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Abstract

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The experimentally-simulated hydrothermal studies of the basaltic nuclear waste repository rocks have, at this time, produced a data base that receives a strong confirmation from the Icelandic analog. Furthermore, the Icelandic analog should eventually be employed to extrapolate into higher and lower temperatures, into longer time-base chemical comparisons, and into more realistic mineral deposition studies, than have been possible in the laboratory evaluations of the nuclear waste repository designs. This eventual use of the Icelandic analog will require cooperative work with the Icelandic Geological Survey.

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**ICELANDIC BASALTIC GEOTHERMAL FIELD: A NATURAL HYDROTHERMAL
BASALT-WATER DATA ANALOG FOR NUCLEAR WASTE ISOLATION IN BASALT**

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ABSTRACT

Analog studies of Icelandic geothermal fields have shown that the design of nuclear waste repositories in basalt can benefit by comparison to the data base already available from the development of these geothermal fields. A high degree of similarity exists between these two systems: Their petrology, groundwater geochemistry, mineral solubilities, hydrologic parameters, temperature ranges, water-rock redox equilibria, hydrothermal pH values, and secondary mineralogies all show considerable overlap in the range of values.

The experimentally-simulated hydrothermal studies of the basaltic nuclear waste repository rocks have, at this time, produced a data base that receives a strong confirmation from the Icelandic analog. Furthermore, the Icelandic analog should eventually be employed to extrapolate into higher and lower temperatures, into longer time-base chemical comparisons, and into more realistic mineral deposition studies, than have been possible in the laboratory evaluations of the nuclear waste repository designs. This eventual use of the Icelandic analog will require cooperative work with the Icelandic Geological Survey.

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INTRODUCTION

Philosophical value of analogs

The task of the Basalt Waste Isolation Project (BWIP) is to determine the feasibility of long-term storage of high-level nuclear waste in a mined repository located in basalt. Many previous studies of feasibility have used results from hydrothermal interactions between basalt and other phases and simulated groundwater in Dickson rocking autoclaves. These studies have generated data on changes in solution composition and secondary phases formed during these experiments. However, these experiments have been conducted over periods of only a few thousand hours, whereas the repository must isolate nuclear waste for periods of hundreds to thousands of years. Therefore, there has been concern whether these short term experiments could adequately simulate conditions and reactions occurring over much longer periods of time. This concern has prompted a search for natural analogs to a nuclear waste disposal site located in basalt. In such a natural analog reactions should have occurred over long periods of time. One possible site or series of sites are the geothermal fields of Iceland.

The formal definition of analog is, according to Webster,

"a form of inference in which it is reasoned that if two things agree with one another in one or more respects they are likely to agree with each other in yet other respects."

An analog study is therefore an exercise in first establishing that there are similarities between two objects by using data that already exists for both objects. If an analog looks strong, then one is logically inclined to extrapolate from the known data for one object to parallel, but unknown data for the second object.

Similarities versus dissimilarities

Accordingly, the first section of this analogue study must be concerned with the similarities and dissimilarities between the two objects to be compared, namely, the natural geothermal fields of Iceland and the engineered nuclear waste repositories proposed for the Columbia Plateau region of the state of Washington. Generally for both objects there will be abnormal heat generated in a portion of the Earth's crust that contains groundwater. In both areas the bedrock is volcanic and basaltic in composition. As is presented in detail below, the heat involved can develop nearly the same range of temperature at both sites. Furthermore, the volcanic nature of the crust in both locations provides a permeability to groundwater that is at least approximately the same. Studies of rock-water interactions in laboratory experiments in autoclaves have been performed for the basalts of Washington

state, but on a shorter time base and with less water throughput than in the Icelandic basalts of the natural geothermal system. If Icelandic geothermal fields do represent a strong analogue to the nuclear waste isolation desired, then the Icelandic data gathered on systems that have had 'geologic' time to react, should provide legitimate insight to the nuclear waste repository design.

The Icelandic data base has been generated by the Icelandic government because geothermal, and perhaps solar, or wind energies are their only inherent energy sources. Their geothermal data base has resulted from a concentrated effort over two decades to develop electric generation from natural or injected geothermal wells. The tectonic instability of Iceland has provided dangers like intersecting live magmas in a geothermal well and has caused problems like 7° tilting of an entire power generating plant (pers. comm. Amonsson, 1983). Thus, the Icelandic government has been forced for many societal reasons to enlarge their scientific data base on the geothermal fields. They realize that they would also benefit by reverse-analog studies of our governmental Basalt Waste Isolation Project (BWIP).

Types of data available

The Icelandic data base contains much information on

- * geochemistry of the basaltic rocks
- * geochemistry of geothermal waters
- * redox equilibria in basalt-hydrothermal interactions
- * acidity of geothermal waters
- * secondary (well-clogging) phases
- * hydrologic parameters in basalt flows
- * temperature
- * variations in the above parameters within both historic and geologic time

Since Icelandic geothermal fields do generally have properties analogous to basalt waste isolation repositories, and the Icelandic geothermal data base is so large, we have attempted herein to establish the validity of analog extrapolation from Icelandic data to the BWIP.

BACKGROUND COMPARISONS

Geologic Settings

Icelandic and Columbia Plateau geology are reviewed in The Basaltic Volcanism Study Project (1981). In addition, general papers on Iceland are exemplified by Sigurdsson et al. (1978), by Sigvaldson (1969) and Sigvaldson and Steinthorsson (1974), and Schilling et al. (1978). Similarly, data on the Columbia Plateau are summarized in papers such as Waters (1955 and

1961), Hooper (1974), Bottomly and York (1976), Goles (1971), Swanson and Wright (1978), and Swanson et al. (1979).

Iceland sits astraddle the Mid-Atlantic Ridge and has been the site of 10,000 km³ of sub-aerial and submarine basaltic volcanism since at least the Tertiary. The oldest exposed flows are Eocene, 60-40 m.y. in age. The extensional tectonics and the resulting rift fault-graben system is summarized in Fig. 1a. Over 35% of Iceland's surface is covered with Tertiary flows; the remainder with Quaternary flow. The average single flow thickness is about 10 m. On the west of Iceland the aggregate basalt thickness is about 3 km., while in the east of Iceland the pile is over 12 km. thick. The large high temperature geothermal areas are also shown in Fig. 1a, one in south-central Iceland and one in north-central Iceland. In Iceland there are alkali-olivine, high-Fe, high-Ti alkali, tholeiitic basalts and hyaloclastites with only minor amounts of acid volcanics. The tholeiitic Icelandic basalts are herein after referred to as IBs.

In the Columbia Plateau Basalts (hereinafter, CBs), there are typically at least 15 Picture Gorge Flows overlain by typically at least 15 Yakima flows, the entire package being of the Miocene age (approx. 13-16 m.y. old) as judged both by ⁴⁰Ar/³⁹Ar dating and by palynology data. That these flows were produced by a rift system is clear from the dike swarms that have been found in the Plateau. While the average flow is generally tens of meters thick (i.e., thicker than in Iceland), there are even two flows that are more in the range of 100 m thick and the entire Plateau is estimated to contain close to 200,000 km³ of lava. The location of the Grande Ronde Formation basalts, their feeder dikes, and the location of the possible Hanford underground nuclear waste site are shown in Fig. 1b. All of the flows in the Columbia Plateau are quite similar in chemistry with rare-earth total signatures or wt.% MgO as the only chemical variables that can distinguish separate flows for correlation purposes. The Grande Ronde flows currently under consideration for nuclear waste mined-repository-use are specifically the Umtanum and the Cohasset. Both are Yakima Subgroup flows and both are tholeiitic basalts.

Temperatures of Geothermal Wells and Nuclear Repositories

The temperatures of the geothermal waters in Iceland range from 18 to 340°C. (Kristmannsdottir, 1979; Arnorsson et al., 1983 a). However, most reservoir temperatures are less than 250°C. Geothermal areas in Iceland may be divided into two groups. First, high-temperature areas where the rock temperature exceeds 200°C at 1 km depth; and second, low-temperature areas where the rock temperature is below 150°C at that depth. The high-temperature areas are generally confined to the active zones of rifting and volcanism in central Iceland (see Figure 1a). By comparison the design criteria for the potential nuclear repository at the Hanford

Fig. 1 a.) Icelandic Geology. Rj=Reykjanes; Sv=Svartsengi; Hv=Hveragerdi; N=Namafjall; and K=Krafla. See text for discussions of these areas

Fig. 1 b.) Columbia Plateau Geology. See text for details.

Basalt site provide that the arrangement of packing, i.e., the density of waste, will not produce temperatures which exceed 200 - 250°C at the cannister centerline even though the design of near-field parameters such as cannister, overpack, and backfill will have a safety factor that would still allow peak temperatures of 300 C.

Obviously, heat flow in Iceland is related to magmatism which arises from the Mid-Atlantic Ridge whereas in the Columbia Plateau Miocene volcanism has decayed to steady state continental heat flow. Nevertheless, most of the temperatures in Icelandic geothermal reservoirs are very similar to the maximum design temperatures planned for basalt waste isolation in the Columbia Plateau.

Basalt Chemistries

The Columbia Plateau Basalts (CBs) of interest to nuclear waste storage considerations are typically on the silica rich side of the olivine tholeiite volume in the Yoder-Tilley basalt tetrahedron (Yoder and Tilley, 1962). Thus, the basaltic rocks of most analogous chemistry in Iceland are the olivine tholeiites which are Tertiary and Quarternary in age and geographically found respectively in East Iceland and Reykjanes. See their analyses in Table 1, as well as the analyses of the two CBs potentially involved as well as average compositions of the CB and the world average composition for tholeiitic basalt.

The comparative rock chemistries in Table 1 summarize two important points in evaluating the use of Icelandic geothermal data as an analog for nuclear waste isolation in the Columbia Plateau Basalts (CBs):

(1) The two main types of Icelandic tholeiite have quite a different $\text{Fe}^{2+}/\Sigma\text{Fe}$ ratio each from the other; the Rekjanes value for this ratio is 0.16 and the East Icelandic value is 0.51. This increase in Fe^{3+} between these two types of flow is related mainly to the subsequent hydrothermal - geothermal oxidation of these Tertiary lavas with the passage of time.

and

(2) The entablatures chemistries of the two Columbia Plateau basalt flows listed are similar to each other and are also more similar in total chemistry to the Reykjanes lavas than to the East Icelandic lavas, although all CBs are lower in MgO and higher in K_2O than either of the IBs.

Hence, with regards to point number one, the evolution by geothermal oxidation shown between the rock chemistry data in the two types of Icelandic tholeiite may be of interest to the evaluation of oxidation evolution of the nuclear repositories. With regards to point number two, the salinities of the

Table 1. SELECTED BASALT ANALYSES FROM COLUMBIA PLATEAU, ICELAND, AND WORLD AVERAGES

	W. Iceland Olivine Tholeiite ¹	E. Iceland Olivine Tholeiite ¹	Columbia Plateau (avg of 13) ²	Tholeiitic Basalts (avg of 137) ²	Umtanum Entablature ³	Cohasset Entablature ³
SiO ₂	48.01	46.73	52.31	50.83	55.5	52.81
TiO ₂	1.87	2.51	2.10	2.03	2.21	1.79
Al ₂ O ₃	14.09	14.83	14.38	14.07	13.71	13.70
Fe ₂ O ₃	2.69	6.40	2.47	2.88	3.68*	—
FeO	10.06	6.74	9.95	9.00	10.24*	11.62**
MnO	0.21	0.21	0.21	0.18	0.24	0.19
MgO	8.29	6.70	4.46	6.34	3.79	5.41
CaO	11.77	10.82	8.37	10.42	7.31	8.79
Na ₂ O	2.17	2.53	2.94	2.23	2.95	2.66
K ₂ O	0.29	0.38	1.26	0.82	1.63	1.11
P ₂ O ₅	0.19	0.31	0.36	0.23	0.35	0.27
H ₂ O ⁺	<u>0.28</u>	<u>1.78</u>	<u>0.74</u>	<u>0.91</u>	<u>—</u>	<u>—</u>
TOTAL	99.92	99.94	99.55	99.94	101.70	98.08

1. Quoted from comparative literature reviewed in Basaltic Volcanism of the Terrestrial Planets Pergamon Press, 1286 p.p. (1981).

2. Quoted from "Volcanic Rocks and the Tectonic Cycle", A.C. Waters (1955) Geol. Soc. Amer. Spec. Paper 62, 703 - 722.

3. X-ray Fluorescence analyses. Analyses conducted at Franklin and Marshall College, Lancaster, Pa. Mr. Steven Sylvester, analyst.

* Permanganate titration for Fe²⁺ iron done at Temple University.

** Total iron as FeO

Reykjanes geothermal field fluids are 40 to 50 times higher than the Grand Ronde groundwater that would be involved in the nuclear repository. However, as is developed in later sections, this dissimilarity in salinity is not as weakening to the analog as might first be suspected. The groundwaters at the North-Central geothermal fields are generally very similar in salinity to the Grande Ronde waters. Additionally, as is developed later in this manuscript, the differences in K_2O and MgO do not seem to be very important to water geochemistry and mineral solubilities.

Hydrologic Parameters

Flow stratigraphic sub-units

The morphology and internal differentiation of basaltic flows has been treated, for example, by Hooper (1974) and by Haggerty (1968). In any flow thicker than about 10 m, the flow cooling pattern will produce a triplet of stratigraphic units. This 'triplet' is characteristic of Columbia Plateau Basalts:

- * Basal colonades formed by massive vertical co-parallel polygonal cooling joints spaced so as to form columns 20 - 200 cm. wide; occasionally jointing is not vertical but rather radial i.e. perpendicular to a non-horizontal cooling surface (e.g. channel) in pre-existing topography; this flow sub-unit typically has a very high glass content (chilled margin) at its very base and typically has a highly vesicular narrow (1-2 meters) zone at its top which is notable in surface outcrops as a "spring-line" of lush vegetation due to water flow.

- * The colonnade is overlain by an entablature which has fluted sub-vertical cooling joints that pinch out, doubly truncating the column at lengths typically from 0.5 to 2.0 meters long; the fluted columnals are 20-90 cm. in diameter; surface outcrops of this sub-unit collapse quickly to a vertical profile, because of the jointing; permeability at surface outcrops is enhanced by the high number of fluted joints (hundreds per m²), but little vesicularity is usually present in this unit.

- * The entablature is overlain by the flow top sub-unit which is highly interbedded with scoreaceous/vesicular beds and solid lava beds; this sub-unit may be up to half the thickness of the entire flow; in outcrop it weathers to a less proud slope than either of the lower sub-units; its very top may develop a soil profile that becomes a burnt soil interbed if a subsequent flow occurs; permeability in the vesicular interbeds may be quite high.

Permeability

Because Icelandic flows are often less than 10 m thick, they may not always develop this pattern. With regards to ground-

water residence time in the low temperature Icelandic geothermal fields, the bedrock, which can be of either Tertiary or Quaternary age, tends to have little primary permeability and Icelandic underground water flow tends to be associated with vertical secondary structures, such as dikes, faults, and fissures. In the high-temperature fields, which are located in the active volcanic belts, or at their margins, permeability may also be created by fracturing and fissuring, but primary permeability which is partly horizontal, is also important. The permeable features include cooling cracks and scoraceous tops and bottoms of lava flows. Hydrothermal alteration is characterized by its localized distribution. In either horizontal or vertical directions, completely altered rocks are found close to rocks which are only very slightly affected by alteration. The Quaternary rock formations have much higher porosity and permeability than the older Tertiary rocks which have suffered compaction by burial and whose vesicles and cracks have been filled to a large extent with secondary minerals.

Specifically for the intended CBs, the Umtanum and Cohasset, Gephart et al. (1983) have characterized groundwater movement as having:

- o high horizontal flow along the flow tops
- o low vertical leakage through basalt interiors
- o leakage along structural discontinuities

Thus, in general, IBs are tectonically more rifted than CBs, and as already noted, vertical groundwater flow may be more important in Iceland than in many parts of the Columbia plateau. However it is significant to realize that the range of reported groundwater residence times in Iceland is within the range of residence times reported for the Columbia Plateau (see just below). It is also worth emphasizing that Arnorsson et al. (1978 and 1983) have determined that the permeability range in Iceland has little influence on the resulting groundwater geochemistry...a point that is presented in the next section. The residence time of Icelandic geothermal waters is at least several tens of years and may be as much as 10,000 years (Arnason, 1977).

By comparison, in the Miocene flows of the Columbia Plateau (pre-repository-emplacement) residence times with only the ambient geothermal gradient have been reported to range from 500 to 5,000,000 years with a median of 17,000 years (Clifton et al., 1984). It is to be anticipated that with the emplacement of nuclear-waste related heat gradient, at least some near-field convection and or circulation will locally shorten the residence time.

Water Chemistries

The content of dissolved solids in geothermal waters in Icelandic geothermal waters is highly variable. It ranges from about 150 ppm to about 32,000 ppm (sea-water salinity). The low salinity fluids result from geothermal interactions with meteoric waters whereas the high salinity geothermal waters (Reykjanes, for example) result from infiltration of sea-water. This infiltration takes place along the zones of secondary permeability, e.g. faults or fractured dike contacts. Hydrothermal reactions of basalt with seawater, such as those that occur at mid-ocean ridges and in saline Icelandic geothermal fields such as Reykjanes and Svartsengi have been investigated experimentally by Bischoff and Dickson (1975), Seyfried and Bischoff (1977, 1979, 1981), Mottl and Holland (1978), Mottl et al. (1979), Mottl and Seyfried (1980), Seyfried and Mottl (1982) and others. Basalt-seawater interactions including changes in seawater composition and the secondary phase assemblages observed at Reykjanes and Svartsengi have proven, in many respects, to be adequate analogs for the basalt-seawater experiments (for example, Mottl and Holland, 1978; Ragnarsdottir et al., 1984).

The low salinity geothermal waters of Iceland are usually slightly alkaline (room temperature pH values range from 6.1 to 10.1 with a median value of ca. 9.1). Sodium is the dominant cation (concentrations for hot spring and hot water wells tabulated by Arnorsson et al. (1983) range from 26 to 500 mg/L). Chloride is usually the dominant anion (concentration range from 6 to 700 mg/L), but occasionally bicarbonate (ca. 15 to 200 mg/L) or sulfate (6 to 300 mg/L) may occur in greater concentrations than chloride. However, most Icelandic geothermal waters may be described as of the sodium chloride chemical facies (see Table 2).

Arnorsson et al. (1978, 1983a, b) have analyzed a number of the geothermal fluids and have calculated their speciation and high-temperature properties. They have discovered that the activities of neutral species (H_2S or H_4SiO_4 , for example), or cation/hydrogen activity ratios (Na/H or K/H , for example) are solely functions of the aquifer temperature (as determined by Na/K or silica geothermometry, or by direct measurement). See Figure 2 for some examples. They have shown that variables such as salinity do not discernibly alter these properties. Further, it appears that variations in basalt composition and mineralogy do not have appreciable effect (Arnorsson et al., 1983a).

Although pressure is also a significant thermodynamic variable, in Icelandic geothermal fields the hydrostatic pressure is generally less than ca. 200 bars (20 MPa) (Arnorsson et al., 1983a). Therefore, the influence of pressure is much less than that of temperature.

Table 2. COMPOSITION OF LOW SALINITY ICELANDIC GEOTHERMAL WATERS, HANFORD GROUNDWATERS, AND REPOSITORY REFERENCE SOLUTIONS

	Range of values from Icelandic geothermal waters (1)	Range of values from the Hanford area(2)	GR#3 ³	GR#4 ⁴
Na ¹⁺	26. - 500	2.9 - 360	263.	334.
K ¹⁺	0.1 - 36	2.4 - 19	1.9	13.8
Ca ²⁺	0.7 - 140	0.5 - 92	1.3	2.2
Mg ²⁺	<0.002- 21	0.0 - 30	0.04	0.03
ΣCO ₂	6. -1350	40. - 230	70.	67.
Cl ¹⁻	6.0 - 670	2.7 - 350	148.	405.
SO ₄ ²⁻	3.9 - 204	2.7 - 180	109.	4.
NO ₃ ¹⁻	-	0.1 - 270	0.	0.
F ¹⁻	0.2 - 19.8	0.1 - 37	37.	19.9
SiO ₂	29. - 486	8.8 - 130	121.	96.3
pH	6.1 - 10.1	8.1 - 10.1	9.92	9.7

1. Arnorsson et al. (1983a) Table 2.

2. Smith (1980)

3. M. I. Wood (1980). BWIP Data Package for Reference Data of Groundwater Chemistry. SD-BWI-DP-007, 13 p.

4. Jones, T. E. Letter Report #10311-83-001, October 3, 1983, Rockwell International,

Therefore, because the properties of Icelandic geothermal fluids vary predictably, Arnorsson et al. (1978, 1983) suggested that knowledge of only two parameters, generally temperature and one compositional variable such as total dissolved solid or chloride concentration, is required to semi-quantitatively predict the major element chemistry of the fluid. They concluded that this predictability requires that the geothermal fluids in Iceland have attained, or closely approached equilibrium (saturation) with respect to secondary alteration phases. Classic application of the phase rule requires that of fixed temperature and pressure, the number of components equals the number of phases for this observed predictability. They concluded that, given the number of components in geothermal fluids, equilibrium with 10 phases is required (for the complete discussion of the number of phases required to completely specify the solution composition see the original discussion in Arnorsson et al. 1983, pp 557-558). Their calculations indicated that the low salinity Icelandic geothermal fluids in basalt generally attained equilibrium with respect to the minerals: chalcedony (or quartz at temperatures above ca. 180°), calcite, albite, k-feldspar, fluorite, smectite (or chlorite above ca. 200°), marcasite (or pyrite), pyrrhotite, iron hydroxides, and at the highest temperatures anhydrite and epidote (see Appendix A for mineral formulae).

From the compilation of Browne (1978) and others, Arnorsson et al. (1983a) observed that only a relatively limited number of minerals were found in geothermal systems occurring in volcanic rocks ranging in composition from basaltic to rhyolitic. This suggests that geothermal fluids in most volcanic areas might equilibrate with the same mineral assemblage. Therefore, they suggested that the empirical relationships based on data from Iceland might also be applicable to volcanic rocks elsewhere, and that semi-quantitative prediction of geothermal fluid compositions could be made.

The composition of groundwater in the Pasco Basin of the Hanford area, the proposed repository locality, is also somewhat variable. For example, the concentration of total dissolved solids in various groundwater samples varies from 150 to ca. 700 mg/L. In most samples sodium is the dominant cation, and either chloride or bicarbonate the dominant anions. Most samples are also quite alkaline, with pH values in the range 9 to 10 (Smith, 1980). The range of tabulated species concentrations for groundwaters in the Pasco Basin, low-salinity geothermal waters of Iceland, and the selected reference compositions for the Grande Ronde groundwater are given in Table 3. As may be seen the compositions of the Repository Reference Solutions (GR #3 and #4) and the range of composition of Hanford groundwaters are similar to those of Iceland for most major dissolved species.

Glass Chemistry.

Regardless of whether one is considering IBs or CBs there is another physical-chemical parameter that does determine the initial resulting geochemical solution of these tholeiitic basalts... namely the glass composition and its volume percent. That there is more than one glass in a typical flow is well documented in basalts wherever they have been studied. However, the bulk glass is produced during cooling and in the CBs' glass, the bulk has been found not to be close to the bulk rock composition. Only in flows thicker than ten meters does the margin and the flow center seem to be significantly differentiated. The major mesostasis glass in CBs has been shown to be "rhyolitic", i.e. varying from 62.6 - 71.2 % SiO_2 , respectively for the Umtanum entablature and colonnade (Allen and Strope, 1983) and varying from 65.1 - 72.5% SiO_2 respectively in the Cohasset entablature and colonnade.

In the CBs of interest, the Cohasset is 53-76 m thick with a flow top thinner than 12 m and an entablature with about 30v% glass; similarly, the Umtanum is 40 to 87 meters thick with its entablature varying from 23 to 52 meters with about 47v% glass (DOE, 1982). In Iceland, the average flow may vary from submarine (high amounts of quenched glass) to subaerial flows (at <10 m thick, there may still be a fast quench), it is impossible to estimate the glass composition or glass percentage in communication with a given geothermal well. However, as shown above, Arnorsson et al. (1978, 1983a,b) have concluded that temperature is the dominant variable in the development of Icelandic geothermal water chemistry. They have found that neither the primary basalt chemistry, nor the geothermal fluid origin, nor the effects of the overburden pressure, nor the permeability vary enough to perturb the resulting water geochemistry development in any significant way. By inference then, neither the glass composition nor the glass content would matter as long as glass is present and not totally dissolved. They have also inferred that geothermal water chemistry may be independent of volcanic rock type ranging from rhyolitic to basaltic. This water geochemistry predictability is one of the main reasons that the Icelandic analog looks so promising for the use in anticipating groundwater geochemistry that would develop with basaltic nuclear waste repositories..

Background Summary

Thus, the similarity in peak temperature of the two environments, the congruency in the ranges of groundwater residence time, the closeness of salinity range (excluding seawater intrusion), and the similarity in total petrology and bulk composition between Iceland and the Columbia Plateau are compelling reasons for the study of Iceland as an analog to basalt nuclear waste isolation. The Icelandic Government has had to do exhaustive research on their country's geothermal potential. The data base that the Icelandic Geological Survey

has amassed on their geothermal wells and fields in basaltic terrain is certainly the largest existing data base on the geochemistry of basalt-water hydrothermal interactions. As was pointed out above, the data base is large enough to allow Arnorsson and his co-workers to predict groundwater geochemistry, given a temperature and a salinity. Accordingly, in the sections that follow, a close comparison of the Icelandic data base is made with the growing data base from autoclave studies of hydrothermal geochemistry in the system Grande Ronde Water-Columbia Plateau Basalt.

EXISTING DATA BASES: COMPARISON OF VALUES

Solution Composition

A number of experiments have been undertaken in which basalt from the Umtanum and Cohasset flows, two potential repository horizons, have been reacted with synthetic Hanford groundwater in Dickson rocking autoclaves at temperatures of 100, 200, and 300 °C, at a pressure of 30 MPa, for periods up to 10,000 hours, utilizing water rock ratios of 5 to 50. Samples of solution were taken during the experiments and solid phases were characterized at the end of the experiments. In order to assess the value of these results as predictors of interactions which might occur in a repository, the results may be compared with the solution chemistries and alteration phases observed in Iceland.

Comparison of solution composition from the Dickson autoclave experiments with the Icelandic trends of Arnorsson et al. (1983a) is shown in Figure 2. Each panel of the figure shows the envelope of Icelandic data (the region between the curved lines), and the averaged Icelandic value (the curved solid line). All of the panels (except B, hydrogen sulfide activity) also show three paired vertical lines at 100, 200, and 300 °C. These lines indicate results of autoclave experiments at those temperatures. The vertical extent of each line indicates the range of values obtained during the experiments. The small box indicates the final or stable value achieved at each temperature. In each pair of lines the left-hand line (labelled U in some cases) indicates the results for experiments in which Umtanum entablature material was reacted with synthetic Hanford groundwater (GR-#3 formulation, see Table 2) (results calculated from Moore, 1983; and Moore et al., in press), the left-hand line in each pair (labelled C in some cases) indicates results for Cohasset Colonnades material reacted with synthetic Hanford groundwater (GR-#4 formulation, see Table 2) (unpublished results of R. Korn). Both the inter-flow CB comparisons and the intra-flow, i.e. CB vs. IB, comparisons are of interest. As may be seen in each case, the results for the Umtanum and Cohasset experiments are very similar, both in the total variability observed and in the final, or stable value observed during the experiments. This indicates the differences in basalt composition (Table

Fig. 2.) Water geochemistries in Icelandic geothermal fields compared to hydrothermal autoclave studies of the Grande Ronde water-rock interactions. See text for meaning of symbols and detailed discussions.

1), glass composition, mineralogy, or differences in the composition of the two reference groundwaters (see Table 2) had no appreciable effect on the values. These results are consistent with the contention of Arnorsson *et al.* (1983a) that variation in salinity and basalt composition do not have a major effect on activities of some neutral species or cation/hydrogen activity ratios. The results also indicate that, in most cases, values of these parameters lie in or near the envelope of Icelandic data. In three of the sixteen cases shown, the results do lie outside of the Icelandic envelope. These discrepancies may result from slow rates of precipitation or from the nucleation, growth, and persistence of metastable phases. For example, formation of cristobalite during the autoclave experiments, rather than the less soluble polymorph, quartz, probably accounts for the higher concentrations of dissolved silica observed in the experiments (Panel (A) Figure 2). However, all of these comparisons generally support the use of Iceland as an analog.

Redox Equilibria vs. Temperature

In both Icelandic geothermal electricity production and in the design of basaltic nuclear waste isolation, "corrosivity" of the aqueous fluids is of major concern. Respectively, the generator turbine blades and the waste canisters must be able to withstand oxidative corrosion as well as acidic dissolution. Thus, knowledge of the Eh (electron concentration) of the fluid as well as knowledge of the pH (hydrogen ion activity) of the fluid environment is desirable.

In aqueous fluids, if one can assume equilibrium conditions, the following equation is pertinent:

for which

$K_w = f_{\text{H}_2} \cdot f_{\text{O}_2}^{0.5} / f_{\text{H}_2\text{O}}$ where f indicates the fugacity of the species. Additionally, in aqueous fluids, the ionization equation for water is equally important:

which may also be written

for which it may be shown that the Nernst equation has the form:

$$\text{Eh} = \Delta G^\circ / nF + 2.303RT(0.5 \log f_{\text{O}_2} - 2 \text{pH}) / nF \quad (4)$$

in which F is the Faraday constant, R is the gas constant, T is the temperature in K, and ΔG° is the standard Gibbs Free Energy of reaction (3). With these equations it is clear that to obtain data for the Eh or pH, it may also be useful to have information on the redox potential, i.e., the fO_2 of the environment.

Hence, in Icelandic research on their geothermal fields and in hydrothermal laboratory autoclave research on CB's, an emphasis on obtaining fO_2 data has been made. In the work of Gíslason and Eugster² (1984) on the Krafla, Icelandic geothermal system, four redox equations were used to calculate fO_2 - T relationships from the Icelandic hydrothermal data base:

Their results are superimposed on Figure 3 on our similar calculations done using the Arnorsson et al. (1983a) SO_4 - H_2S data base for all the Icelandic geothermal fields. In Figure^{2,3} the known redox reactions,

after Eugster and Wones (1962)

and

after Eugster and Wones (1962)

are also plotted for comparison. It is interesting that both sets of Icelandic data form a congruent and coherent envelope in fO_2 - T space. Gíslason and Eugster (1984) have pointed out that at any fixed temperature equation (D) gives the highest fO_2 values while equation (A) or (B) gives the lowest. They further note that boiling-induced-precipitation of sulfides or calcite would raise the apparent fO_2 values calculated with equation (D) and lower the apparent fO_2 values calculated with equations (B) or (C). With regards the similarities between their work at Krafla and the calculated fO_2 values of Hardie (1983) on the seawater-dominated Reykjanes geothermal field, they feel that "the oxidizing power of sulfate in seawater is lost through anhydrite precipitation". Ragnarsdóttir et al. (1984) have calculated that saline geothermal fluids in the Svartsengi, Iceland geothermal fields have a $\log fO_2$ of -36.3 at 240°C. This fO_2 value is also well within the envelope of other Icelandic data and confirms that salinity does not greatly affect redox conditions. Hence, all the Icelandic

fO_2 -T data are in reasonable agreement and define an fO_2 -T trend portrayed in Figure 3.

Thus, it is very significant that the shaded area, BR, in Fig. 3, represents the fO_2 calculated from the SO_4^{2-} - H_2S data for the Umtanum (Moore *et al.*, in press) and Cohasset flows (R. Korn, unpublished data). In terms of fO_2 -T data, the IBs and CBs do seem to be analogues for each other.

Since, as we noted, Eh and pH are also of interest in corrosivity considerations, Figure 4 presents Eh/pH data comparisons for Icelandic springs and geothermal fields and for our laboratory hydrothermal studies of the CB Umtanum flow. The Icelandic Eh values were calculated from fO_2 data derived from equation (D) and pH values calculated as discussed in Arnorsson *et al.* (1982). Our Umtanum autoclave study provided the aqueous geochemical data to calculate the high temperature pH from the HIPH computer program (Moore *et al.*, in press). The pH was combined with our fO_2 -T data (Fig. 3) to calculate the Eh using equation (4). The coherency and congruency of the Eh/pH x 100 data envelope again supports the idea that the aqueous redox behavior of the IBs and CBs are analogous.

Thus despite some differences in salinity, in total chemistry, in temperature, and in tectonic settings, the redox conditions in two major basalt-water geochemical studies are analogous.

Hydrothermal pH values.

The pH of many geothermal fluids has been measured at room temperature. However, the pH of a solution will change with temperature due to changes in the equilibrium constants. Therefore, the room temperature pH may not be a reliable indicator of the high-temperature pH. Commercial pH electrodes cannot be used at temperatures much above 85°C, and other pH sensors such as the ZrO_2 electrode have not yet been used successfully to measure the high-temperature pH of fluids emanating from geothermal wells. Therefore, the pH of high-temperature geothermal solutions must be calculated from high-temperature aqueous speciation and from solubility relationships. The calculated pH values of most geothermal solutions apparently lie within about 1 - 2 pH units of neutral pH ($a_H = a_{OH}$) at a given temperature; at 25°C neutral pH is 7.0 but, at 300°C, for example, the neutral pH is approximately 5.5. Therefore, at 300°C, we would expect that most geothermal solutions lie between ca. pH 4 and 7.

Basalt-seawater interactions produce quite acidic high-temperature solutions, probably due to liberation of hydrogen ion during the precipitation of dissolved magnesium ion in the sepiolite component of smectites (for a complete discussion, see Seyfried and Bischoff, 1981). However, the interaction of basalt and low salinity, meteoric waters does not produce such

Fig. 3.) The fO_2 -T relationships for Icelandic geothermal fields compared to the hydrothermal autoclave data for Grande Ronde water-rock interactions. For a discussion of these redox equilibria please see the text.

acidic solutions. The calculated high-temperature pH values for Icelandic solutions are indeed neutral to slightly alkaline, ranging from ca. 6 to 8. The calculated high-temperature pH values for solutions produced during the autoclave experiments range from ca. 7 to 7.8. Although these pH values lie within the range of Icelandic values, they are probably slightly more alkaline than the Icelandic average. The discrepancy may be due to the fact that the autoclave experiments are conducted in a closed system. In a closed system carbonic acid is exhausted whereas in geothermal fields it is replenished by movement of the groundwater.

Secondary minerals

Alteration phases in geothermal areas of Iceland show a sequence of mineral assemblages relating to increased temperature. The variety of secondary hydrothermal minerals which have been identified from various Icelandic geothermal fields have been summarized by Browne (1978). These minerals and their generalized temperature distribution are listed in Table 3 and formulae are listed in Appendix A. Hydrothermal alteration is characterized by its localized distribution. Zones of completely altered rocks are found close to rocks which are only very slightly affected. The flow of hydrothermal fluids and the pattern of alteration is highly governed by faulting and fracturing.

The clay minerals are the most voluminous alteration minerals. Smectites form at the lower rock temperature. Montmorillonite is found in weathering zones and in mudpots at the surface. Smectites formed at slight depth by the action of hydrothermal fluids are iron-rich saponites (Kristmannsdottir, 1976). XRF analyses suggest that, although smectites formed in individual geothermal fields are chemically similar, major variations in composition occur from one field to another. At temperatures somewhat less than 200°C mixed-layer clay minerals of smectite and chlorite begin to form. These mixed-layer minerals are dominant in the temperature range 200-240°C. Chlorite becomes the dominant sheet silicate at temperatures of 230-250°C. The chlorites are also iron-rich, and their composition also varies from one geothermal field to another.

A variety of zeolites are found at rock temperatures less than 100°C. Two groups of zeolites occur; mordenite, heulandite, stilbite, and epistilbite; which are common in tholeiitic basalts; and chabazite, thomsonite, and mesolite-scolecite; which are found in olivine-tholeiite basalts. At temperatures of 100-120°C laumontite replaces other zeolites. Wairakite appears at ca. 180°C and all other zeolites disappear at temperatures of about 200°C. The calcium silicates gyrolite, reyerite, zeophyllite, and truscottite are found at temperatures less than ca. 200°C.

Table 3. Hydrothermal minerals identified from Icelandic Geothermal Fields and their generalized temperature distribution (Modified from Browne, 1978). X indicates the presence of a mineral. Low-temperature indicates temperatures generally less than 150°C.

	Low-temperature	High-temperature
Cristobalite	X	
Quartz		X
Smectite	X	X
Illite-smectite	X	
Chlorite-smectite		X
Chlorite		X
Celadonite	X	
Anhydrite	X	X
Calcite	X	X
Ankerite		X
Analcime	X	X
Wairakite		X
Gmelinite	X	
Gismondine	X	
Laumontite	X	X
Scolecite	X	
Chabazite	X	
Thomsonite	X	
Heulandite	X	X
Stilbite	X	X
Mordenite	X	X
Prehnite		X
Amphibole		X
Epidote		X
Albite		X
Magnetite		X
Hematite	X	
Pyrite	X	X
Pyrrhotite		X
Anhydrite	X	X
Leucoxene	X	X
Sphene	X	X
Gyrolite	X	
Reyerite	X	
Zeophyllite	X	
Truscottite	X	

Chalcedony is precipitated at temperatures below ca. 100°C, whereas quartz forms at higher temperatures.

Epidote is common at temperatures above ca. 260°C and occurs sporadically at temperatures between 200 and 260°C. Actinolite is found at temperatures greater than ca. 280°C. Albite is found commonly at temperatures exceeding 280°C.

Pyrite is precipitated over the whole temperature range. Pyrrhotite is formed together with pyrite in areas of low salinity fluids. It appears that all high-temperature low-salinity geothermal fluids are in equilibrium with pyrite and pyrrhotite.

Anhydrite is found in all areas. It appears to form most commonly during inflow and rise in water temperature because its solubility decreases with increasing temperature (Tomasson and Kristmannsdottir, 1972). Calcite is also common at all temperatures. High-temperature geothermal fluids are generally saturated with respect to calcite. In near surface, low-temperature fluids, precipitation of calcite may be caused by boiling or degassing of the solution with loss of carbon dioxide by the reaction:

The generalized temperature-stability relationships exhibited by the most common secondary minerals are given in Table 4.

The secondary minerals identified after Umtanum basalt-water hydrothermal experiments at 100, 200, and 300°C, 300 bars total pressure, and water:rock mass ratios between 5 and 50 are shown in Table 5. No secondary mineral found in the autoclave testing is absent from the list of alteration minerals found in Iceland (Table 4). Naturally, addition of nuclear waste materials, such as spent fuel, to a repository could result in formation of additional minerals such as uraninite, coffinite, weeksite, braggite, and others, which would incorporate the radionuclide elements. However, from results of experiments, Grandstaff et al. (1983) have suggested that the addition of spent fuel as a waste material, for example, would not greatly alter the fundamental assemblage of secondary silicate phases.

The list of phases produced in the experiments includes metastable phases such as cristobalite, a more highly soluble polymorph of quartz. From the temperature distribution of alteration phases in Iceland (Table 4) and elsewhere one would expect quartz to form at the higher temperatures. Further, a mixed-layer smectite-chlorite phase was produced at 300°C, rather than chlorite, as might be expected from the Icelandic analog. Finally, heulandite, a relatively low temperature zeolite, was found in the 300°C experiment. Therefore, although the phases found in the experiments were generally

Table 4. General temperature distribution of hydrothermal minerals in Icelandic geothermal fields (from Kristmannsdottir, 1979; Arnorsson *et al.*, 1983).

Table 5. Secondary minerals identified from Umtanum basalt-synthetic Hanford groundwater experiments in Dickson rocking autoclaves at temperatures of 100, 200, and 300°C (from Moore et al., in press).

100°C	200°C	300°C
Smectite ¹	Smectite	Smectite-chlorite
	Cristobalite	Cristobalite
Illite	Illite	Illite
Potassium-feldspar	Potassium-feldspar	Potassium-feldspar ²
Scapolite?		Scapolite?
		Heulandite
		Wairakite

1. Smectite is iron-rich saponite.

2. Probably sanidine (from X-ray diffraction)

the same as those found in Iceland, some are found at higher temperatures than in the natural analog. This distribution probably results from early rapid dissolution rates of glass and other primary phases, and consequent high degrees of supersaturation. The high supersaturation would tend to produce metastable phases, which would then persist, at least for the duration of the experiments. The occurrence of low-temperature and metastable phases in the high temperature experiments may account for some of the discrepancies observed in solution composition parameters (Figure 2).

A far greater number of minerals occur in Iceland than in the hydrothermal experiments (compare Tables 3 and 5). This may be due, in part, to the fact that geothermal fields occur in a variety of basaltic rocks having different bulk compositions; this could result in production of different phases. However, the greater variety may also result from secular changes. Arnorsson *et al.* (1983) point out that during the lifetime of a geothermal system its temperature changes and the composition of reaction phases may change as a result of proportional changes in leaching rates of different rock constituents. This evolution, coupled with incomplete dissolution of the first-formed alteration minerals would result in production of a larger number of alteration phases than would be otherwise expected. In contrast, the hydrothermal experiments were conducted using a single basalt composition. The glass was the most rapidly dissolved phase and its composition determines the secondary phases. The experiments were conducted in rocking autoclaves and therefore minimized the extent of solution inhomogeneities. All of these factors would result in formation of fewer phases in the experiments.

DISCUSSION OF OTHER POTENTIALLY ANALAGOUS DATA

Mineral Deposition

Typical of geothermal wells the world over, the Icelandic geothermal wells are subject to mineral-deposit-clogging. With natural or injection-enhanced steam being ejected from the well, there are temperature drops both from the up-geothermal gradient (as the fluids/steam rise), as well as from the necessary ΔT drop in turbine use of the steam. During these temperature drops, the precipitation of dissolved material can be intense. Quantitative data on these are, in general, lacking. For example, the U.S. Government geothermal project at Valles Caldera in New Mexico in a prehistoric rhyolitic caldera has not been able to keep the wells open due to deposition. Some mineral deposition thermal gradient studies have been done in laboratories, but no general data base has been published. The data that have been accumulating for Icelandic geothermal fluids, for wet-steam and for dry-steam mineral deposition should all be examined for their analog-value to near-field and far-field mineral deposition

around basaltic nuclear waste repositories. As a waste repository is first closed and groundwater re-enters the area, there may be an early period of vapor (steam) generation until P (and T) increase more and provide later conditions conducive to fluids. During either the early or the late periods, the Icelandic data may provide insight into expected mineral deposition associated with temperature drops in water-basalt systems.

Higher than planned temperatures

In at least some of the Icelandic geothermal wells, temperatures are reported as high as 450°C. The data for these geothermal wells should be more closely studied for their analog-value to worst-case scenarios in nuclear waste repositories. For example Gisslasson and Eugster (1984) report that in the Krafla geothermal field in Iceland, that well-bottom temperatures range from 200 to 350°. Note that their data, shown here in Figure 3 closely agree with the lower temperature Icelandic data and also lie along the f_{O_2} -T trend that projects to the 300°C autoclave work. Higher temperature data than shown in figures 3 and 4 exist, but the Icelandic workers have not yet published them (Amonsson, pers. comm., 1983). If the higher temperature Icelandic data can be added to Figures 2, and 3 for example, then the corrosivity (Eh-pH relations of nuclear waste canister could be analogously discussed even for higher-than-planned temperatures.

Density of Packing of Nuclear Waste

The heat flow/heat conductivity data in Icelandic geothermal fields could and should be analog-checked against the calculated similar data for the nuclear waste isolation repository designs for basalt. The density of packing of nuclear waste canisters, of course, is the main parameter in determining peak repository temperatures. Many scenarios for the thermal decay of nuclear waste have been investigated (for example Westinghouse Electric Corp, 1982). The designs and subsequent testing have concentrated on peak temperatures (for example Westinghouse Electric Corp, 1982). The potential analog value of Icelandic data lies in the fact that it covers a temperature range of ambient to at least 270°C already published and reviewed here in Figures 2, 3, and 4. Hence, one could and should consider the lower temperature data of the Icelandic geothermal fields to assist in evaluating the longer term, post-peak, temperature effects on the geochemistry of the repository rock-water interactions. Because of sensible time limits to laboratory work, and because of sluggish kinetics at lower temperatures, the laboratory focus has been on maximum temperatures with extrapolation to what will happen at lower temperatures and longer times. The Icelandic data with essentially a geologic-time base, may represent the only data that are available to evaluate lower temperature geochemical behavior of a basalt repository.

The Role of Glass

One major question which may be answered by analog studies involves the role of glass in controlling water chemistry and secondary mineralogy. Glass dissolves more rapidly than other silicate phases. Therefore, so long as it is present in more than minor amounts, its bulk composition will largely determine the secondary minerals that form and the composition of the fluid. However, once the glass is largely dissolved, the composition of other, more slowly dissolving phases, such as pyroxene and plagioclase will control formation of secondary phases. If the bulk composition of species released by dissolution of glass is different from that of pyroxene, plagioclase, etc. then the secondary phases formed might differ and the composition of the solution could change significantly.

Although the concentration of most dissolved species in autoclave experiments reached fairly stable values, glass is still present in the reactants. Therefore, the concern is that the experiments are not valid indicators of long-term conditions due to the persistence of glass as well as formation of metastable phases.

The data on Icelandic secondary hydrothermal minerals constitute a long list of phases that can be used for comparison to the autoclave works on the hydrothermal alteration of the CBs being investigated for nuclear waste disposal. These comparisons show that no secondary phase has been found in the autoclave work that was not 'anticipated' by the Icelandic alteration mineralogy.

However, the Icelandic list of geothermal secondary minerals is perhaps three times longer than is the combined list of autoclave-produced secondary minerals (see Table 5). This would seem to indicate that the Icelandic analog is very weak, but there is one explanation that may be involved, and, if true would in the end make the analog invaluable.

Specifically, the single factor in Iceland that may make Iceland worthy of much more study is the question of whether the glass phase in Icelandic geothermal fields has been exhausted. The consumption of all glass in the Icelandic geothermal areas would allow a greater diversity of alteration than has been seen in the autoclave experiments which have had water rock ratios of 5/1 to 50/1 and have had only thousands of hours of duration with the result that glass was never exhausted. By comparison the Icelandic geothermal fields are many orders of magnitude greater in age than the longest autoclave experiment, thus allowing a much greater through-put of water (even with long residence times). The greater age in Iceland has also perhaps allowed the Icelandic basalt glass to devitrify. This latter point may be quite possible given that

the Tertiary (Eocene) Icelandic basalts can be as much as twice as old as the Miocene Columbia basalts. Thus, the Icelandic glass may be exhausted either generally or locally either by solution or by crystallization or by both. This idea of glass exhaustion can easily be checked by additional research on the thin-sections of drill core from the Icelandic geothermal fields.

The value of such a study is that it will produce very useful results regardless of what is found:

(A) If the glass is consumed, the secondary mineralogy should be found to correlate at those wells where no glass is left. Interpretation of this secondary mineralogy will be extremely useful in considering the longer term aspects of nuclear waste containment.

(B) If the glass is found not to be consumed, this will allow the existing short duration autoclave work to be validly extrapolated to much longer times than the duration of the autoclave experiments.

The fact that Arnorsson et al. (1983a,b) find that the geothermal fluid chemistry is more affected by temperature than by rock type, permeability, or age of the geothermal field suggests either that the original basaltic glass is not exhausted, or that its removal had little effect on the water chemistry (see Ragnarsdottir et al. (1984) for a discussion of how changes in bulk chemistry and reacting minerals may influence secondary minerals and water chemistry.). It would seem worthwhile to investigate which of these is the case. If the glass is not exhausted after long time periods in geothermal fields, it is unlikely that it would become exhausted in a repository environment. If its exhaustion has no appreciable effect on the water chemistry then this would also be significant to nuclear waste disposal. In any case, the study of the Icelandic parameters to attempt to understand the longer list of geothermal alteration products can not but add greatly to the understanding of nuclear waste isolation problems in the CBs. The main philosophical reason for an analog is to increase knowledge in the lesser known half of the analogy; the Icelandic mineralogic alteration pattern, if understood, will greatly increase the utility of the autoclave data.

CONCLUSION

The ultimate utility of an analog study resides in the strength of proof of similarities between the suspected analogous objects.

We have presented evidence to confirm that Icelandic geothermal fields and the currently designed nuclear waste

repositories in basalt are distinctly similar with regards to many parameters:

- Rock chemistry
- Groundwater geochemistry including Eh-pH value
- Permeabilities despite different volcanic subunit stratigraphy
- Redox equilibria of the water-rock interactions
- * Secondary minerals in so far as they have developed in hydrothermal autoclave studies of the nuclear waste repository country rock.

The similarities in all these parameters are convincing enough that the extensive Icelandic geothermal data base becomes pertinent for discussions concerning nuclear waste isolation in basalt. Furthermore, we feel that the analog is sufficiently strong to warrant considerable future effort in at least the areas of:

- * mineral deposition along temperature gradients
- * the effects of both historic and geologic time on temperature and chemistry at a given geothermal well or field
- the role of glass in the development of ensuing aqueous geochemistry and secondary minerals

Knowledge from Iceland about these latter three aspects of geothermal fields should greatly extend understanding of data already on hand from shorter duration hydrothermal autoclave studies of Columbia Plateau basalts intended for nuclear waste receptors. Search and study of the entire Icelandic geothermal data base should continue to the exhaustion of all other possible analogous parameters of benefit to nuclear waste discussions.

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APPENDIX A
SECONDARY MINERAL CHEMISTRY

actinolite	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
albite	$\text{NaAlSi}_3\text{O}_8$
amphibole	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
analcime	$\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$
anhydrite	CaSO_4
ankerite	$\text{CaFe}(\text{CO}_3)_2$
calcite	CaCO_3
celadonite	illite group
chabazite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 6\text{H}_2\text{O}$
chalcedony	amorphous SiO_2
chlorite	$(\text{Mg}, \text{Fe})_6\text{Si}_4\text{O}_{10}(\text{OH})_8$
cristobalite	SiO_2
epidote	$\text{Ca}_2\text{FeAl}_2\text{Si}_3\text{O}_{12}(\text{OH})$
epistilbite	$\text{CaAl}_2\text{Si}_6\text{O}_{16} \cdot 5\text{H}_2\text{O}$
gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$
gmelinite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 6\text{H}_2\text{O}$
gyrolite	$\text{Ca}_4(\text{Si}_6\text{O}_{15})(\text{OH})_2 \cdot 3\text{H}_2\text{O}$
hematite	Fe_2O_3
heulandite	$\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 6\text{H}_2\text{O}$
ILLITE GROUP	$\text{K}_{1-x}\text{Al}_2\text{Al}_{1-x}\text{Si}_{3+x}\text{O}_{10}(\text{OH})_2$
laumontite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 4\text{H}_2\text{O}$
leucoxene	hydrated TiO_2
magnetite	Fe_3O_4
mesolite	$\text{Na}_2\text{Ca}_2\text{Al}_6\text{Si}_9\text{O}_{30} \cdot 8\text{H}_2\text{O}$
montmorillonite	$\text{Ca}_{.33}\text{Al}_{1.77}\text{Mg}_{.33}\text{Si}_4\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O}$
mordenite	$\text{CaAl}_2\text{Si}_{10}\text{O}_{24} \cdot 7\text{H}_2\text{O}$

prehnite	$\text{Ca}_2\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_2$
pyrite	FeS_2
pyrrhotite	Fe_{1-x}S
quartz	SiO_2
reyerite	$\text{KCa}_{14}\text{Si}_{24}\text{O}_{60}(\text{OH})_5 \cdot 5\text{H}_2\text{O}$
saponite	$\text{Ca}_{.33}\text{Mg}_3\text{Al}_{.33}\text{Si}_{3.77}\text{O}_{10}(\text{OH}) \cdot n\text{H}_2\text{O}$
scolecite	$\text{CaAlSi}_3\text{O}_{10} \cdot 3\text{H}_2\text{O}$
smectite group	$(1/2\text{Ca}, \text{Na})_{.33}(\text{Al}, \text{Mg}, \text{Fe})_2(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O}$
sphene	$\text{CaTiSiO}_4(\text{OH})$
stilbite	$\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 7\text{H}_2\text{O}$
thomsonite	$\text{NaCa}_2[(\text{Al}, \text{Si})_5\text{O}_{10}]_2 \cdot 6\text{H}_2\text{O}$
truscottite	$\text{CaSi}_4\text{O}_9(\text{OH})_2$
wairakite	$\text{CaAlSi}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$
zeophyllite	$\text{Ca}_4(\text{Si}_3\text{O}_8) \cdot (\text{OH})_2\text{F}_2 \cdot 2\text{H}_2\text{O}$