A STUDY OF ROCK-WATER-NUCLEAR WASTE
INTERACTIONS IN THE PASCO BASIN, WASHINGTON

PART II

PRELIMINARY EQUILIBRIUM-STEP SIMULATIONS OF BASALT DIAGENESIS

L. V. Benson, C. L. Carnahan, and M. Che

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 92740

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INTRODUCTION

The migration of radionuclides leached from a nuclear waste repository occurs within an evolving hydrochemical system. The rate of migration of any chemical species is directly related to its residence time in the aqueous phase which in turn is governed by several interacting chemical processes including dissolution, precipitation, sorption and complexation. A prerequisite to study of the migration of introduced waste materials is understanding the chemical processes which have occurred in the undisturbed, natural system.

In this report are presented the results of simulations of chemical interaction between meteoric water and basalt. These simulations have been accomplished in order to gain insight into the chemical processes which have governed the diagenesis of basalts in the Pasco Basin of Washington state. The simulations were performed using Wolery's (1979) computer program EQ6.

THE EQ6 COMPUTER PROGRAM

The theoretical basis of the EQ6 program includes the assumption that chemical changes can be approximated by a series of equilibrium states; therefore, the only data required for a simulation are the free energies of formation of the aqueous and solid species of interest together with the relative rates of dissolution of "reactant" mineral species.

The principal disadvantage of the equilibrium-step model is that it ignores kinetic constraints on chemical reactions. For example, use of EQ6 assumes that fluid flow rates are sufficiently small so that equilibrium is achieved at each point along the hypothetical flow path. In practice, rates of mass transfer at any point due to precipitation and dissolution may depend on local fluid velocity.

Other disadvantages center around the lack of appropriate thermochemical data. Free energies and mixing models for mineral species which exhibit extensive solid solution (e.g., clays, zeolites) are generally not available. In addition, sorption data for chemical species and substrates common to the basaltic environment have yet to be included in the EQ6 data base.

In this report we attempt to test the usefulness of the equilibrium-step approach and, in addition, ascertain the conditions under which it may afford a good approximation to chemical processes common to the natural environment.

METEORIC WATER-BASALT INTERACTIONS IN THE PASCO BASIN

Assumptions

For the purposes of modeling, a number of assumptions were made which are simplifications of the real system. All simulations were done at 25°C and 1 bar even though ambient temperature and pressure at repository depth (~1000 m) are estimated to be 65°C and 100 bars. This assumption was made because the thermodynamic data are best known at 25°C; and the pressure and temperature dependencies of the mass transfer calculations were estimated to be relatively small over the given ranges of P and T. In addition, there are a number of assumptions regarding the Pasco Basin hydrochemical system implicit in the modeling effort.

- (1) The basalt host rock is assumed to be physically and chemically homogeneous; i.e., the bulk composition, phase assemblages, and phase proportions are assumed identical throughout the system. All basalts are assumed to possess identical values of porosity, permeability and tortuosity.
- (2) There is assumed to be an infinite reservoir of reactant phases.

- (3) There is assumed to be a simple relationship between depth and the extent of reaction, i.e., it is assumed that deep groundwaters have passed through and reacted with more basalt than shallow groundwaters.
- (4) Present-day groundwater is assumed to be in equilibrium with one or more of the secondary minerals observed lining vesicle and fracture surfaces.

Input Data

Mean compositions of the principal primary (reactant) and secondary (product) phases are shown in Table 1. The $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio for ground mass was set equal to that of mean bulk basalt, i.e., approximately 1.0/3.0 (Carmichael et al., 1974). The starting fluid composition was taken to be that of snowmelt (Table 6). The partial pressures of oxygen and carbon dioxide were set at 0.2 and 0.1 bars, respectively.

Since the free energies of formation of the smectite and clinoptilolite phases are unknown, it was necessary to approximate them. Various methods of approximation including those of Karpov and Kashik (1968), Tardy and Garrels (1974), Chen (1975), Nriagu (1975), and Mattigod and Sposito (1978) were examined. Unfortunately the methods often appear based on erroneous or arbitrary assumptions and have in certain cases been calibrated or tested against faulty thermodynamic data (see Appendix 1 for a more thorough discussion). We were therefore forced to treat the free energies of smectite and clinoptilolite as adjustable parameters. In order to provide an initial approximation of the smectite free energy, the method of Tardy and Garrels (1974) - corrected for the "sepiolite problem" discussed in Appendix 1 - was used to estimate the free energy of the smectite framework. In order to estimate the free energy of the exchange component, it was assumed that the free energy of exchange of the potassium oxide component in the exchange site

was identical to its "silicated" free energy in muscovite. It was also assumed that the free energies of exchange (on an equivalent basis) of potassium oxide, sodium oxide and calcium oxide were all equal. The total free energy of the Hanford smectite having a structural formula $(Ca_{.139}Na_{.456}K_{.149})(Si_{3.64}Al_{0.36})(Al_{.232}Fe^{3+}_{.717}Fe^{+2}_{.199}Mg_{1.115})O_{10}(OH)_2$ was calculated to be $-5190 \text{ kJ mole}^{-1}$ ($-1240 \text{ Kcal mole}^{-1}$).

For all other chemical species, the data of Helgeson et al. (1978) were used.

Simulation Strategies

Although EQ6 does not explicitly provide for the differing dissolution rates of the three reactant phases (feldspar, pyroxene, and groundmass) common to basalts of the Pasco Basin, they are implicitly accounted for by appropriate weighting of their proportions in the reactant assemblage. The relative rate of dissolution of each the reactant phases was treated as an adjustable parameter since both their surface areas and absolute rates of dissolution are unknown.

Minerals permitted to precipitate included those observed by Benson and Teague (1979), i.e., smectite, clinoptilolite and silica. Beta-cristobalite was used as the silica phase. Other potential precipitates (product phases) included magnetite, gibbsite, kaolinite and calcite. Magnetite was chosen to proxy for an unidentified iron oxide phase found intergrown with smectite by Benson and Teague (1979). Gibbsite and kaolinite were allowed as potential product phases because laboratory studies indicate that their rates of precipitation are relatively rapid (Busenberg, 1978; La Iglesia et al., 1974). It should be noted, however, that these phases were not observed in either the studies of Benson and Teague (1979) or Ames (1976). Calcite was

allowed as a potential product phase since it was found as a minor component of the secondary mineral assemblage in a few instances.

Computer runs were discontinued when an extent of reaction (Z) (moles of reactants added per kilogram of fluid phase) of 0.10 was reached because the simulated pH at this point often exceeded the highest recorded field pH by more than two units.

The strategy used in the simulations was to vary the ratios of the reactant phases and adjust the free energy of clinoptilolite in order to match the observed precipitation sequence. A free energy of formation of -5190 kJ mole⁻¹ was used for smectite and a free energy of formation of -35,150 kJ mole⁻¹ was used for clinoptilolite. The composition of the clinoptilolite, based on 72 oxygens and containing only tightly bound water is $\text{Si}_{29.84}\text{Al}_{6.34}\text{Fe}^{+3}_{.042}\text{Ca}_{.527}\text{Ba}_{.072}\text{Na}_{2.61}\text{K}_{1.68}\text{Mg}_{.013}\text{O}_{72} \cdot 9.44\text{H}_2\text{O}$. The success of any simulation was judged by comparing predicted groundwater compositions with observed groundwater compositions and also by comparing the relative amounts of predicted and observed secondary mineral phases.

RESULTS

The Effect of Reactant Ratio on the Sequence of Precipitation

Table 2 shows the results of five simulations in which reactant ratios were varied by factors of ten. The precipitation sequence magnetite->gibbsite->kaolinite->smectite is common to the initial stages of each of the simulations. The sequence beta-cristobalite->calcite is common to late stages of simulations weighted in favor of a clinopyroxene reactant (runs 10/1/1 and 10/10/1). The sequence beta-cristobalite->clinoptilolite->calcite is common to the late stages of the other runs.

The Effect of Reactant Ratio on the Volumes of Secondary Minerals

Table 3 lists the volumes of secondary minerals produced up to a pH of approximately ten. Runs weighted in favor of a clinopyroxene reactant resulted in relatively small volumes of gibbsite and kaolinite and relatively large amounts of magnetite. Runs weighted towards the plagioclase and groundmass components tended to produce relatively large amounts of clinoptilolite and beta-cristabolite and relatively small amounts of magnetite. The run in which all components were evenly weighted (run 1/1/1) is unique in having produced a relatively large amount of smectite.

The Effect of Reactant Ratio on Groundwater Composition

Simulated groundwater compositions at a pH of approximately 10 are shown in Table 4. In general, the compositions of the simulated groundwaters parallel the overall composition of the weighted reactant assemblages. The run dominated by the clinopyroxene reactant (run 10/1/1) produces an aqueous solution rich in magnesium and poor in sodium and potassium. The run dominated by the plagioclase reactant (run 1/10/1) produces an aqueous solution rich in sodium and poor in magnesium and potassium. The run in which groundmass receives an equal or greater weighting than the other components (run 1/10/10) produces an aqueous solution rich in potassium, moderately rich in sodium and poor in magnesium.

Groundwater Composition as a Function of the Extent of Reaction

The evolution of groundwater composition as a function of the extent of reaction is illustrated in Table 5 and Figure 1. In this simulation the clinopyroxene/plagioclase/groundmass ratio was set at 1/10/1. The effect of solubility constraints on the evolution of groundwater composition can be summarized as follows:

- (1) The precipitation of magnetite ($Z = .30E-06$) causes the amount of magnesium in solution to remain at the trace level.
- (2) The precipitation of smectite ($Z = .75E-03$) results in a decrease in dissolved magnesium.
- (3) The precipitation of cristobalite ($Z = 2.4E-03$) fixes the concentration of silica at 57 mg/l.
- (4) The precipitation of clinoptilolite ($Z = 5.9E-03$) results in a decrease in the amount of dissolved potassium.
- (5) The precipitation of calcite ($Z = 6.4E-03$) causes decreases in the concentrations of both calcium and total carbon.
- (6) pH increases rather monotonically as a function of the extent of reaction.

COMPARISON OF SIMULATIONS WITH OBSERVATIONS OF THE NATURAL SYSTEM

Benson and Teague (1979) have observed that in the Pasco Basin the common sequence of precipitation was smectite->clinoptilolite->silica->clay (smectite or illite). An iron oxide phase was also found intergrown with the smectite phase. In two of the simulations (runs 10/1/1 and 10/10/1 or Table 2), clinoptilolite failed to precipitate when clinopyroxene dominated the reactant assemblage. In the other runs, the precipitation sequence iron oxide->gibbsite->kaolinite->smectite->silica->clinoptilolite->calcite occurred. Although the latter runs compare more favorably with observations of Benson and Teague (1979), the silica->clinoptilolite sequence remains at variance with observation.

Secondary Mineral (Precipitate) Volumes

Volumetric studies performed by Benson and Teague (1979) indicate that smectite, clinoptilolite and silica dominate the secondary mineral assemblage in basalts of the Pasco Basin. Smectite and clinoptilolite appear to be

roughly equal in abundance and silica is usually a minor constituent of the natural assemblage. Simulations in which clinoptilolite formed (runs 1/10/10, 1/1/1 and 1/10/1 of Table 3) compare favorably with observation except for the rather large amounts of kaolinite produced in the simulations. Gibbsite was produced in the simulations but was not observed by Benson and Teague (1978); however, this phase may have been overlooked due to its insignificant amount.

Groundwater Composition

Deep Groundwater. The chemical compositions of 17 selected groundwater samples are listed in Table 6. Deep groundwaters (> 950 m) are characterized by high pH (~10), high silica (~115 mg/l), high chloride (~100 mg/l), high sodium (~200 mg/l), and high carbonate (~120 mg/l) concentrations. Potassium, calcium, and magnesium values are small (~4, ~1, and ~.1 mg/l respectively) compared to sodium.

The simulated deep groundwater composition produced using a 1/10/1 clinopyroxene/plagioclase/groundmass ratio (Tables 4 and 5) compares favorably with the compositions of actual deep groundwaters (Table 6). Each of the other simulated groundwaters contain at least one chemical species whose concentration is not in the correct proportion. For example, potassium, calcium and magnesium are much too concentrated with respect to sodium in the 1/1/1 run. Simulated values of sodium (data from $Z = .015$ through $.020$, Table 5) are low compared to values for deep groundwaters, i.e., 36-47 mg/l compared to 176 - 242 mg/l. This discrepancy is reduced if we assume that a portion of the sodium and all chloride in actual groundwater come from the dissolution of halite (NaCl). The "corrected" range of sodium for deep groundwaters then becomes 115-138 mg/l.

Shallow and Intermediate Depth Groundwaters. Shallow (< 300 m) groundwaters from the Pasco Basin include samples taken from Bennett, Benson and

Juniper Springs (Table 6). All three springs drain surficially exposed basalts; the sample from Juniper Springs represents a water which has resided in the Umtanum Unit. The spring waters are slightly basic, ranging in pH from 7.3 to 8.3, and are characterized by low chloride (3-6 mg/l), and potassium (1.5-5.2 mg/l) concentrations. Both calcium (23-24 mg/l) and magnesium (7-13 mg/l) concentrations are high relative to the concentrations found in deep groundwaters. Silica values (39-50 mg/l) range from about one-third to one-half deep-water concentrations.

A comparison of simulated shallow groundwater compositions (data from $Z = .0024$ through $.0075$ of Table 5) with actual shallow groundwater compositions indicate that, with the exception of magnesium, the waters are remarkably similar.

Waters from intermediate depths (300-500 m) in the Columbia River Basalts are characterized by high potassium (7.7-17 mg/l) and high bicarbonate (154-277 mg/l) concentrations. Concentrations of silica, sodium, calcium and magnesium vary widely, but tend to lie between deep and shallow groundwater values. The pH's of intermediate groundwaters range from 7.6 to 8.8.

The compositions of simulated intermediate waters (data from $Z = .0100$ through $.0125$ of Table 5) is not unlike the composition of actual intermediate groundwaters (Table 6) with the exception of potassium.

SUMMARY

Interactions between a large number of complex chemical and physical processes have resulted in significant changes in the Pasco Basin hydrochemical system since emplacement of the first basalt flow. In order to perform preliminary simulations of the chemical evolution of this system, certain

simplifying assumptions and procedures were adopted and a computer model which operates on the principal of local equilibrium was used for the mass transfer calculations. Significant uncertainties exist in both the thermodynamic and reaction rate data which were input to the computer model. In addition, the compositional characteristics of the evolving hydrochemical system remain largely unknown, especially as a function of distance along the flow path. Given these uncertainties, it remains difficult to assess the applicability of the equilibrium-step approach even though reasonable matches between observed and simulated hydrochemical data were obtained. Given the uncertainties mentioned, the predictive abilities of EQ6 are difficult, if not impossible to evaluate; our simulations produced, at best, only qualitative agreement with observed product mineral assemblages and sequences, and fluid compositions.

RECOMMENDATIONS

Further testing of the applicability of the equilibrium-step approach to the Pasco Basin hydrochemical systems is necessitated. The following procedures are recommended:

- (1) Absolute dissolution rates of unstable mineral phases should be obtained. These rates should be measured as a function of both temperature and composition.
- (2) Free energies of formation of secondary minerals common to the natural environment, e.g., clays and zeolites, should also be obtained from laboratory experiments.
- (3) Free energies of exchange must be obtained for minerals with significant cation exchange capacities. Structural and compositional effects on ion exchange selectivity should be incorporated in the ion exchange formalism.

- (4) Data on the compositions, volumes, and surface areas of primary and secondary minerals as well as the composition of the aqueous phase should be obtained as a function of distance along the flow path.
- (5) An unambiguous relation between the extent of reaction (Z) and distance along the flow path must be obtained if the results of simulations are to be compared with data from the natural hydro-chemical system.

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APPENDIX 1. A CRITICAL OVERVIEW OF THERMODYNAMIC ESTIMATION METHODS FOR LAYER SILICATES.

Chen's (1975) method was tested by estimating the free energy of muscovite. Muscovite is of particular interest since it possesses a structure similar to smectite whose free energy must be approximated in this study. Although Chen (1975) claimed to be able to estimate the free energy of muscovite within 1.7 kJ mole^{-1} ($0.4 \text{ Kcal mole}^{-1}$), our study showed that Chen's method becomes indeterminate when subtraction of components is permitted in the reaction set. If the reaction set is limited to equations formed solely by the addition of components, accurate extrapolation of the exponential regression function is difficult since the reaction data become few in number.

Since Mattigod and Sposito (1978) used Chen's method to calibrate their calculations, it follows that their approximation procedure is also rendered invalid. Other features of their method which appear incorrect or arbitrary are the formation of only a few of the many possible combinations of compounds in the reaction set, the use of up to seven significant figures when no greater than four can be justified, and the use of a single free energy of exchange for a reaction when two or more values for the same reaction are available in the literature.

The method of Nriagu (1975) contains ad hoc calibrations for the free energies of formation of the alkali hydroxides. In addition, these calibrations were made using free energies of formation obtained from solubility studies which had not reached equilibrium.

In their calculations, Tardy and Garrels (1974) used a sepiolite stoichiometry of $\text{Mg}_8\text{Si}_{12}\text{O}_{28}(\text{OH})_4 \cdot 14 \text{ H}_2\text{O}$ which differs from the commonly accepted stoichiometry of $\text{Mg}_8\text{Si}_{12}\text{O}_{28}(\text{OH})_4 \cdot 12\text{H}_2\text{O}$ determined by Brauner

and Preisinger (1956). When the accepted stoichiometry is substituted into the set of equations formulated for the system $\text{Mg}(\text{OH})_2 - \text{MgO} - \text{SiO}_2$, the equations are found to be linearly dependent and therefore a solution cannot be obtained. In addition, Tardy and Garrels treat the free energy of exchange of any cation pair as a constant. Experimental studies do not generally support this procedure (Benson, 1980).

A general criticism of all the estimation methods centers on their empirical nature. Each method must be calibrated against free energy data extracted from low-temperature solubility studies of layer silicates, yet none of these experiments have been shown to have reached an equilibrium state.

T A B L E S

TABLE 1

MEAN COMPOSITION (WEIGHT PERCENT) OF PRINCIPAL
REACTANT AND PRODUCT PHASES USED IN SIMULATIONS

COMPONENT	SMECTITE	CLINOPTILOLITE	GROUNDMASS	PLAGIOCLASE	CLINOPYROXENE
SiO ₂	50.2	68.5	68.4	55.1	41.7
Al ₂ O ₃	5.7	12.3	13.0	27.0	2.0
Fe ₂ O ₃	24.1	0.13	1.1	1.4	---
FeO	---	---	3.4	---	16.6
CaO	1.7	1.1	2.5	10.2	13.0
Na ₂ O	1.7	3.1	1.2	5.3	.25
K ₂ O	1.3	3.0	6.3	0.47	.01
MgO	6.9	0.02	0.5	0.6	16.4
H ₂ O	8.3	11.3	---	---	---

TABLE 2

SEQUENCE OF PRECIPITATION

<u>Run 1/10/10</u>		<u>Run 1/1/1</u>		<u>Run 10/1/1</u>		<u>Run 10/10/1</u>		<u>Run 1/10/1</u>	
<u>Min</u>	<u>Z</u>	<u>Min</u>	<u>Z</u>	<u>Min</u>	<u>Z</u>	<u>Min</u>	<u>Z</u>	<u>Min</u>	<u>Z</u>
Mag	‡ .233E-06	Mag	‡ .118E-06	Mag	‡ .632E-07	Mag	‡ .103E-06	Mag	‡ .300E-06
Gibb	‡ .131E-05	Gibb	‡ .177E-05	Gibb	‡ .457E-05	Gibb	‡ .172E-05	Gibb	‡ .107E-05
Kao	‡ .518E-04	Kao	‡ .546E-04	Kao	‡ .605E-04	Kao	‡ .596E-04	Kao	‡ .576E-04
Gibb	† .518E-04	Gibb	† .546E-04	Gibb	† .605E-04	Gibb	† .596E-04	Gibb	† .576E-04
Smec	‡ .766E-03	Smec	‡ .501E-03	Smec	‡ .363E-03	Smec	‡ .468E-03	Smec	‡ .748E-03
Mag	† .766E-03	Mag	† .501E-03	Kao	† .363E-03	Mag	† .468E-03	Mag	† .748E-03
Mag	‡ .132E-02	β-cris	‡ .212E-02	Kao	‡ .831E-03	Mag	‡ .124E-02	β-cris	‡ .242E-02
β-cris	‡ .158E-02	Clin	‡ .776E-02	β-cris	‡ .181E-02	β-cris	‡ .246E-02	Mag	‡ .521E-02
Clin	‡ .689E-02	β-cris	† .776E-02	Cal	‡ .347E-02	Cal	‡ .464E-02	Clin	‡ .589E-02
β-cris	† .689E-02	Cal	‡ .814E-02	β-cris	† .775E-02	β-cris	† .101E-01	β-cris	† .589E-02
Cal	‡ .868E-02							Cal	‡ .644E-02
Kao	† .820E-01								

LEGEND

‡ = Start of precipitation

† = End of precipitation

TABLE 3

VOLUMES (cm³) OF SECONDARY MINERALS PRODUCED UP TO A pH OF APPROXIMATELY 10

CPX/PLAG/GM	1/10/10	1/1/1	10/1/1	10/10/1	1/10/1
MAGNETITE	.0098	.00079	.019	.0094	.0015
GIBBSITE	.00061	.00047	.00018	.00052	.00083
CALCITE	.084	.12	.073	.085	.10
KAOLINITE	.27	.21	.026	.14	.33
β-CRISTOBALITE	.080	.052	.045	.048	.031
CLINOPTILOLITE	.42	.23	---	---	.16
SMECTITE	.084	.45	.11	.14	.098

TABLE 4
SIMULATED GROUNDWATER COMPOSITIONS (mg/l)

CPX/PLAG/GM	pH	*I	Eh	HCO ₃	CO ₃	SiO ₂	Na	K	Ca	Mg	Fe	Z
1/1/1	9.9	.0030	.632	1.6	.75	49	.72E-04	21	15	11	<10 ⁻⁶	.0275
1/10/1	10.0	.0020	.629	17	8.7	25	41	.16E-03	1.2	<10 ⁻⁶	.46E-03	.0175
1/10/10	9.9	.0021	.634	41	17	12	21	33	.59	<10 ⁻⁶	.38	.0225
10/1/1	10.1	.0070	.623	30	21	51	<10 ⁻⁶	.69	.63	53	.61E-03	.0100
10/10/1	9.9	.0047	.634	31	15	53	16	<10 ⁻⁶	1.0	35	.40E-03	.0125

LEGEND

*I = Ionic strength

TABLE 5
SIMULATED EVOLUTION OF GROUNDWATER COMPOSITION (mg/l). RATIOS OF REACTANTS
CLINOPYROXENE/PLAGIOCLASE/GROUNDMASS HAVE BEEN SET AT 1/10/1.

Z	PPT	pH	*I	Eh	HCO ₃	H ₂ CO ₃	CO ₃	SiO ₂	Na	K	Ca	Mg	Fe
0		4.9	.12E-03	.930	7.1	193	.26E-04	.051	2.4	.041	.082	.0071	.10E-11
.30E-06	Mag	4.9	.13E-03	.930	7.1	193	.26E-04	.068	2.4	.041	.084	.0075	.70E-03
.11E-05	Gibb	4.9	.13E-03	.930	7.2	193	.27E-04	.11	2.4	.042	.089	.0083	.69E-03
.58E-04	Kao	5.0	.17E-03	.924	9.0	191	.43E-04	3.3	2.6	.086	.48	.068	.48E-03
.75E-03	Smec	5.6	.71E-03	.887	33	167	.69E-08	23	4.7	.63	5.2	.80	.74E-04
.0024	Crts	6.1	.0017	.857	78	120	.0055	57	9.2	1.5	16	.50	.20E-07
.0025		6.2	.0018	.856	81	118	.0059	57	9.4	1.5	17	.48	.16E-07
.0050		6.8	.0032	.818	150	49	.049	57	16	2.8	34	.037	.41E-09
.0059	ClIn	7.2	.0038	.796	170	24	.14	57	19	3.3	40	.14E-05	.25E-05
.0064	CaI	7.5	.0040	.779	180	13	.28	50	19	2.7	43	.34E-06	.23E-05
.0075		7.6	.0036	.773	160	9.2	.33	47	21	2.2	36	.19E-06	.25E-05
.0100		8.0	.0025	.750	120	2.8	.58	41	25	.79	19	.25E-07	.45E-05
.0125		8.9	.0016	.695	76	.21	2.9	40	30	.0013	3.6	.19E-09	.35E-04
.0150		9.6	.0018	.654	42	.024	8.0	36	36	.42E-04	1.4	.54E-11	.17E-03
.0175		10.0	.0020	.629	17	.0036	8.7	25	41	.16E-03	1.3	.55E-12	.46E-03
.0200		10.5	.0024	.601	2.0	.14E-6	2.9	13	47	.026	3.8	.51E-12	.0013

LEGEND

*I = Ionic strength
PPT = Precipitate

TABLE 6

CHEMICAL COMPOSITION (mg/l) OF SIERRA SNOW AND SELECTED GROUNDWATERS FROM BASALTS
IN THE PASCO BASIN AND SURROUNDING AREAS IN SOUTH-CENTRAL WASHINGTON

SAMPLE	DEPTH(m)	pH	SiO ₂	HCO ₃	CO ₃	Cl	SO ₄	Na	K	Ca	Mg	Fe	REFERENCE
Sierra Snow	—	4.9	.051	.4	*n.d.	.19	.2	.1	.041	.082	.0071	n.d.	Brown and Skau (1975)
Bennett Springs	<150	7.5	46	104	n.d.	6	10	5	1.6	23	7	.003	Apps et al. (1979)
Benson Springs	<250	7.3	39	85	n.d.	3	11	6	1.5	23	8	.005	"
Juniper Springs	<300	8.3	50	186	n.d.	6	18	21	5.2	24	13	.016	"
DB1	300	8.2	28	209	n.d.	12	n.d.	75	14	3.5	.7	.16	Deju (1978)
DB2	300	8.6	32	196	n.d.	130	.5	150	12	4.2	.2	.53	"
11/26-34R1	305	8.8	75	154	15	81	n.d.	122	15	1.0	n.d.	.05	La Sala et al. (1973)
9/30-18H1	315	8.6	54	277	10	15	n.d.	115	11	1.9	.5	.04	"
14/31-36J1	335	8.8	70	139	10	11	27	72	9.0	3.1	.3	.03	"
13/25-30G1	338	8.1	57	175	n.d.	4.5	n.d.	30	8.3	16	8.8	.08	"
13/28-13N1	341	8.6	67	182	1	14	19	78	17	.8	.4	.04	"
12/24-20N1	366	8.0	56	170	n.d.	3.8	.2	21	7.7	18	11	.08	"
10/22-25F1	480	7.6	62	157	n.d.	4.8	16	16	7.4	29	9.7	.03	"
DC1	959-986	10.1	116	49	101	98	13	182	3.3	.8	n.d.	.10	La Sala and Doty (1971)
DC1	965-974	9.8	120	—	125	94	12	181	3.9	.7	.1	.15	"
DC1	977-989	9.7	105	2	120	98	10	176	5.9	.6	.1	.65	"
DC6	75%>1130	10.1	115	51	127	148	96	242	3.2	1.3	2.0	n.d.	Apps et al. (1979)

LEGEND

*n.d. = Not detected

XBL 808-7289

FIGURE 1