DATA FROM LABORATORY DISSOLUTION

EXPERIMENTS USING A WELDED TUFF FROM

SNOWSHOE MOUNTAIN NEAR CREEDE, COLORADO

By Michael M. Reddy and Marilyn G. Werner

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CONVERSION FACTORS

The metric units used in this report may be converted to inch-pound units by use of the following conversion factors:

Multiply metric units	By	To obtain inch-pound units
kilogram (kg)	2.205	pound, avoirdupois
micrometer (μm)	0.00003937	inch
millimeter (mm)	0.03937	inch

The following terms and abbreviations also are used in this report:
second (s)
revolutions per minute (r/min)

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ABSTRACT

Data from controlled laboratory rock-dissolution experiments are presented. Material used in these experiments consisted of two size fractions of ground welded tuff from Snowshoe Mountain near Creede, Colorado, and two size fractions of a reactive-mineral component of the welded tuff, an augite. Dissolution experiments were performed under acidic conditions with pH ranging from 1 to about 6.7. Several experimental configurations were used to obtain data for evaluating the effect of rock dispersion in the reacting solution on the dissolution-reaction kinetics.

INTRODUCTION

Recent geochemical research has focused on the interaction of precipitation and recharge water with subsurface rock (Paces, 1985). Characterization of rock-water interactions assists in describing many geochemical processes, including: (1) Acid rain-soil interactions; (2) radionuclide migration; (3) toxic-substance movement in the subsurface; and (4) ground-water quality genesis. However, a lack of understanding of kinetic processes involved in rock-water interaction currently (1987) is hampering progress in these areas.

Kinetic descriptions of silicate-rock and mineral dissolution are not well understood (Holdren and Adams, 1982). Numerous investigators have examined pure-mineral dissolution in aqueous solution with conflicting results. Several studies indicate that the rate-determining step is a surface-controlled reaction; that is, the reaction rate is controlled by removing mineralogic units directly from the grain surface. Other investigators report that the reaction rate is regulated by the rate of dissolved mineral species diffusing through a film attached to the mineral surface.

Holdren and Adams (1982) point out that mineral dissolution generally is governed by a parabolic rate law, implying a diffusion-process, rate-limiting step. However, the parabolic rate law also is consistent with a reaction mechanism involving precipitation of secondary aluminosilicates with variable composition during a dissolution reaction. These aluminosilicates are commonly amorphous, or crypocrystalline intermediate phases. The uncertainty of reaction-product phases and their thermodynamic stability is a complication in understanding processes that occur during mineral dissolution. In addition, the effect of reaction surface area on rock-dissolution processes is an area of much uncertainty. Mineral-surface composition during dissolution, the kinetic effect of precipated phases at the interface and the mechanistic rate determining step are current (1987) subjects of research.

PURPOSE

Understanding of the effect of rock-water interactions on natural-water composition requires a systematic integration of laboratory and field investigations. The purpose of this report is to present the data from laboratory experiments that will assist in identifying processes regulating ion release and subsequent reaction during rock weathering. Data from the laboratory dissolution experiments will be used with field data (Claassen and others, 1983) in subsequent studies designed to determine the relation between surface-water chemical composition and rock-water interaction in watersheds on Snowshoe Mountain near Creede, Colorado.

SCOPE

In this report, data from laboratory dissolution experiments using a single rock type and a reactive-mineral component of that rock type are presented. The rock used in these experiments, a welded tuff, is from the site of a long-term hydrologic study in the San Juan Mountains of southwestern Colorado. The reactive component of the welded tuff selected for study is an augite.

WELDED-TUFF DISSOLUTION EXPERIMENTS

Previous investigations of inorganic heterogeneous reactions in aqueous solution have demonstrated the importance of maintaining a constant solution composition when attempting to characterize mineral dissolution (Reddy, 1983). Solution variables that may have a profound effect on the rock and mineral dissolution include, but are not limited to,: (1) Ionic strength; (2) pH; (3) redox potential; (4) presence of complexation agents; (5) solid-to-solution ratio; (6) the extent of reaction needed to reach equilibrium; and (7) the presence of trace-reaction inhibitors. In addition to these solution variables that may affect the dissolution process, several characteristics of the rock or mineral may affect the heterogeneous reaction kinetics including: (1) Presence of ultrafine rock and mineral particulates on the surface of, and mixed with, the dissolving material; (2) presence of damaged surfaces on the dissolving material; and (3) formation of secondary phases on the surface of the dissolving rock or mineral.

In order to minimize the effect and interaction of the solution and rock variables listed above, dissolution reactions were conducted using solutions that controlled or kept constant many of the regulating variables (Holdren and Adams, 1982, and references therein). The experimental data, thus, consist of measured values of elemental release from the rock surface under well-defined and reproducible experimental conditions. Three different series of experiments were performed with the aim of isolating the effect of a specific reaction variable on the elemental removal processes from the rock surface. The three factors examined were: (1) Solution pH; (2) solution ionic strength and composition; and (3) solid-to-solution ratio.

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Both the first and second series of experiments were conducted in a well-stirred, thermostated batch reactor (See Reddy, 1983 for a discussion of this technique). The first series of experiments (experiments PD-1 through PD-4) involved dissolution of tuff in dilute solutions of hydrochloric acid; solution pH was 1 and 2 in these experiments.

The second series of experiments (experiments B1-B8) included tuff dissolution (experiments B1-B3 and B5-B7) in dilute solutions of potassium bicarbonate saturated with carbon dioxide; solution pH values ranged from about 4.9 to about 6.7 in these experiments. In addition to tuff dissolution, two experiments (experiments B4 and B8) were conducted using a pure mineral, augite, which is a reactive-mineral component of the tuff; solution pH values ranged from about 5.1 to about 5.8 for these experiments. Solution pH was monitored with a glass combination electrode immersed in the reacting solution during part or all of the experiments. Solution pH values were recorded on a strip-chart recorder when monitored continuously during the initial phase of the experiments. Solution pH was measured manually when a sample was removed after the initial phase. Solution alkalinity values, reported as bicarbonate, were determined by titration for all samples.

A third series of experiments (experiments AD10-AD15), performed in dilute potassium bicarbonate solution saturated with carbon dioxide, did not completely disperse the tuff sample within the volume of the reacting solution. The reacting solution circulated through a bed of reacting rock; this procedure minimized mechanical damage by grain collision.

Solution pH values measured in the third series of experiments are not believed to accurately reflect complete saturation of the solution by carbon dioxide. This situation resulted from solution loss of carbon dioxide during the pH measurement. Solution pH was monitored during the course of the experiments each time a sample was collected. These measurements indicate that for all sampling times equal to or less than 21,600 s the solution pH was in the range of 6.0 to 6.5.

Analytical reagent-grade chemicals, doubly distilled and deionized water and class A glassware were used throughout the study unless otherwise noted. Either hydrochloric acid or potassium bicarbonate (Baker Reagent Lot #720384)[1] was the background electrolyte in all experiments. Hydrochloric-acid solutions were at the ambient carbon-dioxide pressure; potassium bicarbonate solutions were bubbled with water-saturated carbon dioxide. A Metrohm Model 605 pH meter with an Metrohm combination electrode (AG9100) was used to monitor pH of the potassium bicarbonate solutions. Solution alkalinity values were determined by potentiometric titration.

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[1] Any use of trade names is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

Several dissolution experiments were performed using a Model DS500S Automated Dissolution Module (manufactured by Applied Analytical Laboratories Inc.) that allowed adjustment of the effective solid-to-solution ratio. Multiple dissolution experiments were conducted simultaneously at the same solution temperature and stirring rate. Water-saturated pure carbon dioxide was bubbled into each solution.

Preparation of Reaction Material

Several blocks (10 to 20 kg each) of welded tuff were collected from a talus slope on the north face of Snowshoe Mountain (37° 45´ N latitude, 106° 55´ W longitude) near Creede in southwestern Colorado (Ratte´ and Steven, 1964). These blocks were ground and sieved to yield two grain-size fractions used in the dissolution experiments; a fraction that passed an 18-mesh sieve but was retained on a 50-mesh sieve (hereafter referred to as 1 to 0.3 mm in diameter) and one fraction that passed a 70-mesh sieve (hereafter referred to as less than 0.212 mm in diameter). The larger size fraction was washed briefly with distilled water to remove dust introduced by grinding. This brief wash did not remove particles attached to the grain surface (see Holdren and Adams, 1982, and references therein). Augite (samples from Harcourt Township, Ontario, Canada, and purchased from Ward Scientific Co., Rochester, New York) used for dissolution experiments was prepared in the same manner as the tuff samples.

Scanning-electron and polarized-light microscopy of the ground tuff indicated that the grains of the coarse-size fraction were composed of aggregates of the minerals comprising the tuff: quartz, feldspar, biotite, and augite (Ratte´ and Steven, 1964). These mineral grains were bonded together by a crystalline matrix. Fracture of the tuff during grinding occurred chiefly along grain boundaries. The surface of each reacting-rock grain exposed to the solution during dissolution consisted of mineral grains and matrix.

Preparation of Solutions

Hydrochloric acid solutions were prepared by dilution of certified hydrochloric acid (Fisher Scientific Company).

Potassium bicarbonate solutions were prepared by dissolving a weighed aliquot of reagent-grade potassium bicarbonate in distilled water. Prior to the start of each experiment, solutions were transferred to the thermostated reaction vessel and equilibrated with water-saturated carbon dioxide. Water-saturated carbon dioxide was bubbled continuously through this solution during the experiment.

Experimental Procedures

A typical rock or mineral dissolution experiment was begun by inoculating the solution with a known weight of ground tuff. Experiments conducted in the jacketed reaction flask were stirred rapidly enough (150 r/min) to disperse tuff throughout the cell volume.

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Solution pH, alkalinity, and chemical composition of the starting solution were determined before the start of each experiment, using procedures of Fishman and Freidman (1985). Ionic-species concentrations obtained from these initial analyses were in agreement with ionic-species concentrations anticipated from the composition of the component solutions.

Ionic-species concentrations in aliquots removed from the reaction vessel at various times and filtered through a Whatman filter (0.1-μm pore-size, WCN Type) were determined by inductively coupled plasma/atomic-emission spectroscopy (Fishman and Friedman, 1985). Samples from the automated dissolution apparatus were filtered with an in-line, 10-μm pore-size filter (polyethylene DF-510P). Because the solid was not dispersed in the reacting solution in these experiments, this filtration procedure was considered appropriate.

Solution alkalinity was determined by titration of the filtrate with 0.01 normal sulfuric acid to the appropriate end point (pH of 4.55). Electrodes were standardized before and after each measurement with standard buffer solutions at pH 4.00, 7.00, and 9.00. Concentrations of metal ions in the starting solution (before addition of the ground tuff) were commonly at or less than the detection limit for the analytical procedure used.

As discussed previously, tuff samples used in the automated-dissolution-apparatus experiments were not fully dispersed in the available solution volume and mechanical damage to the grains was minimized. In these experiments, effective solid-to-solution ratios were decreased to values less than those of well-stirred experiments using one of two approaches. In the first approach, the solution was stirred with a large propeller that had rotational velocity insufficient to completely suspend the tuff. The tuff settled to the bottom of the reaction flask and the solution was stirred above it. In the second approach, the tuff was placed within a stainless-steel basket. This basket was rotated at the same velocity as a paddle that stirred the solution above the settled ground tuff.

DATA FROM WELDED-TUFF DISSOLUTION EXPERIMENTS

A summary of experimental conditions used in the dissolution experiments is given in table 1. Data from the welded-tuff dissolution experiments are given in tables 2 to 19.

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Table 1.--<u>Summary of experimental conditions</u>

[HCl, hydrochloric acid; KHCO$_3$, potassium bicarbonate; <, less than]

Experiment number	Particle diameter (millimeters)	Tuff concentration (grams per liter)	Temperature (degrees Celsius)	Background electrolyte	Background-electrolyte concentration (moles per liter)	Carbon-dioxide partial pressure (atmospheres)	Solution pH (units)
PD-1	1 to 0.3	10	20	HCl	0.1	0.0003	1.0
PD-2	1 to 0.3	10	20	HCl	.01	.0003	2.0
PD-3	<0.212	10	20	HCl	.1	.0003	1.0
PD-4	<0.212	10	20	HCl	.01	.0003	2.0
B1	1 to 0.3	10	5	KHCO$_3$	.001	.82	4.86
B2	<0.212	10	5	KHCO$_3$	.01	.82	5.73
B3	<0.212	10	5	KHCO$_3$	.1	.82	6.69
1/ B4	<0.212	10	5	KHCO$_3$	.01	.82	3/5.51
B5	<0.212	10	25	KHCO$_3$	.01	.80	5.70
B6	1 to 0.3	10	5	KHCO$_3$	.01	.82	5.72
B7	1 to 0.3	10	5	KHCO$_3$	.01	.82	5.70
1/ B8	1 to 0.3	10	5	KHCO$_3$	0.01	0.82	2/5.75
AD10	1 to 0.3	5	25	KHCO$_3$	.02	.80	4/6.4
AD11	1 to 0.3	5	25	KHCO$_3$	.02	.80	4/6.3
AD12	1 to 0.3	5	25	KHCO$_3$	.01	.80	4/6.2
AD13	1 to 0.3	5	25	KHCO$_3$	.01	.80	4/6.1
AD14	1 to 0.3	5	25	KHCO$_3$	.005	.80	4/6.2
AD15	1 to 0.3	5	25	KHCO$_3$	.005	.80	4/6.2

1/ Augite.

2/ Initial value at start of experiment.

3/ Value at 60 seconds.

4/ Approximate.

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Table 2.—Experiment PD-1

[Experiment conducted with welded tuff, 1 to 0.3 millimeter
diameter; at 20 degrees Celsius; in 0.1 molar hydrochloric-acid
solution; s, seconds; ---, data not available]

Sampling time (s)	Micromoles per liter					
	Calcium	Magnesium	Sodium	Potassium	Iron	Silica
0	0	0	0	0	0	0
60	122	21	26	15	11	31
4,200	559	67	36	36	41	66
7,620	655	89	43	47	51	86
10,800	710	118	43	63	64	107
82,320	896	632	74	78	292	457
170,520	933	740	78	95	367	752
496,320	960	923	142	142	522	1,545
579,120	989	979	190	187	----	----
665,520	945	794	194	175	----	----
752,820	1,026	1,036	227	229	667	2,055
1,097,520	1,097	1,164	317	205	810	2,746
1,098,000	1,079	1,147	606	286	784	2,708

Table 3.—Experiment PD-2

[Experiment conducted with rock of 1 to 0.3 millimeter diameter; at 20 degrees Celsius; in 0.01 molar hydrochloric acid solution; s, seconds; ---, data not available]

Sampling time (s)	Micromoles per liter					
	Calcium	Magnesium	Sodium	Potassium	Iron	Silica
0	0	0	0	0	0	0
60	81	17	20	12	8	6
4,200	358	83	221	72	0	150
7,200	448	85	34	60	37	177
10,800	466	58	15	34	22	32
14,400	495	64	16	37	23	38
83,700	670	165	25	54	43	120
432,900	969	638	61	107	100	535
514,800	1,002	733	71	116	106	622
892,100	1,119	840	120	128	128	774
687,600	1,238	956	154	153	148	920
774,600	2,297	2,115	250	80	315	2,126
776,400	2,227	1,960	347	304	---	---

Table 4.--Experiment PD-3

[Experiment conducted with welded tuff, less than 0.212 millimeter diameter, at 20 degrees Celsius; in 0.1 molar hydrochloric acid solution; s, seconds; ---, data not available]

Sampling time (s)	Micromoles per liter					
	Calcium	Magnesium	Sodium	Potassium	Iron	Silica
0	0	0	0	0	0	0
60	437	68	42	74	97	60
3,600	822	115	121	69	344	104
7,200	826	136	134	78	389	138
10,800	852	160	94	78	---	---
14,400	850	196	72	76	399	192
84,300	875	603	83	84	587	553
163,500	913	684	109	115	652	832
254,700	979	862	250	183	---	---
346,200	991	928	233	197	935	1,801
447,300	996	911	302	221	951	1,931
522,000	1,017	916	272	217	---	---
522,900	1,080	1,014	344	292	---	---

Table 5.—Experiment PD-4

[Experiment conducted with welded tuff, less than 0.212
millimeter diameter; at 20 degrees Celsius; in 0.01 molar
hydrochloric acid solution; s, seconds; ---, data not
available]

Sampling time (s)	Micromoles per liter					
	Calcium	Magnesium	Sodium	Potassium	Iron	Silica
0	0	0	0	0	0	0
60	298	54	24	61	---	---
3,600	314	41	47	50	---	---
7,200	721	90	58	60	---	---
10,800	716	89	110	60	---	---
14,400	816	103	40	57	323	67
90,000	868	155	48	65	331	128
169,740	891	248	46	71	312	195
520,440	1,015	513	116	98	402	454
607,740	1,073	587	127	108	---	---
713,340	1,173	661	134	108	---	---
787,740	1,215	722	127	119	---	---
792,000	3,186	2,362	346	371	1,589	---

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Table 6.—Experiment B1

[Experiment conducted with welded tuff, 1 to 0.3 millimeter diameter; at 5 degrees Celsius; in 0.001 molar potassium bicarbonate solution saturated with carbon dioxide; s, seconds]

Sampling time (s)	pH (units)	Calcium	Magnesium	Sodium	Iron	Bicarbonate ($\times 10^{-2}$)	Silica
			Micromoles per liter				
0	4.86	3	0	0	0	10	3
1,800	4.97	120	34	42	7	12	0
3,600	4.97	148	37	36	48	13	24
5,400	4.98	150	38	43	32	12	40
81,900	5.03	247	58	81	245	15	75
88,200	5.04	290	60	65	250	17	59

Table 7.—Experiment B2

[Experiment conducted with welded tuff, less than 0.212 millimeter diameter; at 5 degrees Celsius; in 0.01 molar potassium bicarbonate solution saturated with carbon dioxide; s, seconds]

Sampling time (s)	pH (units)	Calcium	Magnesium	Sodium	Iron	Bicarbonate ($\times 10^{-2}$)	Silica
			Micromoles per liter				
0	5.73	1	0	0	0	100	1
60	5.70	206	94	66	92	103	384
68,940	5.77	220	44	35	107	103	17
76,140	5.76	211	44	26	114	103	19
82,440	5.75	252	46	33	124	103	14
93,240	5.74	211	45	40	67	103	16
167,940	5.72	225	46	38	184	103	6
181,440	5.73	242	47	34	193	103	14
252,540	5.75	314	48	39	225	103	11
334,440	5.74	254	49	39	209	103	22
339,840	5.74	373	50	47	240	103	17
357,840	5.76	244	48	41	245	103	21
436,140	5.76	237	48	42	245	103	39

Table 8.—Experiment B3

[Experiment conducted with welded tuff, less than 0.212
millimeter diameter; at 5 degrees Celsius; in 0.1 molar
potassium bicarbonate solution saturated with carbon
dioxide; s, seconds; ---, data not available]

Sampling time (s)	pH (units)	Micromoles per liter					
		Calcium	Magnesium	Sodium	Iron	Bicarbonate ($\times 10^{-2}$)	Silica
0	6.69	4	1	---	1	1000	0
60	6.65	189	40	173	1	1000	0
3,180	6.59	84	44	165	8	1000	345
68,280	6.58	211	44	161	1	1000	0
86,280	[1] 8.75	126	43	68	1	1000	0
88,680	6.58	206	43	163	2	1000	5
150,180	6.56	207	43	171	6	1000	11
171,480	6.56	199	44	174	7	1000	20
238,080	6.56	205	43	177	1	930	14

[1] Carbon-dioxide flow through solution temporarily interrupted.

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Table 9.--Experiment B4

[Experiment conducted with augite, less than 0.212 millimeter
diameter; at 5 degrees Celsius; in 0.01 molar potassium
bicarbonate solution saturated with carbon dioxide; s, seconds]

Sampling time (s)	pH (units)	Micromoles per liter					
		Calcium	Magnesium	Sodium[1]	Iron	Bicarbonate $(\times 10^{-2})$	Silica
0	---	15	2	0	0	103	5
60	5.51	212	21	270	31	98	11
3,180	5.63	318	22	288	305	105	17
86,580	5.79	907	36	306	1364	104	105
148,380	5.83	495	56	300	997	105	192
243,780	5.84	476	30	296	743	102	121
329,880	5.84	395	29	282	59	93	89
412,080	5.71	604	31	271	331	94	122

[1] A value of 52 micromoles per liter, at time zero has been
subtracted from each value.

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Table 10.--Experiment B5

[Experiment conducted with welded tuff, less than 0.212
millimeter diameter; at 25 degrees Celsius; in 0.01 molar
potassium bicarbonate solution saturated with carbon
dioxides; s, seconds]

| Sampling time (s) | pH units | Micromoles per liter | | | | | |
		Calcium	Magnesium	Sodium	Iron	Bicarbonate ($\times 10^{-2}$)	Silica
0	5.70	3	1	0	0.4	104	0
60	5.70	107	26	0	3	96	0
20,700	5.73	200	43	15	218	100	12
82,500	5.83	274	53	13	367	105	34
179,100	5.84	260	58	41	386	106	71
264,300	[1]7.10	244	86	72	63	109	200
347,100	5.77	245	59	60	3	108	104
368,100	5.71	241	61	60	3	112	111
433,800	5.75	259	63	69	4	111	124
516,660	5.75	245	64	77	1	113	139
522,360	5.79	265	69	83	1	117	140
538,500	5.80	261	69	79	1	124	147

[1]/ Carbon-dioxide flow through solution temporarily interrupted.

Table 11.--Experiment B6

[Experiment conducted with rock of 1 to 0.3 millimeter diameter;
at 5 degrees Celsius; in 0.01 molar potassium bicarbonate solution
saturated with carbon dioxide; s, seconds]

| Sampling time (s) | pH (units) | Micromoles per liter | | | | | |
		Calcium	Magnesium	Sodium	Iron	Bicarbonate ($\times 10^{-2}$)	Silica
0	5.72	3	0	0	0	103	0
60	5.72	42	8	2	1	99	0
1,200	5.75	115	20	11	1	99	0
81,900	5.80	161	37	28	5	97	15
83,700	5.79	171	37	56	3	97	4
161,160	5.77	171	37	39	2	96	10
162,300	5.77	178	38	36	3	95	7

Table 12.—Experiment B7

[Experiment conducted with rock of 1 to 0.3 millimeter diameter;
at 5 degrees Celsius; in 0.01 molar potassium bicarbonate solution
saturated with carbon dioxide; s, seconds]

| Sampling time (s) | pH (units) | Micromoles per liter | | | | | |
		Calcium	Magnesium	Sodium	Iron	Bicarbonate $(X \ 10^{-2})$	Silica
0	5.70	5	3	0	0	100	5
60	5.75	33	10	0	1	99	0
3,720	5.76	27	28	0	2	99	0
9,300	5.76	151	33	2	2	100	12
12,900	5.77	148	32	4	2	99	0
16,440	5.77	150	33	7	2	99	0
79,200	5.76	158	35	8	3	95	4
82,800	5.76	164	36	20	3	94	6

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Table 13.--Experiment B8

[Experiment conducted with augite 1 to 0.3 millimeter diameter; at 5 degrees Celsius; in 0.01 molar potassium bicarbonate solution saturated with carbon dioxide; s, seconds]

Sampling time (s)	pH (units)	Micromoles per liter					
		Calcium	Magnesium	Sodium[1]	Iron	Bicarbonate (X 10^{-2})	Silica
0	5.75	1	1	0	0	100	0
60	5.75	18	5	85	0	98	0
4,260	5.76	45	9	112	2	101	5
7,620	5.76	54	8	119	3	99	0
11,220	5.77	64	9	119	3	100	0
72,420	5.76	130	15	129	11	100	0
75,720	5.76	134	15	131	8	99	0
86,820	5.77	140	16	136	10	101	4
157,920	5.76	171	22	134	11	97	11
169,620	5.77	174	23	136	10	96	13
180,420	5.77	181	25	140	19	96	9
590,820	5.68	252	49	124	17	86	43
605,220	5.69	253	49	127	18	85	46
851,820	5.73	260	58	125	24	83	67

[1] A value of 106 micromoles per liter, at time zero has been subtracted from each value.

Table 14.—Experiment AD10

[Experiment conducted with welded tuff, 1 to 0.3 millimeter
diameter; at 25 degreees Celsius; in 0.02 molar potassium
bicarbonate solution saturated with carbon dioxide. Solution
stirred over rock; s, seconds]

Sampling Time (s)	Microlmoles per liter			
	Calcium	Magnesium	Sodium[1]	Silica[2]
0	2	1	0	0
600	28	8	63	18
1,200	38	10	152	18
1,800	46	11	163	42
2,400	48	12	144	26
3,000	51	12	121	18
3,600	57	13	97	24
7,200	70	16	147	30
18,000	85	19	151	26
21,600	85	18	90	18
84,600	95	21	143	32

[1] A value of 119 micromoles per liter, at time zero has been
subtracted from each value.

[2] A value of 72 micromoles per liter, at time zero has been
subtracted from each value.

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Table 15.--Experiment AD11

[Experiment conducted with welded tuff, 1 to 0.3 millimeter diameter; at 25 degrees Celsius; in 0.02 molar potassium bicarbonate solution stirred with carbon dioxide. Rock moved through unstirred solution; s, seconds]

Sampling Time (s)	Micromoles per liter			
	Calcium	Magnesium	Sodium[1]	Silica[2]
0	2	0	0	0
600	16	4	31	6
1,800	33	9	108	17
3,600	44	11	26	14
7,200	60	15	117	7
18,000	80	18	83	3
21,600	81	18	37	11
84,600	98	21	277	16
86,400	95	20	46	38

[1] A value of 164 micromoles per liter, at time zero has been subtracted from each value.

[2] A value of 63 micromoles per liter, at time zero has been subtracted from each value.

Table 16.—Experiment AD12

[Experiment conducted with welded tuff, 1 to 0.3 millimeters
diameter; at 25 degrees Celsius; in 0.01 molar potassium
bicarbonate solution saturated with carbon dioxide. Solution
stirred over rock; s, seconds]

Sampling Time (s)	Micromoles per liter			
	Calcium	Magnesium	Sodium[1]	Silica[2]
0	1	0	0	0
600	23	6	25	17
1,800	37	9	105	25
3,600	46	11	13	23
7,200	57	14	103	0
18,000	73	17	91	0
21,600	72	16	28	17
84,600	89	20	89	0
86,400	87	20	58	0

[1] A value of 134 micromoles per liter, at time zero has been
subtracted from each value.

[2] A value of 87 micromoles per liter, at time zero has been
subtracted from each value.

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Table 17.—Experiment AD13

[Experiment conducted with welded tuff, 1 to 0.3 millimeters diameter; at 25 degrees Celsius; in 0.01 molar potassium bicarbonate solution saturated with carbon dioxide. Solution stirred over rock; s, seconds]

Sampling Time (s)	Micromoles per liter			
	Calcium	Magnesium	Sodium[1]	Silica[2]
0	5	0	0	0
600	13	3	0	0
1,800	22	6	77	8
3,600	32	8	29	0
7,200	46	12	97	0
18,000	64	16	93	7
21,600	64	15	30	0
84,600	85	19	107	19
86,400	83	18	33	16

[1] A value of 140 micromoles per liter, at time zero has been subtracted from each value.

[2] A value of 94 micromoles per liter, at time zero has been subtracted from each value.

Table 18.--Experiment AD14

[Experiment conducted with welded tuff, 1 to 0.3 millimeters diameter; at 25 degrees Celsius; in 0.005 molar potassium bicarbonate solution saturated with carbon dioxide. Solution stirred over rock; s, seconds]

Sampling Time (s)	Micromoles per liter			
	Calcium	Magnesium	Sodium[1]	Silica[2]
0	2	0	0	0
600	19	5	10	0
1,200	26	7	33	9
1,800	31	8	45	18
3,000	37	10	7	0
3,600	39	10	21	14
7,200	47	12	50	11
18,000	58	14	48	29
21,600	60	14	8	36
25,200	60	15	61	35
84,600	66	17	89	0
86,400	65	15	49	0

[1] A value of 122 micromoles per liter, at time zero has been subtracted from each value.

[2] A value of 53 micromoles per liter, at time zero has been subtracted from each value.

Table 19.—Experiment AD15

[Experiment conducted with welded tuff, 1 to 0.3 millimeters diameter; at 25 degrees Celsius; in 0.005 molar potassium bicarbonate solution saturated with carbon dioxide. Solution stirred over rock; s, seconds]

Sampling Time (s)	Micromoles per liter			
	Calcium	Magnesium	Sodium[1]	Silica[2]
0	2	0	0	0
600	15	3	6	12
1,200	13	4	28	0
1,800	21	5	43	0
3,000	22	6	39	11
3,600	23	6	31	7
7,200	33	9	44	4
18,000	48	13	64	0
21,600	51	13	21	0
25,200	54	14	57	1
84,600	73	17	75	0
86,400	75	17	70	0

[1] A value of 117 micromoles per liter, at time zero has been subtracted from each value.

[2] A value of 63 micromoles per liter, at time zero has been subtracted from each value.