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Application of Stable Isotope Techniques
to Tracing Recharge of Geothermal Systems
on the Reykjanes Peninsula in Iceland

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ABSTRACT

The deuterium content of water has become an important tracer in mapping hydrological flows and in determining recharge for geothermal systems. In most cases, the technique is simple to apply and is usually consistent with other geochemical methods. There are, however, instances where the methods give diverging results. An example of this is the depletion in the deuterium content of some geothermal brines below levels that can be accounted for by meteoric feed. The evolution of stable isotope methods is examined with particular emphasis on fractionation processes active within geothermal systems. Models and theories which reconcile anomalies between geochemical and isotope analyses are developed and discussed. The geothermal systems of the Reykjanes Peninsula in southwestern Iceland, specifically Reykjanes and Svartsengi, are used for this investigation. The brines of the two systems have identical deuterium concentrations, yet differ in salinity, the existence of mineral-brine equilibria that could affect the deuterium levels in these systems is discussed. Questions are raised concerning the application of deuterium analyses in systems where alteration processes have changed the hydrogen isotope composition of the host rocks. It is concluded that caution should be exercised in interpreting analyses of brines evolved from high-temperature geothermal systems. A model is presented for the Reykjanes and Svartsengi systems which reconciles their divergent characteristics on the basis of differing sources of meteoric water recharge and recirculation of flashed reservoir fluids.

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1. INTRODUCTION

Stable isotope hydrology is a technique which can be used to trace groundwaters to their point of origin through analyses of their deuterium and oxygen-18 concentrations. The technique often presupposes a meteoric origin for the waters being traced, yet may be expanded to accommodate possible contributions from other sources. Connate water and seawater may contribute to subaerial water flows in addition to meteoric water. In applying isotope hydrology to determine geothermal recharge, allowances must be made for the natural mechanisms which alter isotope levels in these systems. Evaporation will cause isotopic fractionation between vapor and the remaining liquid. Often, the effect of partial vaporization on the isotopic concentrations of the brine is unknown. Further difficulties in applying isotope techniques to geothermal systems are encountered in the oxygen isotope exchange which may occur in some reservoirs between the brine and silicates and/or carbonates in the rock matrix.

This paper reviews the development of stable isotope techniques and their application to geothermal systems. Models for the isotopic modification of geothermal brines are then constructed. Geochemistry as a complementary analytical technique is used as an aid in constructing and criticizing these models. The Reykjanes Peninsula in southwestern Iceland is an area with several geothermal systems whose recharge characteristics have frequently been debated. The Reykjanes system is one that is well documented geochemically and one that serves well for particular emphasis.

2. ISOTOPE TECHNIQUES

Measurements of isotope concentrations; are performed through mass spectrometry. Water is reacted to form either hydrogen or carbon dioxide. These gases are ionized and passed through a potential where the momentum of the heavier species retards their deflection in a magnetic field and creates a separation of flow on the basis of weight. Absolute concentrations are difficult to ascertain and relative abundances are therefore reported as ratios of the proportion of light to heavy species in the sample to those in a standard. Data are presented in terms of δD 's and $\delta^{18}O$'s where:

$$\delta = \left[\frac{R_{sample}}{R_{standard}} - 1 \right] 1000$$

R_{sample} is the ratio of deuterium to hydrogen or of ^{18}O to ^{16}O in the sample and $R_{standard}$ is the ratio in the standard. The common reference for oxygen and hydrogen isotopes is Standard Mean Ocean Water (SMOW). A sample of $\delta D = -30$ is depleted in deuterium by thirty parts per thousand (per mil) relative to SMOW. SMOW has an absolute deuterium concentration of 158 ± 2 atomic parts per million and oxygen-18 concentrations of 1989.5 ± 2.5 atomic parts per million. Most meteoric waters do not differ greatly in isotopic ratios from that of seawater and hence the standard is within appropriate range for hydrology applications.

Fractionation is a process by which one isotopic species is enriched relative to another as a result of a chemical reaction or phase change. A fractionation constant, α , may be defined for a process:

$$\alpha_1 = \frac{([H_2^{18}O]/[H_2^{16}O])_{liq.}}{([H_2^{18}O]/[H_2^{16}O])_{vap.}}$$
$$\alpha_2 = \frac{[H_2^{18}O]/[Si^{16}O_2]^{1/2}}{[H_2^{16}O]/[Si^{18}O_2]^{1/2}}$$

where α_1 denotes the fractionation or partition constant between ^{18}O and ^{16}O in liquid-vapor equilibrium and where α_2 denotes the fractionation constant in the equilibrium of silica with water. In these cases, the fractionation constants are the same as equilibrium constants for the reactions. This is an important point, because only in equilibrium fractionation processes are the isotope compositions of the products known with any degree of certainty.

With the development of an accurate isotope ratio mass spectrometer, considerable attention was given to the investigation of isotope levels in the hydrological cycle. In a series of papers by such authors as Friedman (1953), Epstein and Mayeda (1953), and Dansgaard (1954), the trends in isotopic variations for meteoric and groundwater flows were elaborated. Heavy isotope concentrations in atmospheric water vapor are reduced with increasing distance from the sea and with higher altitude and latitude. Temperature is a key factor. Precipitation from polar regions is depleted in heavy isotopes relative to precipitation from more temperate regions. As a cloud moves across a land mass arid releases moisture, the cloud will become increasingly depleted in heavy isotopes, especially in movements toward the poles, away from the sea, or over elevated terrain. Patterns of depletion have proven to be sufficiently consistent that rough contour maps may be drawn outlining the mean deuterium or oxygen-18 concentrations of the precipitation.

Craig (1961) reported on the isotopic analyses of 400 samples of precipitation from sources scattered globally. Plotting δD as a function of $\delta^{18}\text{O}$, a line with a slope of 8 and intercept 10 was found to fit the data with minimal scatter. This relation is due to the proportionality of the D/H fractionation to that of $^{18}\text{O}/^{16}\text{O}$. Condensation of vapor in the atmosphere is essentially an equilibrium process. The dependence of the fractionation constants on temperature is reflected in the slope of the meteoric water line.

Assuming that vaporization within geothermal reservoirs occurs with phase equilibrium and net removal of steam, changes in the isotope concentrations may be quantified. Craig *et al.* (1953) reported isotope fractionation constants for water-vapor equilibrium at 100°C. Bottinga *et al.* (1968) found that fractionation constants for the interphase equilibrium may be given by the equation:

$$1000\ln\alpha=A+B(10^3/T) + C(10^6/T^2) + D(10^9/T^3)$$

where T is in degrees Kelvin and the constants for the two partitions are given in Table 1.

	D/H	18/16
A	559.69	-7.174
B	-808.06	4.716
C	372.81	-.058
D	-54.41	-

Equilibrium cannot always be assumed in the vaporization process. Craig (1963) has shown that for low-temperature acid springs, kinetic effects dominate, and changes in the isotopic composition do not reflect liquid-vapor equilibrium. Nonequilibrium kinetic effects also dominate during evaporation under low humidity conditions or during evaporation from a system without circulatory or convective flows, but they are reduced with increasing pH in geothermal systems.

Another consideration in applying isotope techniques to geothermal systems, is that reservoir rocks contain substantial weight percentages of oxygen. Isotopic exchange between rock and fluid may therefore occur, especially in systems with silicate and carbonate rocks. Clayton and O'Neil (1972) determined fractionation constants for the silica-water system and found that the fluid phase is consistently enriched in oxygen-18 relative to the solids with increasing temperature. Rocks may

become leached of the heavier species with time, and the fluids which circulate through them will no longer show noticeable enrichment in oxygen-18. The oxygen-isotope shift is dependent on lithology, water to rock ratios and the relative concentrations of isotopic species in the reactants. Most geothermal systems extend deeper than the probe of a borehole and, therefore, little is known about the mineral species in the deep aquifers or their isotopic concentrations. Water to rock ratios at depth are also difficult to ascertain.

3. WATER TYPES

Meteoric water is by far the dominant contributor to the volume of most geothermal brines. Some systems located close to the sea, such as in Japan and Iceland, show substantial influx of seawater. The sources of waters which contribute to geothermal reservoirs were first investigated by White (1957) after he discovered geochemical inconsistencies in the model of strictly meteoric recharge for several systems. In order to explain such phenomena as the distinct chemical profiles of waters in proximity to recent volcanism, and the high mineral content of some low-temperature fluids, White (1957) proposed the model of distinct generic waters contributing to these systems. He subsequently (White, 1973, 1979) defined and delineated each of the various generic waters as follows:

Meteoric Water- This refers to water which has been recently involved in atmospheric circulation, including pluvial, vadose and other groundwaters. Recent means no more than a small fraction of a geological period. Rain waters which undergo changes in their solution chemistries as a result of hydrothermal alteration processes or other interactions with the ground in the course of their flows would still be considered meteoric.

Evolved Connate Water- These waters are often referred to as sedimentary or formation waters and consist of fluids evolved from the interstices of unmetamorphosed sediments and water which may have been driven therefrom. Evolved connate water by definition can only refer to water which has been out of contact with the atmosphere for appreciable portions of geological time.

Ocean Waters- These are simply the brines of the oceans. The term excludes the waters of inland seas which may have acquired salinity through the solution of evaporites.

Metamorphic Waters- These are waters that were associated with rocks during metamorphism and can be considered waters of dehydration. This water type is

distinct from the evolved connate variety by having undergone a near-complete exchange of oxygen atoms with those of the rock crystals in the course of metamorphism; however, there is no clear line and the two divisions form a continuum.

Magmatic Waters- This term generally refers to waters which have been derived from or equilibrated with magma without distinction made regarding the ultimate source of the water (*i.e.* meteoric, evolved connate). The term includes both plutonic (at depth) and volcanic (near surface) magmas.

The isotopic composition of evolved connate brines varies greatly. Generally they tend to be depleted in deuterium relative to ocean water and somewhat enriched in oxygen-18 relative to meteoric water. The isotope evidence indicates infiltration of formation waters with meteoric waters in almost all cases (Clayton *et al.*, 1966). According to Taylor (1979), the depletion in the deuterium content of the connate brines follows the general deuterium-depletion trend in meteoric waters.

Metamorphic waters present problems because it is impossible to take samples of these waters. Isotope values for metamorphic waters are obtained through the analysis of the isotopic compositions of rocks and the estimated temperatures at which they are thought to form. In some cases, fluid inclusions can be analyzed, but the results may prove misleading; metamorphic rocks cool slowly and associated waters would change composition by reequilibration at lower temperatures. No references have yet been found that characterize metamorphic waters in terms of solution chemistry. Metamorphic waters in general must be said to play a minor role as a component in geothermal systems.

Ocean water is the only generic water that is relatively constant in terms of its chemical and isotopic compositions. According to White (1957), the iodide concentrations of the Oceans are negligible to evolved connate waters. Seawater is also relatively depleted in boron. Sulfur is present in seawater only as sulfate. Lithium

is usually absent. An important characteristic of seawater is its isotopic composition. The enrichment in heavy water isotopes of any coastal geothermal system will usually be due to the influx of marine waters. The presence of seawater in such systems is an obvious consideration and several cases have been documented. The work of Truesdell *et al.* (1981) with regard to the Cerro Prieto geothermal field is an example.

Magmatic waters are of special interest here because volcanic systems provide the heat source for most geothermal systems. Contributions to the geothermal fluids from magmatic sources are almost certain. Burnham (1979) gives a good summary of the water-magma interactions with reference to geothermal systems. Water in magma greatly affects its viscosity. Hydration breaks silicate bonds which impede flow. The solubility of water in magma increases with increasing pressure, so that at great depth magma may contain as much as 30 weight percent water. In surfacing, decreasing pressure will drive water from the melt, thus increasing viscosity. The dissolution of water is a natural and important aspect of the mechanics of volcanic intrusion. According to Burnham (1979), the initial H₂O contents of the magmas with which extensive hydrothermal activity is associated generally range from about **2.5** to **6.5** weight percent with the median close to **3.0** weight percent. It would appear that the role of magmatic waters in geothermal systems has been significantly underplayed. Dilution of magmatic waters with meteoric or ocean waters will likely occur; nonetheless, some residual volcanic water should be found at depth. Many researchers tend to interpret the presence of volcanic volatiles as an indication of the proximity of the reservoir to the magmatic intrusion, and do not consider the evolution of water with the volatiles.

4. FIELD STUDIES

Deuterium levels of precipitation and groundwater flow paths in Iceland have been studied in detail by Arnason (1976). His work is thorough and includes examination of the climatic record through isotope studies of glacial ice. With regard to the Svartsengi and Reykjanes systems, Arnason (1976) suggests a model involving mixture of meteoric water flowing from the area of the Krisuvik system with increasingly greater proportions of seawater flows at depth toward the Reykjanes system. Arnason (1976) completes the model by suggesting that the water becomes more saline by solution of evaporites as it flows through volcanic sediments.

Problems have arisen in the application of deuterium studies to tracing recharge. Craig (1963) showed that for most geothermal water the deuterium content is approximately equal to that of the local meteoric water. Where deuterium levels are depleted relative to the local precipitation, it is probable that the system is fed from an aquifer originating in higher terrain where deuterium levels are lower. But what if the brine is more depleted in deuterium than any possible meteoric source water Mariner *et al.* (1983) discusses this question with regard to a number of geothermal systems in the Northern Basin and Range Province (California-Nevada). If the assumption of a deep aquifer is correct then the nearest recharge for thermal waters near Elko, Nevada is in western Montana. This seems to be stretching plausibility. A similar but more acute problem was encountered by Arnason (1976) in his study of the hydrology of low-temperature geothermal fields near Husavik and Akureyri in northern Iceland. There is no location in Iceland where meteoric waters are so depleted in deuterium as to provide recharge for a system of $\delta D = -142$ at depth. The same situation arises in the Kristmannsdottir and Johnsen (1982) examination of the thermal waters of the Akureyri region. In all these cases, an argument is made for an aquifer by water that precipitated during an Age of colder climate.

One of the assumptions made in applying deuterium studies to hydrology is that the climate of the earth has not changed appreciably during the last two hundred years. Dansgaard *et al.* (1968) attempted to verifying the constancy of meteorological events through study of ice cores in northern Greenland. This study traced climatic history stable isotopes of ice. The ice cores from Camp Century were not appreciably disturbed by the melting and percolation of surface ice during summer periods. The studies at Camp Century clearly showed that if the climatic changes of northern Greenland **are** indicative of the earth as a whole, then the stable isotope ratios of precipitation have remained relatively constant for the past 10,000 years, or since the end of the last Ice Age in the Pleistocene.

Pronounced deuterium depletions in Icelandic geothermal systems may have other explanations than a prehistoric water source. Muehlenbachs *et al.* (1974) have documented the presence of several granitic rocks from Iceland with abnormally low ^{18}O concentrations. Studies have shown that nearly all unaltered basalts from oceanic islands and mid ocean ridges have $\delta^{18}\text{O}$ values of $+6.0 \pm .5$ permil relative to SMOW. Several samples of unaltered basalts have been found in Iceland with $\delta^{18}\text{O}$ values as low as $+1.7$ permil. Basalt samples on the Reykjanes Peninsula have been found with values of $+4.9$ and $+4.8$ permil. Muehlenbachs *et al.* (1974) show that these depletions are not the result of weathering of the extruded magmas by meteoric water; rather they are solidified from magma which was abnormally depleted in these heavier species. Possible explanations for this include 1) unusual properties of Icelandic magmas, 2) assimilation or exchange of oxygens from rocks which had previously been depleted in oxygen-18 through the action of meteoric waters in geothermal systems. The second explanation is more probable and has been given considerable attention by Taylor (1974, 1978, 1979).

5. REYKJANES PENINSULA

The Reykjanes Peninsula is located in southwestern Iceland and straddles an active volcanic belt in which many high temperature geothermal fields are located. The Reykjanes field is located at the tip of the southwestern peninsula and Svartsengi 15km inland (see Figure 1). Both areas are covered by post-glacial lava flows protruded by a scattering of hyaloclastite ridges, Surface manifestations of recent volcanic activity include shield volcanos and eruptive fissures.

The Reykjanes Peninsula is highly faulted and fractured. General characteristics of the formations are derived through drill cuttings from geothermal wells. Subaerial lava flows, tuffaceous sediments, hyaloclastic tuffs, and breccia dominate the stratigraphic section in the uppermost 1000m. Below this, 50% of the rock is basalt with the rest comprised of tuffaceous rocks.

According to Tomasson and Kristmannsdottir (1972), the groundwaters in the peninsula are comprised of seawater to a distance of 30km inland. Substantial precipitation of secondary minerals has occurred on the boundaries of the Reykjanes system which has lead to the formation of a mineral cap. This cap effectively isolates the system's brine from the surrounding fresh groundwaters. A hole drilled 100m deep a distance of 100m from the edge of the geothermal field shows 30% of the local tidal variation and a temperature the same as the surrounding sea. A hole drilled to the same depth within the system shows a temperature of 150°C with no tidal variation. Pressure differentials of 10 atm. between within and without the system have been measures at the 1700m level. Svartsengi is thought to have a similar mineral shell (Franzson, 1983).

Properties peculiar to the Reykjanes field are discussed by Bjornsson *et al.* (1972). The field is one of the smallest high temperature areas in Iceland, covering only 1 km². There are numerous surface manifestations including a geyser, fumaroles,

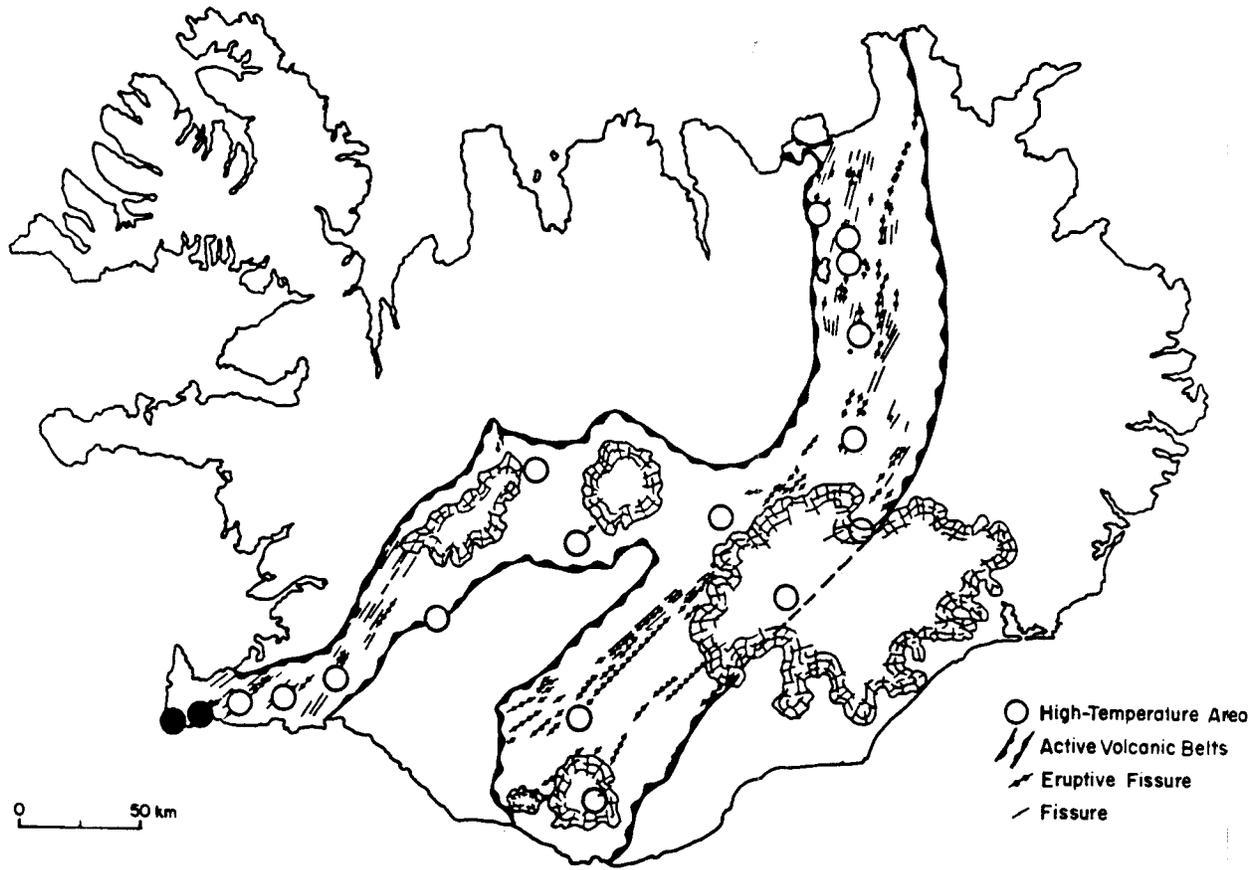


Figure 1. The distribution of high-temperature geothermal activity in Iceland in relation to tectonic features. Compiled by K. Saemundsson; from Arnorsson (1978).

mudpots, steam vents and boiling springs. Figure 2 shows the main geologic features of the Reykjanes geothermal area.

The debate over the origins of the Reykjanes brine has continued for several years. Early researchers assumed that because of the field's proximity to the sea and the high salinity of its fluids, the brine must consist entirely of heated ocean water. White *et al.* (1963) cited similarities between the Reykjanes brine and those of mineral springs of connate origin and oil field brines of the sodium-calcium-chloride variety, and suggested a connate origin. While the geology of the area does not support such a theory, it is apparent that modification of seawater is occurring and that a 'young' connate brine may more accurately describe the Reykjanes brine.

Bjornsson *et al.* (1972) suggested that the differences between the chemistries of the Reykjanes brine and seawater were due to water-rock interactions. Specific references were made to concentrations of Mg^{+2} , SO_4^{-2} , SiO_2 , K^+ and Ca^{+2} . Their reported brine sample compositions are compared to seawater in Table 2 (all concentrations are in ppm):

	pH/T(C)	Na^+	K^+	Ca^{+2}	Mg^{+2}	SO_4^{-2}	Cl^-
Reykjanes 8	6.1/20	9610	1348	1530	16	30.3	19260
Seawater	7.6/20	10500	416	386	1282	2640	19800

Table 2
Brine composition in Reykjanes Well 8, compared to seawater.

Bjornsson *et al.* (1972) state that sodium levels in the geothermal brine would decrease due to the ion exchange of Na^+ for Ca^{+2} in the formation of alacime. As alacime will not form above $230^{\circ}C$ and its presence in the system is confined to the uppermost sections, this exchange would be minor. A more suitable mechanism might be the albitization of calcic feldspars. Differences between the Reykjanes brine and seawater cannot all be explained by water rock interactions. Deuterium levels were not discussed in the Bjornsson *et al.* (1972) paper. Also, CO_2 levels are quite elevated

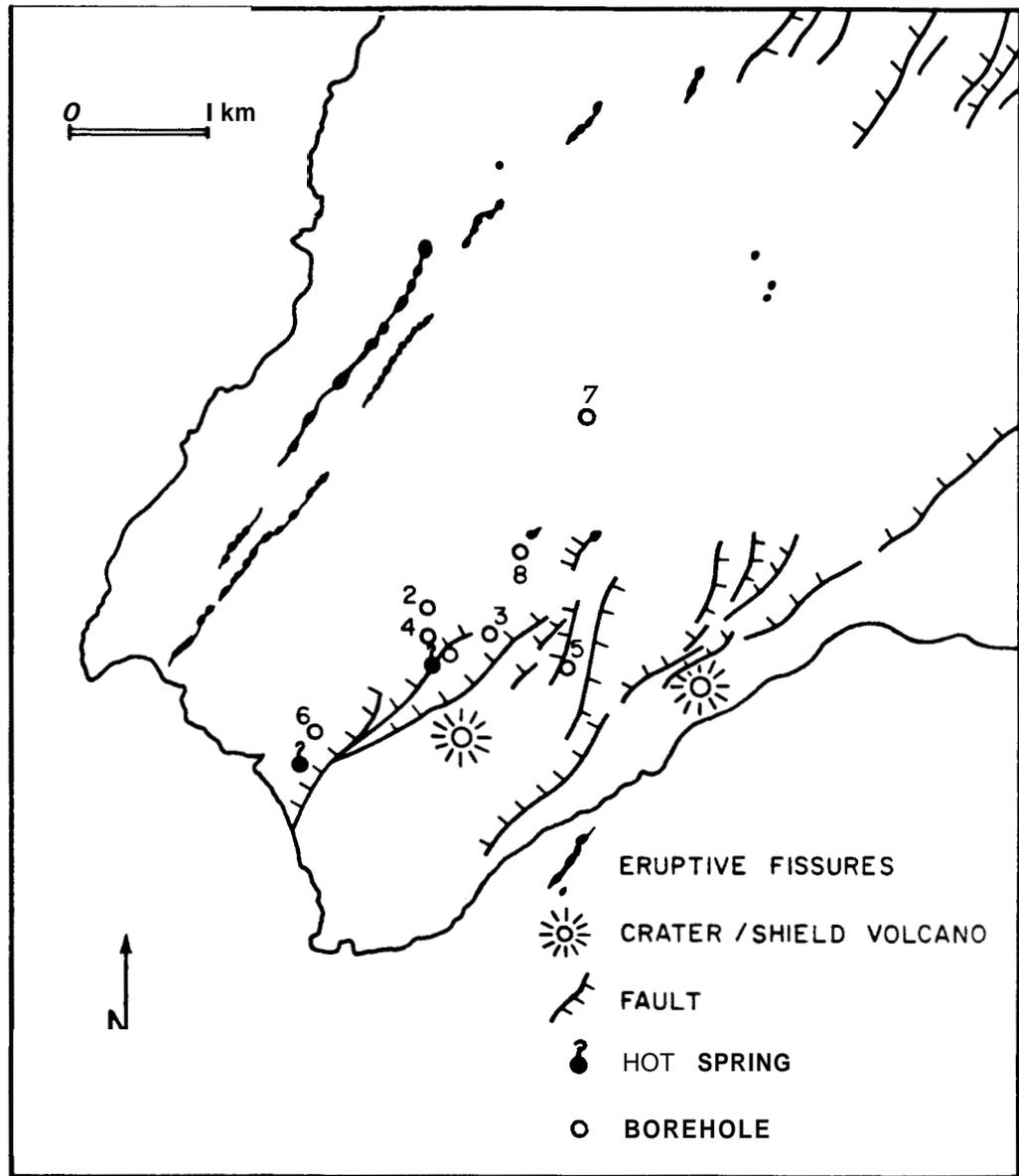


Figure 2. Geologic features of the Reykjanes geothermal area. Based on geologic map by J. Jonsson.

in the brine. This could be due to leaching of carbonate in reservoir rocks or occluded gases or a contribution of juvenile CO_2 .

The work of Tomasson and Kristmannsdottir (1972) documents the alteration species present and shows trends in the geologic column. At Reykjanes they examined drill cuttings from the surface to a depth of 1710m. The primary alteration minerals found in the upper zones were zeolites, forming at temperatures below 230°C. The main zeolites were mordenite, stilbite, mesolite and analcime. Lesser amounts of prehnite spanned the transition from zeolite to epidote alteration product zones. Prehnite is believed to occur between 260 to 270°C. Clay minerals were found throughout the depths examined. Smectites predominated in the upper zones and were mixed with chlorites in the area of prehnite formation. Chlorites also appeared in the deeper zones with epidote. The chemical formulas for each of these minerals is given in Table 3.

Basalt	
calcic plagioclase	$CaAl(SiAl)Si_2O_8$
clinopyroxene	$CaAlSi_2O_6$
olivine	$(MgFe)_2SiO_4$
Zeolites	
analcime	$NaAlSi_3O_8 \cdot H_2O$
mordenite	$(CaNaK)Al_2Si_{10}O_{24} \cdot 7H_2O$
stilbite	$NaCa_2Al_5Si_{13}O_{36} \cdot 16H_2O$
mesolite	$Na_2Ca_2Al_6Si_9O_{30} \cdot 8H_2O$
wairakite	$CaAl_2Si_4O_{12} \cdot 2H_2O$
Clay minerals	
smectites	$Ca_{.33}(AlMg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$
chlorites	$Mg_6(AlSi_3)O_{10}(OH)_8$
Epidote	$Ca_2Al_2FeOSi_4Si_2O_7(OH)$
Prehnite	$Ca_2Al_2Si_3O_{10}(OH)_2$

Table 3
Host **rock** and alteration minerals.

The relative enrichment of the alteration minerals in hydrogen should be apparent. Further hydrogen species may be incorporated into the rock matrix through the precipitation of brucite (magnesium hydroxide). This mineral is commonly associated with seawater geothermal systems. Kristmannsdottir (1976) estimated that between 50 to 80 percent of the original rock matrix at Reykjanes has undergone alteration to clay minerals, calcite, quartz, zeolites, prehnite or epidote.

Alteration at the Svartsengi field has been studied by Franzson (1983). The same basic pattern as a Reykjavik is repeated. Franzson's (1983) study was based on drill cuttings to the 2000m level. He mapped alteration histories through analysis of amygdale fillings in order to establish present mineral-brine equilibria.

The work of Olafsson and Riley (1978) on the Reykjanes system argued that meteoric water entering the system has acquired considerable salinity; total dissolved solids of 12,100 ppm. Their analysis was based upon correlations relating salinity with oxygen-18 and deuterium levels as follows. Consider the Rayleigh distillation formula given by Friedman et al. (1964):

$$R = R_0 \Theta^{(\alpha-1)}$$

where R_0 = initial isotope ratio of the liquid R = isotope ratio at any stage in process
 α = fractionation constant for temperature of process θ = proportion of liquid remaining
Salinity at any stage in this process is given by:

$$S = S_0 \theta^{-1}$$

where S_0 is the initial salinity and S the salinity at any stage. Olafsson and Riley (1978) combined the two equations to give:

$$\ln S = -1/(\alpha-1) \ln R + 1/(\alpha-1) \ln R_0 + \ln S_0$$

By performing a regression analysis on salinity data as a function of deuterium and oxygen-18 concentrations for individual drillholes and springs, the researchers extrapolated to find the point S_0 where these two lines intersected the mixing line between local meteoric water and seawater. The correlation coefficients for the deuterium and oxygen-18 lines are impressive; however, the extrapolated S_0 of about 11.9g/kg for meteoric water entering the system is excessive. The analysis fails to account for the enrichment of the brine in oxygen-18 that would be expected with water-rock interactions. Sigvaldason and Fridriksson (1968) are cited in Olafsson and Riley (1978) with regard to the leachable salt residues found in ash deposits on the island of Surtsey. After 2-3 years of weathering, ash deposits at the 80m level still contained 1.2 g/kg of leachable salts. The volcanic sediments beneath the Reykjanes area may also be expected to contain significant amounts of salts. With the highly fractured nature of the rift zone, they argued that evaporated seawater could have become trapped, thereby providing a supply of concentrated brine to the Reykjanes system. Other criticisms of the Olafsson and Riley (1978) analysis are that no evaporites have been found in the geologic column and that any incorporation of evaporated seawater into the brine mixture would effect the isotope concentrations as well.

Correcting for oxygen shifts caused by evaporation is difficult because additional shifts may occur at depth by the convective mixing of flashed reservoir fluids. If the fluid of drillhole 8 is a good approximation of the brine at depth, the regression line shown in Figure 3 for the Reykjanes samples may be moved so that the drillhole 8 sample lies on the mixing line for seawater and meteoric water. The oxygen-18 enrichment with this assumption works out to be 2.4 permil, which is a bit greater than expected. The salinity that meteoric water must acquire before entering the system with this correction is 9.8 g/kg; the initial brine appearing to be a mixture of equal parts seawater and local meteoric water. The value of 9.8 g/kg does not present a

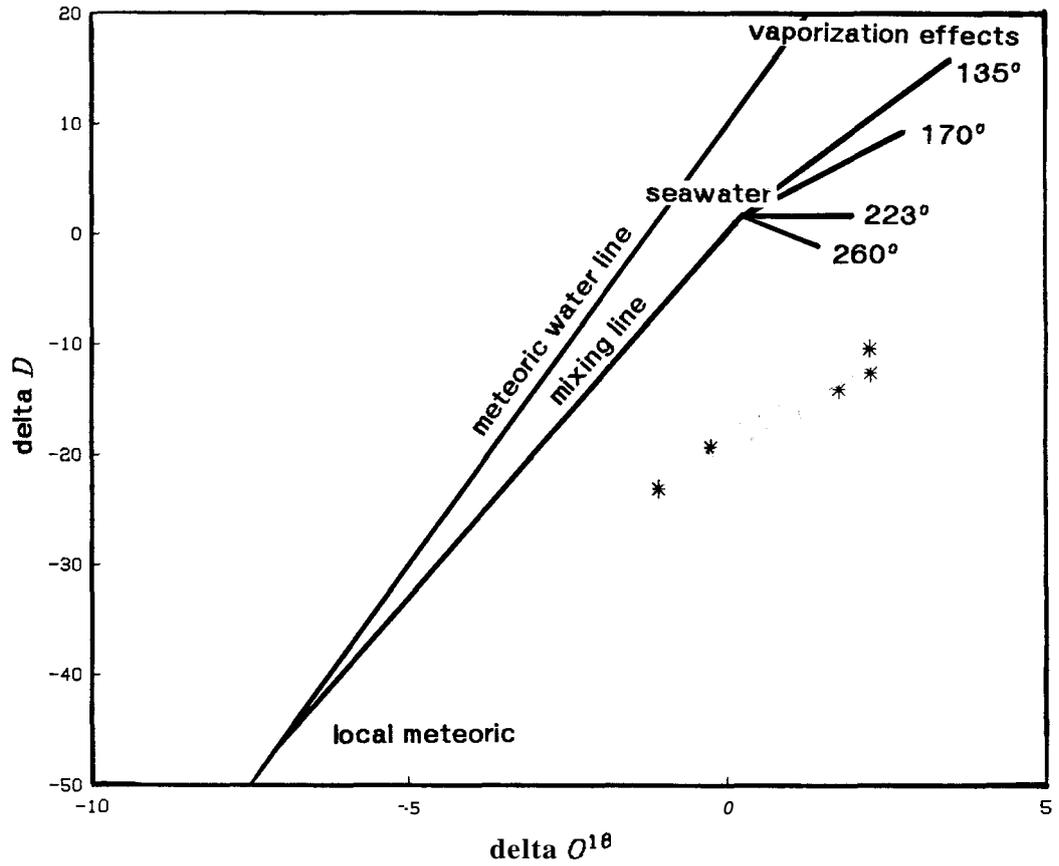


Figure 3. Deuterium and oxygen-18 data from Olafsson and Riley (1978). Also shown are the meteoric water line, mixing line for local meteoric water and seawater, and vaporization effects on seawater.

significant improvement over the value of 11.9 g/kg. It is likely that the fluids of drillhole 8 do not give a good approximation of the deep brines of the system. It is also quite possible that the recharge water is not locally derived.

The main problem addressed in this paper was originally posed by Gudmundsson *et al.* (1981). The concentrations of chloride and stable isotopes are listed in Table 4 for the Reykjanes 8 brine and a brine from similar depth in the Svartsengi field. The chloride concentration would suggest the Reykjanes brine consists entirely of seawater. The deuterium levels, however, suggests that the brine contains at least 48% meteoric water, assuming that this water is of local origin. Svartsengi in comparison has an identical deuterium concentration, yet a salinity much less than that of Reykjanes. The challenge here is to reconcile the deuterium and chloride analyses into a consistent hydrological model.

	<i>Cl</i> ppm	δD 0/00	$\delta D^{18}O$ 0/00	<i>T</i> (°C)
Reykjanes	19,727	-23	1	283
Svartsengi	12,070	-23	3	239
Seawater	18,980	1.5		13
Rainwater	-0-	-48	-7.25	-

Table 4
Concentration of chloride and stable isotopes in Reykjanes and Svartsengi brines, also in local rainwater and seawater.

6. WATER-ROCK INTERACTIONS

Basalt-seawater interactions have been given considerable attention by scientists whose particular interests are in plate tectonics and processes along mid-ocean ridges. Considerable work has been performed since the publication of Bjornsson *et al.* (1972); Bischoff and Dickson (1975); Seyfried and Bischoff (1981); Seyfried and Mottl (1982). Mottl (1982) gives a good review of this research.

Seawater when heated will begin to precipitate brucite (magnesium hydroxide). This mineral has decreasing solubility with increasing temperature. Its formation will lower the pH of the solution. Acid conditions will in turn catalyze the hydrolysis of silicates, and Ca^{+2} will be released in ionic exchange. Increasing levels of calcium will lead to precipitation of anhydrite (calcium sulfate) which, like brucite, has decreasing solubility with increasing temperature. The amount of leachable Ca^{+2} should be in sufficient excess of SO_2 to make appreciable concentrations in the resulting solution.

Hydrothermal alteration is a type of metamorphism involving recrystallization of a parent rock to new minerals which are more stable under changed conditions (Rose and Burt, 1979). Several factors influence the formation of alteration minerals and these may vary in importance from field to field. The main factors are a) temperature b) pressure c) rock type d) permeability e) fluid composition and f) the duration of hydrothermal activity (Browne, 1978). In his review of alteration mineralogy, Browne (1978) includes a table showing the main alteration species found in several systems from around the world. Despite the diversity of geology in these systems, a group of 50 minerals are listed, most of which are common to a number of systems. For example, quartz, smectites, chlorites, anhydrite, calcite, wairakite and epidote are a few of the minerals formed in both the Imperial Valley of California and in the high temperature areas of Iceland. The host rocks of the Icelandic fields are primarily basalt while those of the Imperial Valley are sedimentary. Host-rock types influence

alteration processes mainly by controlling permeability. The initial composition of the rock has little effect on the alteration products above about 280°C. Alteration can seldom be achieved with very low water-rock ratios. Access of fluids to the host rock, along with temperature are the most important variables in determining the rate and extent of alteration. The water to rock ratio, defined as the total mass of water that has passed through the system, integrated through time and divided by the total mass of altered rock in the system, is often determined through examination of the alteration products (Mottl, 1983).

Considerable laboratory work has been performed to establish values for clay mineral-water fractionation constants. The main thrust of these investigations was to clarify sedimentary processes. Most experiments were carried out at temperatures far below those applicable to geothermal systems. In almost all cases studied, no large-scale hydrogen or oxygen isotope exchanges were found to occur. All evidence indicates that isotope equilibrium is established at the time of clay formation and that little to no fractionation occurs after this except in the disintegration and recrystallization of the clay structures. O'Neil and Kharaka (1976) performed fractionation experiments at temperature of 100°C. They found only minor isotope exchange, even after periods as long as two years. D/H exchanges of 8-23 percent could be expected to occur in clay-seawater systems at ambient seawater temperatures only after the passage of 2 to 3 million years. It is, therefore, evident that clay-water interactions are responsible for buffering deuterium in the brines at Reykjanes and Svartsengi only if new clays are formed as alteration products. It is doubtful that alteration has preceded as rapidly or to the extent necessary to effect brine deuterium levels.

Zeolites cannot take part in any deuterium buffer system as their structural hydrogens are quite unstable and cannot provide effective fractionation. Also, zeolites are only peripherally involved in the geothermal systems. They do not form above'

fractionation values from these experiments were then applied to epidote and fluid samples from the Reykjanes and Svartsengi systems. Both Reykjanes and Svartsengi epidotes record the presence of a significant deep- source non-seawater contribution to the brine. The deuterium values of the epidotes are consistent with formation and equilibration in a brine of $\delta D = -23$. Judging from the alteration mineralogy as outlined by Mottl (1983), both systems have water to rock ratios greater than 10. Clearly, it follows that the epidote deuterium levels are set by the brine.

7. MIXING MODEL

To reconcile the diverse aspects of the Reykjanes system, a simple mixing model has been constructed which depends upon circulation in a convection cell. The framework for this approach was given by Arnorsson (1978) with reference to the Reykjanes, Svartsengi and Krisuvik systems. Arnorsson (1978) did not consider deuterium data, nor did he probe the possible sources for recharge for the Reykjanes system. As was seen from the evidence presented by Tomasson and Kristmannsdottir (1978), the mineral shell which caps the Reykjanes system is an effective barrier to fluid flow and serves well to isolate the system from any intrusion of the surrounding near surface groundwaters.

In order to account for deuterium depletions in the brine of the Reykjanes system, some meteoric-water contribution must be involved. The possibility of a deep alteration mineral-brine equilibrium acting to depress deuterium levels is not considered. In most traditional approaches, the deuterium concentrations of the local precipitation and groundwater are used to determine if the recharge occurs locally. Utilizing the reported analyses of brines from the Reykjanes field of Olafsson and Riley (1978), a geochemical profile of the deep brine may be obtained by referring to the drillhole 8 samples. This particular well is 1754m deep and is lined to a depth of 1685m with perforations for aquifers from 980m downward. According to Tomasson and Kristmannsdottir (1972), the zone of greatest calcite deposition in the formation occurs in the uppermost 500-700m of the system. This deposition may delineate the zone of flashing for the reservoir. Decreasing CO_2 pressures in the liquid and subsequent changes in pH associated with boiling cause calcite to precipitate. Therefore, drillhole 8 samples fluids from below the zone of flashing.

In modeling the Reykjanes system, equilibrium separation of vapor and liquid, and removal of the vapor phase are assumed. The remaining liquid recirculates to become a component in the deep brine. The assumption of equilibrium separation can be

tested by utilizing the Bottinga et al. (1968) equation and iterating to solve for the temperature necessary to derive the shallow brine from that of the deep. This temperature was found to be 160°C, which corresponds very well to measured downhole temperatures at the depths of calcite deposition. Chloride concentrations in two spring brines indicate a 40-50 percent reduction in volume from the deep brine. The assumption that significant amounts of vapor escape from the system is sound in view of the geyser and profusion of mudpots and fumaroles at Reykjanes. Evaporative processes are clearly evident in restoration of the mineral shell after seismic fracture as calculated by Tomasson and Kristmannsdottir (1972) with regard to anhydrite deposits.

A schematic for the mixing model is shown in Figure 4. The bottom brine is a mixture of recirculated surface brine, ocean water and meteoric water. The proportions of these components based on hypothetical chloride and deuterium concentrations are listed in Table 6. The signature of local meteoric water ($\delta D = -48$; $Cl = 0.0$) is such that recirculated brine would need comprise over 70% of the deep mixture for both 20% and 5% reduction cases. In view of the highly fractured geology of the peninsula, it is unlikely that the system would be so isolated at depth so as to be 70% closed. Also, for an area so saturated with seawater, it is doubtful that any down-flowing of meteoric water into the convection cell would result in a brine with a greater proportion of rain-water to seawater. It should be noted that because of the precipitation of brucite and anhydrite (both associated with seawater-basalt systems) the flow paths for meteoric water (Mg^{+2} and SO_4^{-2} free) into the system will be favored relative to those for seawater.

Clearly, the assumption of local meteoric-water recharge does not work well in this model. It is evident that the meteoric-water source must come from a deep aquifer, in which case the water would not necessarily be local in origin. As Reykjanes and Svartsengi are both located in the highly fractured and permeable rift zone, it may also contain a large cold-water aquifer. Consider the work of Arnason

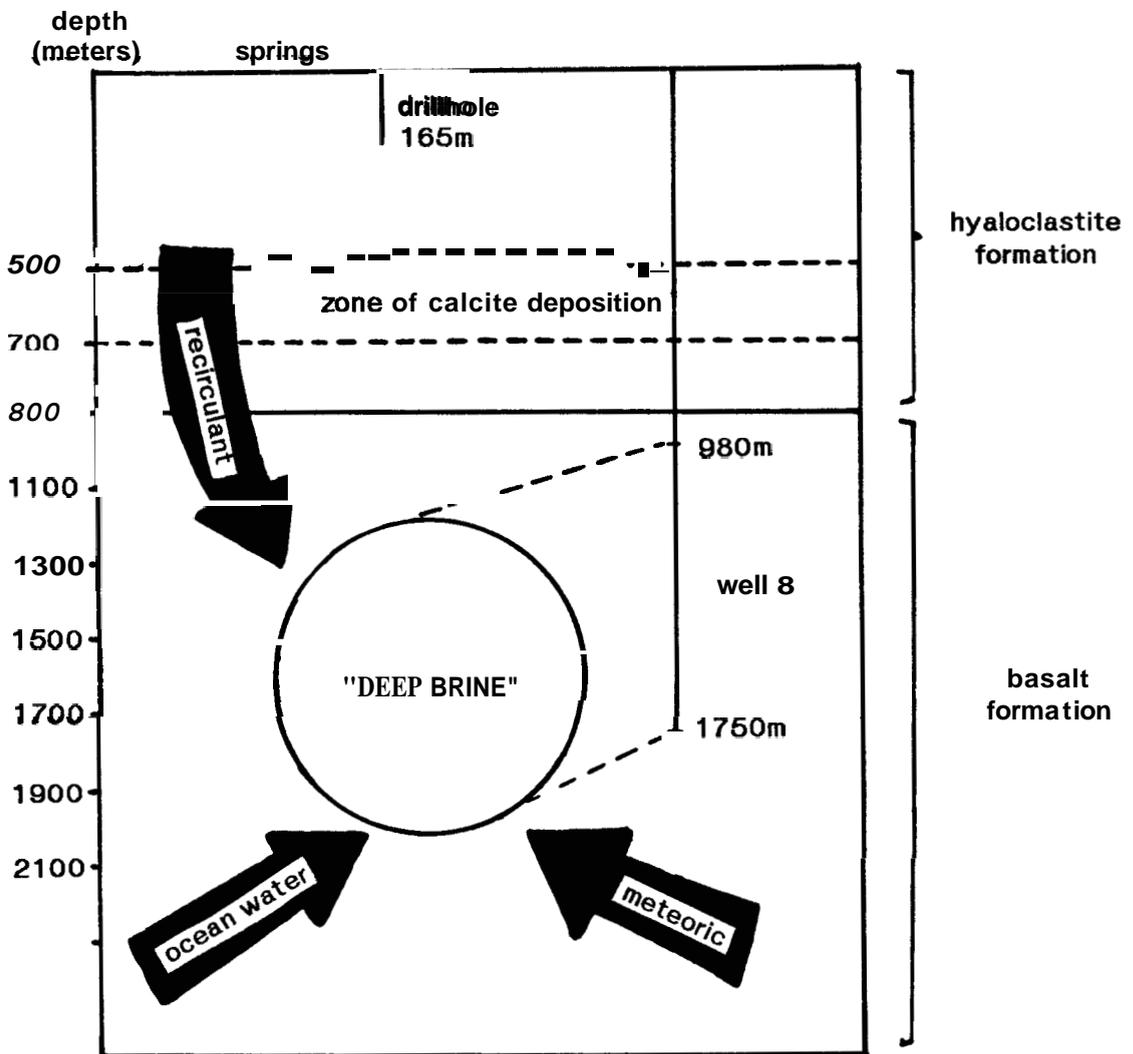


Figure 4. Schematic of mixing model. Well 8 brine is composed of mixture of meteoric, ocean, and recirculant water. The recirculant water is modeled by reducing the volume of well 8 brine with isotope adjustments by 5 and 20 percent. Equilibrium conditions were assumed. If an average spring and drillhole chemistries may be taken as the Rayleigh distillation end-points, then fractionation occurred at 160°C, which matches with temperature of calcite deposition.

Reduction	Meteoric Composition		Percent Composition Deep Brine		
	δD (0/00)	[Cl] (ppm)	seawater	meteoric	surface brine
20	-48	0.0	10.48	17.97	71..55
	-48	19.1	48.00	48.10	3.90
	-54	0.0	14.24	17.24	68.52
	-54	5.0	19.12	20.46	60.42
	-66	0.0	20.92	15.95	63.14
	-66	5.0	26.51	18.66	54.83
	-80	0.0	27.54	14.66	57.80
	-80	10.0	41.95	20.02	38.03
5	-48	0.0	11.77	13.51	74.72
	-48	19.1	37.76	38.09	24.15
	-54	0.0	12.99	14.45	72.56
	-54	5.0	19.12	20.46	60.42
	-66	0.0	20.92	15.95	63.14
	-66	5.0	26.51	18.66	54.83
	-80	0.0	24.01	11.14	64.86
	-80	10.0	34.24	15.44	50.32

Table 6
 Mixing model results. Deuterium depletions
 which would suggest recharge areas.

(1976) with regard to the groundwater and brine sources for the area on and around the Reykjanes Peninsula. In discussing the thermal waters of Reykjavik and Mosfellssveit, both 10km north of the rift zone, Arnason (1976) suggests on the basis of deuterium levels that their origin is 25km inland. In both these examples, aquifers of relatively shallow depth were sampled, yet deuterium depletions indicate origins at distance.

Arnason (1976) suggests a freshwater feed from the Krisuvik area for the Reykjanes and Svartsengi fields He claims that the Krisuvik field itself is likely fed by waters of local meteoric origin. If a value of $\delta D = -54$, an approximation for the Krisuvik precipitation, is used in the mixing model equations, the deep brine at Reykjanes would still need be comprised of over 60% recirculant water. Testing the assertion by both Arnason (1976) and Olafsson and Riley (1972), that meteoric water will acquire salinity as it passes through sedimentary deposits, chloride concentrations of

5000mg/kg were used in the mixing equation with the same deuterium depletions. Recirculant still made up over 60% of the deep brine.

It is difficult to judge what an acceptable level of recirculation would be. In the model proposed by Bjornsson *et al.* (1972), no significant recirculation is claimed to occur. The authors suggest an up-welling of fluids from the basalt formation through the porous hyaloclastic formation. Arnorsson (1978) states that chloride concentrations in the drillhole 8 fluids are identical to those of seawater. The leaching of chloride from basalt is therefore ruled out and the implication made is that recirculation is not feasible. Such a conclusion must also preclude the possibility of a meteoric water contribution. Arnorsson (1978) does not address the problem of reconciling deuterium levels with his analysis. While the egress of some fluid to the sea through the hyaloclastic formation may well occur that downward flow of fluids back into the fractured basalt layers is also likely, especially in consideration of the pressure differentials that would drive such flow. Chloride levels do not by any means diminish the likelihood of significant recycling of brine.

This mixing model yields better results when meteoric water of appreciable deuterium depletion and significant chloride levels are used in the equations. Table 6 lists some deuterium depletions which would suggest some hypothetical recharge areas. Other means by which the brine may have become deuterium deficient need be considered, such as magmatic water.

Evidence suggests that magmatic water does contribute to the Reykjanes brine; the high temperature of the system and the concentration of volatiles are both indicative of volcanic influences. The brine has significant concentrations of CO_2 and H_2S with some methane at depth. What the effect of the volcanic contribution is, is largely uncertain. Arnason (1972) in his discussion of Reykjanes and Svartsengi rules out the possibility of juvenile influences. On the basis of the deuterium ranges for vented steam at the Surtsey volcano (Arnason and Sigurgeirsson, 1968) deuterium values of

$\delta D = -58$ may be expected at Reykjanes. The oxygen-18 concentrations of the Surtsey steam was not measured. If it is assumed to follow the trends outlined by Craig (1961), any brine deuterium depletion due to a contribution of magmatic water would also show enrichments in oxygen 18 which are inconsistent with the levels found. It must be pointed out that Craig's (1961) statements were based upon global averages and did not take into account the possibility of unusual ^{18}O depletions found in many Icelandic magmas. The effect of any magmatic contribution to the peninsula brines will be to lower deuterium levels. Magmatic water would also play a role in the basalt aquifer model. Water flowing in from higher elevations should sweep residual volcanic water along with it. It should also be mentioned that magmatic water is considerably saline. Water-rock interaction and dilution with seawater will act to mask the chemical profile of this type water.

A convection cell model for the Svartsengi system has been discussed by Kjaran *et al.* (1979). The same basic feed sources as for the model proposed for the Reykjanes system in this paper are seen in in the Kjaran *et al.* (1979) model. The deep brine consists of meteoric water and seawater which then evaporates near the surface. The recharge source for the meteoric component was determined through utilization of a flow equation and the fitting of a streamline between source and ocean outlet. By assuming an average permeability for the earthquake zone based on the permeability of the Svartsengi field, a mass flux at depth of 20 kg/sec/km^2 was obtained. This flux would result in a calculated pressure at depth in the reservoir which matched well with measured reservoir pressure. Recharge is generally thought to be in the area of Lake Kleifarvatn, some 18km distance and in the immediate vicinity of the Krisuvik geothermal system. This matches the recharge scenario proposed by Arnason (1976) which was based on deuterium analyses. The assumption is made in both the Arnason (1976) and Kjaran *et al.* (1979) models that the primary meteoric water flow would be through the earthquake or volcanic belt. Fault swarms which intersect the volcanic

belt are believed responsible for the increases in permeability which would allow for free convection. Arguments made by Kjarian *et al.* (1979) in support of the convection model are general and may be applied to the Reykjanes system as well. Free convection (either involving recirculation or not) may exist to some degree in all geothermal systems. This process increases the heat flow from the system. Heat flux at Reykjanes must penetrate several rock layers and the cap rock; it is improbable that this occurs through conduction alone. Outflow of steam and hot brine effectively dissipate heat. Consideration of **mass** balance would necessitate the inflow at depth of new fluid. Permeability and flow conditions favor recirculation. In the Kjarian *et al.* (1979) model for Svartsengi, meteoric water from the area of Lake Kleifarvatn would comprise the major portion of inflow into the system.

8. SOLUTION CHEMISTRY

Major element chemistry for the Reykjanes well-8 brine shows values which are consistent with equilibria between minerals and waters with a large marine component. Seawater-basalt interactions are clearly evident. Ca^{+2} concentrations increase four-fold over seawater levels; K^+ is 2.9 times enriched, while Mg^{+2} decreases to 1/135 of seawater concentration, and SO_4^{-2} decreases to 1/126 of its concentration in seawater. These figures document the alteration process and the extent to which it occurs. They are not unique to Reykjanes, nor do they favor seawater recharge to the exclusion of mixing. Arnorsson (1978), Bjornsson *et al.* (1972) and Olafsson and Riley (1978) discuss the fluid chemistry for Icelandic geothermal systems. Seawater is definitely a major component in the geothermal brine; because of its salinity in relation to the other possible sources of recharge, it will dominate the solution chemistry. Whether the depression of sodium levels relative to seawater is due to the albitization of calcic feldspars or to the formation of analcime becomes irrelevant to the brine's origin. Neither meteoric water nor volcanic water, in the amounts that it would be expected to contribute, have sufficient solute concentrations to effect concentrations of major ionic species in the brine. Figure 5 shows the log concentrations (ppm) for major ionic species for four brines from systems believed to be made up of significant seawater fractions. Reykjanes and Svartsengi are included. Note the dominant effects of mineral-brine equilibria. The effects appear to be independent of the host geology. Reykjanes and Svartsengi are basalt systems while Cerro Prieto in Mexico is sedimentary. The Shimogamo system in Japan is in Neogene andesite. Cases for the presence of volcanic or meteoric water must be made on the basis of trace elements. Analyses are not available for a variety of species whose presence or absence would be of particular interest in the Reykjanes and Svartsengi brines.

The contribution of magmatic water to the brine provides a mechanism for lowering deuterium levels and raising CO_2 concentrations. The high temperature of the

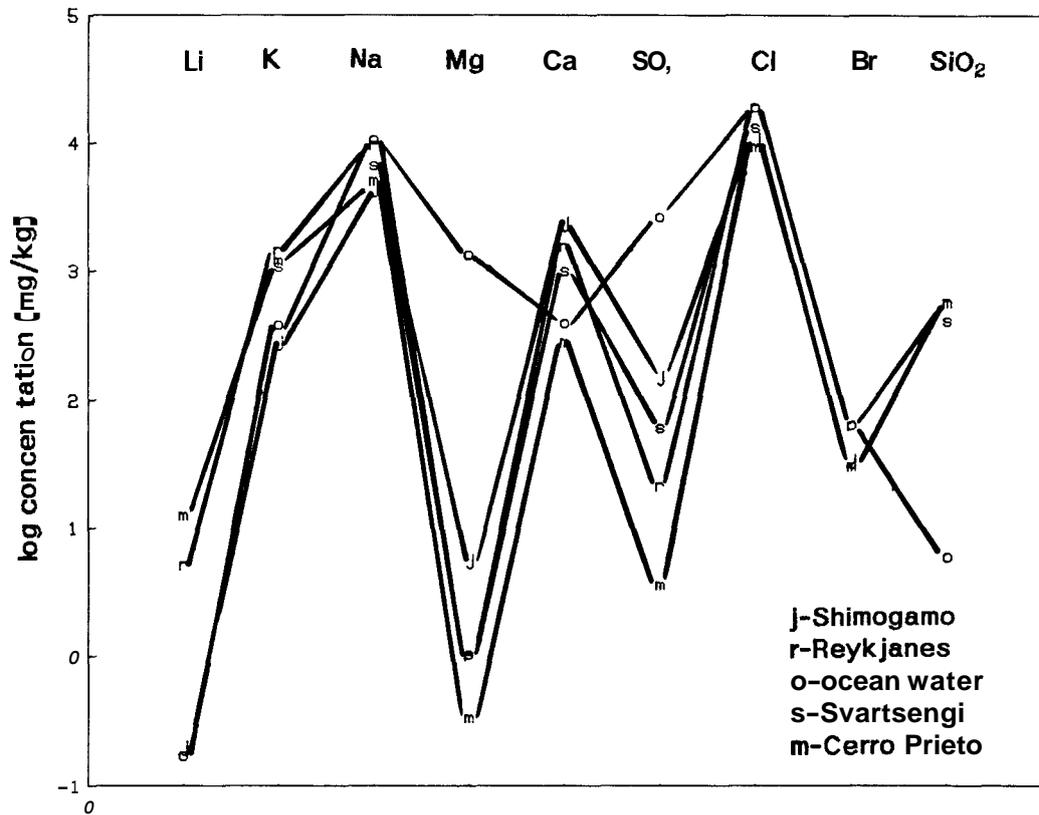


Figure 5. Trends of component concentrations for four geothermal systems with strong marine influences. Changes with reference to seawater are apparent and are not markedly affected by geology (after Truesdell et al., 1981).

Reykjanes system is indicative of its proximity to volcanic activity. Olafsson and Riley (1978) point out that the concentration of *As* in the brine is 50 times greater than of seawater and while this may be due to leaching of volcanics, the volatile nature of the element suggests its origin as volcanic gas. Also, concentrations of *Hg* in fluid from one drillhole are two orders of magnitude higher (246 ng/l) than in seawater. Again the volatile nature of the element discounts leaching and also may explain its absence from other samples. Lithium concentrations might also be indicative of the proximity of the system to volcanic activity. Evidence of volcanic volatiles is difficult to find. According to White and Waring (1963), the composition of volcanic gases is dependent upon a number of factors which include the original abundances of the volatiles in the magma, the time since emanations began, and the degree of mixing with meteoric water and air. Steam is almost always the most dominant volatile; CO_2 is also evolved in significant quantities. The high concentrations of CO_2 in the Reykjanes brine may result from a volcanic source. It may also be leached from reservoir rocks. *HCl* and *HF* may also evolve as volatiles; however, as the concentration of *F* in the brine is less than a tenth that in seawater, it is evident that some reaction sequence involving alteration is affecting its concentration. The *Br/Cl* ratio of volcanic water is within the range of seawater is therefore not useful here. Analyses of the isotopic composition of noble gases in the fluid have not been reported in the literature. In all, the analyses reviewed give little evidence to confirm or deny a magmatic contribution to the brine.

Dilution by meteoric water will not affect the ratio of solute species to one another in the brine. It will, however, affect concentrations. Chloride concentrations vary little in the analyses and the average tends to be less than marine concentrations. Some dilution is evident.

It is interesting that in both the Olafsson and Riley (1978) analysis of the Reykjanes brine and in the Truesdell et al. (1981) analysis of the Cerro Prieto brine,

models are proposed that call for the contribution of evaporated seawater to the brine in order to explain both salinity and deuterium levels. In both cases, the argument is made that very little recirculation of evaporated or flashed reservoir fluids takes place; the systems appear to be open. In the case of the Cerro Prieto brine, plots of enthalpy as a function of chloride concentrations indicate cooling through mixing with colder waters. This discourages a convection cycle as the trend shows the colder water to be less saline. Data for the Reykjanes brine are not as complete as for the Cerro Prieto brine; however, a plot of the few points given in the Olafsson and Riley (1978) paper are consistent with a convection-cell model (Figure 6).

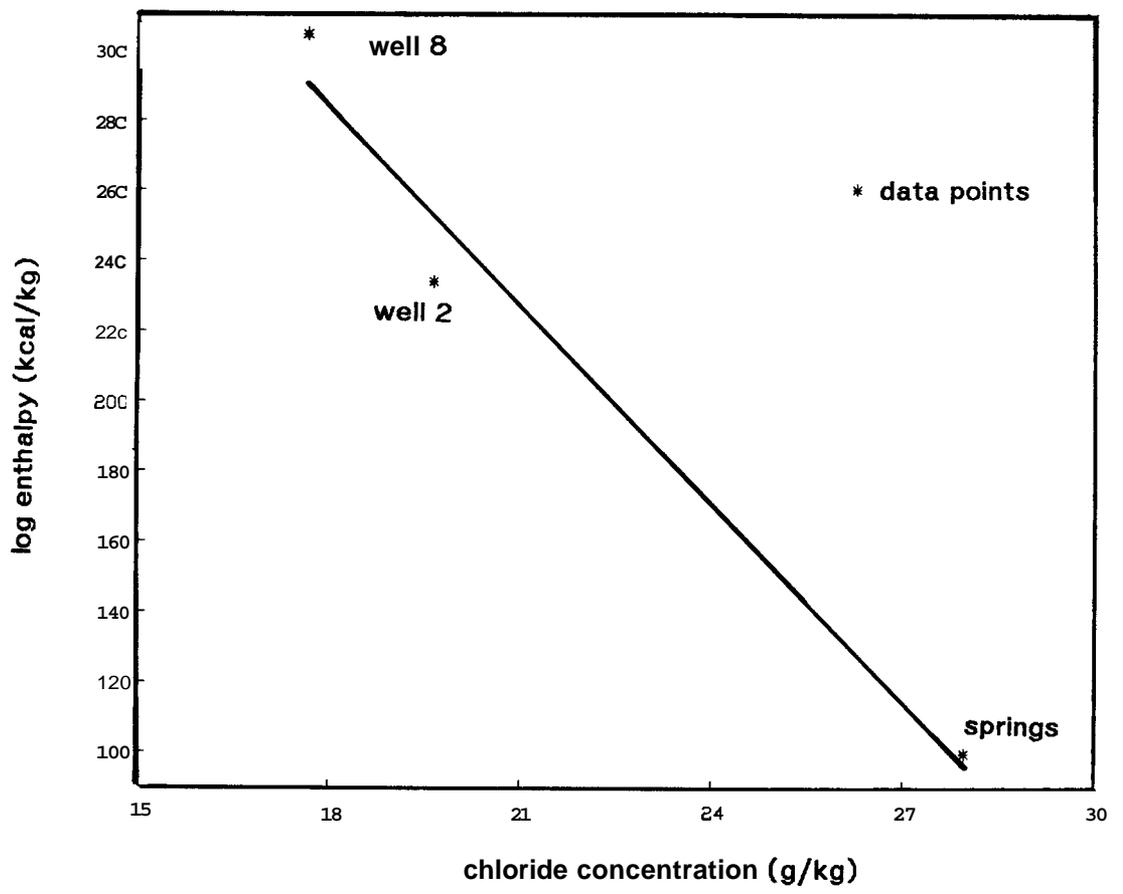


Figure 6. Enthalpy and chloride concentration for the data of Olafsson and Riley (1978).

9. DISCUSSION

Three mechanisms have been discussed by which deuterium levels at Reykjanes may have been depressed. Each would maintain salinity in the brine at levels similar to seawater. These mechanisms are 1) mixture of seawater with meteoric water which has acquired salinity in its flow through volcanic sediments and/or recirculation of flashed fluids, 2) mixture of meteoric water and seawater with magmatic water of low deuterium and oxygen-18 concentrations, 3) equilibration of the brine with alteration minerals. .PP Discussions with regard to alteration processes concentrated on known mineralogical species in the uppermost 2000m of the system. All known alteration minerals in this region were eliminated as candidates for the depression of deuterium levels. A clear pattern was seen in the increasing weight percentages of hydrogen in the rock matrix with progressive alteration. Isotope partitioning which would enrich the brine in deuterium was seen to decrease with increasing temperature, and in the case of epidote, with increasing salinity. Although these observations are contrary to the proposed mineral-brine equilibria mechanism for deuterium depletion, they do not eliminate such a model. The close similarity between the deuterium levels of the Reykjanes, Svartsengi and Shimogamo systems may well be indicative of a high temperature mineral-brine equilibrium involving seawater. Documentation of near-surface alteration processes have provided important insights into brine chemistry. Laboratory simulation of deeper processes may prove equally as enlightening.

The possible contribution of volcanic water to the Reykjanes and Svartsengi brines is an important consideration. CO_2 levels in both systems indicate a significant volcanic influence; however, there are some shortcomings to this theory. It is clear from the salinity levels of the two systems that the brines are formed by the mixture in differing proportions of ocean water with a significantly less saline water. Meteoric water would be a better candidate than volcanic on this account. Very little is known about the solution chemistry of volcanic water as it is impossible to obtain a pure

sample of this generic type water. Following the general trends of volatile emanations (White, 1966), it would appear that significant amounts of CO_2 in the fluids indicate that the major portion of volcanic water had already been passed by the cooling magma (*i.e.* a cooling magma is expected to release first steam and then CO_2). Consideration of the solubility of water in magma would also suggest that the evolution of water by the cooling magma would be abrupt with most evolving in a single pulse of steam. In any case, while maintaining the validity of the volcanic role in models for systems in northern Iceland (in these cases, residual water rather than steam actively being evolved), it must be concluded that volcanic water is probably not a significant factor contributing to the depression of deuterium levels in the Reykjanes and Svartsengi systems. Because the flow rates of produced fluids and the differing salinity levels of the two fields, they preclude the feasibility of such a model.

The contribution of meteoric waters to the peninsula brines has been proposed by Arnason (1976) and Olafson and Riley (1978). Both these models require meteoric water to acquire considerable salinity in the course of flow prior to entering the system. This is the most consistent model for the peninsula systems; however, certain modifications must be made with regard to the source of this meteoric influx and the actual mechanism involved in modification of the brine chemistry. Bjornsson *et al.* (1972) and Arnorsson (1978) have presented arguments against significant recirculation of flashed fluids in the Reykjanes system. It appears, however, that recirculation is an important if not dominant factor in the chemical character of the shallow brine. Most chemical analyses of the deep brine at Reykjanes are on samples from well 8. This well is fed by aquifers from 980m downward to 1750m. The porous hyaloclastic seismic zone extends to the 900m level. While the aquifers sampled are from within the basalt formations, consideration of series permeabilities may favor a significant down-welling of surface fluids. The salinity that meteoric water would need to acquire in both the Arnason (1976) and Olafson and Riley (1978) models could well be

provided in this recirculation of flashed fluids. Recirculation is consistent with the enthalpy-chloride plots and is the most viable way to explain both deuterium and salinity levels. Another consideration which should be examined is the source of meteoric water.

In the models presented previously, meteoric water was assumed to have flowed from the inner portions of the Reykjanes Peninsula. Groundwater flow patterns are in large part based on deuterium concentrations and are difficult to determine with certainty. The mixing model presented in this paper worked well with meteoric water of significant deuterium depletion. Though some of the hypothetical values used would indicate a recharge from a meteoric source tens of kilometers inland, this really is not an absurd suggestion. Consider the work of Tomasson *et al.* (1975) with regard to hydrological models for the Reykir and Reykjavik thermal areas. The Seltjamames, Laugames, and Ellidaar low temperature fields present an interesting anomaly in that the deuterium levels of the systems decrease with increasing proximity to the sea. Seltjamames which sits on the end of a narrow peninsula has $\delta D = -75$ permil relative to SMOW while Ellidaar, some 8km inland has $\delta D = -62$ permil. Groundwater flows are clearly not in the direction of Ellidaar to Seltjamames. In order to accommodate the deuterium values in the Seltjamames, recharge must originate in the highlands in the immediate area of Langjokull. The authors propose a hydrological model which calls for flow through Quaternary volcanic structures running parallel to the volcanic rift zone (Figure 7). This would call for a conduit of over 100km, some of which would be beneath ocean waters. If this flow pattern is extended into the rift zone, it would cross the Reykjanes and Svartsengi systems (Figure 8). Tomasson *et al.* (1975) demonstrate that the geology of the area permits long-range flow conduits. While the meteoric feed into the Reykjanes and Svartsengi systems may not be within the same flow regimes as the thermal systems of Reykir and Reykjavik, it is possible for it to be from a distance of 100km inland or more. Another important factor is that the volcanic

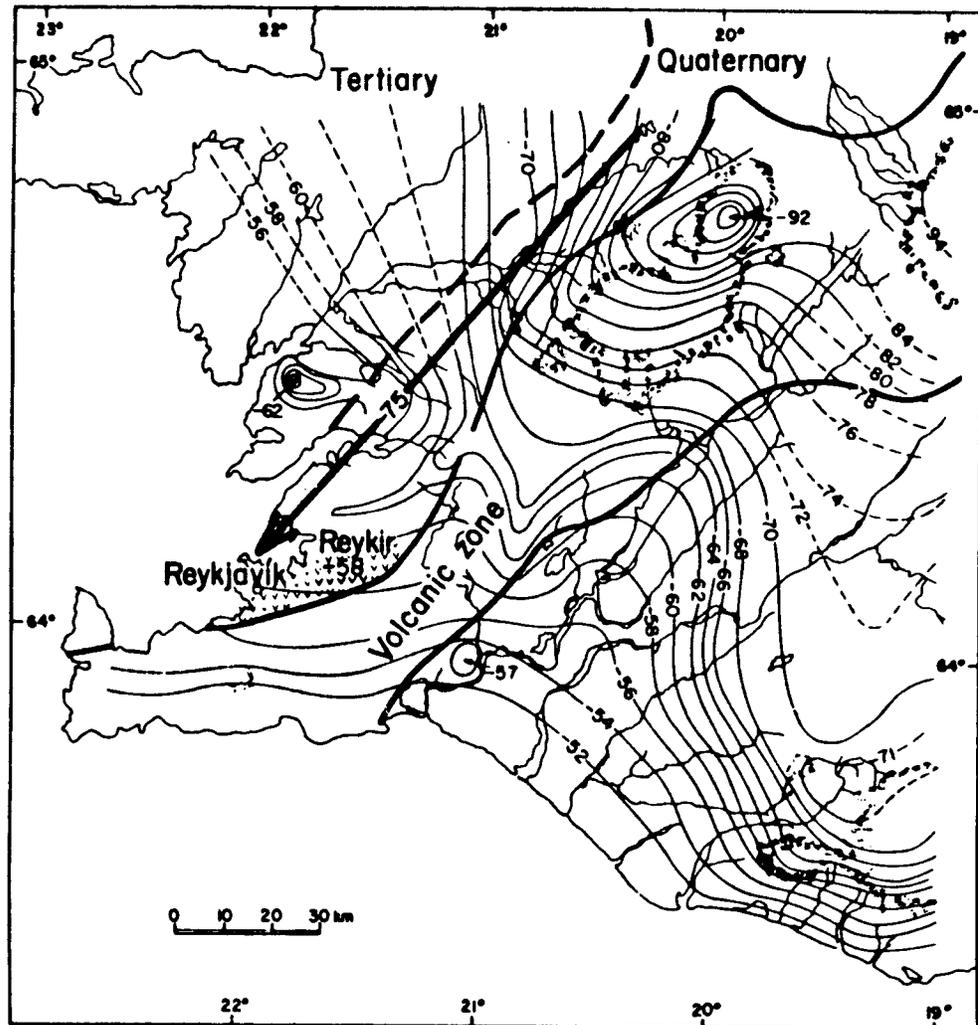


Figure 7. Concentration of deuterium in precipitation in south-west Iceland (from Arnasson, 1976), and boundaries of the active volcanic zone. The arrow indicated the direction of flow at depth of water low in deuterium; parallel to the volcanic zone. The shaded area indicates a local deuterium concentration of -58 permil in geothermal water (from Tomasson et al., 1975).

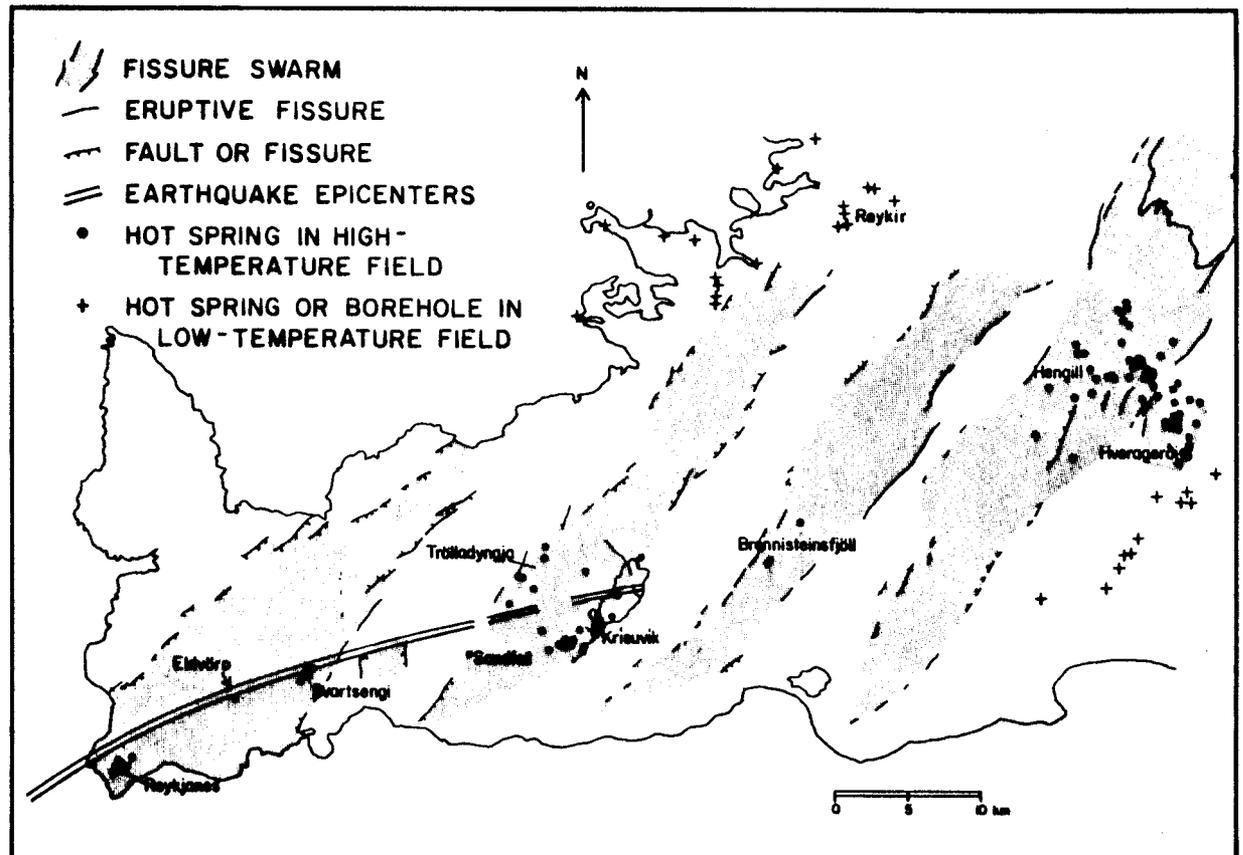


Figure 8. Geothermal features on the Reykjanes Peninsula, showing fault swarms in relation to volcanic rift zone and the Reykjanes and Svartsengi geothermal fields (based on map by Saemundsson and Fridleifsson).

belt is that the volcanic belt is not the only conduit for meteoric water. Tomasson *et al.* (1975) show rather well that flow through the fractured fault swarms is quite possible. If their model is valid, there may be a multiple meteoric aquifers flowing into the lower peninsula. These aquifers may include local meteoric drainage, flows through the volcanic rift zone, and flows through the fault swarms.

The data used in the present work may indicate that sufficient knowledge of the mechanisms of fractionation in geothermal systems is still lacking and that deuterium should not be used as a tracer in ascertaining recharge characteristics. Arnason (1976) successfully used deuterium concentrations to trace groundwater flow except as applied to the low temperature systems near Husavik and Akureyri. Problems with deuterium depletions may be cited with regard to the deep brine of Heimaey and Hveravellir, and in many thermal areas in northern Iceland. In all these cases, feed from glacial melt or from meteoric waters of an ancient climate were proposed. Kristmannsdottir and Johnsen (1982) also encountered problems in explaining deuterium depletions in the Akureyri (Eyjafjordur) area. Other problems were cited in Mariner *et al.* (1983) with regard to the Northern Basin and Range Province. This indicates that the deuterium problem is not unique to Iceland.

It is reasonable to expect that the recharge characteristics of geothermal systems will be more complex than the simple case of tracing groundwater flows. Other factors must also be considered: the nature of geothermal systems with heat derived from deep-seated magmas; fractures and fissures associated with volcanic activity; convective flows; and other factors contributing to the disruption of the geologic column and the formation of conduits between otherwise isolated layers. Combined with uncertainties regarding the possible consequences of mineral-brine equilibria at critical pressures and temperatures, a more general question must be asked. What conclusions can realistically be drawn from appraisal of the deuterium levels of a geothermal brine?

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