Helium isotopes in geothermal systems: Iceland, The Geysers, Raft River and Steamboat Springs

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Abstract—Helium isotope ratios have been measured in geothermal fluids from Iceland, The Geysers, Raft River, Steamboat Springs and Hawaii. These ratios have been interpreted in terms of the processes which supply He in distinct isotopic ratios (i.e. magmatic He, $\sim$10 R_a; atmospheric He, R_a; and crustal He, $\sim$0.1 R_a) and in terms of the processes which can alter the isotopic ratio (hydrologic mixing, U-Th series alpha production and weathering release of crustal He, magma aging and tritiugenic addition of ³He). Using this interpretational scheme, Iceland is found to be an area of hot-spot magmatic He implying an active volcanic source although the data are suggestive of high-temperature weathering release of crustal He incorporated in the geothermal fluids. By comparison to fumarolic gases from Hawaii and Juan De Fuca and Cayman Trench basaltic glass samples, The Geysers contains MOR type magmatic He again implying an active volcanic source possibly a "leaky" transform related to the San Andreas Fault System. Raft River contains only crustal He indicating no active volcanic sources. Steamboat Springs He isotope ratios are distinctly less than typical plate margin volcanics but must still have a magmatic source. A preliminary assessment of the cause for this low ratio is made assuming an "aging" magma source.

INTRODUCTION

RECENT work by Clarke et al. (1969), Baskov et al. (1973), Mamyrin et al. (1974), Krylov et al. (1974), Craig et al. (1975), Lupton and Craig (1975), Craig and Lupton (1976), Kamenskiy et al. (1976), Jenkins et al. (1978), Kurz and Jenkins (1981), Torgersen et al. (1981) and others indicate that the light isotope of helium, ³He, is enriched in volcanics of plate margins and in hydrothermal plumes of the Galapagos area. ³He/⁴He ratios associated with mid-ocean ridge volcanics have ratios of 8-10× the atmospheric ratio, R_a (³He/⁴He = 1.384 × 10⁻⁶; Clarke et al. 1976). The data of Torgersen et al. (1981) from New Zealand, Craig et al. (1978a) from circum-Pacific volcanoes and Baskov et al. (1973) from Kurile-Kamchatka show subduction margins have ratios of 5-8× R_a although some overlap with mid-ocean ridge basalt (MORB) values does occur. The work of Poreda and Craig (1979) indicates that even lower ratios can occur in some cases, particularly Boninites. Hot-spots have very high ratios; 14-25× R_a (Craig et al., 1978b, Craig and Lupton, 1976, Kononov and Polak, 1975) as exhibited in areas such as Hawaii, Yellowstone, the Ethiopian Rift valley and Iceland.

Aldrich and Nier (1948) showed that gas and oil wells contain helium with ratios 0.1-0.01 R_a due to the accumulation of ⁴He from alpha decay of naturally occurring uranium and thorium series elements. The more recent data of Kamenskiy et al. (1971) and Torgersen (1980) support these earlier results. Morrison and Pine (1955) calculated a ³He/⁴He production ratio of 10⁻⁷ ($\sim$0.1 R_a) for average granitic

crust based on their analyses of ⁶Li(α,n)³H(β^-)³He reactions. Torgersen et al. (1981) modified the original Morrison and Pine (1955) equations to simulate a limestone (5 ppm Li, 2.2 ppm U, 1.7 ppm Th) and using more recently measured cross sections, obtained a limestone ³He/⁴He production ratio of 1 × 10⁻⁹ ($\sim$0.001 R_a).

The alteration, evolution and interpretation of helium isotopes in nature has been discussed by many authors. Craig and Clarke (1970), Tolstikhin and Kamenskiy (1969), Jenkins and Clarke (1976), Torgersen (1980) and others discuss the evolution of ³He from ³H in ocean and groundwaters. Clarke and Kugler (1973), Torgersen (1980) and Davis and DeWeist (1966) are among the many authors who have considered the addition of ⁴He to groundwaters. Torgersen and Clarke (1978), Torgersen et al. (1981) and Campbell and Torgersen (1980) have considered various helium mixtures in lakewaters. Clarke et al. (1969), Lupton et al. (1977a), Lupton et al. (1977b), Jenkins et al. (1978) and Lupton (1979) have discussed the interaction of seawater and mid-ocean ridge volcanism. Mamyrin et al. (1974), Lomonsov et al. (1976), Kononov and Polak (1975) and Craig et al. (1978a,b) and others have discussed helium in thermal springs and volcanic gases.

From this previous work, it can be seen that helium isotope ratios can be used to evaluate a variety of geologic and hydrologic problems. Geothermal systems like other porefluid systems, contain distinctive helium isotope signatures with a possible "overprint" due to high-temperature weathering reactions, mixing of fluids derived at the surface and at-depth, as well as in situ production of helium. In this study,

Location	Date	^{3}He/^{4}He $\times 10^6$	R/R_a
'71 Fissure	13 Aug 1976	18.0	13.0
	13 Aug 1976	19.4	14.0
	1 Dec 1976	18.5	13.4
Sulfur Bank	5 Aug 1976	19.9	14.4
	13 Aug 1976	19.5	14.1
	1 Dec 1976	19.4	14.1

Helium isotope ratios from Sulfur Bank and the '71 Fissure on Kilauea volcano, Hawaii. Note that this volcanic hot-spot has helium isotope ratios of ~14 R_a.

the helium isotope composition of geothermal fluids is used to evaluate the local tectonic environment (hot-spot, ridge, trench, stable crust) in the light of possible "overprint" mechanisms and to infer a probable source for the thermal anomaly.

METHODS

Samples were collected in ⅜ inch refrigerator-type copper tubing flushed with several volumes of fluid and sealed with plumbers' pinch-off tools (Imperial Eastman 105-ff) after the method of Weiss (1968). The Geysers samples were collected through and, in some cases, separated by a stainless steel condenser supplied by A. H. Truesdell, USGS, Menlo Park. Natural spring samples were collected with a hand-operated vacuum pump and gases were collected by gas displacement and the inverted funnel technique of Mazor and Wasserburg (1965).

After transport back to the laboratory, the samples were attached to a stainless steel high-vacuum extraction system via a high vacuum O-ring connector. The water and/or gas sample was admitted to the closed evacuated system by removing the pinch-off tool and by a slight reopening of the "pinch". The condensible gas fraction was separated in two stages with a dry-ice acetone trap and an activated charcoal trap at −195°C. The noncondensible gases (He, Ne, H) were toepler pumped into breakseal tubes and precisely divided into 50/50 splits for later analysis. Lead-glass or Corning 1720 Alumina-silicate breakseal tubes were used. The extraction blank from the stainless steel extraction line was nearly always less than the mass spectrometer blank for ^{3}He, ^{4}He and Ne and always less than 1% of the sample.

Helium isotope measurements were conducted on the Woods Hole Oceanographic Institution double collection, branch tube, ^{3}He mass spectrometer. This instrument uses the same flight tube design as the original McMaster University ^{3}He mass spectrometer (Dr. W. B. Clarke). ^{3}He/^{4}He ratios were determined by comparison to an air standard and absolute helium content was by peak height comparison. The instrument blank for ^{4}He is ~10^{-9} ccSTP and the precision of the ratio determination and ^{4}He concentrations is known from repeated measurements to be about 3% for this type of sample.

Neon measurements were conducted on the same mass spectrometer by adjusting the magnet current and the accelerating voltage. Suitable operating characteristics were obtained for total neon less than 10^{-6} ccSTP and known sample aliquots were admitted to insure operation in this range. Both ^{20}Ne and ^{22}Ne were determined by peak jumping and peak height comparison to a known calibration curve. Although of lesser abundance, ^{22}Ne proved to have

better operating characteristics and total Ne was determined from ^{22}Ne assuming an abundance of 9.27%. Instrumental blanks for Ne were 1–5 × 10^{-8} ccSTP as calculated from the ^{22}Ne peak. For samples in which the Ne blank was ≥50% of the total Ne, the He/Ne ratio is reported as a lower limit.

RESULTS AND SAMPLING AREAS

Helium isotope results for Hawaii are shown in Table 1. These data will be used as a framework to discuss Iceland (Table 2), The Geysers (Table 3), Raft River (Table 4) and Steamboat Springs (Table 5) which constitute the primary effort of this work. A short discussion of nomenclature is presented and the results for each area will be presented separately.

In this report, helium and neon data are reported both as absolute ^{3}He/^{4}He and He/Ne ratios and normalized to the ratios in air.

$$R/R_a = \frac{(^3He/^4He)}{(^3He/^4He)_{air}}$$

and

$$X = \frac{(He/Ne)}{(He/Ne)_{air}}$$

Since the He/Ne ratio of air is 0.29 and the He/Ne ratio of the primordial and crustal components is typically of the order ≫100, neon can be used to correct the measured helium isotope ratio for air incorporated during sampling or naturally incorporated as a part of the hydrologic cycle. If it is assumed that each sample is a mixture of (i) atmospheric He and Ne, and (ii) a separate "added" component of pure helium, then corrected helium isotope ratio (assuming that the neon is entirely of atmospheric origin) is (Craig et al., 1978a):

$$(R/R_a)_c = \frac{[(R/R_a)X] - 1}{X - 1}$$

Where Ne measurements are not available, the He concentration provides some measure of the effects of air. Because helium in air (5.24 ppm) and in water (4.5 × 10^{-8} ccSTP/g H_2O at 20°C 0% salinity) is at very low concentrations compared to concentrations usually encountered in geothermal fluids; and since crustal or primordial helium are added components, the higher the He concentration, the less significant air contamination. For helium samples presented without Ne data in this study, water samples were generally >5× saturation and gas samples were generally >60× air concentrations.

The question of ^{3}He increases due to ^{3}H decay produced from nuclear weapons testing will be discussed later with respect to The Geysers samples.

Hawaii—The Hawaiian samples were collected by Don Thomas (Hawaiian Institute of Geophysics, University of Hawaii) and by one of the authors (TT) and are presented in Table 1. The fumarole gases obtained from Sulfur Bank on the caldera edge (sampling from a 5–20 m pipe set into rock in 1923) and from the '71 Fissure opening (sampled with a titanium tube and a hand pump) all have uniformly high helium isotope ratios. These measurements are in

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agreement with a previous analysis of Craig and Lupton (1976). In contrast to typical plate margin volcanics (Craig and Lupton, 1976; Jenkins et al., 1978; Kurz and Jenkins, 1981) primordial helium at the Hawaiian "hot-spot" has a distinctly higher helium isotope ratio, 14 R_a as opposed to 8-9 R_a. In addition to the measurements of Table 1, analyses from water of the Hawaiian Geothermal Project Well are up to 5× saturation in ⁴He and have ratios of up to 12.3 R_a.

Iceland—The Iceland samples were obtained from geothermal wells at various locations by John Goddard (Lamont-Doherty Geological Observatory). The results are shown in Table 2. The Icelandic hot-spot, tectonically more complicated than Hawaii, shows helium isotope ratios distinctly between those of Hawaii and typical plate margins. Helium is >5 times saturation (at 20°C) indicating that little if any air contamination is present. These ratios are in the range of values obtained by Russian investigators (Kononov and Polak, 1976; Mamyrin et al., 1972). Due to the difficulties encountered during sampling, the range on the triplicate analysis of Krafla #8 should serve as a guide to possible sampling contamination.

The Geysers—The Geysers-Clear Lake region of California (39°52'N; 122°45'W) has the world's largest production of commercial power from a dry steam geothermal reservoir. Pacific Gas and Electricity currently produces ~500 MWe of power and plants under construction will produce an additional 400 MWe (Crow, 1978).

A suite of gas and condensate samples were obtained with the help of A. H. Truesdell, U.S.G.S., Menlo Park. The results are shown in Table 3. Helium isotope ratios in the gas are 6.6 < $(R/R_a)_c$ < 9.5. Ratios measured in the condensate are generally erratic and lower presumably due to fractionation and partial equilibration effects.

Raft River—The Raft River geothermal area lies on the southern border of the Snake River Plain at the edge of the Basin and Range Province. In 1975 a 1526 m deep well produced a flow of 2000 l/m at bottom hole temperatures of 147°C. The site has since been designated for an experimental binary-fluid geothermal plant by DOE.

The results of helium isotope measurements for wells of the Raft River Geothermal Exploration area are shown in Table 4. The samples were obtained through Gerry Crostwaite, U.S.G.S., Boise. In addition, the authors sampled gas and liquid from an initial well drilled by the Bureau of Land Management (BLM). The helium isotope ratios of Raft River are all very low, 0.13 to 0.17 $(R/R_a)_c$ indicating a dominant crustal helium component.

TABLE 2: ICELAND: GEOTHERMAL WELL WATERS

Location	NEAI* No.	Date	[⁴He] ccSTP/gH₂O x10⁻⁸	³He/⁴He	R/R_a
Reyjavik, E-5	G-31	Jun 1977	20.1	16.0	11.6
			20.1	14.8	10.7
Reyjavik, U-5	G-10	Jun 1977	17.2	17.6	12.7
Krafla #7	KJ-7	Jun 1977	2357	11.6	8.4
Krafla #8	KG-8	Jun 1977	1174	10.9	7.9
			416	12.4	9.0
			107	11.5	8.3
Hafralaehur	-	Apr 1977	20.3	12.4	9.0

* National Energy Authority of Iceland well identification.

Helium isotope ratios from geothermal well fluids in Iceland. Note that higher helium isotope ratios are observed for the low-temperature Reyjavik wells. National Energy Authority of Iceland well identification numbers are given for these wells. Hafralaehur is a 101 m deep well on a farm of the same name located at 65°52'N, 17°26'W, approximately 35 km WNW of Krafla.

TABLE 3: THE GEYSERS

Location	Type	³He/⁴He x10⁶	He/Ne	R/R_a	X	(R/R_a)_c
GW-1	Gas	7.36	0.3	5.3	1.04	
	Cond.	4.85	>2.6	3.5	>9.0	3.8
GW-2	Gas	9.95	>500	7.2	>1735	7.2
	Gas	9.50	2.3	6.9	8.0	7.7
GE-1	Gas	13.11	28	9.5	97	9.6
	Gas	12.23	29	8.8	101	8.9
	Cond.	6.17	>3.4	4.5	>11.8	4.8
GE-2	Gas	11.16	>500	8.1	>1735	8.1
	Gas	9.22	498	6.7	1728	6.7
	Cond.	9.21	>5	5.9	>17	6.2
GE-3	Gas	9.48		7.11		
	Cond.	1.86	>4	1.34	>13.9	1.37
GE-4	Gas	10.89	1.9	7.9	6.6	9.1
	Gas	11.88	>500	8.6	>1735	8.6
	Cond.	9.36	>11	6.8	>38	7.0
GE-5	Gas	12.23	>500	8.8	>1735	8.8
	Gas	12.40	>500	9.0	>1735	9.0

Helium isotope ratios and neon corrected ratios for geothermal gases and steam condensates of The Geysers. Ratios measured in the condensate are generally lower but erratic, presumably due to kinetic and fractionation effects. The gas ratios range from 6.7 to 9.6 R_a indicative of an active magmatic source.

Steamboat Springs—Steamboat Springs is a presently active area of hydrothermal ore formation. Geologic studies of the area began after the Comstock Lode discovery (silver, etc.) in the 1850's, but the regional geology and structure have only recently been described. He and Ne measurements in gas and liquid phases are shown in Table 5. The location numbers refer to the vent numbering scheme of White (1968, plate 3).

$(R/R_a)_c$ are in the range 3.7 to 6.1. This is significantly less than the ratio observed for The Geysers and for plate margin volcanics. Two data points cause concern: (1) #4 gas whose ³He/⁴He ratio is less than the corresponding water ratio and whose He/Ne ratio is less than air; (2) #24 gas which also has a lower ³He/⁴He and lower He/Ne than the corresponding water. If these samples do represent some contamination it must have occurred during sampling or have been associated with "self-contamination" by the vent.

TABLE 4: RAFT RIVER

Well	[⁴He]*	³He/⁴He x10⁶	He/Ne	X	R/R_a	(R/R_a)_c
RR-3	447	0.238	47	163	0.17	0.16
	876	0.236	108	375	0.17	0.17
RR-1	838	0.186	234	812	0.13	0.13
	707	0.192	118	409	0.14	0.14
CH-3	4134	0.216	>500	>1735	0.16	0.16
	2889	0.215	413	1432	0.16	0.16
BLM	330	0.201	64	222	0.15	0.15
	Gas	0.256			0.18	
	Gas	0.214	10	35	0.15	0.13

* ccSTP/g-H₂O x 10⁸

Helium isotope ratios and neon corrected ratios for geothermal waters of Raft River. The ratios measured here indicate a crustal helium source.

TABLE 5: STEAMBOAT SPRINGS

Spring No.	$[^4He]^*$	$^3He/^4He$ $\times 10^6$	He/Ne	X	R/R_a	$(R/R_a)_c$
4	4.20	6.13	13	45	4.4	4.5
4	Gas	5.16	0.03	0.1	3.7	-
6	1.41	5.19	>17	>59	3.8	3.9
6	Gas	8.09	>11	>38	5.9	6.0
10	Gas	8.36	117	403	6.0	6.0
24	3.40	6.04	>41	>141	4.4	4.4
24	Gas	1.48	6.2	21	1.1	1.1

*   ccSTP/g-H₂O x 10⁻⁸

Helium isotope ratios and neon corrected ratios for Steamboat Springs. The sample collection method seems to suggest that gas samples are better than the water samples. However, samples such as #4 gas and #24 gas are difficult to explain and should be viewed skeptically. The general helium isotope ratio for Steamboat Springs, ~5 R_a, is at the low end of what is considered typical for magmatic sources.

The variation of #24 gas could be the result of non-equilibrium mixing with air, thus lowering the $^3He/^4He$ and the He/Ne ratios (if #24 H₂O can be considered representative). The extremely low He/Ne ratio of #4 gas however is of a less obvious origin. These two data points must therefore be viewed with some scepticism.

DISCUSSION

Renner et al. (1975) considered the principal heat sources for geothermal systems to be "(1) heat directly related to volcanic sources localized as 'hotspots' in the shallow crust of the earth and (2) heat related to the geothermal gradient or general increase in temperature with depth as a consequence of conductive heat flow". (This first category shall be referred to as volcanic heat and the second as gradient heat). In the Smith and Shaw (1975) context within which this classification is presented, there appears to be no differentiation between Quaternary volcanism and Tertiary-Mesozoic volcanism, although the list of Smith and Shaw (1975) includes only Quaternary volcanic fields. Gradient heat is presented as a "catchall" for the remainder of geothermal systems. However, to geophysically, thermally, seismically or geochemically model geothermal systems, it is advantageous to determine whether the system is (1) active volcanic or (2) passive volcanic. This is a possibility with helium isotopes. The passive volcanic mode would fall under the gradient heat source category of Renner et al. (1975) because such a system can transfer heat by conduction through a perturbation in the "normal" geothermal gradient.

In the results of this study and Craig and Lupton (1976) it was shown that Hawaiian volcanic gases maintain R/R_a ~ 14-25. Mid-ocean ridge processes are characterized by R/R_a ~ 8 as shown by Craig and Lupton (1976) and Kurz and Jenkins (1981) as are "leaky" transform faults. Zones of plate destruction and trench related volcanics have R/R_a ~ 5-8 (Craig et al., 1978; Torgersen et al., 1981; Baskov et al., 1973) and can be as low as R/R_a ~ 2 (Poreda

and Craig, 1979). On the other hand, stable tectonic systems reflect the dominant addition of crustal helium (0.1-0.01 R_a; Aldrich and Nier, 1948; Kamenskiy et al., 1971; Torgersen, 1980). This leads to the following logic and hypothesis: (1) Because magmas and magma sources contain helium in ratios that are definitive of certain tectonic processes and (2) because magmas and magma sources are high temperature heat sources, and (3) because mass transfer of magmatic helium to a fluid is geologically improbably without the accompanying transfer of heat, THEN the presence of magmatic helium in a geothermal fluid implies a direct transport of heat and mass between that fluid and a magma. Furthermore, because (a) crustal rocks generate helium at R/R_a ~ 0.1 which can be released to the pore space and (b) because high thermal gradients existing solely within the crust can transfer heat to pore fluids and significantly raise their temperatures, THEN geothermal fluids containing only added crustal helium must be heated by enhanced thermal gradients. This second premise would include, for example, cases where secondary mineralization may effectively seal hydrologic subsystems in a volcanically heated geothermal area. This mineralization could block the mass transfer of helium and volcanic gases but would conduct heat down-gradient through the secondary mineralization. Identification of such a subsystem would certainly alter the geochemical evaluation of the associated pore fluids.

Given the above, the observed helium isotope ratios of geothermal fluids can, within certain limits, be used to classify volcanic heat and describe the type of tectonic process with which the magma is associated; or to indicate that all transfer of heat is the result of temperature gradients in the crust alone. Obviously, there are deviations and variations in the helium isotope ratio that will complicate this broad classification and the following will be used as examples: (1) geothermal fluids originally containing magmatic helium can gain crustal helium by country rock weathering and/or equilibrium production from U and Th series decay and thereby lower the helium isotope ratio, a crustal overprint (2) magmas which become isolated from their source will begin to accumulate crustal helium by in situ U and Th series decay thus lowering the helium ratio in a magma "aging" process. After sufficient time, all memory of the original magmatic helium will be lost but this isolated body could still retain some heat causing a perturbed crustal gradient. This is referred to as a system gradiently heated by passive volcanism. (3) Fluids with significant amounts of ^3H will produce ^3He by decay and thus increase the $^3He/^4He$ ratio. This can result in crustal helium-tritiugenic helium mixtures that would appear to be magmatic. Fortunately, tritium is usually still detectable in these fluids and corrections can be made. This case is best illustrated by the Lardarello data of Torgersen (1980).

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River, and Steamboat Springs can now be interpreted in the context of the heat and helium sources and the geochemical processes which "overprint" these sources.

Iceland—Iceland is located astride the axis of the Mid-Atlantic Ridge and offers a unique opportunity to study MOR processes. Rifting however, is probably by a much more complicated process than for MOR as is indicated by the prominent topographic high as well as the belt of earthquake epicenters which detour across Iceland. This island is composed almost entirely of subaerial Cenozoic basalt with some intermediate and acid rocks. The geochemistry of these volcanic rocks has been actively investigated by a number of workers in past years (see O'Nions *et al*, 1976) and has led to considerable speculation on the nature of the underlying mantle.

Bödvarsson (1961) has classified the physical characteristics of Icelandic geothermal resources as high- and low-temperature systems. Low-temperature systems are located in Tertiary and Lower Quaternary age rocks while all high-temperature areas are closely linked with central volcanic complex (Arnorsson and Sigurdsson, 1974). The Reyjavik wells (Table 2) are located in a low-temperature system whose waters possess a composition quite suitable for direct use. Krafla is subject to periodic influxes of volcanic emanations from a magma chamber at ~3 km depth (Steinthorsson and Sveinbjörnsdottir, 1981). The Krafla high-temperature system was seismically active in September 1977 when the volcano deflated with some basaltic out-flow (Brandsdottir and Einarsson, 1979). Hafralaehur is a 101 m deep well on a farm (65°52'N, 17°26'W) of the same name located approximately 35 km WNW of Krafla wells 7 and 8.

The data of this study are in general agreement with the extensive work of Kononov and Polak (1976), who mapped the distribution of helium isotope compositions in Icelandic thermal manifestations. The high R/R_a ratios at all sampling locations in this study and elsewhere indicates a dominant magmatic helium component although there is a large difference between the high-temperature Krafla system and the low-temperature Reyjavik system which approaches the hot-spot helium isotope ratio of 14–25 R_a. In view of the more clearly defined affinity between Krafla and active volcanism, the respective water chemistries, and almost general agreement on Iceland as a hot-spot (from basalt studies), the most probable explanation for these data is a hot-spot volcanic source for helium and heat, but considerable hydrologic contamination of geothermal waters by weathering release of He from alpha decay (Torgersen, 1980). This is an agreement with the generally greater concentrations of chemical species in the high-temperature Krafla systems.

The Geysers—The Geysers–Clear Lake has a geologic history of tectonically controlled events and volcanism. The Clear Lake volcanics cover 400 km² and range in age from 2.5 m.y. to less than 30,000

yrs. being progressively younger from north to south. The older lavas are quartz-bearing olivine basalts whereas the most recent activity has produced basaltic to andesitic cinder cones and maar-type pyroclastic deposits (Hearn *et al.*, 1975). Cobb Mountain, a prominent volcanic dome is surrounded on three sides by the Geysers steam field and Mount St. Helena, another volcanic pile, lies ~20 km to the southeast.

This volcanic sequence unconformably overlies rocks of the Franciscan assemblage and the Great Valley sequence which forms the basement complex of this area and much of the California Coast Range. The Late Mesozoic and Early Tertiary Franciscan is thought to represent a deep-ocean trench or an arc-trench gap deposit (Blake and Jones, 1974). The Great Valley sequence and the ophiolite complex beneath were originally deposited east of the Franciscan (McLaughlin and Stanley, 1975) but now generally overlie the Franciscan rocks of equivalent age along a zone of regional thrust faulting. Atwater (1970) has described this present structure as the result of eastward subduction of the Franciscan beneath the ocean crust and the overlying Great Valley sediment strata. This subduction process which consumed the Farallon Plate as a result of the convergence of the North American Plate and the Pacific Plate most likely ceased 5–30 m.y. B.P. when convergent motion gave way to transform motion initiating strike-slip along the San Andreas Fault System. Large scale strike-slip motion continues to the present and contributes to the dominant NW-SE trend of the geologic structure of the California Coast Ranges.

Heat flow in The Geysers region as a whole tends to be somewhat high, 4 HFU (0.17 w/m²) compared to an estimated background of 2 HFU (0.08 w/m²) (Urban *et al.*, 1975). Above the steam zone, heat flow is about 10 HFU (0.42 w/m²) with very nearly linear temperature profile indicating that heat transport between the depth of first steam (1.5 km, 240°C) and the surface is largely by conduction. Urban *et al.*, (1975) have estimated that electric power production liberates 100 times more heat by steam removal than is lost by conduction.

McLaughlin and Stanley (1975) indicate that The Geysers is a structurally controlled geothermal reservoir whose steam production is dependent on faults and fractures to supply meteoric water and provide pore-space for a steam reservoir. A caprock roof provides a structural trap and sealing mechanism (Urban *et al.*, 1975). Isherwood (1975) identified a residual gravity low (~30 mgal) over Mount Hannah with a diameter of ~20 km. Local magnetic highs correlate with surficial expressions of serpentinite and volcanic rocks, but the Mount Hannah gravity low appears to have no deep magnetic expression (Isherwood, 1975). Isherwood (1975) attributed these features to a magma chamber, above its Curie temperature, centered more than 10 km below the SW edge of the volcanic field.

TABLE 6:   MAGMA AGING

Time Yrs.	$^3He/^4He$ x 10^7	He/Ne	$^3He/^4He$ x 10^7	He/Ne
Holocrystaline "Tholeiite"			"Granite"	
0	140.0	0.1	140.0	0.1
10^3	130.0	0.1	50.0	0.3
10^4	90.0	0.2	7.6	2.1
10^5	22.0	0.7	1.7	20
10^6	3.4	5.8	1.1	200
10^7	1.2	57.0	1.0	2000
10^8	1.0	570.0	1.0	20,000
Glassy "Tholeiite"			"Granite"	
0	140.0	10.0	140.0	10
10^6	140.0	10.0	120.0	12
10^7	130.0	11.0	47.0	30
10^8	89.0	16.0	7.6	210
10^9	22.0	67.0	1.7	2010
10^{10}	3.4	580.0	1.1	20,000

The initial conditions for this illustra-
tion of the time scale and evolution path
of aging magmas are emplacement of a homoge-
neous magma which, at time zero is removed
from contact with its source and solidifies
instantaneously to (i) a "holocrystaline"
or (ii) a "glassy" state with He and Ne con-
centrations as observed by Dymond and Hogan
(1974). For a "tholeiite" magma U and Th
were taken as 0.1 and 0.18 ppm (Tatsumoto,
1966). A "granitic" magma has 2.5 and 10.2
ppm U and Th, respectively (Shaw, 1967).
The U and Th series daughters were assumed
to be in radioequilibrium with the parent
and ^{4}He production rates were calculated
from the equation of Craig and Lupton
(1976) using a ^{3}He / ^{4}He production ratio of
10^{-7} based on Morrison and Pine (1955).
The magma then evolves as a closed system.
The "holocrystaline" mixing line is illust-
rated in Figure 1.

The Geysers' helium isotope composition is within the range of typical plate margin volcanics but generally less than that for hot-spot volcanics such as Hawaii and Yellowstone. In fact, the range in corrected end member ratio, $6.0 < (R/R_a)_c < 9.6$, is typical of fluids from the New Zealand volcanic zone (Torgersen et al., 1981) and the circum-Pacific region in general (Craig et al., 1978); but the helium isotope ratios in basaltic glasses from the Juan De Fuca Ridge and the Cayman Trench (Kurz and Jenkins, 1981) and other midocean spreading centers are also distinctly within the range of samples from The Geysers. The values at GE-1 ($(R/R_a)_c = 9.6$ and 8.9) are on the high side of MORB ratios but this helium is certainly not typical of hot-spot volcanics.

Several mechanisms exist to cause the lowering of the helium isotope ratio in places like The Geysers: (i) Most commonly, crustal type helium ($R/R_a \sim 0.1$) can be added to the geothermal fluid as a part of the hydrologic cycle from the weathering of rocks (see Torgersen, 1980). (ii) Crustal material and hence crustal helium can be incorporated into the primary magma as is suggested by the generally lower trench ratios relative to ridge ratios and most certainly in the case of Boninites (Poreda and Craig, 1979). (iii) As is shown in Table 6 and discussed later in relation to Steamboat Springs, a magma can "age" and generate its own crustal helium by the α-decay of uranium and thorium series elements within the magma. In the case of The Geysers, though, to identify the heat source and magma type, the problem is not explaining the low ratios encountered but explaining the high ratios.

Only one viable mechanism exists for raising the $^3He/^4He$ ratio other than magmatic addition. This mechanism involves the decay of nuclear weapons produced ^{3}H incorporated into rain and added to the hydrologic cycle. Figure 1 shows that if 1000 T.U. rain from 1963 were allowed to decay in a closed system for 25 years, $^3He/^4He$ ratios similar to magmatic helium would be evident. (This water would still contain ~250 T.U.). Mixing this 1000 T.U. 1963 rain with crustal helium produces the mixing line shown in Figure 1. The He/Ne (or X) gives an indication of the relative effects of a ^{3}H enriched helium component just as it indicates the relative atmospheric component. For The Geysers, He/Ne is generally larger than ~50 indicating a primordial/atmospheric ratio of ~50. Certainly, ^{3}He from ^{3}H decay is insignificant in these measurements from The Geysers.

The helium isotope measurements therefore confirm the presence of an active magma beneath The Geysers' steam field and a volcanic heat source is implied. From The Geysers tectonic position and its ocean-ridge type mantle helium, it is suggested that the area probably represents a short ridge section or a "leaky" transform like the Cayman Trench rather than a trench remnant. The extent and occurrence of other such features along the San Andreas and associated fault systems certainly deserves inquiry.

Raft River—The Raft River geothermal area lies in a basin (Id.-Ut. border at ~113°W, 10 km SSW of Malta, Id.) that was warped and downfaulted in the late Cenozoic and filled with Pleistocene alluvium, Miocene-Pliocene tuffaceous sediments, conglomerates and felsic volcanic rocks, to a depth of 1800-2000 m. (Williams et al., 1975). Large gravity, magnetic and total field resistivity highs indicate the presence of a deep igneous body that is too old to serve as a heat source. Structural control would seem to funnel the high precipitation (800 mm/yr) from the Raft River mountains to a deep aquifer which is apparently self-sealing. Secondary calcite and silica occur at depth and provide an insulating caprock for the area. Heat flow of 2-3 HFU (~0.1 w/m²) provides temperatures of 150°C at depths of 3-5 km. This heated water then migrates along fault controlled paths to the Bridge, Id. area.
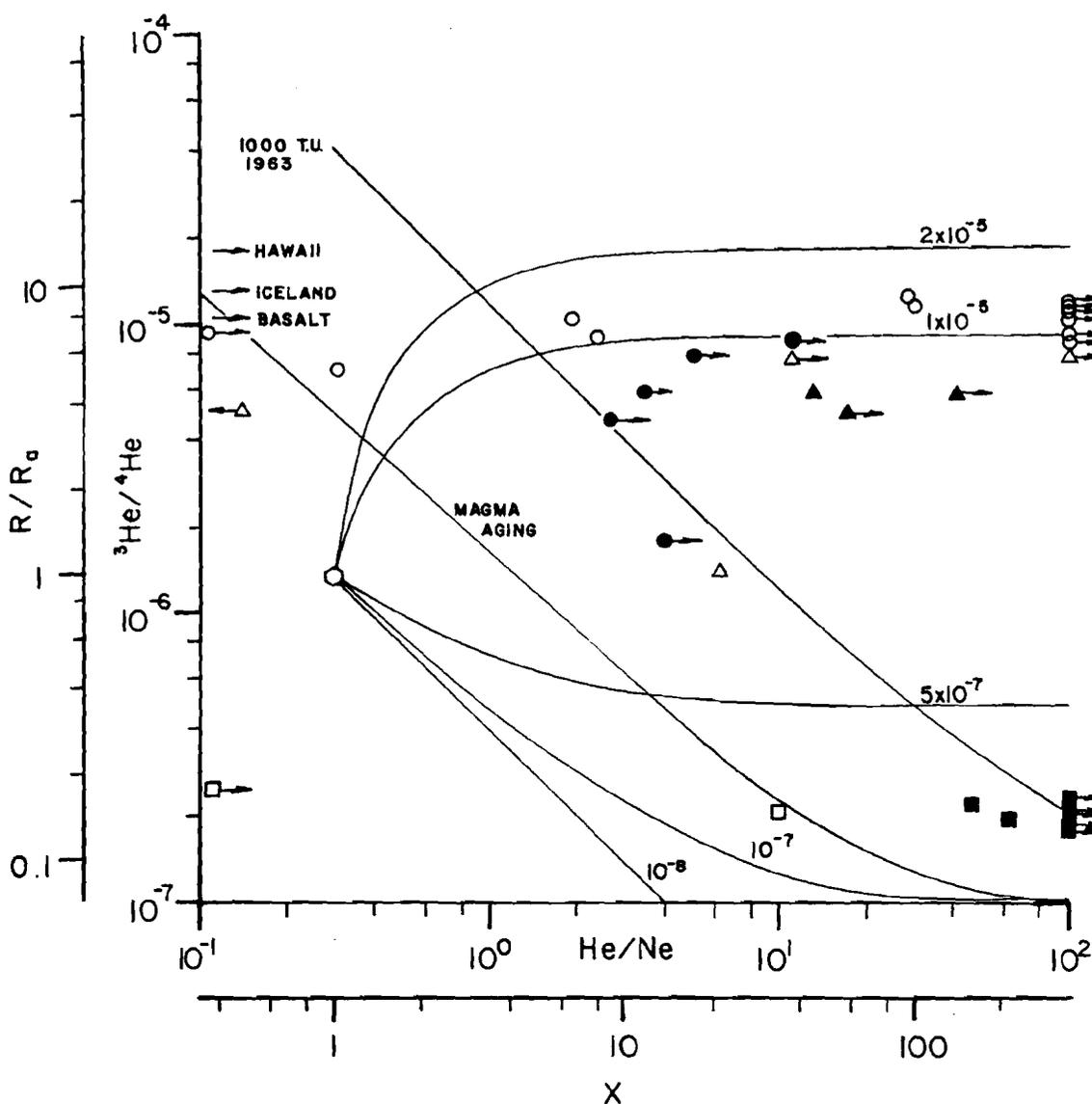
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FIG. 1. The helium isotope ratios and the He/Ne ratios from this study are plotted using both absolute ratios ($^3He/^4He$; He/Ne) and air normalized ratios (R/R$_a$; X). Mixing lines between air (O) and primordial helium with an absolute helium ratio of 2×10^{-5} and 1×10^{-5} are shown as well as mixing lines between air and crustal helium of absolute helium ratios 5×10^{-7} 1×10^{-7} and 1×10^{-8}. Also shown are the holocrystalline magma "aging" line detailed in Table 6 and the 1000 T.U. 1963 mixing line mixed with crustal helium ($^3He/^4He = 10^{-7}$) as explained in the text. The Hawaiian mean, Icelandic mean of this study and basalt glass values of Kurz and Jenkins (1981) are indicated by arrows on the left. Circles (O, ●) represent The Geysers, triangles (△, ▲) represent Steamboat Springs, and squares (□, ■) represent Raft River. Filled symbols (●, ▲, ■) indicate water samples while open symbols (O, △, □) indicate gas. Arrows on the symbols indicate limits.

wells clearly represent helium of crustal origin. The ratios (0.1–0.3 R$_a$) imply that the buried igneous body is not an active volcanic heat source. This area would have to be classified as having a gradient heat source in agreement with the geophysical evidence. The buried igneous body may be the cause of thermal gradient perturbations and the label passive volcanic would require a thermal model of the area.

Steamboat Springs—The Steamboat Springs area borders broad and complex geologic zones. The motions of the North American Plate and the Pacific Plate prior to ~30 m.y. provided an active trench system along most of the California coast. Differing

plate motion models presented by Atwater (1970) indicate the termination of subduction in the San Francisco-Steamboat Springs latitude 5–30 m.y. B.P. Since then, strike-slip motion has dominated. If the western U.S. is considered a broad soft margin for plate interaction (Hamilton and Myers, 1966) which explains the seismicity pattern, the strike-slip motion undoubtedly contributes to the extensional features of the Basin and Range Province which Steamboat Springs borders. This extension contributed to the voluminous Cenozoic volcanics and sedimentary deposits which overlie a deeply eroded basement complex of Pre-Tertiary metamorphic and granitic rocks.

Intense hydrothermal activity initiated prior to volcanism (dating to 3 m.y. and continuing to the present, Silberman *et al.*, 1979) has generated extensive epithermal gold and silver deposits.

The Lousetown Formation, the last surficial volcanic event within a series of volcanic events, initially produced basaltic andesites and later rhyolites (Thompson and White, 1964). Steamboat Springs lies approximately on a line with four rhyolite domes which erupted at 1.1–1.5 m.y. (Silberman *et al.*, 1979). The magma chamber supplying pumice and rhyolite for these domes is thought to be at least 50 km^2 at a depth of 6 to 9 km. A magma water content of 6 to 8% and an eruption temperature of 675°C are indicated (White *et al.*, 1964). Generally, the Steamboat Springs thermal features have a history of volcanism, favorable topography and hydrology, and a balance between uplift and erosion (White *et al.*, 1964).

The helium isotope data for Steamboat Springs are certainly not as simple to evaluate as was The Geysers, or Raft River. The range of ratios, 3.7 < $(R/R_a)_c$ < 6.0, are certainly higher than atmospheric or crustal sources and values in this range were found in the active volcanic region of New Zealand (Torgersen *et al.*, 1980). As can be seen in Fig. 1, the input of ^3H to the groundwater could not be the cause of the $^3He/^4He$ ratios. 1000 T.U. water, a generally improbable groundwater value, mixed with crustal helium at $R/R_a \sim 0.07$, produces helium isotope ratios much lower than those observed. It must be concluded therefore that a component of magmatic helium is observed at Steamboat Springs. However, Steamboat Springs contains helium ratios lower than $R/R_a \sim 8$ and hence is not the typical plate margin volcanic source.

In view of the limited number of samples obtained from Steamboat Springs, it is possible that a more extensive sampling survey might have yielded helium isotope ratios up to 8–9 R_a. However, more plausible explanations can be invoked without resorting to the idiosyncrasies of chance sampling: (1) hydrological controls on the flow of water to the Steamboat Springs system could introduce significant amounts of crustal helium thus diluting the magmatic endmember and lowering the ratio; (2) the magmatic source may be "aging" and the $^3He/^4He$ ratio would therefore be lowered by the *in situ* α-decay of U and Th series elements within the magma. Table 6 and Fig. 1 show that a "holocrystalline" basalt would "age" to a ratio of 0.1 R_a in ~ 1 m.y. If the magma chamber was tightly sealed, retaining higher ^4He concentrations more like "glassy" magmas, this "aging" would take place on a longer time scale. The rhyolitic domes in the area (1.1–1.5 m.y.) or younger subsurface intrusives could then be the helium source; (3) the parent magma body from which Steamboat Springs helium emanates may be very young but have $^3He/^4He$ ratios indicative of a high percentage of slab or continental material in the melt.

The past history of the area certainly suggests extremely acid rock and a high percentage of water.

Without further geochemical or geophysical work, these choices are hard to distinguish. In all probability Steamboat Springs has some type of volcanic heat source. However, the history and characteristics of the unobserved magma source are unknown. The area certainly represents a complicated system which deserves further study.

CONCLUSIONS

The helium isotope signature of geothermal fluids can be used to identify the source: 14–25 R_a for hotspots, ~ 9 R_a for spreading centers, 2–9 R_a for subduction zones depending on the extent of slab or crustal contamination, and ratios much less than R_a for crustal production. Helium ratios in geothermal fluids can then be used to infer a classification of heat source type: magmatic helium implying active volcanic heat and crustal helium implying heat transfer by conduction which includes hydrologically isolated subsystems and passive volcanism (*i.e.* remnant heat in volcanic intrusions which is separated from its source region by significant space and time). Several scenarios for helium ratios in fluids not specifically identifiable are possible; (1) hydrologic mixing (2) weathering release of crustal helium from the country rock (3) ^3He addition by ^3H decay (4) "aging" of magma sources (5) alpha products by U-Th series elements and (6) non-typical sources. The results of this study indicate a volcanic source for geothermal fluids in Iceland with a suggestion of greater weathering release of crustal helium in the high-temperature system. The Geysers is interpreted as a MOR volcanic source probably related to a "leaky" transform associated with the San Andreas Fault System. Raft River contains only crustal helium. Steamboat Springs has been preliminarily interpreted in relation to an aging magmatic source although the possibility of a trench volcanic system with a large crustal contaminant cannot be eliminated.

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