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GEOLOGICAL SURVEY

THE RECHARGE AREA FOR THE COSO, CALIFORNIA, GEOTHERMAL SYSTEM
DEDUCED FROM δD AND $\delta^{18}O$ IN THERMAL AND NON-THERMAL WATERS
IN THE REGION

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ABSTRACT

Thirty-nine water samples from the Coso geothermal system and vicinity were collected and analyzed for δD and $\delta^{18}O$ plus major chemical constituents. Non-thermal ground waters from the Coso Range were found to be isotopically heavier than non-thermal ground waters from the Sierra Nevada to the west. The δD value for the deep thermal water at Coso is similar to that of the Sierra water, and we conclude that the major recharge for the hydrothermal system comes from the Sierra Nevada rather than from local precipitation on the Coso Range. However, the $\delta^{18}O$ values of the thermal water are about 7‰ heavier than those of the Sierra water. This shift in $\delta^{18}O$ is the result of water-rock reaction at high temperatures, and the magnitude of the shift indicates that movement of recharge water through the hydrothermal system has been very slow (a large ratio of rock to total water for the system up to its present stage of development).

INTRODUCTION

The concentrations of the stable isotopes of oxygen and hydrogen in water are generally expressed in terms of $\delta^{18}\text{O}$ and δD , where

$$\delta^{18}\text{O} = \frac{(\text{180/160})_{\text{sample}} - (\text{180/160})_{\text{standard}}}{(\text{180/160})_{\text{standard}}} \times 1000 \quad (1)$$

and

$$\delta\text{D} = \frac{(\text{D/H})_{\text{sample}} - (\text{D/H})_{\text{standard}}}{(\text{D/H})_{\text{standard}}} \times 1000 \quad (2)$$

and the standard is usually mean ocean water (SMOW). Craig (1961) found that on a plot of δD vs $\delta^{18}\text{O}$, meteoric waters from throughout the world lie close to a straight line given by the equation,

$$\delta\text{D} = 8\delta^{18}\text{O} + 10 \quad (3)$$

This straight-line relationship comes about because ocean water is the source of most of the water vapor that precipitates over landmasses. When ocean water evaporates, the lighter isotopes of oxygen and hydrogen are preferentially partitioned into the vapor phase. Because the reservoir of ocean water is very large compared to the amount of water vapor in the atmosphere at any given moment, and because most rain water eventually returns to the ocean, the isotopic composition of the ocean remains relatively constant. Over long periods of time, however, there are small but significant changes in the isotopic composition of ocean water as the amount of water tied up in polar ice caps changes. When and where the water vapor condenses and precipitates, the heavier isotopes in the vapor partition preferentially into liquid droplets (rain) and ice (snow). This leaves the remaining vapor relatively depleted in D and ^{18}O so that the

last rain that falls from a given initial quantity of vapor will be isotopically lighter than the first rain that falls from that vapor. The partitioning or fractionation of light and heavy isotopes between vapor and liquid is also temperature dependent; the lower the temperature of the reaction, the greater the fractionation. The processes that control the concentrations of stable isotopes in precipitation are presented by Dansgaard (1953, 1964), Ehhalt and others (1963), Friedman and others (1964), Craig and Gordon (1965), and Stewart and Friedman (1975). The net result of these processes is that rain water falling from a given storm becomes isotopically lighter as the storm moves inland, and rain (or snow) that forms at colder temperatures (high elevations and latitudes closer to the poles) is lighter than rain that forms at higher temperatures. Although the isotopic composition of rain that falls in a given region will be different for each storm, the average over a long period of time remains relatively constant. The isotopic composition of ground water reflects that average.

Smith and others (1979) measured the deuterium concentrations in rain and snow at 26 stations in California and Nevada during the exceptionally wet 1968-69 season. They showed that the winter precipitation upon the Sierra Nevada was isotopically slightly lighter than the summer and fall precipitation on the nearby Mojave Desert. Most of the Sierra ground water recharge comes from winter storms moving generally from west to east. These winter storms drop most of their moisture before reaching the Coso Range. In contrast, most of the Coso Range recharge is from large,

but infrequent tropical storms that come from the south. On the basis of these data, we expected the isotopic composition of the normal, non-thermal ground water in the vicinity of the Coso geothermal field to be different from the isotopic composition of nearby Sierran waters. The purpose of the present study was to determine if variations in isotopic composition of ground waters in the region around Coso indicate whether the recharge for the Coso geothermal system comes from precipitation on the Sierra Nevada or from local precipitation at Coso.

SAMPLES STUDIED

The locations and descriptions of the samples used in this study are given in table 1. A total of 39 samples from 37 different sources were collected and analyzed. Eleven samples are of cold ground waters flowing from springs and wells in the Coso Range, north and east of Coso Hot Springs within the China Lake Naval Reserve. Eight samples are of Sierra Nevada ground water and five samples are from wells in alluvium in Rose Valley, between the Coso Range and the Sierra Nevada. The details of the collection and chemical analyses of two samples from the CGEH (Coso Geothermal Exploration Hole) No. 1 well (CC77-4 and CF78-1) are given elsewhere (Fournier and others, in press). The two downhole samples from the Coso No. 1 well (CF79-1 and CF79-2) were collected by using a modified version of the Fournier and Morganstern (1971) sampling tool designed for use on wireline equipment. It is lowered in the open position and water flows through it as it descends. The tool is closed at any desired depth in a well by means of a spring-loaded trigger that is tripped by an inertial weight attached to a second spring.

Table 1. Sample locations and descriptions

Sample No.	Latitude	Longitude	Category ¹	Description
CT-74- 2	36° 7.03'	117°45.34'	C	Haiwee Spring.
CT-74- 3	36° 7.00'	117°47.90'	T	Steam condensate at corrosion test site, Devil's Kitchen.
CT-74- 5	36° 2.30'	117°47.44'	T	Steam condensate from fumarole in Nicol area.
CT-74- 6	36° 2.96'	117°45.98'	T	Steam condensate from corrosion test site, Coso Hot Springs.
CT-74- 8	36° 2.69'	117°46.33'	T	Steam condensate from fumarole southernmost end, Coso Hot Springs.
CT-74- 9	36° 2.62'	117°56.77'	R	Well water at Junction U.S. 395 and Coso Road.
CT-74-10	36°19.76'	117°56.87'	T	Dirty Socks Springs.
CC-77- 4	36° 3.25'	117°48.22'	T	CGEH No. 1 well. Samples at well head after separation of steam at atmospheric pressure. Corresponds to sample 4 in table 1 of Fournier and others, 1980.
CF-78- 1	36° 3.25'	117°48.22'	T	CGEH No. 1 well. Downhole sample collected at about -1,100 m. Corresponds to sample 8 in table 1 of Fournier and others, 1980.
CF-79- 1	36° 2.96'	117°45.98'	T	Coso No. 1 well. Downhole sample collected just below the top of the water column at about -50 m.
CF-79- 2	36° 2.96'	117°45.98'	T	Coso No. 1 well. Downhole sample collected from near the bottom of the well at about -95 m.
CF-79- 3	36° 7.03'	117°45.31'	C	Haiwee Spring. Estimated flow 100 to 150 L/min.
CF-79- 4	36° 2.03'	117°47.89'	T	Vigorously boiling pool at Devil's Kitchen. No overflow from pool.
CF-79- 5	36° 2.75'	117°58.56'	S	Spring flowing from pipe in side of hill at Wild Rose Ranch (old name, Louis Ranch).
CF-79- 6	36° 5.01'	117°57.06'	R	Deep "house pump" well at Phil Hennis Ranch. About 206 m deep, pumping at about 10,600 L/min.
CF-79- 7	36° 2.61'	117°46.29'	T	Well 31.4 m deep at old house at South end of Coso Hot Springs. Water from well once used for drinking. Downhole sample collected from about -27 m when water level in well was about -18 m.
CF-79- 8	35°58.30'	117°57.75'	S	Water from stream flowing in canyon S.W. of Red Hill. Sampled at concrete collection box near upper end of dirt road.
CF-79- 9	36° 8.18'	118° 1.73'	S	Stream in Haiwee Canyon. Sampled at upper end of dirt road.
CF-79-10	36°11.06'	117°57.45'	M	Water from Haiwee Reservoir at narrows, just upstream of flood control gate.
CF-79-11	36°12.78'	118° 1.36'	S	Small spring coming from crack in granite at Earl Price ranch near Summit Creek.
CF-79-12	36°12.66'	117° 1.39'	S	Main spring supplying water to house at Earl Price ranch.
CF-79-13	36°19.76'	117°58.87'	T	Dirty Socks Spring.
CF-79-14	36°12.05'	117°36.39'	C	Spring at China Garden. Estimated flow 3 to 6 L/min from pipe supplying water to concrete-lined pool.
CF-79-15	36°10.64'	117°38.78'	C	Water flowing from abandoned mine tunnel at old town of Coso.
CF-79-16	36° 9.00'	117°40.13'	C	Coles Spring.
CF-79-17	36° 7.66'	117°41.62'	C	Spring at town of Dead End. Sampled where water flows from a pipe next to a dry gully at the end of the road.
CF-79-18	36° 5.13'	117°29.58'	C	Spring in gully east of Junction Ranch. Estimated flow 10 to 20 L/min.
CF-79-19	36° 6.05'	117°30.28'	C	Tennessee Spring. Very slow rate of discharge.
CF-79-20	35°56.64'	117°31.53'	C	Spring in Mountain Springs Canyon. Flowing from pipe by abandoned road at Wild Rose Mine.
CF-79-21	35°56.89'	117°33.89'	C	Mountain Spring in Mountain Spring Canyon. Estimated flow 30 to 50 L/min.
CF-79-22	35°51.74'	117°31.36'	C	Spring in Wilson Canyon. Estimated total flow from several seeps was 10 to 20 L/min.
CF-79-23	35°53.02'	118° 3.47'	S	Chimney Peak Spring, Kennedy Meadows. Estimated flow 20 to 35 L/min from pipe at concrete basin.
CF-79-24	35°56.84'	118° 4.85'	S	Spring 3/4 mile S.W. of Big Pine Meadows. Flowing 5 to 10 L/min from pipe set in circular rock and concrete structure.
CF-79-25	35°59.34'	118° 5.93'	S	Well supplying water to Grumpy Bear Restaurant, Big Pine Meadows.
CF-79-26	35°46.43'	117°38.20'	M	Artesian well near Center Line Road (25S/40E-11K1). Estimated flow less than 3 L/min.
CF-79-27	35°41.04'	117°44.81'	M	Well at S.W. region of Naval Base (26S/39E-2C1). Sampled using bailing equipment. Water level -58 feet.
CF-79-28	36° 4.58'	117°57.03'	R	Rose Valley Ranch 724-ft-deep well. Water level -212 ft. Pumped first water at 14:07.
CF-79-29	36° 4.58'	117°57.03'	R	Same as CF-79-28, collected at 14:26.
CF-79-30	36° 4.58'	117°57.03'	R	Same as CF-79-28, collected at 14:41.

¹ S = Sierra water; R = Rose Valley; C = Non-thermal Coso Range; T = Thermal water; M = Miscellaneous.

Table 2.--[Isotopic and chemical analyses of waters from the Coso geothermal area and vicinity. [Analyses reported in mg/kg. Delta values for oxygen and hydrogen isotopes are in parts per thousand relative to standard mean ocean water, SMOW. The Balance column shows the percent difference between the equivalence per million (epm) of cations and anions.]

Sample No.	Temp. °C	pH	SiO ₂	Ca	Mg	Na	K	Li	HCO ₃ ^{3/}	SO ₄	Cl	F	B	Calc. TDS	Cations epm	Anions epm	Balance %	δD	δ ¹⁸ O
CT-74-2	20	7.84	52.6	36	16.5	28.5	5.9	<.01	171	66	18	0.24	0.3	395.04	4.54	4.69	3.2	-98	-13.2
CT-74-3	97																	-105	-9.9
CT-74-5	97																	-109	-10.6
CT-74-6	97																	-132	-12.9
CT-74-8	97																	-125	-10.6
CT-74-9	23	7.53	41.3	60	25	40	3.0	<.01	300	68	26	.27	.2	563.77	6.86	7.08	3.0	-102	-13.6
CT-74-10	33	8.01	130	43.5	70	1970	102	3.61	3070	106	1570	.76	24	7,089.87	96.74	96.85	0.0	-121	-14.9
CC-77-4	-70	8.22	710 ^{4/}	98	2.5	1590	124	10	279	245	2480	4.2	58	5,600.70	78.86	79.85	1.1	-107	-7.1 ^{5/}
CF-78-1	195	5.40	119	55	1	1510	132	13	119	53	2330	3.3	49	4,384.30	73.75	68.95	6.7	-107	-7.8 ^{5/}
CF-79-1	-90	8.25	373	60	3	3600	434	32	354	160	5770	5.7	110	10,901.70	175.54	172.19	1.9	-15	+8.5 ^{6/}
CF-79-2	-140	6.50	209	40	1.5	1640	190	17	212	140	2530	2.6	5 ^{7/}	5,039.10	80.76	77.89	3.6	-99	-5.8 ^{6/}
CF-79-3	17	7.2	51	33	13	31	4.4	<.01	171	47	15	.37	.2	365.97	4.17	4.22	1.0	-96	-13.5
CF-79-4	95	1.7	265	18	11	21	10.1	.03	0	1120	6	.53	1.4	1,453.06	22.97 ^{7/}	23.52	2.4	-77	-4.3
CF-79-5	Cold	7.70	30	66	11	24	4.0	<.01	284	37	9	.26	.2	465.46	5.34	5.69	6.2	-102	-13.9
CF-79-6	22.5	7.2	42	76	25	109	10.2	.10	305	140	65	.47	.95	773.72	10.86	9.77	10.6	-112	-14.5
CF-79-7	Boiling	7.48	164	7	1	26	13.4	.02	133	19	10	.36	.10	373.88	1.90	2.87	40.4	-117	-10.8
CF-79-8	15	7.0	29	76	20	41	9.2	<.01	273	30	32	.23	.35	510.78	7.45	6.01	21.4	-103	-13.7
CF-79-9	10	7.9	25	62	18	39	6.0	.14	327	32	28	.16	.6	537.90	6.44	6.82	5.6	-109	-14.7
CF-79-10	14	7.6	26	21	4	35	3.6	.09	152	17	17	.55	.45	276.69	3.00	3.35	10.9	-117	-14.3
CF-79-11	17.5	7.2	36	43	11	32	3.2	<.01	195	32	20	.20	.2	372.60	4.52	4.43	1.9	-106	-14.3
CF-79-12	17.5	7.2	33	47	10	27	2.1	<.01	212	35	9	.25	.10	375.45	4.39	4.47	1.6	-108	-14.4
CF-79-13	29	7.1	130	48	70	2000	104	3	3130	100	1630	1.2	28	7,244.20	98.23	99.42	1.1	-121	-15.1
CF-79-14	14.5		38	64	19	54	8.1	.01	154	130	55	.59	.40	523.10	7.31	6.81	7.1	-92	-13.1
CF-79-15	15	7.2	42	97	16	33	2.4	.02	159	140	30	.38	.2	520.00	7.65	6.38	18.1	-99	-12.8
CF-79-16	13	7.18	27	150	52	44	3.9	.01	220	320	43	.13	.2	860.24	13.77	11.48	18.1	-98	-12.8
CF-79-17	12	6.95	34	64	13	35	1.7	<.01	263	30	23	.28	.2	464.18	5.82	5.59	4.0	-96	-12.9
CF-79-18	14	7.92	17	59	9	20	1.6	<.01	187	40	17	<.1	.15	350.75	4.59	4.37	4.8	-94	-12.8
CF-79-19	16	7.55	19	47	4	21	2.5	<.01	162	29	16	<.1	.15	300.65	3.65	3.71	1.5	-94	-13.3
CF-79-20	12.5	6.80	30	80	18	39	1.5	.01	317	30	44	.12	.2	559.83	7.20	7.06	2.0	-93	-12.4
CF-79-21	14	7.12	40	97	28	71	1.7	.01	398	66	69	.41	.50	771.62	10.27	9.86	4.1	-89	-11.6
CF-79-22	12	6.2	38	79	27	72	4.3	.02	297	40	126	.37	.5	684.19	9.40	9.27	1.4	-89	-11.3
CF-79-23	9	6.9	29	70	13	18	3.6	.01	273	36	18	.16	.15	460.92	5.43	5.74	5.3	-102	-13.6
CF-79-24	7	7.0	22	48	13	23	3.5	<.01	216	32	12	.25	.12	369.87	4.55	4.55	0.0	-104	-13.8
CF-79-25	Cold		24	84	25	55	5.5	.02	332	90	21	.70	.15	637.37	8.78	7.94	10.0	-106	-13.5
CF-79-26	20	8.36	78	4	2	500	21	.16	836	110	252	3.5	9.5	1,816.16	22.67	23.28	2.6	-94	-11.1
CF-79-27	Cold	7.7	32	38	6	66	4.7	.02	267	1	63	.43	.48	478.63	5.38	6.19	13.9	-95	-12.2
CF-79-28	Cold	8.13	30	111	28	114	11	.09	256	200	75	.58	1	826.67	13.09	10.50	21.9	-109	-14.2
CF-79-29	Cold	7.93	33	110	28	120	11	.10	261	190	70	.56	1	824.66	13.30	10.23	26.1	-109	-13.8
CF-79-30	Cold	7.80	31	109	28	118	10	.09	248	200	72	.58	.8	817.47	13.14	10.29	24.3	-111	-13.9

1/ CT-74 samples collected by A. H. Truesdell in 1974.
 CC-77 sample " " J. Foehr in December 1974.
 CF-78 sample " " R. O. Fournier in July 1978.
 CF-79 samples " " R. O. Fournier and J. M. Thompson in April 1979.

2/ Temperature at point of collection.
 3/ Total HCO₃ plus CO₂ expressed as HCO₃.
 4/ May include silica in colloidal clay.
 5/ Two other downhole samples collected the same day had δ¹⁸O values of -7.59 and -7.54.
 6/ A bottom hole sample collected in July 1978 had a δ¹⁸O value of -5.68.
 7/ Including correction for H⁺.

RESULTS

The analytical results are given in table 2, and the isotopic relations are shown in figure 1. Cold ground waters flowing from the Sierra Nevada and the well waters from Rose Valley all plot near the average meteoric line of Craig (1961) and have δD values less (more negative) than -100. The δD values of the Sierra waters generally become more negative to the north (Smith and others, 1979). The cold ground waters collected from springs and wells within the Coso Range also plot near the meteoric line in figure 1. However, they have δD values heavier than -100, which average -94. The difference in isotopic composition of the Sierra ground water and of the Coso Range ground water is the result of different types of storm systems contributing the major water recharge in the respective areas, as discussed above.

In figure 1, the water samples from the CGEH No. 1 well, CC77-4 and CF78-1, plot far to the right of the meteoric line, as do thermal waters from most geothermal systems throughout the world (White, 1970). As meteoric water flows into a geothermal system and becomes heated, its oxygen exchanges with the isotopically heavy oxygen in the surrounding rock so that the oxygen in the water becomes isotopically heavier and the oxygen in the rock becomes lighter. At the same time, the hydrogen isotopes of the water also exchange with hydrogen contained in minerals in the surrounding rock. However, because the rock contains a very large amount of oxygen and only a small amount of hydrogen, the oxygen isotopic composition of the water is changed considerably while the hydrogen isotopic composition is changed only slightly. Therefore, the amount of

$\delta^{18}\text{O}$ shift away from the meteoric line gives an indication of the relative amount of meteoric water that has reacted with rock, and the δD value is indicative of the δD of the meteoric recharge water. The shift in $\delta^{18}\text{O}$ of 7⁰/oo for samples CC77-4 and CF78-1 is very large and indicates that relatively little thermal water has moved through the system.

The δD value of the CGEH No. 1 water supports the view that recharge for the hydrothermal system comes from the Sierra Nevada to the west and that little or no component of recharge comes from the Coso Range. However, the data do not rule out the possibility that recharge is a mixture of isotopically light Sierra water from the northwest with some isotopically heavy locally derived Coso Range water. The isotopic data do show that recharge for the CGEH No. 1 thermal water could not be entirely from locally derived ground water, nor could it be from Owens Lake which is isotopically very heavy because of extensive evaporation (Friedman and others, 1976).

The two samples from the shallow Coso No. 1 well (CF79-1 and CF79-2) also plot far to the right of the meteoric line, but at δD values of -15 and -99, respectively (figure 1 and table 2). The sample from the top of the well (CF79-1) has about twice the total dissolved solids and is isotopically much heavier than the sample from the bottom of the well (CF79-2). Evaporation from the top of a free-standing column of water having liquid-vapor equilibrium at about 65⁰C accounts for these differences very nicely. Non-equilibrium evaporation from the top of a water column at a temperature different than 65⁰C also is possible.

The relationship of the waters entering the CGEH No. 1 and Coso No. 1 wells is of great interest. On the basis of chemical data obtained from downhole samples, Fournier and others (in press) concluded that a single parental water supplied both wells and that the compositional variations in the waters collected at the wellheads were the result of (1) different amounts of boiling in the wells during upward movement and (2) a higher temperature in the local reservoir feeding the Coso No. 1 well ($\approx 245^{\circ}\text{C}$) than in the reservoir feeding the CGEH No. 1 well ($\approx 205^{\circ}\text{C}$). These reservoirs are places in the rock where fracturing is locally more extensive than elsewhere so that permeability and the ratio of water to rock are higher than in the surrounding rock. In the model of Fournier and others (in press), the water cannot boil as it moves laterally from the 245°C reservoir to the 205°C reservoir. If the water had boiled, then the chloride concentration in the downhole samples from the two wells would have been different. The fact that the chlorides are very similar indicates very slow natural flow and conductive cooling of thermal water as the water moves from the vicinity of the Coso No. 1 well towards the CGEH No. 1 well. The flow could be slow because the permeability within the rock connecting the two reservoirs is very low. Alternatively, the permeability could be high (essentially one reservoir with small vertical extent and a horizontal temperature gradient within it) and convective flow limited by poor permeability on the outflow part of the convection system.

If the model presented by Fournier and others (in press) is correct, the isotopic composition of the water entering the two wells should be

about the same prior to any boiling or evaporation during upward movement after leaving the respective local reservoirs (if little water-rock isotopic reequilibration took place because of very slow reaction rates as the temperature changed from 245°C to 205°C). The slightly different observed isotopic compositions of the downhole sample from the Coso No. 1 well (CF79-2) and of the downhole sample from the CGEH No. 1 well (CF78-1) appears to be the result of slight contamination by evaporated water from the top of the Coso No. 1 well (CF79-1) as shown by the straight line relationship in figure 1 among samples from these wells. A similar conclusion can be reached on the basis of the relations of boron to δD and $\delta^{18}O$ shown in figures 2 and 3. Plots of chloride relative to δD and $\delta^{18}O$ show the same relations as the boron plots.

The total dissolved solids in the non-thermal waters from the Coso Range, the Sierra Nevada, and Rose Valley range from 300 to 860 mg/kg. The anions in these waters are mainly bicarbonate and sulfate as shown in figure 4. In contrast, the dominant anion in thermal waters from deep in the geothermal system is chloride.

In the Coso Range, the non-thermal waters containing the most sulfate are present where sulfide mineralization exists. Apparently sulfides are oxidizing to sulfate in these localities so that the increased sulfate in the water reflects the neutralization of sulfuric acid by water-rock reactions. The other non-thermal waters most rich in sulfate are from deep wells in Rose Valley, where bicarbonate and chloride also increase in response to a general increase in salinity as depth increases.

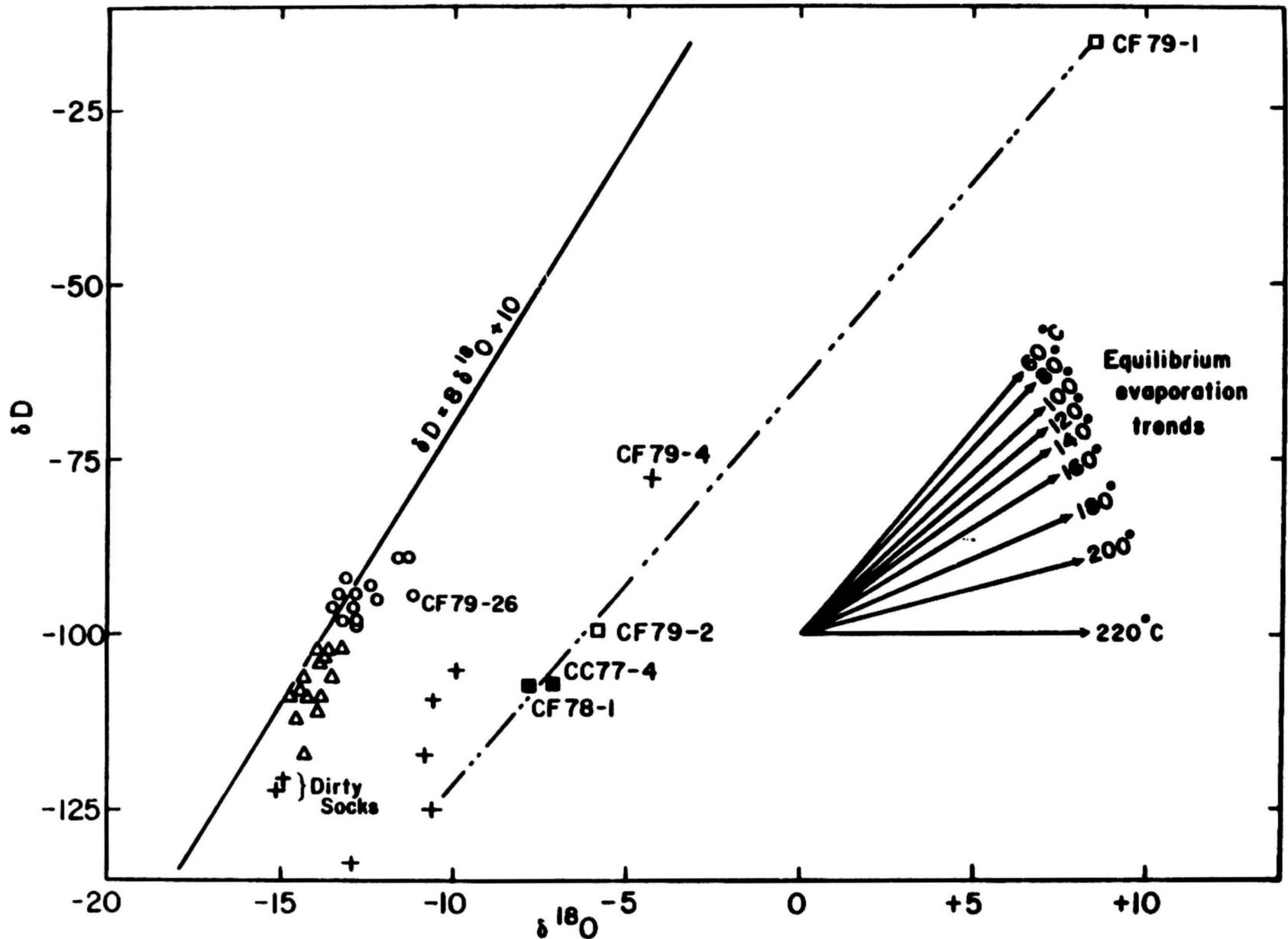


Figure 1 $\delta D - \delta^{18}O$ relations for thermal and non-thermal waters from the Coso region. Circles represent non-thermal waters from the Coso Range, triangles represent non-thermal waters from the Sierra Nevada Mountains and Rose Valley. Solid squares represent waters from the CGEH No. 1 well; open squares represent waters from the Coso No. 1 well, crosses represent other thermal waters and steam condensates. Numbers refer to samples in tables 1 and 2.

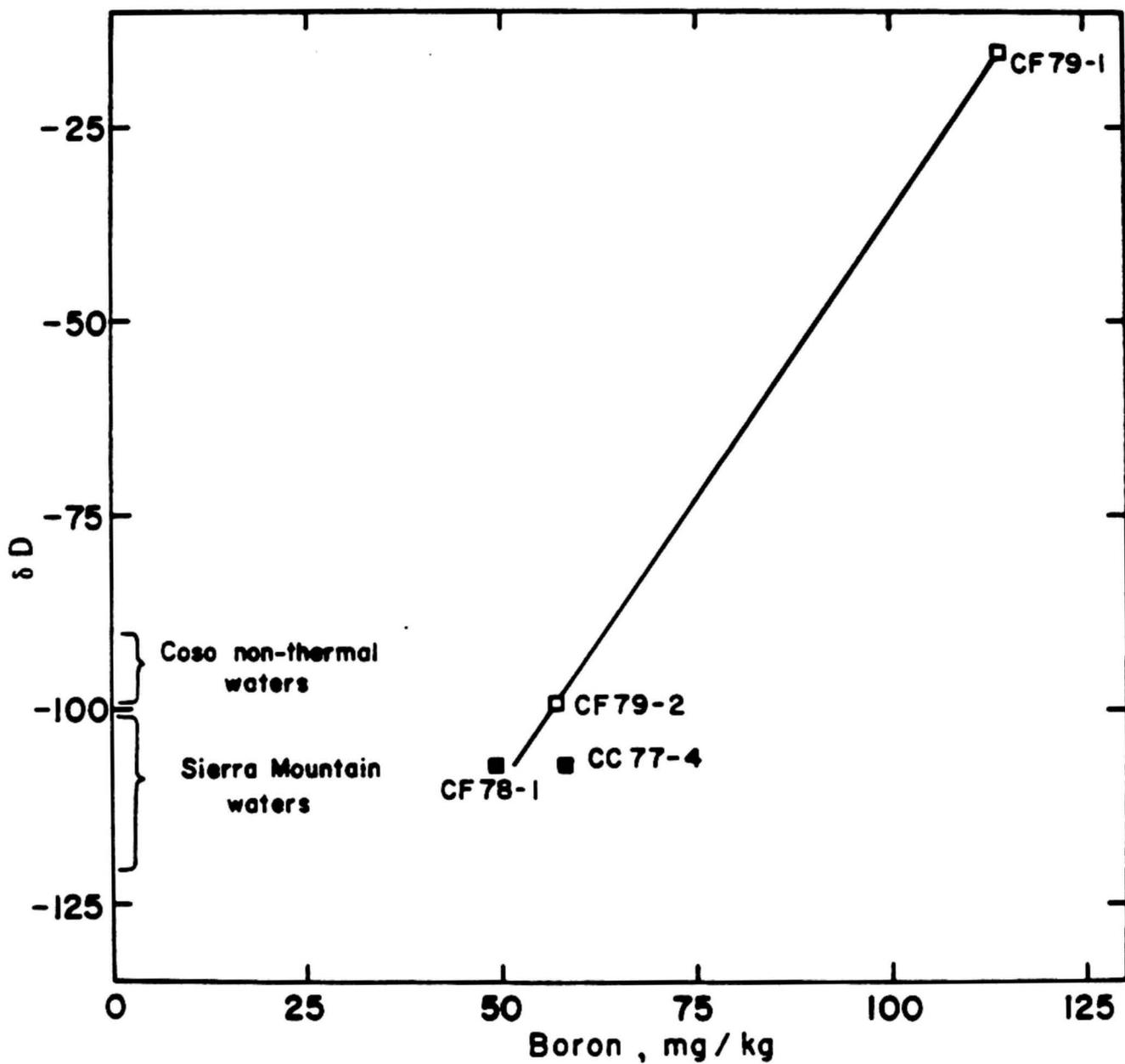


Figure 2 δD - boron relations for waters from the Coso region. Symbols and notations are the same as those for figure 1.

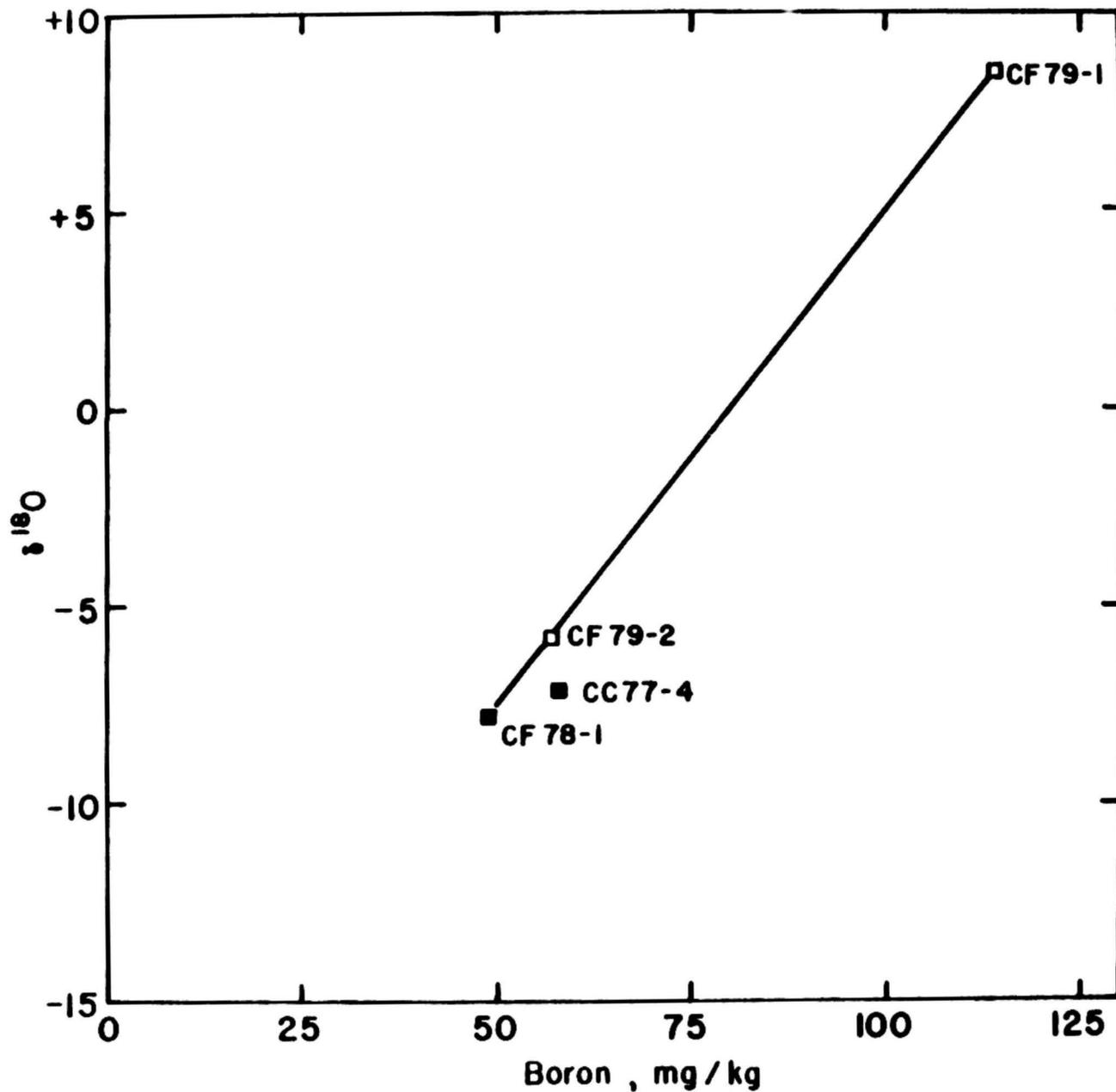


Figure 3 $\delta^{18}O$ - boron relations for waters from the Coso region.
Symbols and notations are the same as those for figure 1.

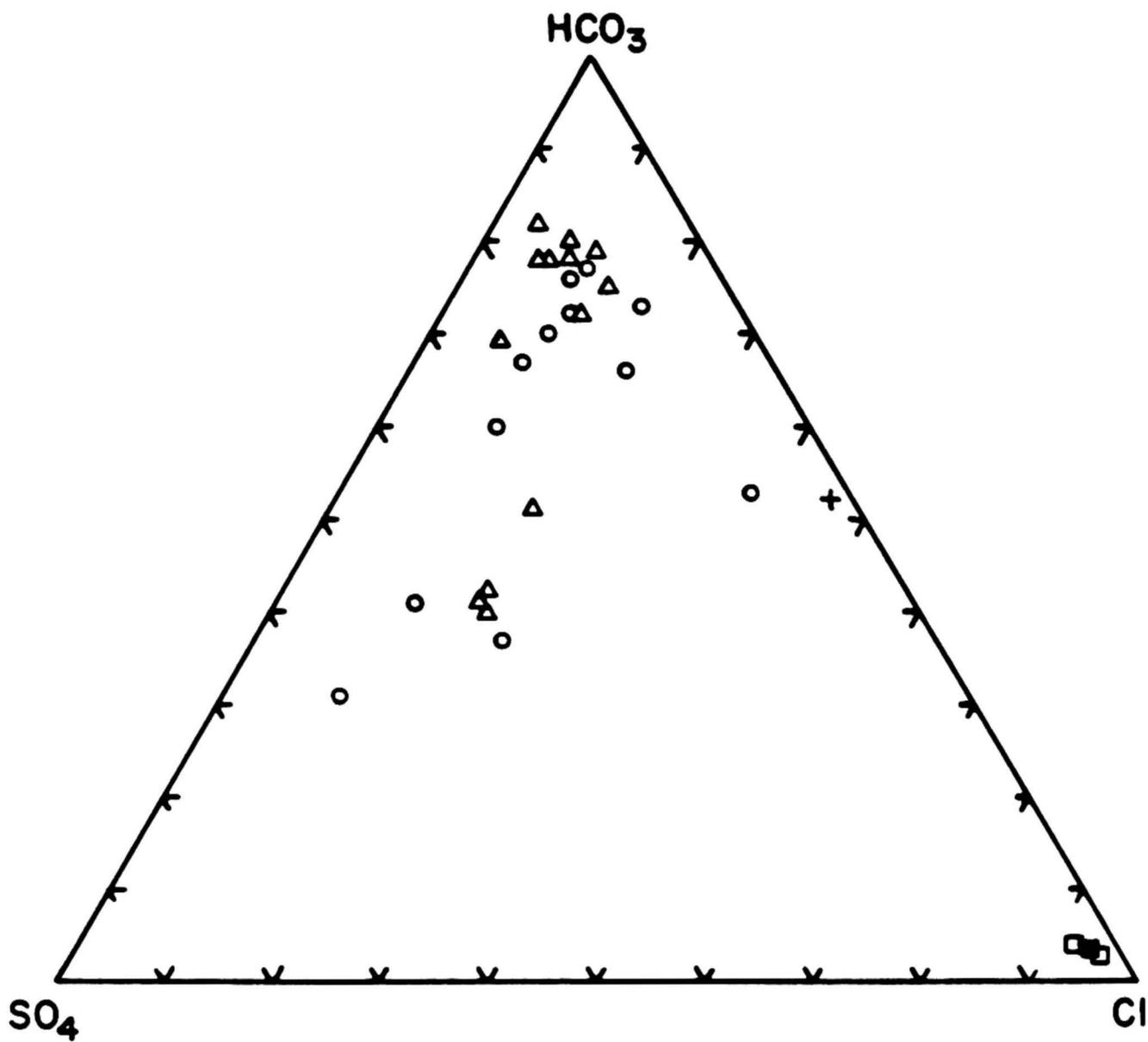


Figure 4 Triangular diagram showing percentage of equivalents of HCO₃, SO₄, and Cl in waters from the Coso Region. Symbols are the same as those for figure 1.

HYDROLOGIC MODEL

Figure 5 is an west-east cross section showing our preferred model for the recharge of the hydrothermal system at Coso. In that model, recharge for a deep, chloride-rich, hot water comes predominantly from rain and snow that falls on the Sierra Nevada about 25 to 45 km west of Coso. This recharge water probably descends along east-dipping faults in the Sierra Nevada granites (Duffield and others, in press) and migrates deep underground toward the Coso geothermal area. In the course of that deep circulation, the water becomes heated to temperatures in excess of 240°C and leaches chloride from the rock. The heated water rises buoyantly wherever it encounters relatively open fractures leading upward. In most places, the natural upflow of the thermal water is so slow that most cooling is by conduction of heat into the surrounding rock. However, the temperature of the ascending water in the most open parts of the channelways may be near the boiling point during much of the upward movement. Some local underground boiling takes place below Coso Hot Springs, Devil's Kitchen, and a few other localities to furnish the steam and acid gases that are responsible for the fumaroles and acid sulfate pools at the earth's surface. The surface distribution of fumaroles and acid sulfate pools, combined with high temperatures calculated by using chemical geothermometers applied to the Coso No. 1 well waters (Fournier and others, in press) suggest that the major channelway for upward migration of hot water is along a north-northeast-trending normal fault passing through Coso Hot Springs. According to W. A. Duffield (written communication, 1980), another line of evidence that this fault zone is the

principal upflow channelway is that the crustal heat source (i.e., magma chamber--partly liquid or not) is probably centered beneath Sugarloaf Mountain, the center of the dome field, and maximum heat flow is offset to the east, toward the fault zone.

As the ascending water cools, its density increases, causing it to convect back underground in a broad cell without reaching the surface. The temperature profile in the CGEH No. 1 well indicates that most of this convective overturn probably takes place below an elevation of 850 meters above sea level. The actual size and depth of the convection cell are unknown, and the dimensions shown in figure 5 are meant only to show a schematic representation of the general nature of the system. Electrical soundings and the surface heat-flow anomaly may give an approximation of the size of the cell, but the true nature of the hydrothermal system can only be determined by drilling many wells. Also, the depth of circulation of the recharge water is unknown. It may be hundreds or thousands of meters deeper than the depth shown in figure 5.

The convective migration of fluids away from the main zone of upflow is limited in part by the initial permeability of the rock and in part by the deposition of minerals at the cool margins of the systems. The stippled areas in figure 5 indicate zones of decreased permeability resulting from mineral alteration and deposition. Silica is likely to be deposited at the top and on the sides of a convection cell where waters that were once very hot ($>220^{\circ}\text{C}$) cool. In contrast, where descending cold waters become heated, calcium carbonate may deposit, particularly in the upper parts of systems where the partial pressure of CO_2 is low.

The net result is that an impermeable barrier is likely to form between thermal and non-thermal waters in the shallow parts of convecting systems. Such a permeability barrier probably prevents ground water from the Coso and Argus Ranges (east of Coso) from mixing with the water in the convecting hydrothermal system. The main zones of downflow and upflow are kept open by repeated seismic activity that reopens the major persistent fractures. Numerous fault scarps in Quaternary rocks (Duffield and Bacon, in press) and high levels of present-day seismicity (Walter and Weaver, in press) indicate high potential for maintaining openings along such fractures.

It is instructive to compare water levels in the two deep thermal wells, CGEH No. 1 and Coso No. 1, with water levels in two wells in Rose Valley near Coso Junction (figure 6). The thermal wells are about 3.2 km apart and both have water levels at an elevation of about 1,056 m. The Rose Valley cold-water domestic wells are about 12 km west of the CGEH No. 1 well and have water levels at an elevation of about 988 m (Moyle, 1977), or 68 m below the water level in the thermal wells. In the shallow part of the system, ground water should flow from the vicinity of the CGEH No. 1 well toward Rose Valley. However, as discussed above, an impermeable barrier formed by mineral deposition probably prevents much migration of the geothermal fluid into the Rose Valley aquifers. We found no chemical indication of influx of thermal water into the Rose Valley gravels. Although the Rose Valley water appears to increase in salinity as depth increases, the increased salinity is mainly the result of increased calcium bicarbonate and calcium sulfate, components in short supply in the hydrothermal water. Also, less than 68 m of head actually exist between

Rose Valley and Coso Hot Springs because a column of hot water weighs less than an equal column of cold water. Assume that the hot and cold columns of water are in two arms of a U-tube, as shown in figure 7, that the cold water maintains a density of about 1 gcm^{-3} at all depths, and that the hot water column is everywhere near the boiling point (the apparent situation near Coso Hot Springs). Then, the depth-pressure curves for the hot and cold columns intersect at about $35.5 \times 10^5 \text{ Pa}$, corresponding to a boiling temperature of 245°C (figure 7). Thus, a reservoir temperature of about 245°C would allow hydrologic equilibrium in which the top of a hot column of water is maintained 68 m above the top of a cold column of water. Previously, on the basis of chemical geothermometers and mixing models, Fournier and others (in press) concluded that a reservoir temperature of 240°C to 250°C was likely beneath Coso Hot Springs.

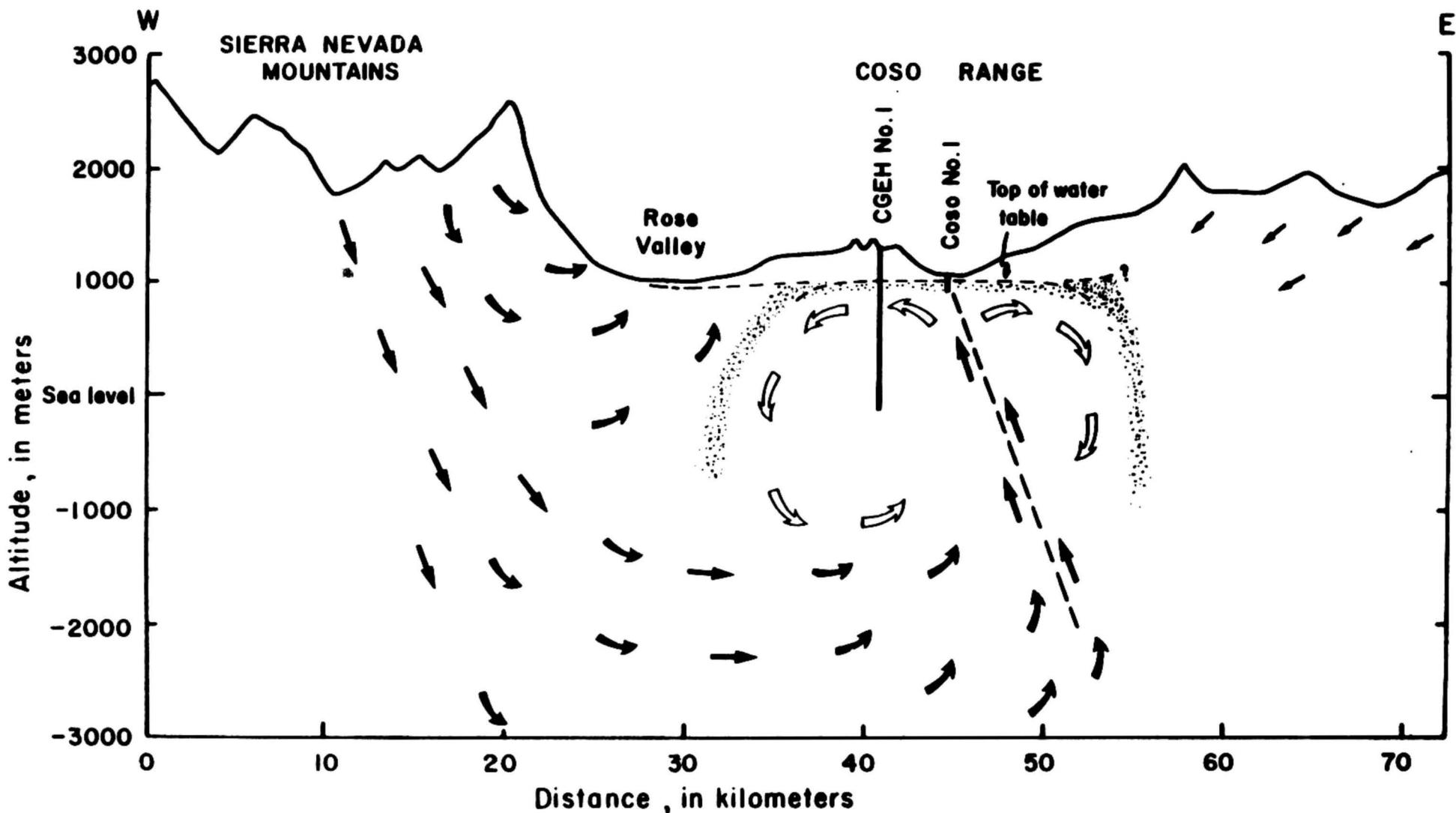


Figure 5 West-east cross section in which arrows show generalized path of recharge water and circulation within the hydrothermal system. The dashed nearly horizontal line is the top of the water table. The stippled zones show decreased permeability caused by mineral deposition. See text for additional discussion.

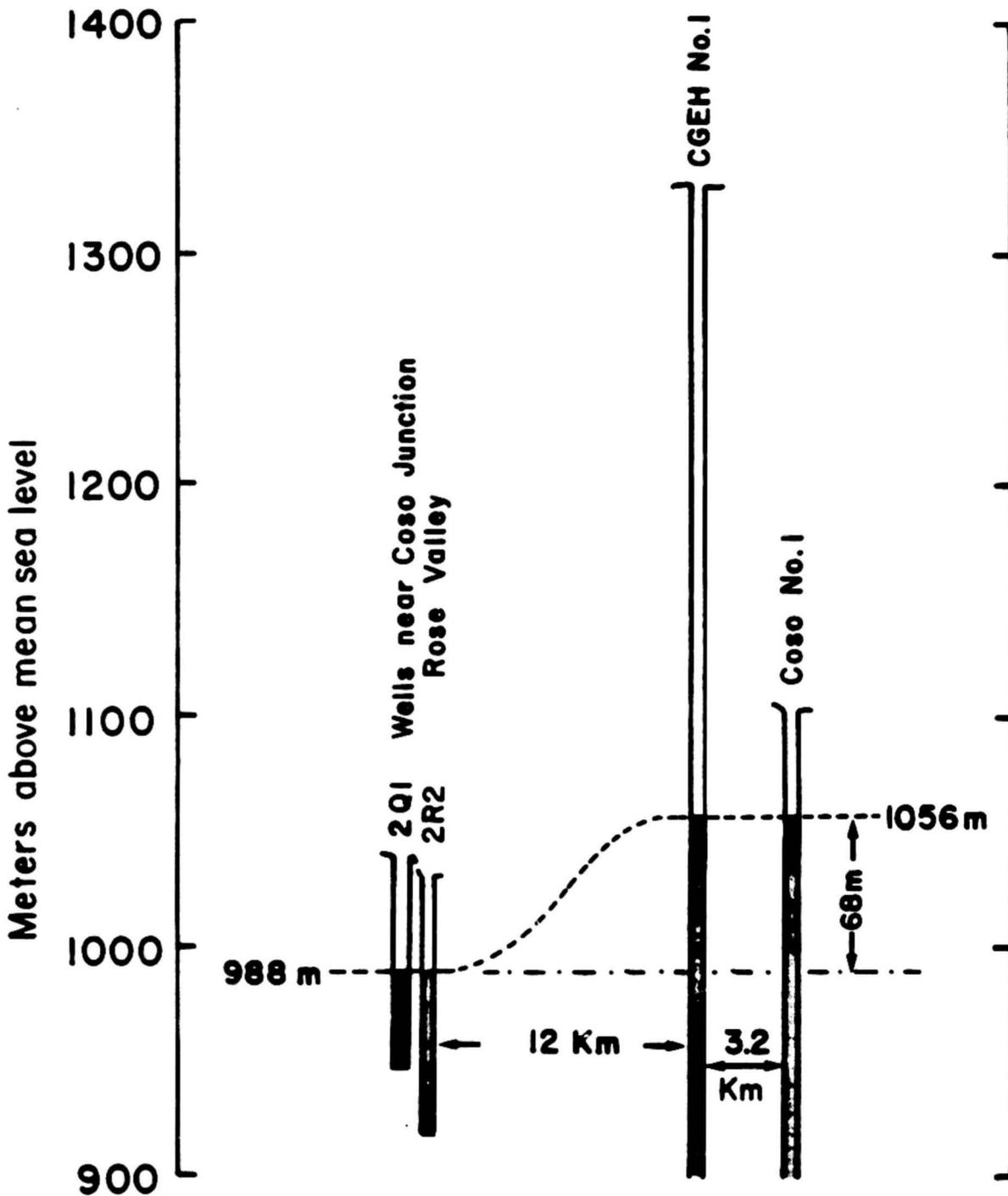


Figure 6 Comparison of water levels in cold-water wells at Coso Junction (Rose Valley) and in thermal wells at the Coso geothermal prospect.

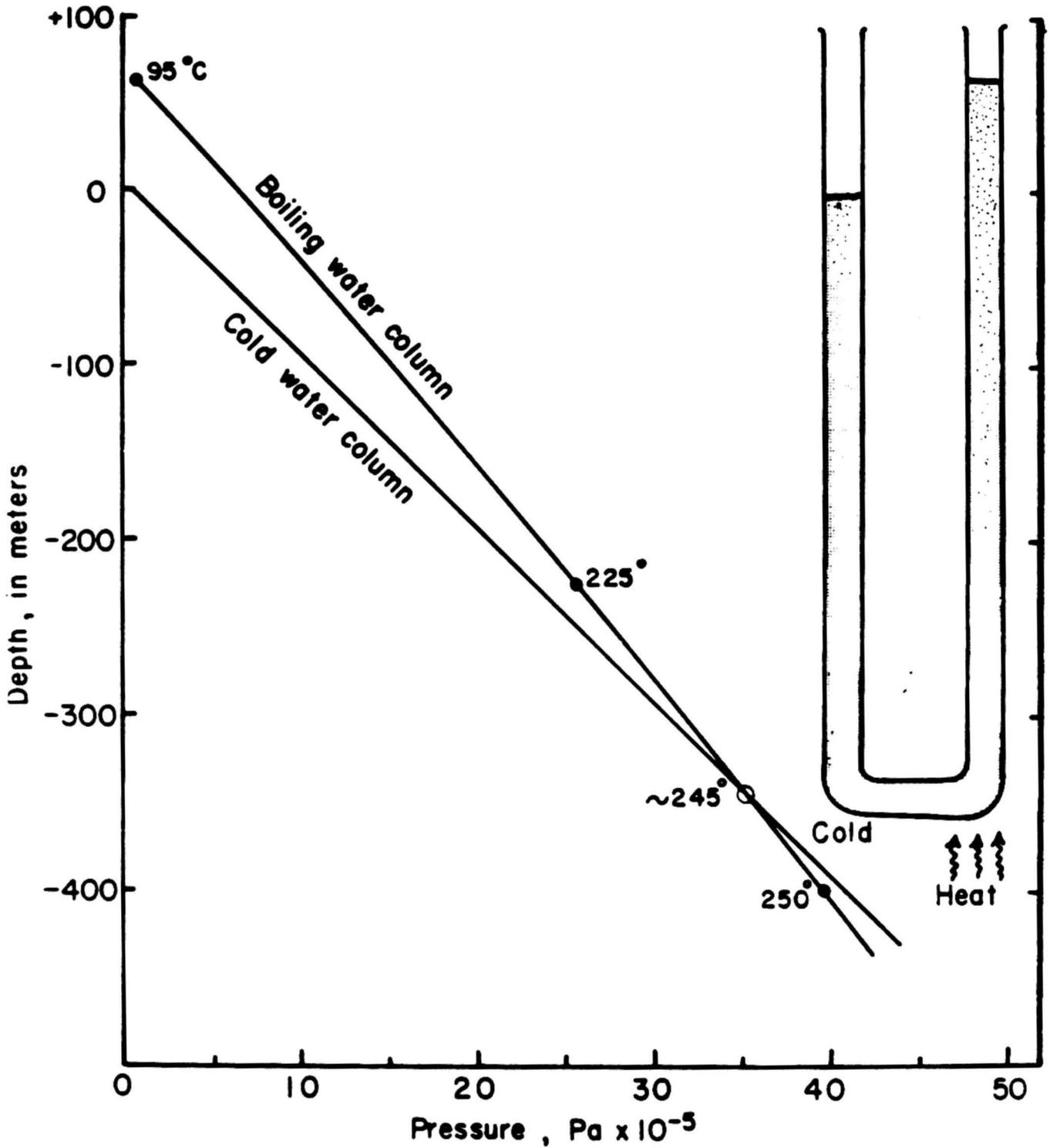


Figure 7 Depth - pressure relations for hydrostatic conditions in a cold well and in a well in which water is everywhere near its boiling point. See text for discussion.

CONCLUSIONS

The average meteoric water falling on the Coso and Argus Ranges is isotopically slightly heavier than the average meteoric water falling on the Sierra Nevada to the west. The deuterium concentration in the deep geothermal water is similar to that in the Sierra Nevada ground water and is different from that in the Coso Range water. Therefore, recharge into the deep part of the geothermal system probably comes predominantly from the Sierra Nevada. The main upflow in the hydrothermal systems appears to be along a north-northeast-trending fault beneath Coso Hot Springs. The large shift in $\delta^{18}O$ of about 70/00 in the thermal water suggests that the relative rock-to-water ratio is large, indicating very slow movement of new water into and old water out of the convection system. The isotopic and hydrologic data are compatible with a reservoir temperature of 240^o-250^oC beneath Coso Hot Springs.

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