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PHYSICAL PROPERTIES OF ROCKS--

POROSITY, PERMEABILITY, DISTRIBUTION COEFFICIENTS, AND DISPERSIVITY

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Abstract

Accompanying the increased emphasis on using the "solid earth" as a repository for waste as well as a source of fluids is the increased need for prediction of effects of these planned stresses on porous media. To fully describe the state of a fluid in a porous media it is necessary to specify: a) the pressure of the fluid, b) the composition of the fluid and e) the energy contained in the fluid. To describe and thus predict the flow and compositional variation of a fluid in porous media in time and space it is necessary to specify: a) the distribution of parameters affecting flow in the space of interest, b) initial conditions of pressure, composition and temperature or enthalpy, c) sources and sinks affecting flow and chemical variation in time and space, and d) boundary conditions. Presented in this paper are tabulations of data on porosity and permeability - factors pertinent to flow; and distribution coefficients and dispersivity - factors pertinent to chemical variation. Reported porosities vary from 0.000 to 87.3%, permeabilities range from "too low to measure" to 8.1 cm/sec. Because of the uncertainties of factors affecting laboratory determined dispersivities and distribution coefficients, only field based values are reported for these parameters.

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The thorough reviews by J. D. Bredehoeft and W. W. Wood as well as the persistent patience of Ines Gore in the preparation of the tables are greatly appreciated.

Physical Properties of Rocks

Chapter 4

Porosity, Permeability, Distribution Coefficents, and Dispersivity

By

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4.1 INTRODUCTION AND SCOPE

The interest in porous media as a source of fluid (water, oil, gas) or as a repository for the storage or disposal of fluids or other materials has been increasing in the recent past and is likely to continue increasing into the foreseeable future. To fully describe the state of a fluid in a porous medium it is necessary to specify, 1) The pressure of the fluid, 2) the composition of the fluid, and 3) the energy contained in the fluid. To predict the flow and compositional variation of a fluid in porous media in time and space, certain parameters must be specified. For flow considerations the primary parameters are porosity and permeability. For compositional variations, one of the major sources or sinks are sorption type reactions which are commonly characterized by utilizing distribution coefficients.

The purpose of this chapter is to present data on these factors as well as dispersivity, a parameter for prediction of composition of mixing fluids.

It is assumed that users of the data presented in this chapter are interested in obtaining reasonable ranges for these parameters. This chapter is an attempt to assemble representative and readily available data. Many laboratories have unpublished data which for proprietary or other reasons have not been made available to the general public and therefore are not included. There are undoubtedly values in the literature that have been unintentionally overlooked. To reiterate, any pretense that this compilation is all inclusive would be false because of the breadth of scientific and engineering endeavors producing such information. For purposes of ease of presentation, the topics; porosity, permeability, distribution coefficients, and dispersivity, are treated in separate sections. As table 11 Chapter 1 indicates, sedimentary rocks, constitute only about eight percent of the earth's crust; however, because most ground water and oil and gas occur in sedimentary rocks most of the available data pertinent to the topics of this chapter are for that group of rocks.

Most of the discretionary discussion found in Chapters 1 and 2 are applicable to the rock properties considered here; i.e., the imprecision of rock terms (Chapter 1), the effects of extraneous chemical composition on the measurement of these properties, the "environmental" conditions (Chapter 2), the representativeness of point data.

Synthesis of the data as presented here has been attempted with the greatest of care, however, errors will have undoubtedly occurred. Apologies for these are offered in advance.

4.2 POROSITY

4.21 General Definitions

Slichter (1899) in his pioneering consideration regarding the role of porosity in the flow of water in porous media did not dwell on the definition of porosity any more than to state"..., the percentage of open space to the whole space, or the so-called porosity,..." However, since that time considerable attention has been focused on questions of total porosity, "the ratio of the volume of voids to the volume of solids generally determined by volumetric-gravimetric techniques", (API - RP - 40, 1960), and effective porosity defined as: "the amount of interconnected pore space available for fluid transmission, expressed as a percentage of the total volume". (after Lohman and others, 1972b, p. 10). Assuming the specific gravity of water equals unity, total porosity, expressed as a percentage, based on four common approaches, can be expressed, after Lohman (1972a, p. 3):

$$n = 100\ \left(\frac{v_i}{V}\right) = 100\ \left(\frac{v_w}{V}\right) = 100\left(\frac{V-v_m}{V}\right) = 100\ (b-G_s) \qquad (1)$$

where

n = porosity (percent by volume),

V = total volume (L^3)

v_i = volume of interstices (L^3)

v_m = aggregate volume of the solid particles (L^3)

v_w = volume of water in a saturated sample (L^3)

G_s = Specific gravity of the dry sample (M/L^3)

b = specific gravity of the saturated sample (M/L^3).

Effective porosity is generally determined by a procedure based on Boyle's Law. The pressures and procedures used, of course, affect the degree or size of interconnections measured. For detailed descriptions of the methodology, including a discussion of the advantages and disadvantages refer to API - RP-40 (1960).

4.22 Historical Aspects

Because the theoretical aspects of the movement of fluids (ground-water) in porous media preceded the commercial development of petroleum from wells, the early ground-water literature contains much of the theoretical development. The early, thorough investigations of Slichter (1899) showed that the porosity of uniformly sized spheres ranged from a maximum of 47 percent for the least stable packing to a minimum of 26 percent for the most stable packing. As deposits of naturally occurring material are seldom composed of uniform sized spherical material, measured porosities, tables 4.2.1 thru 4.2.7, of naturally occurring materials extend beyond these limits. Fraser (1935) extended the factors affecting porosity. He considered the following factors and their relative importance in determining the porosity of unconsolidated natural deposits:

Absolute grain size
Non-uniformity in size of grains
Proportions of various sizes of grains
Shape of grains
Method of deposition
Compaction during and following deposition
Solidification.

The data as presented here provide little if any information regarding these factors. However, Fraser's (1935) paper has served as the basis for numerous studies attempting to develop "laws" governing porosity. Consideration of these aspects is beyond the scope of this paper; however, Pryor (1973) presents a good summary.

4.23 Summary

The maximum porosity of a natural inorganic material is reported by Schoeller (1962) for a pumice sample, 87.3%. Values for minimum porosity are largely a factor of scale because totally fracture-free material is a question of scale. Geophysical evidence (Norton and Knight 1977, p. 93) suggests that interconnected pore spaces exist to a depth of at least 15 km in the earths crust. However, for laboratory samples, the lowest known porosity is that for Sioux Quartzite, Precambrian in age from the Jasser, Minnesota area reported to have a porosity 0.000 percent (Hanley and others, 1978, p. 36).

Table 4.2.1. Porosities of Unconsolidated Sedimentary Rocks (percent) (each rock type arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Beach deposits, Saline Pass, TX	40			45.1	2
Beach deposits, Ship Island, MS	195			45.9	2
Beach deposits, Santa Rosa Island, MS	245			49.6	2
Clay, till or boulder, uniform size, Pomperaug, Valley, CT	9	8.7	21	14.3	9
Clay, plastic, Oligocene	1			26.0	11
Clay, plastic, Austria, Pliocene	2	26.0	26.1	26.1	11
Clay, loam soils, Sacramento Valley, CA	43			37.3	9
Clay, Arlington, VA				40.1	3
Clay, ($<$.0045 mm)	74	34.2	56.9	42	8
Clay, silty, central CA	72	35.6	53.3	43.1	7
Clay, Wealden, Cretaceous, lacustrine (28% $<2\mu$)				43.5	3
Clay, sandy, central CA	2	38.4	49.6	44.0	7
Clay, Boston blue clay				44.4	3
Clay		44	50	45	1
Clay, Wealden, Alamosa, CO	7	41.5	57.9	48.2	4
Clay, blue marine clay, Bosporous (42% $<2\mu$)				49.2	3

Table 4.2.1. Porosities of Unconsolidated Sedimentary Rocks (percent) (each rock type arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Clay, loam soils, Sacramento Valley, CA	148			50.1	9
Clay, Kaolin, Cornwall, residual (45% $<2\mu$)				51.2	3
Clay, Gosport Holocene estuarine (43% $<2\mu$)				52.6	3
Clay, Ganges Delta, Holocene (48% $<2\mu$)				55	3
Clay, London blue clay, Eocene, Marine (46% $<2\mu$)				56.8	3
Clay, "Argile Plastigue", Paris Basin, Eocene, Marine (79% $<2\mu$)				64.5	3
Clay, Kleinbelt ton, Denmark, Eocene, marine (77% $<2\mu$)				68.5	3
Continental deposits, Pliocene, Pleistocene and Holocene, Los Banal-Kettlemen City area, CA	195	28.0	55.8	42.1	12
Deltaic deposits, Holocene, Mississippi River			80-90		1
Drift, washed primarily sand size	3	34.6	41.5	39	8
Drift, washed primarily silt size	31	36.2	47.6	44	8
Drift, washed primarily clay size	5	38.4	59.3	49	8

Table 4.2.1. Porosities of Unconsolidated Sedimentary Rocks (percent) (each rock type arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Dune deposit, Santa Rosa Island, MS	48			47.9	2
Dune deposits, St. Andrew Park, Panama City, FL.	116			50.8	2
Glacial, outwash, Pomperaug Valley, CT	11	18.0	38.5	30.2	9
Gumbo, Mississippi				46.8	3
Loess	5	44.0	57.2	49	8
Marl				47-50	1
Peat	2		92.2	92	8
Peat		80.7	95.2	92	10
Playa deposit, Mohave Desert, CA				38.0	9
River bar deposit, Whitewater River, Cincinnati, OH	151			36.9	2
River bar deposit, Wabash River, Grayville, IL	167			44.9	2
River bar deposit, Mississippi River , Jonesville, LA	30			45.0	2
Sand, marine, Oligocene, Cretaceous (Albian) subsurface, Paris Basin	13	3	35.0	21.5	1
Sand, marine, Cretaceous (Barremian) subsurface, Paris Basin	3	22	26	23.7	1
Sand, upper Miocene	78	17.4	31.9	27.1	5

Table 4.2.1. Porosities of Unconsolidated Sedimentary Rocks (percent) (each rock type arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Sand, marine, Cretaceous (Aptian) subsurface, Paris Basin	3	20	31	27.7	1
Sand, gravel-glacial	8	18.6	37.6	28.1	1
Sand, dune, France	3			31.5	1
Sand, marine, Oligocene, Miocene & Pliocene-Tunisia	25	23.2	41.5	31.5	1
Sand, continental, Quaternary-Tunisia	6	32	34	33.1	1
Sand, dune, Sahara	4	34.3	36.8	35.2	1
Sand, fluvial	25	28.8	39.5	35.3	1
Sand, silty, central CA	92	28.4	50.2	38.1	7
Sand, medium (.5-.25 mm)	127	28.5	48.9	39	8
Sand, coarse (1.0-.5 mm)	26	30.9	46.4	39	8
Sand, silt, clay, central CA	132	30.6	61.2	40.4	7
Sand, beach, Quaternary	25	38.7	44.8	41.2	11
Sand, beach accretion, Holocene, Galveston Barrier Island	17			42.2	6
Sand, central CA	54	35.4	50.0	42.4	7
Sand, fine (.25-.25 mm)	243	26.0	53.3	43	8
Sand, beach accretion, Holocene, New Orleans Barrier Island.	8			43.1	6

Table 4.2.1. Porosities of Unconsolidated Sedimentary Rocks (percent) (each rock type arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Sand, clayey, central CA	13	28.0	52.8	44.4	7
Sand, eolian	6	39.9	50.7	45	8
Sand, fine, stream deposits, "uniform" size, Pomperaug, Valley, CT				48.0	9
Sand, silty, subaqueous, Holocene				49.4	11
Silt, lake deposit-"uniform" size, Pomperaug, Valley, CT.	2	36.0	41.9	38.9	9
Silt, sandy, central CA	36	33.9	55.6	40.9	7
Silt, clayey central CA	120	31.4	61.0	41.8	7
Silt, (.062-.004mm)	281	33.9	61.1	46	8
Silt, central CA	2	50.4	52.2	51.3	7
Silt, loam soils, Sacramento Valley, CA	87			52.2	9
Soils, Holocene	5	45	69.4	58.3	11
Till	6	11.5	21	14.7	1
Till, primarily sand sized	10	22.1	36.7	31	8
Till, primarily silt sized	15	29.5	40.6	34	8

Table 4.2.1. Porosities of Unconsolidated Sedimentary Rocks (percent) (each rock type arranged by increasing mean porosity).

References for Table 4.2.1.

1. Schoeller, 1962;
2. Pryor, 1973;
3. Skempton, 1944;
4. Wolff and Papadopulos, 1972;
5. Morrow and others, 1969;
6. Beard and Weyl, 1973;
7. Johnson and others, 1968;
8. Morris and Johnson, 1967;
9. Meinzer, 1923;
10. Walmsley, 1977;
11. Manger, 1963;
12. Johnson and others, 1968.

Table 4.2.1. Porosities of Holocrystalline Rocks (percent (each rock type arranged by increasing mean porosity)

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Dacite	3	3.5	16	9	6
Dacite, porphyry	101	2.0	29.9	10.4	10
Diabase, Frederick, MD				0.1	2
Diabase, Carroll & Frederick Counties, MD	2	0.47	1.0	0.58	11
Diabase	2	0.90	1.13	1.01	8
Diorite	38			0	7
Diorite				0.25	1
Diorite, quartz				0.6	1
Diorite, quartz (effective flow porosity)				.2-.003	5
Diorite, quartz Sierrita-Esperanza, AZ	1			2.90	6
Diorite	1			3	6
Gabbro, Carroll & Frederick Counties, MD	3	.00	.62	.29	11
Gabbro	1			.84	8
Gabbro				0.6-0.7	1
Granite, Sherman (effective flow porosity)				.002	3
Granite, Barre, VT	1			.079	7
Granite, Westerly, RI	1			.106	7
Granite, Stone Mt. GA				0.3	2

Table 4.2.1. Porosities of Holocrystalline Rocks (percent (each rock type arranged by increasing mean porosity)

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Granite	45			0.4	14
Granite, Tucson, AZ	1			.611	6
Granite	451			0.7	15
Granite	26	0.4	3.0	0.9	16
Granite, Laramie, WY	1			1.08	6
Granite, Westerly, RI				1.1	2
Granite, Carroll & Frederick Counties, MD	17	.44	3.98	1.11	11
Granite, Troy, AZ	1			1.36	6
Granite	322	0.1	11.2	1.4	17
Granite, equigranular Globe-Miami, AZ	1			1.77	6
Granite, Texas Canyon, AZ	1			2.96	6
Granite	9	0.7	5.5	3	6
Granite, (effective flow porosity)				5-.004	4
Granite, porphyritic (altered) Globe-Miami, AZ	1			5.35	6
Granite, porphry, Bingham, UT	1			6.11	6
Granodiorite, St. Cloud, MN	1			.076	7
Granodiorite, Carroll & Frederick Counties, MD	1			.50	11

Table 4.2.1. Porosities of Holocrystalline Rocks (percent (each rock type arranged by increasing mean porosity)

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Griesen	13			5.5	9
Latite, quartz porphyry, Bingham, UT	1			2.64	6
Latite, quartz	2	4	5.2	4.6	6
Latite, quartz porphyry, Silver City, NM	1			5.34	6
Latite, dike, Bingham, UT	1			12.5	6
Monzonite, quartz (altered), Sierrita Esperanza, AZ	4	1.96	2.96	2.51	6
Monzonite, quartz phorphyry (altered), Chino, NM	1			2.60	6
Monzonite, quartz (some altered), Butte, MT	6	.075	6.35	3.03	6
Monzonite, quartz	21	0.1	7	4	6
Monzonite, quartz (altered), San Manuel, AZ	7	1.46	4.1	4.0	6
Pegmatite	3			0.8	9
Pegmatite	4			0.9	13
Quartz, monzonite	25			1.3	11
Quartz, monzonite	42	0.2	10.1	1.7	11

Table 4.2.1. Porosities of Holocrystalline Rocks (percent (each rock type arranged by increasing mean porosity)

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Quartz, monzonite	90	0	35.0	23.8	12
Seynites			1.38	0.5-0.6	1

Table 4.2.2. Porosities of Holocrystalline Rocks (percent) (each rock type arranged by increasing mean porosity)

References for Table 4.2.2.

1. Schoeller, 1962;
2. Brace, 1965;
3. Pratt and others, 1974;
4. Bianchi and Snow, 1969;
5. Villas, 1975;
6. Norton and Knapp, 1977; (values interpolated from bar graph);
7. Hanley and others, 1978;
8. Meinzer, 1923;
9. U.S. Geol. Survey, 1964;
10. Griffith, 1937;
11. Hauser, 1962;
12. Deklotz and Heck, 1964;
13. U.S. Bur. of Reclamation, 1958;
14. Franklin and Hoeck, 1970;
15. Mellor, 1971;
16. Izett, 1960;
17. Kessler and others, 1940;

Table 4.2.3. Porosities of Evaporites (percent) (each rock type arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Anhydrite, Permian, Brazos, TX region	14	0.3	4.4	1.9	12
Anhydrite	21	0.3	40.8	10.3	9
Gypsum, assorted	2	1.3	4.0	2.6	1
Gypsum		1.32	3.96	2.64	4
Gypsum, Paris Basin				4.8	1
Gypsum, Castile, West TX	4	3.42	6.43	4.81	3
Gypsum	3	27.2	30.6	28.4	10
Halite	22	0.5	5.1	2.0	9
Halite	9	0.8	7.1	2.9	10
Non-clastic, sediments	12	0.1	5.5	3.5	2
Salt, rock (610-640m*)		0.1	0.8	0.4	5
Salt, rock (790-823m)		0.3	0.7	0.5	5
Salt, bedded, Hutchinson Salt Member of Wellington Fm., KS				0.59	8
Salt, rock, Winnfield dome				1.28	6
Salt, rock, Grand Saline dome, TX				1.71	8
Salt, rock, bedded	17	0.62	7.17	2.10	7
Salt, rock	11	1.5	8.6	3.7	11

Table 4.2.3. Porosities of Evaporites (percent) (each rock type arranged by increasing mean porosity).

* Sample depth

References for Table 4.2.3.

1. Schoeller, 1962;
2. Norton and Knapp, 1977; (values interpolated from bar graph);
3. Sanyal and others, 1971;
4. Meinzer, 1923;
5. Powers and others, 1978;
6. Guido and Warner, 1960;
7. Aufricht and Howard, 1961;
8. Robertson, 1962;
9. U.S. Geol. Survey, 1964;
10. Gard and Dickey, 1961;
11. Corps of Engineers, 1965;
12. Gloyna and Reynolds, 1961;

Table 4.2.4. Porosities of Volcanic Rocks (percent) (rock types arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Basalt, Dresser, WI	1			0.047	4
Basalt, assorted	8	0.1	2.9	0.80	1
Basalt, Germany	5	0.27	3.37	1.49	1
Basalt	20	1.2	18.7	9.4	7
Basalt	41	1.4	32.7	15.0	6
Basalt				4.40-5.60	1
Dacite, dike, Troy, AZ	1			3.08	3
Dacite, flow, Troy, AZ	1			15.7	3
Obsidian				0.521	1
Phonolite			4.50	2.0-3.50	1
Porphyries, Germany	10	0.4	15.5	5.48	1
Pumice, from Champs Phlegreens				87.3	1
Pumice				50-75	1
Rhyodacite, dike, Troy, AZ	1			7.52	3
Rhyolite, subvolcanic, Chino, N.M.	1			6.74	3
Rhyolite, (altered), Sierrita Esperanza, AZ	1			7.48	3
Rhyolite	3	7	21	12	3

Table 4.2.4. Porosities of Volcanic Rocks (percent) (rock types arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Rhyolite	6	10.2	17.9	14.6	8
Tuff, welded				14.1	2
Tuff, (altered), Red Mtn., AZ	1			21.5	3
Tuff	84	7.3	47.5	28.5	11
Tuff, zeolitized	23	15.8	37.7	29.4	14
Tuff, volcanic Southern Italy	8	6	58.4	31.0	1
Tuff, zeolitized	28	23.2	39.5	31.1	15
Tuff	165	15.5	44.2	31.7	10
Tuff, volcanic Rhine Valley	4	24.74	45.14	32.01	1
Tuff	15	29.3	40.0	33.5	9
Tuff, pumice	31	25.2	46.1	35.3	13
Tuff, friable				35.5	2
Tuff, pumice	16	31.5	43.3	36.2	10
Tuff, pumice	27	28.4	47.8	38.6	12
Tuff, bedded Nevada				38.8	2
Tuff, bedded (pumiceous)				40.2	2
Tuff	180	7.2	54.7	41	5

Table 4.2.4. Porosities of Volcanic Rocks (percent) (rock types arranged by increasing mean porosity).

References for Table 4.2.4.

1. Schoeller, 1962;
2. Keller, 1960;
3. Norton and Knapp, 1977;
4. Hanley and others, 1978;
5. Morris and Johnson, 1967;
6. Saucier, 1969a;
7. Corps of Engineers, 1965;
8. Sargent, 1965;
9. Dickey, 1961;
10. Byers, 1961;
11. Williams and others, 1963;
12. Emerick and others, 1962a;
13. Emerick, 1962;
14. Emerick and others, 1962b;
15. Emerick and others, 1962c;

Table 4.2.5. Porosities of Carbonates (percent) (each rock type arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Chalk, cemented Northern France	2	7.7	8.3	8.0	1
Chalk, Northern France	16	22.2	37.2	29.2	1
Chalk	3	45.9	46.8	46.2	10
Chalk				53	8
Coquina	1			56.7	11
Dolomite, Martinsburg, WV				0	2
Dolomite, Webatuck, NY				0.4	2
Dolomite, (Rustler) west TX	2	0.41	1.37	0.89	6
Dolomite	27	0.8	12.4	4.5	13
Dolomite	5	3.0	8.6	5.5	12
Dolomite	2	19.1	32.7	26	7
Dolomite				1.0-22.2	1
Limestone, Oak Hall, PA				0	2
Limestone, (Bone Springs) West TX	1			0.44	6
Limestone, Carroll & Frederick Counties, MD	7	.27	4.36	1.70	11
Limestone, dolomitic Carroll & Frederick Counties, MD	2			2.08	11
Limestone, Chino, NM	3	.366	4.38	2.44	4
Limestone, dolomite-Lower Ordvician		0.1	12.6	2.5	9

Table 4.2.5. Porosities of Carbonates (percent) (each rock type arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Limestone, Johnson Camp, AZ	4	2.35	3.88	3.20	4
Limestone, (Salem), Bedford, IN	1			3.630	5
Limestone, dolomite, Devonian	92	0.6	12.9	4.4	9
Limestone, dense, Southern Italy	24	0.3	14	4.5	1
Limestone, marble, dolomite	11	.53	13.36	4.85	8
Limestone, dolomite, Ordovician	216	.07	22.3	5.4	9
Limestone, Carboniferous	29	0.6	14.9	5.5	9
Limestone, dolomite, Silurian	31	0.5	15.9	5.5	9
Limestone, dolomite, Cambrian				5.8	9
Limestone, Pennsylvanian	2117	0	31.6	6.3	9
Limestone, Triassic	37	0.4	36.5	9.3	9
Limestone, dolomite, Permian	56	3.2	27.1	9.8	9
Limestone, Germany	6	3.1	28.4	10.4	1
Limestone, assorted	10	1.6	36.5	10.6	1
Limestone, Mississipian	226	0.9	25.9	11.3	9
Limestone, oolite, Triassic	2109	0	34.4	13.4	9
Limestone, chalk, Cretaceous	601	0.2	42.8	17.5	9
Limestone	74	6.6	55.7	30	7

Table 4.2.5. Porosities of Carbonates (percent) (each rock type arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Limestone, dolomitic marine Italy	12	10.5	66.6	34.7	1
Marble				.19	1
Marble, white, Portugal				.26-27	1
Marble, Danbury, VT				0.3	2
Marble, Grenville Complex	9	.01	1.06	0.35	3
Marble, Grenville Complex, Precambrian	9	0.01	1.06	.35	9
Marble, Holston Marble, Knoxville, TN	1			0.52	5
Marble, white, Tyrol				.59	1
Marble, eastern US	100	0.4	0.8	0.6	3
Marble, dolomitic, Carroll & Frederick Counties, MD	2			.60	11
Marble, Carroll & Frederick Counties, MD	7	.31	2.02	.62	11
Marble	6	0.7	1.1	0.9	10
Marble, Johnson Camp, AZ	1			2.62	4
Marble, Carrara, Italy				.11-.22	1
Oolite	8	3.28	12.44	7.18	8
Travertine	5	9	38	18	1
Tufa, calcareous, Quarternary	4	7.0	27.8	19.2	9

12Table 4.2.5. Porosities of Carbonates (percent) (each rock type arranged by increasing mean porosity).

References for Table 4.2.5.

1. Schoeller, 1962;
2. Brace, 1965;
3. Manger, 1963;
4. Norton and Knapp, 1977;
5. Hanley and others, 1978;
6. Sanyal and others, 1971;
7. Morris and Johnson, 1967;
8. Meinzer, 1923;
9. Manger, 1963;
10. Baldwin and others, 1909;
11. Griffith, 1937;
12. Windes, 1950;
13. U.S. Army, 1961;

Table 4.2.6. Porosities of Indurated Sedimentary Rocks (percent) (each rock type arranged by increasing mean porositiy).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Chert, Keewatin, Precambrian	1			0.10	8
Chert, Onverwacht Group, Swaziland, Precambrian	4	.03	.72	.33	8
Chert	2			4.3	14
Chert	2			6.9	13
Claystone	12	22.1	32.3	29.0	13
Claystone	4	41.2	45.2	43	10
Greywacke	2	0.4	4.2	2.3	1
Quartzite, Sioux Quartzite, Jasper, MN	1			0.000	7
Quartzite, Carroll & Frederick Counties, MD	3			.46	19
Quartzite, (Cheshire) Rutland, VT				0.6	2
Quartzite	1			0.8	11
Quartzite, Globe-Miami, AZ	1			1.38	3
Quartzite, Johnson Camp, AZ	3	2.53	5.35	4.0	3
Quartzite	21	0.2	10.0	4.1	15
Quartzite, Chickies Fm., PA	5	3.8	7.8	5.4	20
Sandstone, mottled (Germany)			15.9	3.2	1
Sandstone, Stockton Fm., NJ & PA	5	1.3	7.9	4.0	20
Sandstone, Silurian	13	0.5	17.4	4.9	12

Table 4.2.6. Porosities of Indurated Sedimentary Rocks (percent) (each rock type arranged by increasing mean porositiy).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Sandstone, Bromide Fm. , Carter Knor Field, OK, 4600 m*				5.0	5
Sandstone, clayey, Carroll & Frederick Counties, MD	1			6.10	19
Sandstone, Berea Sandsone, Lorain CO., OH	1			6.400	7
Sandstone, Oil Creek Fm. Lindsay, OK, 3260 m				6.7	5
Sandstone, Southern Italy	16	0.7	15.3	7.4	1
Sandstone, Carroll & Frederick Counties, MD	6	1.62	26.40	9.25	19
Sandstone, Permian	334	0.5	24.8	9.6	12
Sandstone		3.46	22.8	10.22	11
Sandstone, Bradford Fm. (low rank greywacke)	5	9.0	11.6	10.7	6
Sandstone, Cambrian	70	0.2	28.3	11.1	12
Sandstone, Clarendon Fm., PA	6	9.9	12.2	11.5	20
Sandstone, Tensleep Fm., Oregon Basin, South Dome, WY, cores from 12 wells				13	9
Sandstone	88			14.0	16
Sandstone, 3d. Venango Fm., PA	16	7.5	17.8	14.0	20
Sandstone, 3d. Bradford Fm., PA	10	12.2	15.6	14.0	20
Sandstone, Devonian	785	0.5	25.6	14.2	12
Sandstone, Ordovician	134	3.6	30.3	14.3	12

Table 4.2.6. Porosities of Indurated Sedimentary Rocks (percent) (each rock type arranged by increasing mean porositiy).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Sandstone, Weir Fm., (low rank greywacke)	6	12.9	16.6	14.5	6
Sandstone, Bradford Fm., PA	5	13.0	17.4	14.8	20
Sandstone, Kirkwood Fm., ("fairly clean orthoquartzite")	5	12.6	18.7	15.2	6
Sandstone	16	4.81	28.28	15.89	11
Sandstone, Pennsylvanian	6040	0.4	38.7	16.5	12
Sandstone, Cretaceous	1264	0.4	51.2	16.5	12
Sandstone, Triassic	303	0	35	16.9	12
Sandstone, mottled (Germany)	19	2.7	27.2	17.2	1
Sandstone, gas & oil bearing	84	3.4	37.7	17.5	11
Sandstone, Weber, Rangely, CO, 1860 m				17.6	5
Sandstone, Mississippian	375	3.8	27.6	17.6	12
Sandstone, Miocene	many	0.4	50.1	18	12
Sandstone, (assorted)	23	6.8	25.4	18.3	1
Sandstone, Triassic	111	3.6	30.8	18.5	12
Sandstone, Colesville, WI (thin section determination)	87			19.3	4
Sandstone, Tensleep Fm., Big Medicine Bow, WY, 2280 m				19.5	5
Sandstone, Pliocene, Fillmore, CA, 4300 m				20.0	5

Table 4.2.6. Porosities of Indurated Sedimentary Rocks (percent) (each rock type arranged by increasing mean porositiy).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Sandstone, Oligocene	many	0.8	45	22	12
Sandstone, Eocene	344	7	46.5	22.4	12
Sandstone, Scheerhorn b. Nordlawn 1104 m				23	5
Sandstone, Piacenza, Italy 1575 m				23.2	5
Sandstone, Eocene, Davis Lens, TX 2320 m				27.0	5
Sandstone, Piacenza, Italy 1960 m				27.0	5
Sandstone, Scheerhorn b. Nordlawn 1120 m				27	5
Sandstone, Miocene, Univ. Field, TX 2160 m				28.0	5
Sandstone, Piacenza, Italy 1930 m				28.0	5
Sandstone, slightly consolidated - Germany Oilfields Eldingen b. Celle 1483 m				28	5
Sandstone, Frio Clay, Fishers Reef, TX, 2740 m				28.2	5
Sandstone, Miocene, Tunisia	2	20	37	28.5	1
Sandstone, Eldingen b. Celle 1463 m				29	5
Sandstone, Cockfield Fm., Katy, TX, 2100 m				29.8	5
Sandstone, upper Miocene, Budrio Ost b. Bologna, Italy 2530 m				30.0	5
Sandstone, Ruhlermoor b. Meppen 842 m				30	5
Sandstone, Paleocene	18	9.4	53.6	30.8	12

Table 4.2.6. Porosities of Indurated Sedimentary Rocks (percent) (each rock type arranged by increasing mean porositiy).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Sandstone, Eocene, Liberty CO., TX, 2340 m				31.5	5
Sandstone, Piacenza, Italy 1595 m				31.7	5
Sandstone, Ruhlermoor b. Meppen 853 m				33	5
Sandstone, (fine grained)	55	13.7	49.3	33	10
Sandstone, Piacenza, Italy 1555 m				36.0	5
Sandstone, (med. grained)	10	29.7	43.6	37	10
Sandstone, Pliocene - Pleistocene	7	38.1	39.7	39.0	12
Siltstone	6	1.1	24.9	16.7	17
Siltstone	7	21.2	41.0	35	10
Subgraywacke	5	1.9	5.5	3.3	18

Table 4.2.6. Porosities of Indurated Sedimentary Rocks (percent) (each rock type arranged by increasing mean porosity)

References for Table 4.2.6.

1. Schoeller, 1962,
2. Brace, 1965;
3. Norton and Knapp, 1977;
4. Wilson and Sibley, 1978;
5. Engelhardt, 1960;
6. Wyble, 1958;
7. Hanley and others, 1978;
8. Sanyal and others, 1971;
9. Morgan and Others, 1978;
10. Morris and Johnson, 1967;
11. Meinzer, 1923;
12. Manger, 1963;
13. Blair, 1955;
14. Blair, 1956;
15. Cole and Williams, 1962;
16. Wolkodoff, 1953;
17. Gard and Dickey, 1961;
18. Monfore, 1954;
19. Griffith, 1937;
20. Muskat, 1937;

Table 4.2.7. Porosities of Metamorphic Rocks (percent) (each rock type arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Gneiss, Carroll & Frederick Counties, MD	5	.30	2.23	.78	11
Gneiss	56	0.7	1.8	1.2	6
Gneiss	30	0.3	4.1	1.6	7
Greenstone, Silver City, NM	1			.669	2
Hornfels, marble & greenstone	6	0.2	2.5	1.5	2
Schist, argillaceous				.62	1
Schist, gneiss & granite	36	0.02	1.85	.80	4
Schist, siliceous				.88	1
Schist, Pinal Schist, Globe-Miami, AZ	1			1.30	2
Schist, Pinal Schist, Johnson Camp, AZ	1			1.54	2
Schist, slate, gneiss	6	0.2	8	2	2
Schist	39	0.6	6.0	2.6	8
Schist, hornfels, gneiss, metapelite, Globe-Miami, AZ	5	.66	8.42	3.12	2
Schist, (some weathered)	18	4.4	49.3	38	3
Schist, quartz-mica, weathered, Dawson County, GA	21	30.7	58.4	46.9	10
Serpentine	10	0.6	8.5	2.4	7
Shale, Bangor, PA, Ordovician				1.0	5
Shale, Nonesuch Fm., Precambrian	6	1.5	1.7	1.6	5

Table 4.2.7. Porosities of Metamorphic Rocks (percent) (each rock type arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Shale, Ophir Fm., UT, Cambrian	4			.75	5
Shale, Johnson Camp, AZ	1			2.12	2
Shale, Devonian - Mississippian	5	1.6	7.6	5.9	5
Shale	20	1.4	9.7	6	3
Shale, Silurian	7			6.6	5
Shale, Pennsylvanian & Permian	5			8.8	5
Shale, clay, Pennsylvanian	23	7.1	17.2	9.9	5
Shale, Mississippian	2	9.7	11.0	10.4	5
Shale, Wellington Fm., Selma, KS, Permian	2	15.3	15.5	15.4	5
Shale, clays & mudstones, Cretaceous	34	0.8	42.3	18.8	5
Shale, clay, Jurassic	11	8.8	30.7	20.2	5
Shale, Eastern Venezuela, Oligocene & Miocene	40	9.1	35.8	21.7	5
Shale	29	6.2	42.2	23.8	7
Shale, Ft. Union Fm., MT, Paleocene	3	21.2	36.9	27.2	5
Shale, clays, Miocene	8			31.9	5
Shale				20-40	1
Skarn, Silver City, NM	2	3.96	5.24	4.60	2
Skarn, Chino, NM	8	.73	9.43	4.65	2

Table 4.2.7. Porosities of Metamorphic Rocks (percent) (each rock type arranged by increasing mean porosity).

Rock	Number of Samples	Minimum	Maximum	Mean	Reference
Skarn, Johnson Camp, AZ, (tremolite, muscovite, quartz, magnetite, hematites	1			14.7	2
Slate, Carroll & Frederick Counties, MD	3	.00	1.06	-	11
Slate, black	3	.40	.50	.49	5
Slate, Negaunee Iron Fm., Precambrian	2			0.6	5
Slate, Globe-Miami, AZ	1			0.73	2
Slate	76	0.1	4.3	0.8	8
Slate	6	1.91	5.66	3.12	1
Slate, Devonian	21	1.3	13.0	3.3	5
Slate, shale	2	.49	7.55	3.95	4
Slates, silts & clays,Carboniferous		1.2	14.3	5.7	5
Tonalite	9	2.9	11.5	7.0	9

Table 4.2.7. Porosities of Metamorphic Rocks (percent) (each rock type arranged by increasing mean porosity).

References for Table 4.2.7.

1. Schoeller, 1962;
2. Norton and Knapp, 1977 (values interpolated from bar graph);
3. Morris and Johnson, 1967
4. Meinzer, 1923;
5. Manger, 1963;
6. Kessler and others, 1940;
7. U.S. Geol. Survey 1964;
8. Kessler and Sligh, 1932;
9. Saucier, 1969b;
10. Stewart, 1964;
11. Griffith, 1937;

4.3 PERMEABLITY

4.31 General Definitions

The rate of flow of a fluid through any system, porous medium, open pipes etc., is dependent upon two basic properties: 1) the fluid potential gradients and 2) the resistance to the flow of that fluid along the pathway traversed. The determinable "constant" integrating the "resistance" factors for a porous medium has been labeled "permeability". Lohman (1972b, p. 9) defines intrinsic permeability as: "a measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is a property of the medium alone and is independent of the nature of the liquid and of the force field causing movement. It is a property of the medium that is dependent upon the shape and size of the pores".

4.32 Historical Aspects

Preceeded by Hagen's (1837) and Poiseuille's (1846) work on the laws affecting the flow of water through capillary tubes, Darcy (1856) performed a series of experiments on the relationship affecting the downward flow of water through sands proposed as filtering material for the water supply for the town of Dijon, France. His experiments developed the relationship:

$$Q = - k(h_2-h_1)/\ell \qquad (2)$$

where

Q = volume of water crossing unit area in unit time (L^3/T)

h_1,h_2 = the elevation above a reference level of water in manometers terminated above and below a vertical column of sand respectively. (L)

k = a factor of proportionality (L^3/T)

ℓ = height of the sand column (L)

The constant of proportionality as originally defined by Darcy contains properties of both the fluid and the porous medium.

The experiments of Darcy have been reviewed, limits tested, and the law has been generalized to include the relationship of viscosity. This allows isolation of a constant of proportionality with characteristics of the porous medium by itself, commonly referred to as intrinsic permeability (Lohman, 1972b, p. 9).

The generalized Darcy relation, taking into account viscosity, is (after Hubbert, 1940):

$$q = \frac{K\rho g}{\eta} \left(\frac{dh}{d\ell}\right) \tag{3}$$

Where k = intrinsic permeability (L^2)

η = kinematic viscosity (M/LT)

q = rate of flow per unit area (L/T)

$dh/d\ell$ = gradient, unit change in head per unit length of flow

ρ = density of the fluid (M/L^3)

g = acceleration of gravity (L/T^2)

See Hubbert (1940) for a highly comprehensible and thorough discussion on Darcy's law, including permeability.

Much of the testing and generalization of Darcy's relationship was done by the petroleum industry. Wykoff, et al (1933, p. 167) proposed that this unit of permeability be: "... called a 'darcy' after D'Arcy, who first formulated the law of porous flow". Using the consistent units specified in equation 3, a permeability of one darcy means a flow rate of 1 cm^3/sec through a cross section of 1 cm^2 having a length of 1 cm under a pressure differential of 1 atmosphere for a fluid having a viscosity of 1 centipoise. Because the permeability of most porous media is less than one darcy and to reduce the use of decimals, the term milli-darcy (10^{-3} darcy) is commonly used in the petroleum industry.

Investigations involving fluids having relatively uniform properties have superposed the fluid properties onto permeability (matrix) considerations. For example, in ground-water "a porous medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of ground water at the prevailing viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow" (Lohman, 1972a, p. 6).

4.33 Discussion

In the tables of data (4.3.1 thru 4.3.7) which follow, attempts have been made to include information about the testing conditions wherever such data are available. Some of the most important factors affecting accurate permeability determinations are: 1) the laboratory conditions of temperature, (see Weinbrandt and others, 1975; and Potter,

1978) 2) gradient imposed across the sample, 3) whether the sample was reloaded and tested under conditions simulating field conditions (see Zoback and Byerlėe, 1975), 4) the composition of the liquid used to do the testing (See Johnston and Beeson, 1945), and 5) the saturation state. All of these topics have been addressed and are continuing to be refined in the past and current literature.

Theoretically, relationships exist between porosity and permeability for uniform size and shape material. However, in nature the conditions are rarely met to permit quantitative prediction of permeability based on porosity measurements. Attempting to summarize the published literature on this topic is beyond the scope of this chapter, however; recent introductions into this literature are: Zoback and Byerlee, 1975; Beard and Weyl, 1973; and Friedman, 1976. A broader treatment of factors affecting porosity and permeability in sediments can be found in Wolf and Chilingarian (1976, p. 188-241).

The units chosen for permeability for the tables are centimeters/second. Data reported in the literature in specific conductivities or in other units have been converted.

Table 4.3.8 is a conversion chart for the most common "permeability" units.

4.34 Summary

With a few exceptions, only values for naturally occurring samples are presented, i.e., values for artificially prepared mixtures were omitted.

Also, "soils" in the agricultural sense were eliminated from the following tabulation; they open a whole new field which is beyond the scope of this chapter. The minimum permeability reported in tables 4.3.1 through 4.3.7 is zero for bedded salt and a maximum of 8.1 cm/sec for basalt "with cavernous openings".

Table 4.3.1. Permeabilities of Metamorphic Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Argillite, Eleana Fm., NV Test Site, 358m (Lab test-vertical carefully controlled)	1	7.8×10^{-13}	1.1×10^{-12}		water	in-situ	20	NS	6
Argillite, Eleana Fm., NV Test Site, 102 m (Lab test-vertical, carefully controlled)	1	3.1×10^{-12}	3.6×10^{-12}		water	in-situ	20	NS	6
Argillite, Eleana Fm., NV Test Site, 102 m (Lab test-horizontal carefully controlled)	1	5.4×10^{-12}	9.8×10^{-12}		water	in-situ	20	NS	6
Argillite, Eleana Fm., NV Test site, 361 m (Lab test-horizontal carefully controlled)	1	1.1×10^{-12}	2.3×10^{-12}		water	in-situ	20	NS	6
Argillite, Eleana Fm., NV Test Site, 358m, fractured (Lab test-vertical carefully controlled)	1	7.9×10^{-10}	1.1×10^{-9}		water	in-situ	20	NS	6
Argillite, Eleana Fm., NV Test Site, 361 m (Lab test-horizontal carefully controlled)	1	2.3×10^{-9}	3.9×10^{-9}		water	in-situ	20	NS	6

Table 4.3.1. Permeabilities of Metamorphic Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Shale, middle Miocene, Italy, 1957 m (Lab test)	1			$2.6x10^{-9}$	NS	NS	NS	16.6	8
Shale, Cretaceous (Lab test)	NS			$3.9x10^{-9}$	NS	NS	NS	NS	4
Shale, lower Pliocene, Italy, 4295 m (Lab test)	1			$3.9x10^{-9}$	NS	NS	NS	10.3	8
Shale, lower Pliocene, Italy, 1367 m (Lab test)	1			$4.8x10^{-8}$	NS	NS	NS	23.0	8
Shale, fractured (Field pumping tests)	93	$2.4x10^{-6}$	$5.7x10^{-3}$	$3.5x10^{-4}$	water	in-situ	in-situ	NS	7
Slate, Iron River, MI (Lab tests)	12	$2.0x10^{-10}$	$3.9x10^{-8}$	$4.4x10^{-9}$	NS	NS	15.5	NS	1
Slate (Lab tests-vertical)	8	$1.9x10^{-10}$	$4.7x10^{-8}$	$9.4x10^{-9}$	NS	NS	15.5	NS	5

Table 4.3.1. Permeabilities of Metamorphic Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Schist, quartz-mica, weathered, Dawson Cy, GA (Lab tests)	21	1.9×10^{-6}	2.7×10^{-3}	3.8×10^{-4}	NS	NS	15.5	46.9	2
Schist, fractured (Field pumping tests)	481	4.7×10^{-7}	1.2×10^{-2}	1.2×10^{-3}	water	in-situ	in-situ	NS	7
Shale, lower Pliocene, Italy, 4925 m (Lab test)	1			9.7×10^{-12}	NS	NS	NS	5.9	8
Shale, Pennsylvanian (Lab tests)	NS			8.7×10^{-11}	NS	NS	NS	NS	4
Shale, lower Pliocene, Italy, 3532 m (Lab test)	1			1.4×10^{-10}	NS	NS	NS	12.0	8
Shale, upper Triassic, Italy, 6168 m (Lab test)	1			1.6×10^{-10}	NS	NS	NS	12.5	8
Shale, lower Pliocene, Italy, 3054 m (Lab test)	1			2.2×10^{-10}	NS	NS	NS	13.3	8
Shale, lower Pliocene, Italy, 3919 m (Lab test)	1			4.4×10^{-10}	NS	NS	NS	11.8	8

Table 4.3.1. Permeabilities of Metamorphic Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Argillite, Eleana Fm., NV Test Site, 102 m, fractured (Lab test-vertical carefully controlled)	1	6.0×10^{-8}	1.1×10^{-7}		water	in-situ	20	NS	6
Gneiss, fractured (Field pumping tests)	131	4.7×10^{-8}	2.6×10^{-3}	6.6×10^{-5}	water	in-situ	in-situ	NS	7
Greenstone, fractured (Field pumping tests)	134	5.7×10^{-6}	9.9×10^{-3}	7.0×10^{-4}	water	in-situ	in-situ	NS	7
Metasediments, fractured, Placer Cy, CA (In-situ field tracer test)	6	1.7×10^{-5}	7.2×10^{-5}	3.8×10^{-5}	water	field	field	NS	3
Quartzite, NV test site (Lab tests)	9	9.4×10^{-11}	4.7×10^{-9}	9.4×10^{-10}	water	NS	NS	1.9	9
Quartzite, Marquette dist., MI (Lab test)				1.6×10^{-9}	NS	NS	15.5	NS	1
Quartzite, fractured (Field pumping tests)	135	1.9×10^{-7}	2.6×10^{-3}	3.7×10^{-4}	water	in-situ	in-situ	NS	7
Schist, micaceous, Iron River, MI (Lab tests)	1			1.8×10^{-9}	NS	NS	15.5	NS	1
Schist (Lab tests-vertical)	17	1.9×10^{-9}	1.1×10^{-3}	1.9×10^{-4}	NS	NS	15.5	38	5

Table 4.3.1. Permeabilities of Metamorphic Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified)

<u>References for Table 4.3.1</u>.

1. Stuart, et. al., 1954;
2. Stewart, 1964;
3. Lewis, et. al., 1966;
4. Gondouin and Scala, 1958;
5. Morris and Johnson, 1967;
6. Lin, 1978;
7. Rasmussen, 1964;
8. Neglia, 1979;
9. Winograd and Thordarson, 1975;

Table 4.3.2. Permeabilities of Carbonate Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Carbonate, "some with large openings" (Field pumping tests)	513	$4.7x10^{-8}$	$1.1x10^{-1}$	$4.4x10^{-3}$	water	in-situ	in-situ	NS	6
Chalk, London Basin (Field pumping tests)	NS	$5.8x10^{-7}$	$1.4x10^{-5}$		water	in-situ	in-situ	NS	9
Dolomite, 80%, limestone 20%, east TN (Lab tests)	6	$8.7x10^{-11}$	$3.8x10^{-8}$	$9.7x10^{-9}$	NS	NS	NS	NS	11
Dolomite, Rustler Fm., West TX (Lab test-transient)	2	$4.2x10^{-8}$	$9.0x10^{-8}$	$6.6x10^{-8}$	hydr.oil	10342	NS	0.87	7
Dolomite (Lab test)				$9.7x10^{-7}$	NS	NS	NS	6.3	2
Dolomite (Lab test-vertical)	3	$3.8x10^{-9}$	$3.3x10^{-6}$	$1.4x10^{-6}$	water	NS	15.5	26	4
Dolomite, NW Germany (Lab test)				$2.9x10^{-6}$	NS	NS	NS	13.0	1
Dolomite, McKnight, TX + (Lab tests)	1404			$5.3x10^{-6}$	NS	NS	NS	NS	5
Dolomite (Lab test)				$1.5x10^{-5}$	NS	NS	NS	11.9	2
Dolomite, Mississipian (Lab test)				$2.8x10^{-4}$	NS	NS	NS	27.8	2

Table 4.3.2. Permeabilities of Carbonate Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Limestone, Gilman, CO (Lab test)	2			4.2×10^{-13}	air	atmos.	NS	NS	8
Limestone, Bisbee, AZ mining district (Lab test)	many			3.3×10^{-12}	air	atmos.	NS	NS	8
Limestone, 90%, dolomite 10%, east TN (Lab tests)	4	5.8×10^{-13}	6.3×10^{-12}	3.6×10^{-12}	NS	NS	NS	NS	11
Limestone, Tristate district (Lab test)	22			4.4×10^{-11}	air	atmos.	NS	NS	8
Limestone, 80%, dolomite 20%, east TN (Lab tests)	3	6.9×10^{-11}	4.6×10^{-10}	2.8×10^{-10}	NS	NS	NS	NS	11
Limestone, Bone Spring Fm., West TX (Lab test-transient)	1			4.7×10^{-10}	hydr.oil	9652	NS	0.44	7
Limestone, crinoidal, Hanover NM district (Lab test)	8			1.3×10^{-9}	air	atmos.	NS	NS	8
Limestone, Bitter Springs Fm., Australia (Lab test-transient?)	1			3.9×10^{-8}	hydr.oil	9652	NS	0.24	7

Table 4.3.2. Permeabilities of Carbonate Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Limestone, dolomitic NV test site (Lab test)	13	$9.4x10^{-10}$	$4.7x10^{-6}$	$4.7x10^{-7}$	tap water	NS	NS	2.3	10
Limestone (Lab test)				$9.7x10^{-7}$	NS	NS	NS	8.4	2
Limestone, Permian (Lab test)				$7.4x10^{-6}$	NS	NS	NS	10.1	3
Limestone, oolitic, NW Germany (Lab test)				$6.3x10^{-5}$	NS	NS	NS	19.8	1
Limestone, shelly, NW Germany (Lab test)				$2.5x10^{-4}$	NS	NS	NS	23.6	1
Limestone, oolitic (Lab test)				$3.2x10^{-4}$	NS	NS	NS	21.6	3
Limestone (Lab test-vertical)	28	$1.4x10^{-8}$	$7.5x10^{-3}$	$1.1x10^{-3}$	water	NS	15.5	30	4
Limestone, coral-oolitic NW Germany (Lab test)				$2.6x10^{-3}$	NS	NS	NS	19.5	1

Table 4.3.2. Permeabilities of Carbonate Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified)

References for Table 4.3.2.

1. Englehardt, 1960;
2. Murrary, 1960;
3. Archie, 1952;
4. Morris and Johnson, 1967;
5. Warren and Skiba, 1961;
6. Rasmussen, 1964;
7. Sanyal, 1971;
8. Rove, 1947;
9. Satchell and Wilkonson, 1973;
10. Winograd and Thordarson, 1975;
11. Ohle, 1951;

Table 4.3.3. Permeabilities of Volcanic Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Basalt, Oahu, HI (field pumping test)	NS	$9.7x10^{-2}$	$2.9x10^{-1}$		water	in-situ	in-situ	NS	2
Basalt, moderately dense (NS)	NS			$1.4x10^{-8}$	NS	NS	NS	7.7	2
Basalt (Lab tests)	93	$1.9x10^{-9}$	$4.2x10^{-5}$	$9.4x10^{-6}$	water	NS	15.5	17	3
Basalt, rhyolite, trachyte, fractured (Field pumping tests)	37	$6.1x10^{-5}$	$1.3x10^{-2}$	$9.6x10^{-4}$	water	in-situ	in-situ	NS	4
Basalt, Snake R., ID (Estimate from field pumping tests)	11			$9.7x10^{-2}$	water	in-situ	in-situ	NS	2
Basalt, rhyolite,trachyte with cavernous openings (Field pumping tests)	10	$1.2x10^{-1}$	$8.1x10^{-0}$	$1.2x10^{-0}$	water	in-situ	in-situ	in-situ	4
Clastics, volcanic, Wairakei, N.Z. (field pressure build-up.)	8	$6.x10^{-7}$	$1.0x10^{-3}$	$1.3x10^{-7}$	in-situ	in-situ	in-situ	NS	7
Tuff, welded NV test site (Field pumping tests)	NS			$9x10^{-10}$	water	in-situ	in-situ	in-situ	5

Table 4.3.3. Permeabilities of Volcanic Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Tuff, clayey NV test site (Lab tests)	38	$9.4\text{x}10^{-11}$	$1.9\text{x}10^{-5}$	$2.8\text{x}10^{-9}$	water	NS	NS	11.0	6
Tuff, bedded, NV test site (Lab tests)	sev.*	$7.3\text{x}10^{-10}$	$1.6\text{x}10^{-5}$	$3.9\text{x}10^{-8}$	water	NS	NS	38.8	1
Tuff, welded, NV test site (Lab tests)	sev.	$8.9\text{x}10^{-10}$	$5.6\text{x}10^{-5}$	$3.2\text{x}10^{-7}$	water	NS	NS	14.1	1
Tuff, welded, NV test site (Lab tests)	sev.	$2.1\text{x}10^{-8}$	$5.6\text{x}10^{-5}$	$6.4\text{x}10^{-7}$	air	NS	NS	14.1	1
Tuff, bedded, NV test site (Lab tests)	sev.	$6.8\text{x}10^{-8}$	$3.8\text{x}10^{-5}$	$8.7\text{x}10^{-7}$	air	NS	NS	38.8	1
Tuff, friable, NV test site (Lab tests)	sev.	$8.1\text{x}10^{-8}$	$2.6\text{x}10^{-5}$	$1.3\text{x}10^{-6}$	water	NS	NS	35.5	1
Tuff, zeolitized, NV test site (Lab Tests)	34	$2.4\text{x}10^{-9}$	$2.8\text{x}10^{-5}$	$2.4\text{x}10^{-6}$	water	NS	NS	37.7	6
Tuff, friable, NV test site (Lab tests)	sev.	$9.2\text{x}10^{-7}$	$4.0\text{x}10^{-5}$	$5.8\text{x}10^{-6}$	air	NS	NS	35.5	1
Tuff, pumiceous,bedded, NV test site (Lab tests)	sev.	$3.6\text{x}10^{-6}$	$5.9\text{x}10^{-5}$	$1.1\text{x}10^{-5}$	water	NS	NS	40.2	1

Table 4.3.3. Permeabilities of Volcanic Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Tuff, pumiceous, bedded, NV test site (Lab tests)	sev.	$4.0x10^{-6}$	$7.2x10^{-5}$	$2.0x10^{-5}$	air	NS	NS	40.2	1
Tuff (Lab tests-vertical)	44	$4.7x10^{-9}$	$8.0x10^{-4}$	$1.9x10^{-4}$	water	NS	15.5	41	3
Tuff (Lab tests-horizontal)	44	$4.7x10^{-9}$	$8.0x10^{-4}$	$2.4x10^{-4}$	water	NS	15.5	41	3
Tuff, tuffaceous sandstone NV test site (Maximum = fractures lab tests)	1			$6.5x10^{-3}$	NS	NS	NS		8

Table 4.3.3. Permeabilities of Volcanic Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified)

<u>References for Table 4.3.3.</u>

1. Keller, 1960
2. Davis, 1969;
3. Morris and Johnson, 1967;
4. Rasmussen, 1964;
5. Winograd, 1971;
6. Winograd and Thordarson, 1975;
7. Grindley, 1965;
8. Butters et. al., 1976;

Table 4.3.4. Permeabilities of Evaporites (cm/sec) (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Gypsum, Castile Fm., West TX (Lab test- vertical transient?)	1			$1.2\text{x}10^{-10}$	Hydr. oil	11031	NS	4.8	2
Gypsum, Castile Fm., West TX (Lab test- horizontal transient?)	1			$3.0\text{x}10^{-8}$	Hydr. oil	11031	NS	4.6	2
Salt, bedded, Hutchinson, KS (Lab test)	1	$4.9\text{x}10^{-10}$	$2.2\text{x}10^{-8}$		Ker	16892	NS	NS	1
Salt, dome, Grand Saline, TX (Lab test)	1	$2\text{x}10^{-10}$	$5.9\text{x}10^{-8}$		Brine	22063	NS	NS	1
Salt, dome, Grand Saline, TX (Lab test)	1	$4.9\text{x}10^{-10}$	$4.9\text{x}10^{-7}$		Ker.	17236	NS	NS	1
Salt, dome, Grand Saline, TX (Lab test)	1	$2.7\text{x}10^{-8}$	$9.8\text{x}10^{-8}$		Brine	75884	NS	NS	1
Salt, dome, Grand Saline, TX (Lab test)	1	$5.3\text{x}10^{-8}$	$2.1\text{x}10^{-7}$		Ker.	11031	NS	NS	1
Salt, dome, Grand Saline, TX (Lab test)	1	$1.5\text{x}10^{-7}$	$4.3\text{x}10^{-7}$		Brine	7584	NS	NS	1
Salt, dome, Grand Saline, TX (Lab test)	1	$1.4\text{x}10^{-7}$	$4.4\text{x}10^{-7}$		Brine	7884	NS	NS	1

Table 4.3.4. Permeabilities of Evaporites (cm/sec) (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Salt, dome, Grand Saline, TX (Lab test)	1	$1.7x10^{-7}$	$9.8x10^{-7}$		Ker.	3792	NS	NS	1
Salt, dome, Grand Saline, TX (Lab test)	1	$1.1x10^{-7}$	$3.9x10^{-6}$		Brine	3792	NS	NS	1
Salt, dome, Grand Saline, TX (Lab test)	1	$3.1x10^{-6}$	$4.1x10^{-6}$		Ker.	3792	NS	NS	1
Salt, dome, Grand Saline, TX (Lab test)	1	$1.7x10^{-6}$	$6.1x10^{-6}$		Ker.	3792	NS	NS	1
Salt, bedded, Huchinson, KS (Lab test)	1	$0x10^{-0}$	$0x10^{-0}$		Brine	7584	NS	NS	1
Salt, bedded, Hutchinson, KS (Lab test)	1	$0x10^{-0}$	$7.1x10^{-9}$		Brine	7584	NS	NS	1
Salt, bedded, Hutchinson, KS (Lab test)	1	$0x10^{-0}$	$1.5x10^{-9}$		Brine	14824	NS	NS	1
Salt, bedded, Hutchinson, KS (Lab test)	1	$0x10^{-0}$	$0x10^{-0}$		Brine	10342	NS	NS	1
Salt, bedded, Hutchinson, KS (Lab test)	1	$0x10^{-0}$	$0x10^{-0}$		Brine	3447	NS	NS	1
Salt, bedded, Hutchinson, KS (Lab test)	1	$0x10^{-0}$	$0x10^{-0}$		Ker	3792	NS	NS	1
Salt, dome, Grand Saline, TX (Lab test)	1	$0x10^{-0}$	$1.4x10^{-7}$		Brine	7584	NS	NS	1

Table 4.3.4. Permeabilities of Evaporites (cm/sec) (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Salt, dome, Grand Saline, TX (Lab test)	1	$0x10^{-0}$	$4.9x10^{-8}$		Brine	11031	NS	NS	1

Table 4.3.4. Permeabilities of Evaporites (cm/sec). (Porosities are averages, loading conditions are kPa, NS = not specified)

References for Table 4.3.4.

1. Gloyna and Reynolds, 1961; 2. Sanyal, 1971.

Table 4.3.5. Permeabilities of Holocrystalline Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Diabase, Hudson, NY (Lab test)				$8.1\text{x}10^{-13}$	NS	NS	NS	NS	6
Gabbro, weathered (Lab tests)	4	$4.7\text{x}10^{-5}$	$3.8\text{x}10^{-4}$	$1.9\text{x}10^{-4}$	water	NS	15.5	43	2
Granite, 2524 m* (Lab tests)	1	$1.2\text{x}10^{-11}$	$1.9\text{x}10^{-9}$		water	variable	24	NS	4
Granite, 2902 m (Lab tests)	1	$8.6\text{x}10^{-11}$	$1.5\text{x}10^{-8}$		water	variable	24	NS	4
Granite, Barriefield, Ontario (Lab test)				$4.9\text{x}10^{-11}$	NS	NS	NS	NS	6
Granite, Sherman Granite, Laramie, WY (Lab test)				$1.\text{x}10^{-9}$	NS	NS	NS	NS	8
Granite (Field pumping test)	1			$4.0\text{x}10^{-9}$	water	in-situ	in-situ	NS	3
Granite, Quincy, MA (Lab test)				$4.4\text{x}10^{-9}$	NS	NS	NS	NS	6
Granite, Hardhat (Field test-horizontal)				$4\text{x}10^{-8}$	air	in-situ	in-situ	NS	2
Granite, Hardhat (Field test-vertical)				$7\text{x}10^{-8}$	air	in-situ	in-situ	NS	7

Table 4. Permeabilities of Holocrystalline Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Granite, Sherman Granite, Laramie, WY, jointed (Field pumping test)				$9.8x10^{-7}$	water	in-situ	in-situ	NS	8
Granite, diorite & gabbro, coarse grained fractured (Field pumping tests)	106	$4.7x10^{-7}$	$4.2x10^{-3}$	$4.2x10^{-4}$	water	in-situ	in-situ	NS	5
Granite, weathered (Lab tests)	7	$3.3x10^{-4}$	$5.2x10^{-3}$	$1.6x10^{-3}$	water	NS	15.5	45	2
Igneous-metamorphic, undifferentiated fractured (Field pumping tests)	556	$9.4x10^{-8}$	$1.9x10^{-2}$	$8.5x10^{-5}$	water	in-situ	in-situ	NS	5
Intrusive, unspecified, Marquette district, MI (Lab tests)	4	$7.5x10^{-11}$	$2.7x10^{-8}$	$4.6x10^{-9}$	NS	NS	15.5	NS	1
Iron Ore, hematitic etc., Iron River & Marquette districts, MI (Lab tests)	29	$1.3x10^{-10}$	$3.3x10^{-5}$	$1.3x10^{-6}$	NS	NS	15.5	NS	1

Table 4.3.5. Permeabilities of Holocrystalline Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified)

References for Table 4.3.5.

1. Stuart et. al., 1954;
2. Morris and Johnson, 1967;
3. Delisle, 1975;
4. Potter, 1978;
5. Rasmussen, 1964;
6. Ohle, 1951;
7. Boardman and Skrove, 1966;
8. Pratt et. al., 1974;

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Aquicludes, Alberta, Canada (Simulation modeling results-large scale)		$5.x10^{-11}$	$1.x10^{-8}$		water	in-situ	in-situ	NS	22
Aquifers, Alberta, Canada (Simulation modeling results-large scale)		$4.x10^{-5}$	$1.x10^{-3}$		water	in-situ	in-situ	NS	22
Argillite, siltstone NV test site (Lab tests)	9	$3.3x10^{-11}$	$3.3x10^{-10}$	$9.4x10^{-11}$	water	NS	NS	2.0	24
Arkose, coarse, Stockton Fm., S.E. PA (Lab test-vertical)	1			$1.4x10^{-8}$	water	NS	NS	7.9	6
Arkose, med., Stockton Fm., S.E. PA (Lab test-vertical)	1			$4.7x10^{-8}$	water	NS	NS	16.1	6
Arkose, med., Stockton Fm., S.E. PA (Lab test-horizontal)	1			$4.7x10^{-8}$	water	NS	NS	16.1	6
Arkose, fine, Stockton Fm., S.E. PA (Lab test-vertical)	1			$1.4x10^{-7}$	water	NS	NS	14.4	6
Arkose, vy coarse, Stockton Fm., S.E. PA (Lab test-vertical)	1			$3.3x10^{-7}$	water	NS	NS	10.9	6

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Arkose, vy coarse, Stockton Fm., S.E. PA (Lab test-vertical)	1			$4.2x10^{-7}$	water	NS	NS	19.4	6
Arkose, vy coarse, Stockton Fm., S.E. PA (Lab test-horizontal)	1			$4.7x10^{-7}$	water	NS	NS	10.9	6
Arkose, vy coarse, Stockton Fm., S.E. PA (Lab test-horizontal)	1			$4.7x10^{-7}$	water	NS	NS	19.4	6
Arkose, med., Stockton Fm., S.E. PA (Lab test-vertical)	1			$4.7x10^{-7}$	water	NS	NS	25.6	6
Arkose, med., Stockton Fm., S.E. PA (Lab test-horizontal)	1			$9.4x10^{-7}$	water	NS	NS	25.6	6
Arkose, fine, Stockton Fm., S.E. PA (Lab test-horizontal)	1			$1.4x10^{-6}$	water	NS	NS	14.4	6
Arkose, coarse, Stockton Fm., S.E. PA (Lab test-horizontal)	1			$1.4x10^{-6}$	water	NS	NS	19.2	6
Arkose, coarse, Stockton Fm., S.E. PA (Lab test-vertical)	1			$1.9x10^{-6}$	water	NS	NS	19.2	6

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Arkose, med., Stockton Fm., S.E. PA (Lab test-vertical)	1			$9.4x10^{-6}$	water	NS	NS	30.6	6
Arkose, med., Stockton Fm., S.E. PA (Lab test-horizontal)	1			$1.4x10^{-5}$	water	NS	NS	30.6	6
Chert, Onverwacht Group South Africa (Lab test)	1			$4.8x10^{-13}$	brine	NS	NS	0.5	15
Chert, Keewatin, Canada (Lab tests-transient?)	1			$1.1x10^{-10}$	hydr.oil	11032	NS	0.10	14
Chert, Iron R., MI (Lab tests)				$1.6x10^{-10}$	NS	NS	15.5	NS	4
Chert, Onverwacht Group South Africa (Lab tests-transient?)	4	$9.7x10^{-13}$	$2.0x10^{-8}$	$8.x10^{-9}$	hydr. oil	11032	NS	0.72	14
Chert (Lab test)	7	$7.0x10^{-9}$	$6.4x10^{-7}$	$1.9x10^{-7}$	air	2068	NS	1.7	16
Claystone (Lab tests-vertical)	2			$9.4x10^{-8}$	water	NS	15.5	43	9
Coal, Pricetown, WV (Field tests)	sev.	$2.3x10^{-9}$	$8.3x10^{-9}$		in-situ	in-situ	in-situ	NS	2

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Coal Campbell Cy., WY (Field tests-horizontal)	NS	$1.7\text{x}10^{-4}$	$3.5\text{x}10^{-4}$		water	in-situ	in-situ	NS	23
Coal, Campbell CY., WY (Field test-vertical)				$1.2\text{x}10^{-6}$	water	in-situ	in-situ	NS	23
Conglomerate, vy coarse, Stockton Fm., S.E. PA (Lab test-horizontal)	1			$1.4\text{x}10^{-7}$	water	NS	NS	7.1	6
Conglomerate, vy coarse, Stockton Fm., S.E. PA (Lab test-vertical)	1			$1.9\text{x}10^{-7}$	water	NS	NS	7.1	6
Conglomerate, vy coarse, Stockton Fm., S.E. PA (Lab test-vertical)	1			$3.3\text{x}10^{-7}$	water	NS	NS	17.3	6
Conglomerate, vy coarse, Stockton Fm., S.E. PA (Lab test-horizontal)	1			$4.2\text{x}10^{-7}$	water	NS	NS	17.3	6
Graywacke, Iron R., MI (Lab tests)	8	$2.5\text{x}10^{-10}$	$1.3\text{x}10^{-7}$	$2.5\text{x}10^{-8}$	NS	NS	15.5	NS	4
Graywacke, low rank, Weir Fm., (Lab tests-horizontal)	3			$6.8\text{x}10^{-7}$	NS	34473	NS	13.4	12

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Graywacke, low rank, Weir Fm., (Lab tests-vertical)	3			$8.6\text{x}10^{-7}$	NS	34473	NS	13.2	12
Graywacke, low rank, Bradford Fm., (Lab tests-vertical)	2	$9.1\text{x}10^{-7}$	$9.2\text{x}10^{-7}$	$9.2\text{x}10^{-7}$	NS	atmos.	NS	11.0	12
Graywacke, low rank, Weir Fm., (Lab tests-horizontal)	3	$1.0\text{x}10^{-6}$	$3.1\text{x}10^{-6}$	$1.8\text{x}10^{-6}$	NS	atmos.	NS	14.6	12
Graywacke, low rank, Weir Fm., (Lab tests-vertical)	3	$1.6\text{x}10^{-6}$	$4.5\text{x}10^{-6}$	$2.6\text{x}10^{-6}$	NS	atmos.	NS	14.3	12
Graywacke, low rank, Bradford Fm., (Lab tests-horizontal)	3			$2.9\text{x}10^{-6}$	NS	34473	NS	9.2	12
Graywacke, low rank, Bradford Fm., (Lab tests-horizontal)	3	$4.6\text{x}10^{-7}$	$9.9\text{x}10^{-6}$	$3.9\text{x}10^{-6}$	NS	atmos.	NS	10.4	12
Graywacke, fractured, Mendocino Cy., CA (Field tracer test)	11	$7.0\text{x}10^{-6}$	$1.2\text{x}10^{-4}$	$4.5\text{x}10^{-5}$	water	in-situ	in-situ	NS	5
Graywacke, low rank, Bradford Fm.,			4.8	$-7\text{x}10^{\text{NS}}$	34473	NS	10.1	Lab tests-vertical	

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Mudstone, Triassic, SC (field pumping test)	1			3.8×10^{-12}	in-situ	in-situ	in-situ	3	19
Mudstone, Triassic, SC (Field pumping test)	1			1.7×10^{-9}	in-situ	in-situ	in-situ	3	19
Sand, Clarendon Fm., PA (Lab test-vertical)	6	7.3×10^{-8}	3.2×10^{-6}	1.3×10^{-6}	water	NS	NS	14.6	8
Sand, Bradford Fm., PA (Lab test-horizontal)	5	3.5×10^{-7}	3.1×10^{-6}	1.7×10^{-6}	water	NS	NS	13.1	8
Sand, Bradford Fm., PA (Lab test-vertical)	8	5.0×10^{-7}	4.4×10^{-6}	2.1×10^{-6}	air	NS	NS	12.9	8
Sand, Bradford Fm., Pa (Lab test-vertical)	38	6.1×10^{-8}	1.3×10^{-4}	7.0×10^{-6}	water	NS	NS	11.7	8
Sand, 2d Venango Fm., PA (Lab test-vertical)	8	8.0×10^{-7}	1.3×10^{-4}	3.3×10^{-5}	water	NS	NS	14.3	8
Sand, Wanette Fm., OK (Lab tests-horizontal)	7	2.4×10^{-6}	1.6×10^{-4}	3.6×10^{-5}	water	NS	NS	16.8	8
Sand, Kane Fm., PA (Lab test-horizontal)	2	3.2×10^{-5}	5.9×10^{-5}	4.5×10^{-5}	water	NS	NS	22.1	8
Sand, Kane Fm., PA (Lab test-vertical)	5	1.3×10^{-6}	2.1×10^{-4}	6.9×10^{-5}	water	NS	NS	17.6	8
Sand, Wilcox Fm., OK (Lab tests-horizontal)	2	7.3×10^{-5}	8.5×10^{-5}	7.9×10^{-5}	water	NS	NS	14.2	8

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Sand, 3d. Venango Fm., PA (Lab test-vertical)	13	1.5×10^{-8}	5.2×10^{-4}	1.0×10^{-4}	air	NS	NS	11.5	8
Sand, Wanette Fm., OK (Lab tests-vertical)	7	1.1×10^{-5}	4.7×10^{-4}	1.1×10^{-4}	water	NS	NS	16.5	8
Sand, Johnson Fm., OK (Lab tests-horizontal)	4	7.7×10^{-7}	2.7×10^{-4}	1.2×10^{-4}	water	NS	NS	15.9	8
Sand, Woodbine Fm., E.TX (Lab test-horizontal)	2	1.9×10^{-5}	3.3×10^{-4}	1.7×10^{-4}	water	NS	NS	26.3	8
Sand, Cromwell Fm., OK (Lab tests-horizontal)	13	3.7×10^{-5}	6.4×10^{-4}	2.2×10^{-4}	water	NS	NS	20.0	8
Sand, Johnson Fm., OK (Lab tests-vertical)	6	7.9×10^{-7}	6.7×10^{-4}	2.5×10^{-4}	water	NS	NS	14.1	8
Sand, Berea Fm., OK (Lab tests-vertical)	2	2.5×10^{-4}	2.8×10^{-4}	2.6×10^{-4}	water	NS	NS	19.4	8
Sand, Cromwell Fm., OK (Lab tests-vertical)	14	5.2×10^{-5}	7.4×10^{-4}	2.8×10^{-4}	water	NS	NS	19.8	8
Sand, Wilcox Fm., OK (Lab tests-vertical)	4	7.6×10^{-5}	6.5×10^{-4}	2.9×10^{-4}	water	NS	NS	13.1	8
Sand, Woodbine Fm., E. TX (Lab test-vertical)	8	1.1×10^{-4}	3.2×10^{-3}	1.2×10^{-3}	water	NS	NS	24.6	8
Sand, 2d Venango Fm., PA (15.5)		$4\times10^{1.1}$	$-5\times10^{6.4}$	$-5\times10^{3.4}$	-5	water	NS	NS	8

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Sandstone, fn-vy fn, clayey & silty, L.Cretaceous, W. Canada, 2012 m (Lab test-vertical d_{50} = 40)	1			$1.6x10^{-13}$	brine	in-situ	36	NS	7
Sandstone, vy fn, clayey & silty, L. Cretaceous, W. Canada, 1414 m (Lab test-vertical d_{50} = 100)	1			$1.9x10^{-12}$	brine	in-situ	35	NS	7
Sandstone, fn-vy fn, silty & clayey, L.Cretaceous, W. Canada 1924 m (Lab test-vertical d_{50} = 100)	1	$1.0x10^{-12}$	$2.9x10^{-12}$	$1.9x10^{-12}$	varied	varied	35-36	NS	7
Sandstone, vy fn, clayey & silty, L.Cretaceous, W. Canada, 1414 m (Lab test-horizontal d_{50} = 100)	1	$4.7x10^{-12}$	$1.1x10^{-11}$	$7.7x10^{-12}$	varied	varied	35-36	NS	7
Sandstone, fn, clayey & silty, L. Cretaceous, W. Canada, 1519 m (Lab test-vertical d_{50} = 135)	1			$1.9x10^{-11}$	brine	in-situ	35	NS	7

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Sandstone, fn, clayey & silty, L. Cretaceous, W. Canada, 1519 m (Lab test-horizontal d_{50} = 135)	1			$3.2x10^{-10}$	brine	in-situ	35	NS	7
Sandstone, med., little clay L. Cretaceous, W. Canada, 1423 m (Lab test-horizontal)	1			$9.7x10^{-9}$	brine	in-situ	35	NS	7
Sandstone, Chocolate Bayou field, Brazoria Cy, TX (Lab & field tests)	NS	$5x10^{-8}$	$1.3x10^{-3}$	$3.x10^{-6}$	in-situ	in-situ	in-situ	2 to 27	17
Sandstone, Kirkwood Fm., (Lab tests-vertical)	2			$5.5x10^{-6}$	NS	34473	NS	15.0	12
Sandstone, N. W. Germany (d_{50} = 0.04 mm, $<20\mu = 15\%$)				$6.8x10^{-6}$	air	NS	NS	10.2	3
Sandstone, Kirkwood Fm., (Lab tests-horizontal)	2			$7.9x10^{-6}$	NS	34473	NS	14.8	12
Sandstone, Kirkwood Fm., (Lab tests-vertical)	2	$7.1x10^{-7}$	$2.1x10^{-5}$	$1.1x10^{-5}$	NS	atmos.	NS	15.8	12
Sandstone, Kirkwood Fm., (Lab tests-horizontal)	2	$2.3x10^{-6}$	$3.4x10^{-5}$	$1.8x10^{-5}$	NS	atmos.	NS	15.6	12

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Sandstone, "Bromide Fm., OK$^+$ (Lab tests)	1371			$3.1\mathrm{x}10^{-5}$	NS	NS	NS	NS	11
Sandstone, N. W. Germany (d_{50} = 0.04 mm, $<20\mu$ = 10%)				$3.4\mathrm{x}10^{-5}$	air	NS	NS	24.5	3
Sandstone, med., little clay L. Cretaceous, W. Canada, 1423 m (Lab test-vertical)	1			$4.0\mathrm{x}10^{-5}$	brine	in-situ	35	NS	7
Sandstone, vy fn to fn, Tensleep, WY (Lab tests, $<2\%$ clay size)	many			$6.6\mathrm{x}10^{-5}$	air	NS	NS	13.8	21
Sandstone, siltstone, shale, fractured (Field pumping tests)	326	$4.7\mathrm{x}10^{-8}$	$7.1\mathrm{x}10^{-3}$	$7.1\mathrm{x}10^{-5}$	water	in-situ	in-situ	NS	13
Sandstone, N. W. Germany (d_{50} = 0.09 mm, $<20\mu$ = 3.1%)				$9.7\mathrm{x}10^{-5}$	air	NS	NS	19.0	3
Sandstone, N. W. Germany (d_{50} = 0.35 mm, $<20\mu$ = 6.5%)				$1.0\mathrm{x}10^{-4}$	air	NS	NS	24.7	3
Sandstone, N. W. Germany (d_{50} = 0.10 mm, $<20\mu$ = 7.5%)				$1.7\mathrm{x}10^{-4}$	air	NS	NS	27.2	3

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Sandstone, oil reservoirs, mostly CA* (Lab tests)	1233	3.9×10^{-9}	2.7×10^{-3}	1.7×10^{-4}	water	NS	15.5	NS	10
Sandstone, fn (Lab tests-vertical)	20	3.8×10^{-7}	1.7×10^{-3}	2.4×10^{-4}	water	NS	15.5	33	9
Sandstone, fn (Lab tests-horizontal)	20	4.7×10^{-7}	2.3×10^{-3}	3.3×10^{-4}	water	NS	15.5	33	9
Sandstone, N. W. Germany (d_{50} 0.11 mm, $<20\mu$ = 9.5%)				3.8×10^{-4}	air	NS	NS	27.4	3
Sandstone, Miocene loosely consolidated TX Gulf coast (Lab tests-sidewall Cores)	2			4.6×10^{-4}	NS	NS	NS	32.5	20
Sandstone, N. W. Germany (d_{50} = 0.4 mm, $<20\mu$ = 6%)				4.9×10^{-4}	air	NS	NS	23.6	3
Sandstone, fractured (Field pumping tests)	182	3.3×10^{-7}	5.4×10^{-3}	5.1×10^{-4}	water	in-situ	in-situ	NS	13
Sandstone, N. W. Germany (d_{50} = 0.09 mm, $<20\mu$ = 2.6%)				5.9×10^{-4}	air	NS	NS	22.8	3

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Sandstone, oil reservoirs, mostly in CA* (Lab tests)	1223	3.8×10^{-7}	4.9×10^{-3}	9.8×10^{-4}	water	NS	15.5	NS	10
Sandstone, No. 1 Woodbine Fm., E.TX (Lab tests)	NS			1.2×10^{-3}	CCl_4	NS	NS	NS	1
Sandstone, N. W. Germany ($d_{50} = 0.31$ mm, $<20\mu \cong 2.3\%$)				1.3×10^{-3}	air	NS	NS	18.5	3
Sandstone, No. 4 Woodbine Fm., E. TX (Lab tests)	NS			1.4×10^{-3}	water	NS	NS	NS	1
Sandstone, No. 2 Woodbine Fm., E.TX (Lab tests)	NS			1.5×10^{-3}	water	NS	NS	NS	1
Sandstone, N. W. Germany ($d_{50} = 0.16$ mm, $<20\mu \cong 2.0\%$)				1.5×10^{-3}	air	NS	NS	26.9	3
Sandstone, No. 3 Woodbine Fm., E.TX (Lab tests)	NS			1.6×10^{-3}	water	NS	NS	NS	1
Sandstone, N. W. Germany ($d_{50} = 0.2$mm, $<20\mu \cong 10\%$)				2.3×10^{-3}	air	NS	NS	28.5	3
Sandstone, oil reservoirs, mostly CA* (Lab tests)	1233	4.2×10^{-6}	1.3×10^{-2}	2.7×10^{-3}	air	NS	15.5	NS	10

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Sandstone, N.W. Germany (d_{50} = 0.25 mm, <20μ = 1.5%)				$3.0\text{x}10^{-3}$	air	NS	NS	25.1	3
Sandstone, N. W. Germany (d_{50} = 0.25 mm, <20μ = 2.5%)				$3.1\text{x}10^{-3}$	air	NS	NS	24.6	3
Sandstone, N. W. Germany (d_{50} = 0.21 mm <20μ = 1.6%)				$3.1\text{x}10^{-3}$	air	NS	NS	27.8	3
Sandstone, med. (Lab tests-vertical)	13	$2.4\text{x}10^{-6}$	$1.0\text{x}10^{-2}$	$3.6\text{x}10^{-3}$	water	NS	15.5	37	9
Sandstone, N.W. Germany (d_{50} = 0.7 mm, <20μ = 2.1%)				$4.7\text{x}10^{-3}$	air	NS	NS	19.9	3
Sandstone, fine to med. poorly cemented, Norfolk, VA (Lab tests)	12			$4.9\text{x}10^{-3}$	water	NS	NS	NS	18
Sandstone, N. W. Germany (d_{50} = 0.35 mm, <20μ = 1.1%)				$5.5\text{x}10^{-3}$	air	NS	NS	24.5	3
Sandstone, N. W. Germany (d_{50} = 0.25 mm, <20μ = 0.8%)				$7.2\text{x}10^{-3}$	air	NS	NS	29.5	3

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Sandstone, N. W. Germany (d_{50} 0.50 mm, $<20\mu = 1.3\%$)				9.5×10^{-3}	air	NS	NS	26.2	3
Siltsone, Iron R., MI (Lab tests)	2	1.5×10^{-9}	4.3×10^{-8}	2.3×10^{-8}	NS	NS	15.5	NS	4
Siltstone, coarse clayey L. Cretaceous, W. Canada, 1605 m (Lab tests-vertical d_{50} = 40)	1	2.3×10^{-13}	4.2×10^{-13}	3.2×10^{-13}	brine	varied	36	NS	7
Siltstone, coarse, clayey L. Cretaceous, W. Canada, 1426 m (Lab test-horizontal d_{50} = 35-40)	1			4.7×10^{-13}	brine	in-situ	36	NS	7
Siltstone, coarse, clayey, L. Cretaceous, W. Canada, 1426 m (Lab test-vertical d_{50} = 35-40)	1			1.3×10^{-12}	brine	in-situ	35	NS	7
Siltstone, coarse clayey L. Cretaceous, W. Canada, 1680 m (Lab tests-vertical d_{50} = 35)	1	3.8×10^{-13}	2.9×10^{-12}	1.4×10^{-12}	varied	varied	35-36	NS	7

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Siltstone, vy coarse, poorly sorted, L.Cretaceous, W. Canada, 1665 m (Lab test-vertical)	1			$2.9x10^{-12}$	brine	in-situ	35	NS	7
Siltstone, vy coarse, poorly sorted, L. Cretaceous, W. Canada, 1665 m (Lab test-horizontal)	1			$2.9x10^{-12}$	brine	in-situ	35	NS	7
Siltstone, sandy, Stockton Fm., S.E. PA (Lab test-horizontal)	1			$1.0x10^{-7}$	water	NS	NS	9.7	6
Siltstone, sandy, Stockton Fm., S.E.PA (Lab test-vertical)	1			$1.4x10^{-7}$	water	NS	NS	9.7	6
Siltstone (Lab tests-vertical)	8	$9.4x10^{-10}$	$1.4x10^{-6}$	$1.9x10^{-7}$	water	NS	15.5	35	9

Table 4.3.6. Permeabilities of Indurated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified)

References for Table 4.3.6.

1. Wyckoff et. al., 1934;
2. Rauch, 1979;
3. Engelhardt, 1960;
4. Stuart et. al., 1954;
5. Lewis et al., 1966;
6. Rima et. al., 1962;
7. Young et. al., 1964;
8. Muskat, 1937;
9. Morris and Johnson, 1967;
10. Johnston and Beeson, 1945;
11. Warren and Skiba, 1961;
12. Wyble, 1958**;
13. Rasmussen, 1964;
14. Sanyal et. al., 1971;
15. Nagy, 1970;
16. Smith et. al., 1970;
17. Bebout et. al., 1978;
18. Brown and Silvey, 1973;
19. Marine, 1973;
20. Donaldson and Johansen, 1973;
21. Morgan et. al., 1978;
22. Toth, 1978;
23. Snoeberger and Stone, 1975;
24. Winograd and Thordarson, 1975;

\+ See original reference for discussion of statistical considerations.

* Selection of samples tested with different permeants, see orginal reference for discussion.

** Tests reported show effect of confining pressure.

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditons are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Alluvium, Arkansas R. (Lab tests)	97	3.3×10^{-7}	2.4×10^{-2}	5.6×10^{-3}	water	atmos.	15.5	38.8	10
Alluvium, Ohio River (Lab tests-vertical)	22	2.4×10^{-7}	3.3×10^{-2}	9.9×10^{-3}	water	NS	15.5	NS	5
Alluvium, Quaternary, Jackson purchase region, KY (Lab tests-horizontal, outcrop samples?)	2	1.1×10^{-2}	2.2×10^{-2}	1.7×10^{-2}	water	NS	15.5	48.6	3
Alluvium, Quaternary, Jackson purchase region, KY (Lab tests-vertical outcrop samples?)	2	1.4×10^{-2}	2.3×10^{-2}	1.8×10^{-2}	water	NS	15.5	49.0	3
Beach deposit, Sabine Pass, TX (Lab test-horizontal)	40			6.6×10^{-3}	water	NS	NS	NS	14
Beach deposit, Ship Island, MS (Lab test-horizontal)	195			5.9×10^{-2}	water	NS	NS	45.9	14
Beach deposit, Santa Rosa Is, MS (Lab test-horizontal)	245			7.3×10^{-2}	water	NS	NS	49.6	14
Clay, montmorillonite (Lab prepared sample)	1			5.3×10^{-15}	NS	121200	NS	30.8	25
Clay, montmorillonite (Lab prepared sample)	1			9.7×10^{-15}	NS	80800	NS	36.0	25

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditons are kPa, NS = Not specified)

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Clay, montmorillonite (Lab prepared sample)	1			$2.6x10^{-14}$	NS	40400	NS	43.3	25
Clay, montmorillonite (Lab prepared sample)	1			$5.3x10^{-14}$	NS	20200	NS	47.8	25
Clay, montmorillonite (Lab prepared sample)	1			$6.4x10^{-14}$	NS	10201	NS	52.1	25
Clay, sodium montmorillonite Cherry lease, TX (lab test-prepared sample)	1			$4.5x10^{-13}$	Brine	33000	NS	est.35	15
Clay, sodium montmorillonite Cherry lease, TX (lab test-prepared sample)	1			$5.5x10^{-13}$	water	33000	NS	est.35	15
Clay, kaolinite (Lab test)	1			$2.2x10^{-9}$	water	34323	NS	22.5	8
Clay, silty sandy aquitards, San Joaquin Valley, CA (Regional modeling analysis result)				$2.9x10^{-9}$	in-situ	in-situ	in-situ	NS	21
Clay, sandy central CA (Lab test-vertical)	1			$9.4x10^{-9}$	water	atmos.	15.5	NS	12
Clay, Eocene, Jackson purchase region,KY (Lab tests-horizontal)	1			$1.4x10^{-8}$	water	NS	15.5	48.5	3

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditons are kPa, NS = Not specified)

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Clay, Paleocene, Porters Creek Fm., Jackson purchase region, KY (Lab tests-vertical)	2	$1.4\text{x}10^{-8}$	$1.9\text{x}10^{-8}$	$1.6\text{x}10^{-8}$	water	NS	15.5	50.2	3
Clay, silty central CA (Lab test-vertical)	45	$4.7\text{x}10^{-9}$	$4.7\text{x}10^{-7}$	$4.5\text{x}10^{-8}$	water	atmps.	15.5	43.1	12
Clay (Lab tests-vertical)	19	$1.4\text{x}10^{-9}$	$4.7\text{x}10^{-7}$	$9.4\text{x}10^{-8}$	water	atmos.	15.5	42	4
Clay, clayey silt, Oxnard, CA (Lab tests)	13	$1.7\text{x}10^{-8}$	$8.7\text{x}10^{-7}$	$1.6\text{x}10^{-7}$	water	in-situ	15.5	NS	1
Clay, silty central CA (Lab test-horizontal)	26	$4.7\text{x}10^{-9}$	$1.4\text{x}10^{-6}$	$2.2\text{x}10^{-7}$	water	atmos.	15.5	NS	12
Clay, silty (Lab tests-vertical)	2	$4.7\text{x}10^{-10}$	$4.7\text{x}10^{-7}$	$2.4\text{x}10^{-7}$	water	atmos.	15.5	39.3	4
Clay (Lab tests-horizontal)	19	$9.4\text{x}10^{-9}$	$1.4\text{x}10^{-6}$	$2.4\text{x}10^{-7}$	water	atmos.	15.5	42	4
Clay, kaolinite (Lab test)	1			$5.5\text{x}10^{-7}$	water	9807	NS	36.5	8
Clay, Salisbury, MD (Lab tests-vertical)	7	$1.5\text{x}10^{-8}$	$2.2\text{x}10^{-6}$	$5.7\text{x}10^{-7}$	water	in-situ	20	NS	6
Clay, kaolinite (Lab test)	1			$4.0\text{x}10^{-6}$	water	2451	NS	46.5	8

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditons are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Clay, kaolinite (Lab test)	1			1.3×10^{-5}	water	392	NS	54.8	8
Clay, kaolinite (Lab test)	1			2.0×10^{-5}	water	98	NS	57.5	8
Clay, kaolinite (Lab test)	1			2.3×10^{-5}	water	49	NS	58.8	8
Clay, San Luis Valley, CO (Lab tests-vertical)	7	3.1×10^{-9}	3.9×10^{-3}	6.1×10^{-4}	water	in-situ	20	NS	7
Dune deposit, sand, Coos Bay, OR (Lab tests-disturbed sample)	4	2.4×10^{-2}	3.0×10^{-2}	2.8×10^{-2}	water	atmos.	15.5	37	11
Dune deposit, St. Andrew Park, Panama City, FL (Lab test-horizontal)	116			3.5×10^{-2}	water	NS	NS	50.8	14
Dune deposit, Santa Rosa Is., MI (Lab test-horizontal)	48			6.9×10^{-2}	water	NS	NS	47.9	14
Gravel, poorly sorted, Humboldt R., Winnemuca, NV (Lab test)	1			4.7×10^{-8}	water	atmos.	15.5	63.4	9
Gravel, sandy well sorted, Humboldt R., Winnemuca, NV (Lab test)	1			3.3×10^{-1}	water	atmos.	15.5	28.2	9

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditons are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Gravel, "waterlaid" (Lab tests-vertical)	3	$1.9x10^{-1}$	$1.9x10^{0}$	$1.2x10^{0}$	water	atmos.	15.5	40	4
Loess (Lab tests)	3	$9.4x10^{-7}$	$1.9x10^{-4}$	$7.9x10^{-5}$	water	atmos	15.5	44.6	4
Loess (Lab tests-vertical)	6	$4.7x10^{-6}$	$1.9x10^{-4}$	$9.4x10^{-5}$	water	atmos.	15.5	49	4
Loess, Pleistocene, Jackson purchase region, KY (Lab test-horizontal outcrop sample)	1			$1.9x10^{-4}$	water	NS	15.5	50.7	3
Loess, Pleistocene, Jackson purchase region, KY (Lab tests-vertical outcrop samples)	2	$9.4x10^{-5}$	$2.8x10^{-4}$	$1.9x10^{-4}$	Water	NS	15.5	42.1	3
Peat, fibrous (Lab tests)	NS	$1.x10^{-7}$	$4.x10^{-5}$		water	variable	NS	NS	18
Peat, reed and Sedge decomposed 46 cm*				$3.3x10^{-7}$	water	NS	NS	NS	19
Peat, sphagnum moss, MN (Field piezometer tests)	3	$1.4x10^{-4}$	$3.8x10^{-2}$	$1.3x10^{-3}$	water	in-situ	in-situ	NS	17
Peat, woody, MN (Field piezometer tests)	2	$5.6x10^{-4}$	$5.0x10^{-3}$	$2.8x10^{-3}$	water	in-situ	in-situ	NS	17

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditons are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Peat, herbaceous, MN (Field piezometer tests)	2	7.0×10^{-6}	1.3×10^{-2}	6.5×10^{-3}	water	in-situ	in-situ	NS	17
Peat (Lab tests-vertical)	2	1.4×10^{-4}	1.3×10^{-2}	6.6×10^{-3}	water	atmos.	15.5	92	4
River bar deposit, Mississippi R., Jonesville, LA (Lab test-horizontal)	30			6.2×10^{-3}	water	NS	NS	45.0	14
River bar deposit, Wabash R., Grayville, IL (Lab tests-horizontal)	167			7.5×10^{-2}	water	NS	NS	44.9	14
River bar deposit, Whitewater R., Cincinnati, OH (Lab tests-horizontal)	151			9.1×10^{-2}	water	NS	NS	36.9	14
Sand, silt and clay, central CA (Lab tests-horizontal)	62	9.4×10^{-9}	3.3×10^{-4}	4.2×10^{-6}	water	atmos.	15.5	40.4	12
Sand, silt and clay, central CA (Lab tests-vertical)	103	4.7×10^{-9}	3.3×10^{-4}	7.5×10^{-6}	water	atmos.	15.5	40.4	12
Sand, clayey central CA (Lab tests-vertical)	12	4.7×10^{-9}	1.9×10^{-4}	2.2×10^{-5}	water	atmos.	15.5	44.4	12
Sand, clayey central CA (Lab tests-horizontal)	3	4.7×10^{-7}	9.4×10^{-5}	3.3×10^{-5}	water	atmos.	15.5	44.4	12

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditons are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Sand, silty central CA (Lab tests-vertical)	83	$1.4\text{x}10^{-8}$	$1.0\text{x}10^{-3}$	$7.2\text{x}10^{-5}$	water	atmos.	15.5	38.1	12
Sand, silty central CA (Lab tests-horizontal)	9	$4.7\text{x}10^{-8}$	$9.0\text{x}10^{-4}$	$1.0\text{x}10^{-4}$	water	atmos.	15.5	NS	12
Sand, Miocene 2440-2900 m (Lab tests)	59	$1.8\text{x}10^{-6}$	$2.7\text{x}10^{-3}$	$6.4\text{x}10^{-4}$	water	in-situ?	NS	27.1	16
Sand, central CA (Lab tests-vertical)	50	$9.4\text{x}10^{-6}$	$3.1\text{x}10^{-2}$	$3.8\text{x}10^{-3}$	water	atmos.	15.5	41.8	12
Sand, fine (Lab tests-vertical)	164	$4.7\text{x}10^{-6}$	$4.6\text{x}10^{-2}$	$4.4\text{x}10^{-3}$	water	atmos.	15.5	43	4
Sand, central CA (Lab tests-horizontal)	16	$1.9\text{x}10^{-5}$	$1.6\text{x}10^{-2}$	$4.6\text{x}10^{-3}$	water	atmos.	15.5	41.8	12
Sand, eolian (Lab tests)	3	$1.0\text{x}10^{-3}$	$3.0\text{x}10^{-2}$	$1.4\text{x}10^{-2}$	water	atm	15.5	43.0	4
Sand, medium (Lab tests-vertical)	112	$4.7\text{x}10^{-5}$	$9.0\text{x}10^{-2}$	$1.6\text{x}10^{-2}$	water	atmos.	15.5	39	4
Sand, Eocene,Jackson purchase region, KY (Lab tests-vertical outcrop samples)	5	$7.6\text{x}10^{-3}$	$3.3\text{x}10^{-2}$	$1.7\text{x}10^{-2}$	water	NS	15.5	42.2	3
Sand, 80-100 mesh (Lab test)	1			$2.3\text{x}10^{-2}$	water&air	NS	NS	NS	13

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditons are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Sand, silty, Ogallala Fm., High Plains-TX & NM (Field pumping tests)	135			2.3×10^{-2}	water	in-situ	in-situ	15	20
Sand, eolian (Lab tests-vertical)	6	1.0×10^{-3}	7.1×10^{-2}	2.4×10^{-2}	water	atmos.	15.5	45	4
Sand, coarse (Lab tests-vertical)	20	8.5×10^{-4}	9.0×10^{-2}	3.2×10^{-2}	water	atmos.	15.5	39	4
Sand, well sorted, Humboldt R., Winnemuca, NV (Lab tests)	4	2.4×10^{-4}	6.6×10^{-2}	3.9×10^{-2}	water	atm	15.5	41.1	9
Sand, Eocene, Jackson purchase region, KY (Lab tests-horizontal outcrop samples)	5	2.5×10^{-3}	4.7×10^{-2}	4.6×10^{-2}	water	NS	15.5	43.2	3
Sand, 40-45 mesh (Lab test)	1			1.3×10^{-1}	water&air	NS	NS	NS	13
Silt, central CA (Lab test-vertical)	1			9.4×10^{-8}	water	atmos.	15.5	51.3	12
Silt, clayey, central CA (Lab tests-horizontal)	43	9.4×10^{-9}	9.4×10^{-6}	2.5×10^{-7}	water	atmos.	15.5	41.8	12
Silt, clayey, central CA (Lab tests-vertical)	61	4.7×10^{-9}	9.4×10^{-6}	4.3×10^{-7}	water	atmos.	15.5	41.8	12

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditons are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Silt, sandy clayey aquitard, Oxnard basin, CA (Field pumping tests)	3			$6.3x10^{-6}$	in-situ	in-situ	in-situ	NS	22
Silt, sandy, central CA (Lab tests-vertical)	30	$2.8x10^{-8}$	$2.4x10^{-5}$	$7.1x10^{-6}$	water	atmos.	15.5	40.9	12
Silt (Lab tests-vertical)	39	$9.4x10^{-9}$	$7.1x10^{-4}$	$2.8x10^{-5}$	water	atmos.	15.5	46	4
Silt, sandy, central CA (Lab tests-horizontal)	14	$2.4x10^{-7}$	$4.7x10^{-4}$	$4.0x10^{-5}$	water	atmos.	15.5	NS	12
Silt, clayey (Lab tests-vertical)	2	$9.4x10^{-6}$	$9.4x10^{-5}$	$5.2x10^{-5}$	water	atmos.	15.5	43.3	4
Silt (Lab tests-horizontal)	39	$1.9x10^{-8}$	$1.1x10^{-3}$	$9.4x10^{-5}$	water	atmos.	15.5	46	4
Silt, sandy well sorted, Humboldt R., Winnemuca, NV (Lab test)	3	$1.9x10^{-7}$	$1.4x10^{-4}$	$1.1x10^{-4}$	water	atmos.	15.5	47.7	9
Soil, weathered granite, grade V eng soil (Lab tests-values vary with void ratio)	NS	$5.x10^{-7}$	$3.x10^{-3}$		NS	NS	NS	NS	2

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditons are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Soil, weathered granodiorite, grade V eng soil (Consolidation test results)	NS	$3.2\text{x}10^{-7}$	$5.6\text{x}10^{-7}$		NS	NS	NS	NS	2
Soil, gneiss, grade V eng. soil (Field & lab tests)	NS	$1.\text{x}10^{-7}$	$1.\text{x}10^{-6}$		NS	NS	NS	NS	2
Soil, weathered granite, grade VI residual soil (Lab tests-values vary with void ratio)	NS	$5.\text{x}10^{-7}$	$2.\text{x}10^{-4}$		NS	NS	NS	NS	2
Soil, gneiss grade V eng soil (Parallel to foliation)	NS	$2.\text{x}10^{-5}$	$5.\text{x}10^{-4}$		NS	NS	NS	NS	2
Soil, gneiss grade V eng soil (Perpendicular to foliation)	NS	$1.\text{x}10^{-5}$	$2.\text{x}10^{-4}$		NS	NS	NS	NS	2
Soil, weathered granite, grade VI residual soil (Lab tests)	NS	$2.1\text{x}10^{-5}$	$4.2\text{x}10^{-4}$		NS	NS	NS	NS	2
Soil, weathered black seams in gneiss, grade VI residual soil (Falling tests perpendicular to seams)	NS	$1.\text{x}10^{-4}$	$2.\text{x}10^{-4}$		NS	NS	NS	NS	2

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditons are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Soil, weathered granite, grade V eng soil (Lab tests)	NS	$2.1x10^{-3}$	$42.x10^{0}$		NS	NS	NS	NS	2
Soil, weathered granodiorite, grade V eng soil (Falling head tests)	NS			$8.9x10^{-6}$	water	NS	NS	NS	2
Soil, quartz diorite, grade V eng. soil (Field & lab tests)	NS	$1.x10^{-5}$	$3.x10^{-4}$	$1.x10^{-5}$	NS	NS	NS	NS	2
Till, clayey (Lab tests-vertical)	7	$3.8x10^{-9}$	$4.2x10^{-7}$	$9.4x10^{-8}$	water	atmos.	15.5	NS	4
Till, silty (Lab tests-vertical)	12	$1.4x10^{-8}$	$1.9x10^{-5}$	$2.8x10^{-6}$	water	atmos.	15.5	34	4
Till, east central SD (Lab tests)	10	$9.4x10^{-9}$	$2.4x10^{-5}$	$3.5x10^{-6}$	water	NS	NS	NS	24
Till, silty-clayey, Hand Cy, SD (Lab tests-vertical)	2	$3.8x10^{-6}$	$4.7x10^{-6}$	$4.2x10^{-6}$	water	atmos.	15.5	36.8	4
Till, Montgomery Cy., OH (Field pumping tests)	5	$1.4x10^{-6}$	$2.3x10^{-5}$	$4.6x10^{-6}$	water	in-situ	in-situ	NS	24
Till, northeastern OH (Lab tests)	16	$3.8x10^{-8}$	$4.2x10^{-5}$	$7.0x10^{-6}$	water	NS	NS	NS	24

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditons are kPa, NS = Not specified).

Sample Description (Comments)	# of Samples	Min	Max	Mean	Permeant	Loading Conditions	Testing Temp (C)	Porosity	Ref.
Till, southern IL (Field pumping tests)	6	$3.8\text{x}10^{-6}$	$2.8\text{x}10^{-5}$	$1.1\text{x}10^{-5}$	water	in-situ	in-situ	NS	24
Till, clayey, "washed drift" (Lab tests-vertical)	5	$4.7\text{x}10^{-5}$	$5.7\text{x}10^{-4}$	$2.3\text{x}10^{-4}$	water	atmos.	15.5	49	4
Till, sandy drift, central Canada (Lab tests)	26	$4.3\text{x}10^{-4}$	$1.8\text{x}10^{-3}$	$8.2\text{x}10^{-4}$	water	NS	NS	NS	23
Till, sandy (Lab tests-vertical)	10	$2.8\text{x}10^{-6}$	$1.0\text{x}10^{-2}$	$1.1\text{x}10^{-3}$	water	atmos.	15.5	31	4
Till, coarse (Lab tests-vertical)	2	$9.4\text{x}10^{-5}$	$4.6\text{x}10^{-3}$	$2.3\text{x}10^{-3}$	water	atmos.	15.5	28.4	4
Till, silty, "washed drift" (Lab tests-vertical)	27	$1.1\text{x}10^{-3}$	$6.6\text{x}10^{-2}$	$1.6\text{x}10^{-2}$	water	atmos.	15.5	44	4

Table 4.3.7. Permeabilities of Unconsolidated Sedimentary Rocks (cm/sec). (Porosities are averages, loading conditions are kPa, NS = Not specified)

References for Table 4.3.7.

1. Mitchell, 1969;
2. Dearman et. al., 1978;
3. MacCary and Lambert, 1962;
4. Morris and Johnson, 1967;
5. Gallaher, 1964;
6. Wolff, 1970;
7. Wolff and Papadopulos, 1972;
8. Olsen, 1966;
9. Cohen, 1965;
10. Tanaka and Hallowell, 1966
11. Brown and Newcomb, 1963;
12. Johnson et. al., 1968;
13. Wyckoff et. al., 1934;
14. Pryor, 1973;
15. Coplen and Hanshaw, 1973;
16. Morrow et. al., 1969;
17. Boelter, 1965;
18. Hanrahan, 1954;
19. Sturges, 1968;
20. Brutsaert et. al., 1975;
21. Helm, 1976;
22. Neuman and Witherspoon, 1972;
23. Cherry et. al., 1973;
24. Norris, 1962;
25. Neglia, 1979;

Table 4.3.8. Permeability Conversion factors-

ratios of common permeability units

relative to cm/sec used in tables 4.3.1-4.3.7

(example: to convert a value in the tables from cm/sec to cm^2 divide by 9.804×10^4)

$9.804 \text{ X } 10^4$ $(cm/sec)/cm^2$ *

$9.109 \text{ X } 10^7$ $(cm/sec)/ft^2$ *

$9.66 \text{ X } 10^{-4}$ (cm/sec)/Darcy*

$9.66 \text{ X } 10^{-7}$ (cm/sec)/millidarcy*

30.48 (cm/sec)/(ft/sec)

$4.72 \text{ X } 10^{-5}$ $(cm/sec)/(gpd/ft^2)$**

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* for water at 20°C

** for water at 60°F = Meinzer unit.

(gpd = U.S. gallons per day)

4.4 DISTRIBUTION COEFFICIENTS

4.41 General Comments

As mentioned in section 4.1, for predicting (modeling) the compositional variation of a liquid in a porous medium in time and space, it is necessary to consider chemical reactions which are sources and sinks of chemical constitutents. Sorption-desorption type reactions are common in natural materials; these can be characterized by the use of distribution coefficients.

4.42 Historical Aspects

The property of natural "rock" materials to sorb -- to permanently sequester or delay movement of aqueous species -- has been of interest to a range of scientific disciplines for many years, starting with Way's (1850) classical paper. Since that time much effort has been concentrated on: 1) evaluation of the ion exchange properties of natural materials, 2) the factors influencing ion exchange, and 3) the best methods to characterize these reactions. As environmental concerns about waste disposal have estalated, the characterization of sorption properties under natural (in-situ) conditions has become of increasing importance. Recognizing that laboratory determinations suffer from all of the difficulties of transferability to the field discussed earlier, a whole new area of research is foreseen for the hydrologist and soil scientists.

4.43 General Definition and Discussion

The most commonly used quantitative expression for the sorption of ions on to or off of the skeletal framework of the porous media is the distribution coefficient, K_d. The distribution coefficient is defined (after Wood, 1978, p. 27) as:

$$K_d = \frac{\bar{c}}{c} \qquad 4)$$

where:

K_d = distribution coefficient (L^3/M)

$\bar{c}$ = concentration of ions sorbed on skeletal framework (M/M)

c = concentration of ions in solution (M/L^3).

The units for K_d (equation 4) are volume/mass. $K_d(L^3/M)$, x ρ_s (M/L^3), where ρ_s is density of the skeletal framework, results in a dimensionless form. In table 4.4.1, the values from Robertson (1974 and 1977) are dimensionless whereas those of Meani and others (1978) have unspecified dimensions, but are assumed dimensionless.

K_d must be empirically determined over the range of concentration of interest to the investigator. "Standardization" of the methodology for laboratory determinations of K_d's is still in the state of evolution. Relyea and Serne, 1979, reporting on their "controlled sample program" found that even though uniform samples were sent to several laboratories for K_d determinations using specified standardized methodology and materials, results varied over three orders of magnitude. Progress is being made in identifying the factors requiring careful control (Means and others, 1978; Apps and others, 1977). Once these factors are standarized, it should be possible to compare results for different rock materials, ions, etc.

Because of the obvious questions remaining regarding laboratory determined values, only values measured in the field, all of which are for saturated conditions are reported in Table 4.4.1. These values have been determined under conditions which integrate the in-situ factors affecting flow and transport of the chemical species of interest. This integration may include phenomena not "normally" considered in laboratory sorption experiments; however, until characterization of the medium being considered for waste isolation evolves to the degree where quantification is complete, values determined by field testing and/or regional modeling may be the most meaningful. However, as shown, the number of "field" determinations is very small.

The primary function to be served by this compilation is to highlight the need for more data both from field experiments, and/or from modeling studies involving enough field derived data for calibration of the model.

Ames and Rai, 1978, have summarized most of the data available on K_d's for radionuclides. They have also made assessments of the factors apparently affecting laboratory determinations for these same isotopes.

Table 4.4.1. Distribution coefficients from field tests and simulation models using field data. n = porosity in percent).

Rock Type	Isotope	K_d	n	Methodology	Ref.
Basalt Snake River Plain aquifer, ID	Strontium-90	3.0	10	Calibrated regional digital model results	1
Basalt Snake River Plain, ID	Strontium-90	15.0	10	Calibrated regional digital model results	2
Basalt Snake River Plain, ID	Strontium-90	5.	10	Calibrated regional digital model results	2
Basalt Snake River Plain, ID	Tritium	0	10-40	Calibrated regional digital model results	2
Sediments Snake River Plain, ID	Strontium-90	100	30-45	Calibrated regional digital model results	2
Shale Conasauga Fm., Oak Ridge, TN	Cobalt-60	65.3	NS	Field determinations - well samples	3
Shale Conasauga Fm., Oak Ridge, TN	Cobalt-60	32.6	NS	Field determinations-well samples	3
Shale Conasauga Fm., Oak Ridge, TN	Cobalt-60	52.3	NS	Field determinations-well samples	3
Shale Conasauga Fm., Oak Ridge, TN	Cobalt-60	30.0	NS	Field determinations-well samples	3
Shale Conasauga Fm., Oak Ridge, TN	Cobalt-60	29.1	NS	Field determinations-well samples	3
Shale Conasauga Fm., Oak Ridge, TN	Cobalt-60	6.1	NS	Field determinations-well samples	3

Table 4.4.1. Distribution coefficients from field tests and simulation models using field data. (n = porosity in percent)

References for Table 4.4.1.

1. Robertson, 1974;
2. Robertson, 1977;
3. Means and others, 1978;

4.5 DISPERSIVITY

4.51 General Definitions

Factors affecting the concentration and movement of solutes (transport) in porous media include advection, dispersion, and chemical reactions (sec. 4.4). The transport of solutes associated with liquid which is moving in response to potential differences, Darcy flow, is referred to as advection. (Convection, although more properly reserved for flow resulting from thermal differences, has been used synonymously.) The process of advection would result in the movement of solutes at an average rate equal to the average linear velocity of the transporting liquid. However, there is a tendency for the solute to spread out from what would be predicted on the basis of pure advection. This spreading phenomenon is called hydrodynamic dispersion. Dispersion is a phenomenon which results from the mixing of fluids of differing compositon. It produces dilution of solutes in the zone of mixing. Dispersion includes the effects of molecular diffusion, usually neglected except at low advection rates, and the mixing resulting from velocity differences affected by microscopic and macroscopic variations in porous media. Dispersion resulting from variations in velocity is referred to as mechanical or hydraulic dispersion. Dispersion has directional properties; spreading of solute in the direction of flow is referred to as longitudinal disperson, spreading perpendicular to the direction flow lines as transverse dispersion.

Assuming steady state conditions, saturation, nonreactive solutes; the longitudinal coefficient of hydrodynamic dispersion can be expressed as:

$$D_\ell = \alpha\bar{v} + D^* \qquad (5)$$

:

D_ℓ = coefficient of longitudinal dispersion along flow path (L^2/T)

α = dispersivity, property of the porous medium (L)

$\bar{v}$ = average linear velocity of liquid (L/T)

D^* = coefficient of molecular diffusion (L^2T)

The considerations necessary to transform equation 5 into more than one dimension or to coordinate systems other than the one dimension assumed here, are beyond the scope of this chapter, for a clear discussion see Freeze and Cherry (1979, p. 549).

The coefficient of dispersion is ultimately of importance in the analysis of transport.

$$\text{Transport by dispersion} = n\, D_\ell \frac{\partial c}{\partial \ell} \qquad (6)$$

where

n = porosity

D_ℓ = longitudinal coefficient of dispersion

$\frac{\partial c}{\partial \ell}$ = longitudinal concentration gradient

It should be noted that the dispersive component of transport, equation 6, is of the form of Fick's first law, which is applicable to diffusion.

4.52 Discussion

As defined by equation 5, dispersivity the topic of this section is a "constant" which characterizes the spreading or dispersion attributable to the medium being considered. It has been shown that values of dispersivity vary depending on the scale at which they are measured. Laboratory determinations range from 10^{-2} to 1 cm, while field values range from 10 to 100 m, (Anderson, 1979). Because dispersivity is an indirect measure of the homogeneity of the sample tested, the larger the sample the more representative the result. For this reason and because of the growing tendency to utilize the solid earth for disposal of a variety of materials including long-lived nuclear wastes, it was decided to report only dispersivity values from: 1) field tests and 2) field investigation of chemical transport in which dispersivities were determined, usually through model analysis. The latter results from the calibration of areal numerical models which may include other factors too involved for discussion here, thus these values should be viewed as "apparent dispersivities".

Anderson (1979) presents an excellent review of simulation modeling of contaminants in ground water flow systems involving dispersion. The dispersivity values reported in tables 4.5.1 and 4.5.2 are adapted from this paper.

Table 4.5.1. Field Determined Dispersivities (After Anderson, 1979).

Rock Type	Long.	Trans.	Unspec.	n(%)	dist. (m)	Method
Alluvium, Chalk River Ontario			.034-1			Single-well test-plane of high velocity
Alluvium, Chalk River, Ontario			0.1		NS	Two-well test-plane of high velocity
Alluvium, Chalk River, Ontario			0.5		NS	Two-well test-full aquifer
Alluvium, Barstow, CA			15.2	40	6.4	Two-well test
Alluvium, Tucson, AZ			15.2	38	79.2	Two-well test
Alluvium, Lyons, France Area	0.10-0.50			NS		Single-well test-stratum scale
Alluvium, Lyons, France Area	12.0	3.1-14.0				Single-well test with resistivity
Alluvium, Lyons, France Area	5.0					Single-well test-full aquifer
Alluvium, Lyons, France Area	5.0	0.14-14.5				Single-well test with resistivity
Alluvium, Lyons, France Area	7.0	0.009-1.0				Single-well test with resistivity
Alluvium, Lyons, France Area	8.0	0.015-1.0				Single-well test with resistivity
Chalk, Dorset, England			1.0	2.3	8	Two-well test
Chalk, Dorset, England (fractured)			3.1	0.5	8	Two-well test
Dolomite, Carlsbad, NM (fractured)			38.1	12	16.8	Two-well test
Schist-gneiss, Savannah River Plant, SC (fractured)			134	.08	538	Two-well test

Table 4.5.2. Regional Dispersivities Based on Simulation Model Results (after Anderson, 1979).

Rock Type	Long.	T/L	n(%)	Model Type	Nodal Spacing (m)
Alluvium, Alsace, France	15	0.067	NS	Profile	NS
Alluvium, Alsace, France	15	0.067	NS	Profile	NS
Alluvium, Sutter Basin, CA	80-200	0.1	5-20	3-D	Variable
Alluvium, Sutter Basin, CA	80-200	0.1	5-20	3-D	Variable
Alluvium, CA	30.5	0.3	NS	Areal	305
Alluvium, CO	30.5	0.3	20	Areal	660 X 1320
Alluvium, CA	30.5	0.3	NS	Areal	305
Alluvium, CO	30.5	0.3	20	Areal	660X1320
Alluvium, Barstow, CA	61	0.3	40	Areal	305
Alluvium, Barstow, CA	61	0.3	40	Areal	305
Alluvium, Lyons, France	12	0.33	20	Areal	NS
Alluvium, Lyons, France	12	0.33	20	Areal	NS
Alluvium, Rocky Mtn., Arsenal, CO	30.5	1.0	30	Areal	305
Alluvium, Rocky Mtn. Arsenal, CO	30.5	1.0	30	Areal	305
Alluvium, Barstow, CA	61	1/330	40	Profile	3 X 152
Alluvium, Barstow, CA	61	1/330	40	Profile	3X152
Basalt, Hanford site, WA (fractured)	30.5	0.6	NS	Areal	NS

Table 4.5.2. Regional Dispersivities Based on Simulation Model Results (after Anderson, 1979).

Rock Type	Long.	T/L	n(%)	Model Type	Nodal Spacing (m)
Basalt, Hanford site, WA (fractured)	30.5	0.6	NS	Areal	NS
Basalt, ID (fractured)	91	1.0	10	Areal	640
Basalt, ID(fractured)	91	1.0	10	Areal	640
Basalt, ID (fractured)	91	1.5	10	Areal	640
Basalt, ID (fractured)	91	1.5	10	Areal	640
Glacial deposits, Long Island, NY	21.3	0.2	35	Areal	Variable
Glacial deposits, Long Island, NY	21.3	0.2	35	Areal	Variable
Limestone, Brunswick, GA	61	0.3	35	Areal	Variable
Limestone, Brunswick, GA	61	0.3	35	Areal	Variable

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