10-B	5.60	5.60	337.45	366.73	21.23	2.477	2.659
H13-B	5.60	5.60	347.53	375.72	20.44	2.520	2.724
H4B	5.60	5.60	331.98	366.64	25.13	2.407	2.658
H4-C	5.40	5.60	322.31	354.53	24.23	2.423	2.666
V10-C	5.50	5.60	343.07	372.54	21.75	2.533	2.750
V6E2	5.70	5.60	311.23	345.70	24.55	2.217	2.462
V8B	5.70	5.60	324.53	358.81	24.42	2.312	2.556
V9A	5.50	5.60	343.09	371.60	21.05	2.533	2.743
V9B	5.50	5.60	325.56	356.01	22.48	2.403	2.628
V9C	5.60	5.60	344.60	373.00	20.59	2.498	2.704
V9'-B	5.70	5.60	345.06	375.40	21.61	2.458	2.674
VA	5.40	5.60	315.60	348.88	25.02	2.373	2.623
VA3	5.60	5.60	328.03	359.20	22.60	2.378	2.604
VA4	5.65	5.60	317.57	355.25	27.08	2.282	2.553
VC10	5.50	5.60	343.44	372.55	21.49	2.535	2.750
VC-2E	5.50	5.60	318.39	367.12	35.97	2.350	2.710
V'9C	5.70	5.60	348.36	379.65	22.29	2.481	2.704
V'9-A	5.70	5.60	344.46	379.90	25.24	2.454	2.706
WC4	5.60	5.60	322.21	355.96	24.47	2.336	2.581
W-13A	5.50	5.60	349.92	378.16	20.85	2.583	2.792
NO.=	72	72	72	72	72	72	72
MEAN=	5.60	5.60	332.45	363.46	22.37	2.40	2.63
MAX=	5.80	5.60	349.92	380.00	35.97	2.58	2.79
NIN=	5.40	5.60	310.49	345.17	4.24	2.14	2.41
STD=	0.08	ERR	10.51	9.46	3.73	0.09	0.08

3.3 Chaves 1988

Tables 3.3-1 to 3.3-5 are results taken from an analysis of four basalt core samples sent to Terra Tek by EG&G Idaho, Inc. for tests. Requested measurements included effective and total porosity, gas and liquid permeability, and capillary pressure by mercury injection.

Table 3.3-1. Summary of porosity and permeability data (from Table 1 of Chaves, 1988).

Sample ID	Effective[a] porosity (%)	Total[a] porosity (%)	Occluded porosity (%)	Grain density (gm/cc)	Gas permeability (mD)	Liquid permeability (mD)
RWMC-1	23.3	23.5	0.2	3.06	6.6	0.789
RWMC-2	12.0	12.4	0.4	3.05	17.0	10.3
RWMC-3	18.0	18.3	0.3	3.11	0.38	0.128
RWMC-4	24.4	24.5	0.1	3.03	2.6	0.587

a. Porosity determined from bulk volume.

Table 3.3-2. Mercury injection/pore throat size data (from Table 2 of Chaves, 1988).

Sample Number	Depth Interval	Permeability (mD)	Porosity (%)
RWMC-1	SURFACE	37.0	28.6
Injection kPa	Pressure PSIA	Pore Throat Radius microns	Injection Phase Mercury Saturation 1
10	1.5	73.522	56.95
20	2.9	36.761	58.74
40	5.8	18.380	62.03
60	8.7	12.254	63.30
80	11.6	9.190	64.94
101	14.6	7.279	66.23
120	17.4	6.127	66.78
140	20.3	5.252	67.20
160	23.2	4.595	67.56
180	26.1	4.085	67.88
200	29.0	3.676	63.15
300	43.5	2.451	69.04
400	58.0	1.838	69.85
550	79.8	1.337	70.88
700	101.5	1.050	72.37
1400	203.1	0.525	73.98
2100	304.6	0.350	74.44
3500	507.6	0.210	75.29
5200	754.2	0.141	76.05
6900	1000.8	0.107	76.52
8600	1247.3	0.085	76.90
10300	1493.9	0.071	77.22
12100	1754.9	0.061	77.45
13800	2001.5	0.053	77.64
17250	2501.9	0.043	77.36
20700	3002.3	0.036	78.04
24150	3502.6	0.030	78.32
27600	4003.0	0.027	78.50
31000	4496.1	0.024	78.65
34500	5003.3	0.021	78.75

Table 3.3-3. Mercury injection/pore throat size data (from Table 3 of Chaves, 1988).

Sample Number	Depth Interval	Permeability (mD)	Porosity (%)
RWMC-2	SURFACE	12.0	12.5
Injection kPa	Pressure PSIA	Pore Throat Radius microns	Injection Phase Mercury Saturation 2
10	1.5	73.522	33.08
20	2.9	36.761	46.28
40	5.8	18.380	68.45
60	8.7	12.254	74.04
80	11.6	9.190	76.98
101	14.6	7.279	78.26
120	17.4	6.127	79.01
140	20.3	5.252	69.63
160	23.2	4.595	79.86
180	26.1	4.085	80.05
200	29.0	3.676	80.21
300	43.5	2.451	80.80
400	58.0	1.838	81.23
550	79.8	1.337	81.83
700	101.5	1.050	82.41
1400	203.1	0.525	83.82
2100	304.6	0.350	84.61
3500	507.6	0.210	86.13
5200	754.2	0.141	87.52
6900	1000.8	0.107	88.46
8600	1247.3	0.085	89.20
10300	1493.9	0.071	89.83
12100	1754.9	0.061	90.24
13800	2001.5	0.053	90.59
17250	2501.9	0.043	91.09
20700	3002.3	0.036	91.52
24150	3502.6	0.030	91.86
27600	4003.0	0.027	92.07
31000	4496.1	0.024	92.23
34500	5003.3	0.021	92.45

Table 3.3-4. Mercury injection/pore throat size data (from Table 4 of Chaves, 1988).

Sample Number	Depth Interval	Permeability (mD)	Porosity (%)
RWMC-3	SURFACE	0.4	20.2
Injection kPa	Pressure PSIA	Pore Throat Radius microns	Injection Phase Mercury Saturation 3
10	1.5	73.522	52.72
20	2.9	36.761	53.76
40	5.8	18.380	55.64
60	8.7	12.254	56.42
80	11.6	9.190	56.92
101	14.6	7.279	57.25
120	17.4	6.127	57.43
140	20.3	5.252	57.57
160	23.2	4.595	57.67
180	26.1	4.085	57.76
200	29.0	3.676	57.82
300	43.5	2.451	58.08
400	58.0	1.838	58.20
550	79.8	1.337	58.39
700	101.5	1.050	58.63
1400	203.1	0.525	60.06
2100	304.6	0.350	61.59
3500	507.6	0.210	63.38
5200	754.2	0.141	64.44
6900	1000.8	0.107	65.03
8600	1247.3	0.085	65.46
10300	1493.9	0.071	65.82
12100	1754.9	0.061	66.07
13800	2001.5	0.053	66.29
17250	2501.9	0.043	66.58
20700	3002.3	0.036	66.83
24150	3502.6	0.030	67.03
27600	4003.0	0.027	67.18
31000	4496.1	0.024	67.33
34500	5003.3	0.021	67.46

Table 3.3-5. Mercury injection/pore throat size data (from Table 5 of Chaves, 1988).

Sample Number	Depth Interval	Permeability (mD)	Porosity (%)
RWMC-4	SURFACE	1.9	21.1
Injection kPa	Pressure PSIA	Pore Throat Radius microns	Injection Phase Mercury Saturation 3
10	1.5	73.522	44.76
20	2.9	36.761	49.00
40	5.8	18.380	56.92
60	8.7	12.254	60.82
80	11.6	9.190	63.70
101	14.6	7.279	66.06
120	17.4	6.127	67.05
140	20.3	5.252	67.77
160	23.2	4.595	68.25
180	26.1	4.085	68.65
200	29.0	3.676	69.00
300	43.5	2.451	69.81
400	58.0	1.838	70.21
550	79.8	1.337	70.90
700	101.5	1.050	71.70
1400	203.1	0.525	74.31
2100	304.6	0.350	75.45
3500	507.6	0.210	77.24
5200	754.2	0.141	78.25
6900	1000.8	0.107	78.70
8600	1247.3	0.085	78.99
10300	1493.9	0.071	79.22
12100	1754.9	0.061	79.39
13800	2001.5	0.053	79.53
17250	2501.9	0.043	79.67
20700	3002.3	0.036	79.78
24150	3502.6	0.030	79.87
27600	4003.0	0.027	79.96
31000	4496.1	0.024	80.05
34500	5003.3	0.021	80.13

As part of the SIP program (DOE 1993), moisture characteristic curves were developed from this mercury injection data but were never published. The results of that estimation are shown in Table 3.3-6.

Table 3.3-6. Moisture characteristic curves developed from the mercury injection/pore throat size data.

	van Genuchten		
Sample ID	α (cm^{-1})	n	Residual Saturation
RWMC-1	21.97	1.1705	0.0314
RWMC-2	0.0741	1.6945	0.0123
RWMC-3	not analyzed		
RWMC-4	0.0427	1.3459	0.0427

3.4 Miscellaneous Information

Table 3.4-1 is a summary of unsaturated zone basalt parameter values used in selected modeling studies.

Table 3.4-1. Unsaturated zone basalt parameter values used in selected modeling studies.

	van Genuchten				
Saturated Hydraulic Conductivity	α	n	Residual Saturation	Porosity	Reference
5 cm/hr	0.161 cm^{-1}	2.11	0.062	0.28	Rawson, S. A., J. C. Walton, and R. G. Baca, 1989
10,690 m/y	3.84 m^{-1}	1.474	0.015	0.228	Baca et al., 1992; Rood, 1994
$6.8x10^{-4}$ cm/s				0.05	Rawson, S. A., J. C. Walton, and R. G. Baca, 1991 (assumed for partially saturated flow in basalt fractures)
0.01 m/day	3.84 m^{-1}	1.474	0.015	0.145	Baca et al., 1992 for massive basalt
43.8 m/y	3.84 m^{-1}	1.474	0.015	0.145	Martian and Magnuson, 1994

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