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WATER AND GAS GEOCHEMISTRY OF THE COVE-FORT SULPHURDALE GEOTHERMAL SYSTEM

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ABSTRACT

The Cove Fort-Sulphurdale geothermal field is part of a large thermal anomaly covering approximately 130 km^2 in eastern Utah. The field presently produces dry steam from a shallow steam cap near Sulphurdale and liquid water from the underlying reservoir. These wells produce fluids with temperatures ranging up to 153°C although temperatures as high as 178°C have been measured elsewhere within the system. Even though the field has been the site of exploration and development efforts since the 1970's, the nature of the underlying resource remains poorly understood. In this paper, we present new data on the geochemistry of the produced fluids, including their noble gas compositions, and then compare these data to those from other systems within the region.

Geochemical studies of the Cove Fort-Sulphurdale geothermal waters has led to the development of a three end-member mixing model that includes a chloride water with a Na/K geothermometer temperature of 280°C and a composition similar to the reservoir water at Roosevelt Hot Springs, a deep groundwater, and steam condensate. The chloride water may be an expression of the primary reservoir water that provides steam to the wells. Gas analyses suggest that before production, the system was the site of a sizeable steady flow of gas to the surface. The flow pattern was probably the same as today. The chemical data suggest that hot fluids migrate upward within a permeability high developed within a shallow secondary reservoir. Water that remains after flashing leaves the system in such a way that it does not interfere with the flow of dry steam. During the initial production of the wells, steady flow conditions changed very fast (one month or less) to a new regime. Helium isotopes indicate that the gases at Cove Fort-Sulphurdale consist of a mixture of **6%** mantle and 94% crustal gas, compared to 23% and 77% respectively at Roosevelt Hot Springs.

GEOLOGY

The Cove Fort-Sulphurdale geothermal system is located in eastern Utah, within the transition zone between the Basin and Range province to the west and the Colorado Plateau to the east. This is an area of active tectonism and young volcanism that includes Roosevelt Hot Springs to the west where reservoir temperatures exceed 250°C, Thermo to the south, Meadow-Hatten to the north, and Monroe Hot Springs to the east. The thermal system at Cove Fort is unique because of the presence of numerous active gas seeps, sulfur deposits, and acid altered ground

The geology of the Cove Fort-Sulphurdale area has been described by Ross and Moore (1985) and Steven and Morris (1983). **A** generalized geologic map and the locations of the production and injection wells are shown in Figure 1. These geologic studies and lithologic logging of Unocal drill holes (Moore and Samberg, 1978) indicate that the reservoir is dominated by a thick sequence of Paleozoic limestones to depths of at least 2000 m. At greater depths, dikes of Tertiary quartz monzonite are present. Geophysical studies indicate that the quartz monzonite may be an important reservoir rock beneath the Sulphurdale area. Between Sulphurdale and Cove Fort, the limestones are capped by Tertiary lava flows in the north and ash-flow tuffs to the south. To the west of Sulphurdale, volcanic activity produced a broad shield volcano of basaltic andesite between about 1 and 0.5 million years ago (Best et al., 1980). Lavas related to this volcanic episode partially fill a deep graben whose geothermal potential is still unknown.

Fluid movement within the Cove Fort-Sulphurdale geothermal system is strongly controlled by faults and fractures. In the Sulphurdale area, low angle faults related to large-scale gravitational glide blocks dominate the near-surface geology to depths of 600

m. Ross and Moore (1985) suggested that these glide blocks form a low permeability cap over the reservoir rocks. These glide blocks consist primarily of ash-flow tuffs that have moved to the west.

The glide blocks cover and are locally cut by northerly- and easterly-trending faults that disrupt the reservoir rocks. Resistivity data suggests that the northerly-trending stuctures are the main conduits for movement of the thermal waters to the north. Easterly-trending structures appear to control the depth to the top of the reservoir rocks at Sulphurdale. The areas of highest permeabilty occur at the intersection of these two structural trends.

Geothermal wells in the Cove Fort-Sulphurdale field produce either dry steam or water. Steam production is currently from five wells or well pairs (refer to Fig. 1) drilled at Sulphurdale, adjacent to the largest and southernmost of the sulfur deposits. Excavation of the deposit shows that the altered rocks consist of alluvium and lake deposits that may fill a phreatic explosion crater. An additional well, P-94-1, taps the underlying liquid reservoir. The production temperature of this well is 153°C. After flashing, the residual water is reinjected into well 42-7, located to the north of the steam wells.

The steam is produced from a fine-grained fractured sandstone (Coconino sandstone of Ross and Moore, 1985) that underlies the volcanic rocks. In general, the depth to the top of the steam reservoir becomes shallower from the north to south. The deepest production is from the northernmost wells, wells 34-7A and B (referred to as Linda and Olga respectively) which encountered steam at 355 m. In the southernmost steam wells, the depth to the top of the reservoir is approximately 260 m.

WATER **AND** GAS GEOCHEMISTRY

Generalized Langelier-Ludwig **Graphs**

In this paper, we have used Langelier-Ludwig graphs to characterize the water types present in the Cove Fort-Sulphurdale area and to determine possible mixing relationships between them. Because these diagrams are not in common usage by the geothermal community, we first describe their general characteristics. We then apply them to data from the Cove Fort-Sulphurdale and Roosevelt Hot Springs geothermal areas.

Generalized Langelier-Ludwig graphs may be visualized using the following procedure. Follow it with the help of Figure 2.

1. First consider a horizontal Langelier-Ludwig graph, and imagine a straight line normal to it going both ways through its center. Let this serve as a TDS scale with the positive direction pointing upwards.

2. Make each point on the TDS axis the center of a Langelier-Ludwig graph, normal to the TDS axis, and with the side length proportional to the TDS.

Let **us** see what the solid volume we have just constructed in the geometric three-dimensional space looks like:

A. It has a square cross-section, in fact it is a Langelier-Ludwig graph, normal to the TDS axis;

B. The cross-section side and area are unity at TDS = 1, its side increases and decreases in proportion to the TDS; and

C. At one length (or TDS unit) below the center of the unit side Langelier-Ludwig graph, at TDS=0, our Langelier-Ludwig graph has become a point, **O.** As TDS is > or = 0, there is no axis beyond **O,** only upwards from it.

D. Now remove the TDS axis, we do not need it anymore.

The volume thus described is the inverted square pyramid of Figure 2. Point **O** at TDS = 0, the origin of the TDS axis and vertex of the pyramid, aptly represents pure water. For the rest, look to Figure 3 and its caption.

Figure 3 depicts the NE quadrant (only) of a Langelier-Ludwig graph with all available sample points from Roosevelt Hot Springs and the Cove Fort-Sulphurdale geothermal systems.

The main feature of the plot is the alignment of Cove Fort-Sulphurdale (empty circles) and Roosevelt Hot Springs samples (full circles). This feature suggests mixing of two end members, one similar to Roosevelt Hot Springs reservoir water (idealized as point R) and one idealized as point G for "Groundwater". The latter is suggested by the correlation with dissolved constituents (arrow). Figure 4 is a "generalized Langelier-Ludwig graph", a two-dimensional projection from the three-dimensional concentration space. It shows the same points and the Roosevelt Hot Springs-groundwater mixing line appears in both projections. The relationships shown on this plot improve the plausibility of the mixing hypothesis because the two projections involve more and different variables, as mixing ***per se*** entails correlation among all variables.

From these relationships, and the composition of water produced by Cove Fort-Sulphurdale well 91-4, we suggest that this well produces a mixture of three water types. These are:

(a) a sodium-chloride water similar to the Roosevelt Hot Springs geothermal reservoir fluid. This water has a Na^+/K^+ temperature of about 280°C.

(b) a groundwater, lato sensu, that is deeper than the main body of groundwater *stricto* ***sensu*** prevalent in the region.

(c) a geothermal steam condensate. This last component is identified by the high NH_4^+ contents of P91-4 water. Based on data available to us, the most plausible content of NH_4^+ in Roosevelt Hot Springs water is 0.58, while 0.8 ppm is the maximum plausible concentration. Therefore, the 1.6 ppm ammonia in well 91-4 water exceeds the maximum 0.38, or more likely the 0.28 ppm contributed to it by the estimated 47% of Roosevelt Hot Springs kind of reservoir water. Groundwater is practically ammonia free. It takes 16-32% steam condensate carrying 5-10 ppm ammonia to contribute all of the 1.6 ppm NH_4^+ contained in well 91-4 water.

These observations, combined with the a geochemical temperature of 300°C estimated from the gas compositions of the geothermal steam from Cove Fort-Sulphurdale wells (see below), and the 153°C measured temperature of well 91-4, suggest that a higher temperature primary reservoir may exist in the Cove Fort-Sulphurdale area. This reservoir feeds hot water to the Coconino Sandstone, which forms a secondary steam reservoir. Hot upwelling fluid is more likely to occur below the dry steam producing area. The high permeability of the dry steam zone is likely to play a significant role in separating the gas from the liquid phase and in allowing disposal of the cooled residual fluid.

GAS CHEMISTRY

Noble-Gas Compositions

Data on the noble gas compositions of samples from the steam wells at Cove Fort-Sulphurdale are reported in Table I and interpreted as follows. Low $^3He/^4He$ ($8.6*10^{-7}$) and high $^4He/^{20}Ne$ ratios indicate negligible atmospheric contamination for samples from wells 34-7B, P-88-1, and P-89-1. For well 34-7B and P-88-1, mantle and crustal (radiogenic) He are estimated from ^4He at **6%** mantle, 94% crustal and from ^{3}He at 98% mantle 2% crustal based on mantle and crustal $^3He/^4He$ ratios that are assumed to be $1.4*10^{-5}$ and $2*10^{-8}$ respectively. In contrast, He isotope ratios indicate that the mantle component in the Roosevelt Hot Springs fluid is 23% (Whelen et al., 1988). Thus, basic magma is closer and interactions with it are stronger at Roosevelt Hot Springs.

The observed relative elemental abundances of noble gases (Table 2) are similar to that of air dissolved in water at equilibrium with the atmosphere, except for the large enrichment of He. These data demonstrate that the noble gases were introduced in the form of dissolved gas at equilibrium with the atmosphere (Takaoka, 1976; Nagao et al., 1979)

Gas/steam Ratios

Figure 5 depicts the early gas/steam ratios of Cove Fort-Sulphurdale wells 34-7A and B. The data indicate that the ratios underwent two changes, a fast one in 1984 and a slower one from 1984-87. The early data were from three tests over one to four days each in three months in 1984. Assuming that the processes were exponential, we tentatively estimate that those occurring during the first stage had a two-week half-life whereas those occurring during the second stage had a 10-15 year half-life.

We suggest that the rapid change in gas/steam ratios corresponds to the initial emptying of a gas trap. The slower process probably included a warm-up period followed by the attainment of steady-state conditions.

During these processes, the noncondensible gas compositions did not change and the CH_4/H_2 gas geothermometer temperatures remained at 300°C This suggests that the noncondensible gases were just reservoir gas enriched in the gas trap by the cold wall effect.

Comment On Gas Geothermometers In General

Let us here point to some basic facts concerning gas geothermometry. As for other gas geothermometers, the CH_4/H_2 ratio "temperature function" depends on the constraints on the system, meaning: a temperature function cannot be defined except by determining those constraints. Let us develop the example here and see the consequences. Based on the available information two different sets of possible constraints were considered:

1) on H_2O, CO_2 and O_2 pressures;

2) on H_2O and O_2 pressures, and on the activity of carbon.

Physically the constraint on water pressure means that liquid water is present, that on carbon dioxide means that pressure is controlled by confining pressure. The constraint on carbon activity means a source at fixed chemical potential, such as organic matter. Constraints on p_{O2} are not even discussed here; that is the real gray area.

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TABLE 1

Sample	^{3}He/^{4}He x1Oex-6	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne	^{40}Ar/^{36}Ar	^{4}He/^{20}Ne
34-7B	.863	9.763	2.998E-2	374.60	2260
	+/-.026	+/-.013	+/-.00043	+/-.032	
P-88-1	.866	9.774	2.906E-2	322.36	860
	+/-.016	+/-.021	+/-.00017	+/-.31	
P-89-1	1.082	9.761	2.883E-2	309.00	241
	+/-.019	+/-.009	+/-.00018	+/-.07	
P-88-2	.921	9.729	2.857E-2	296.30	1.84
	+/-.035	+/-.012	+/-.00013	+/-.18	
Air	1.4	9.800	2.900E-2	296.00	

TABLE 2

Sample	^{4}He	^{20}Ne	^{36}Ar	^{40}Ar	^{84}Kr	^{123}Xe
34-7B	110.	.050	.11	43.	.0038	.00028
P-88-1	23.	.027	.16	51.	.0057	.00037
P-89-1	18.	.075	.54	166.	.018	.00130
P-88-2	5.4	2.9	-		-	
Air	5.24	16.5	31.5	9300.	.649	.0234

Abundances in ppm (error on the order of +/- 10%)

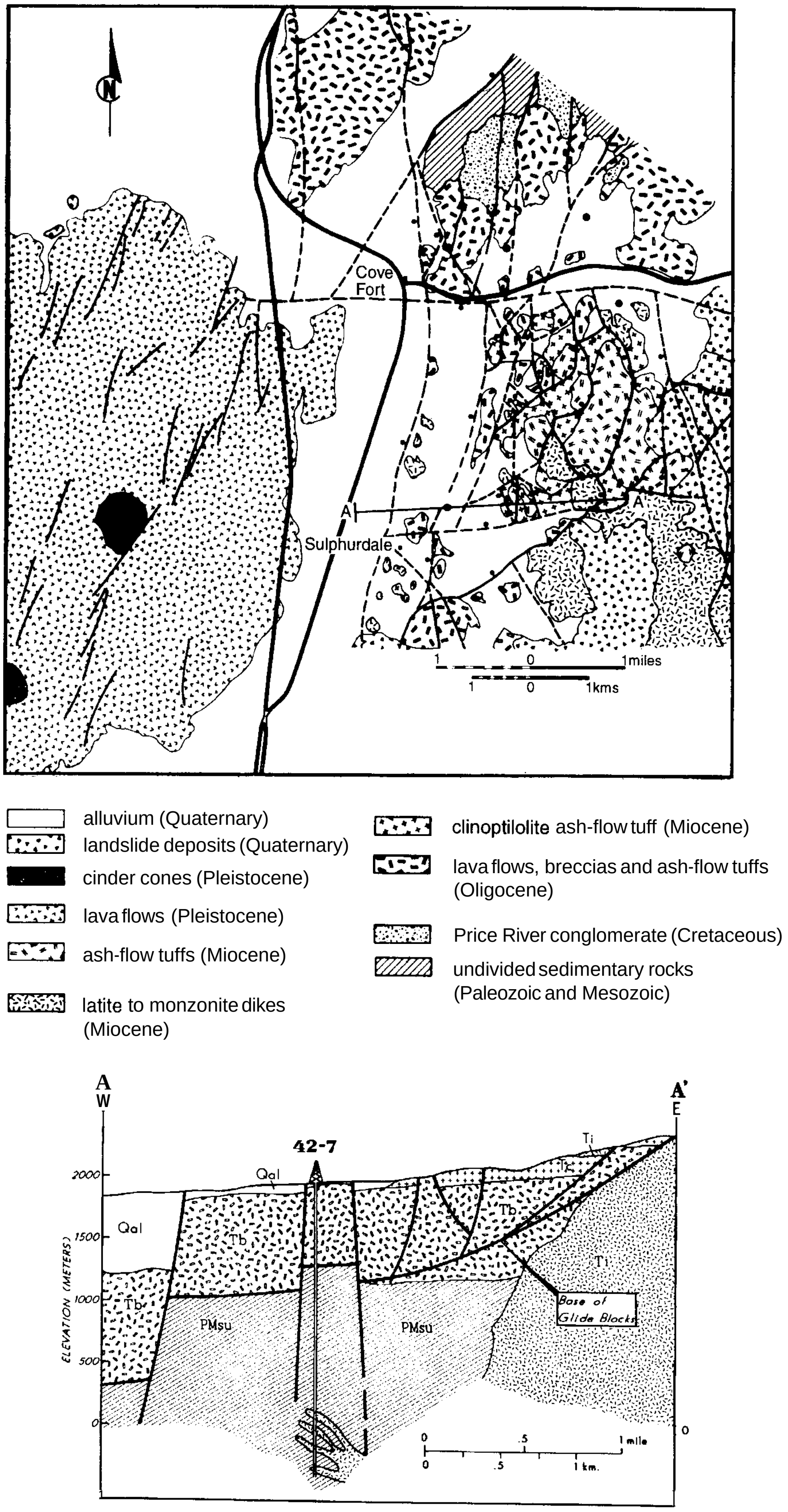

Figure 1a. Geologic map and cross section of the Cove Fort-Sulphurdale area.

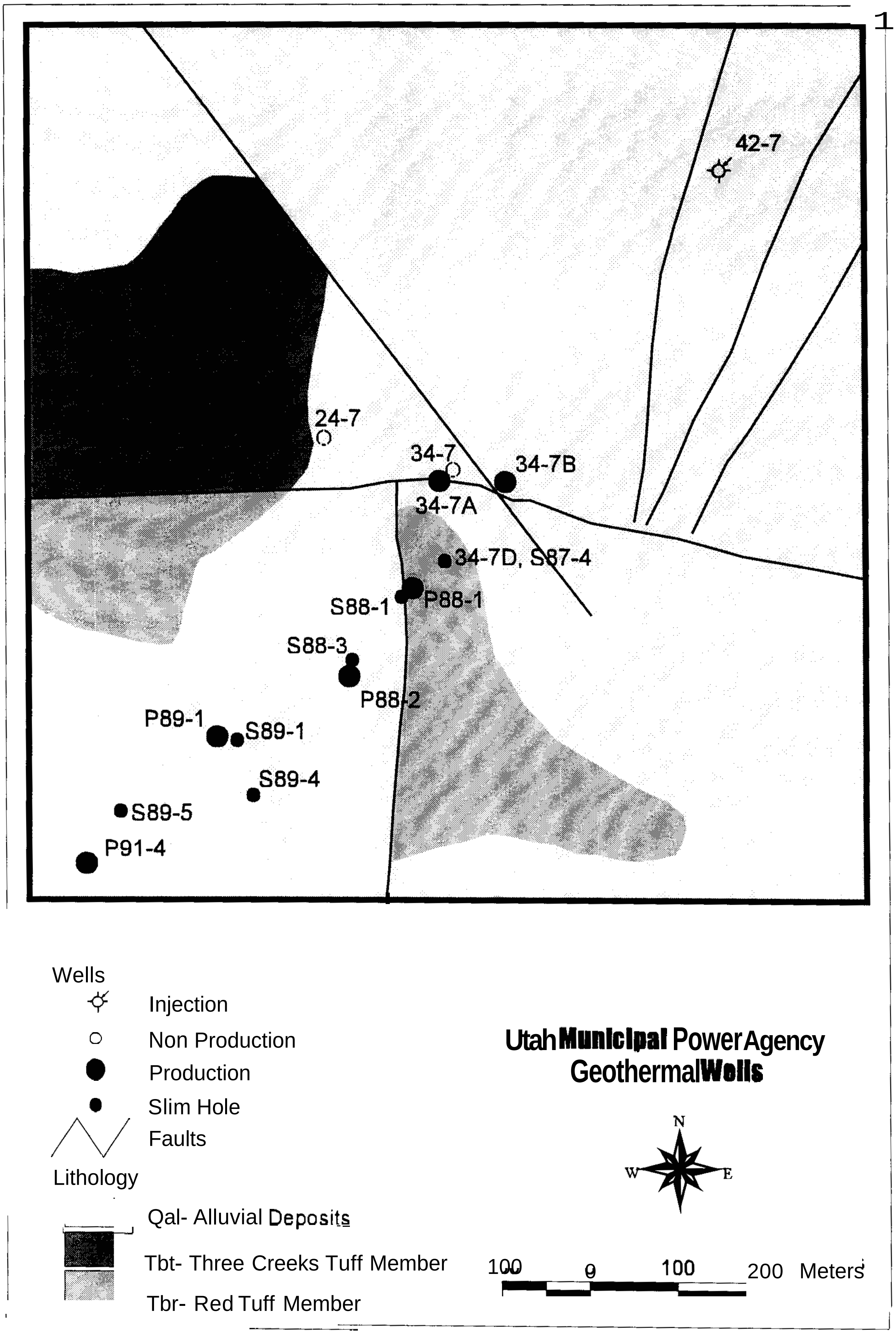

Figure 1b. Enlargement of the Sulphurdale area showing the locations of geothermal wells.

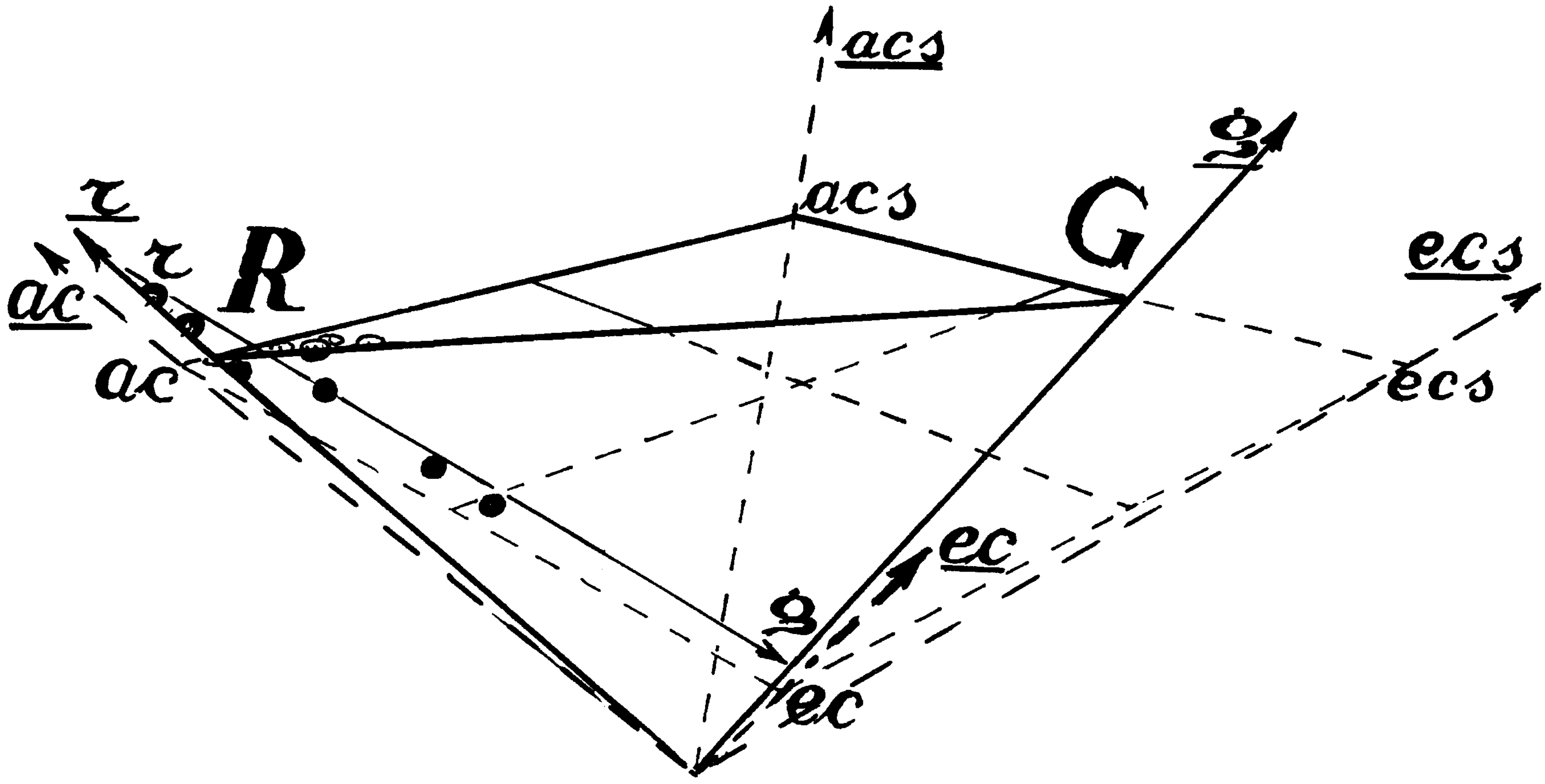

Figure 2: View of Langelier-Ludwig and generalized Langelier-Ludwig graphs showing their mutual relationship in the three-dimensional space of water compositions as expressed by the concentration of different solutes.. Symbols: ac, acs, ecs, ec, are corners of the Langelier-Ludwig graph representing the Cove Fort-Sulphurdale system at TDS = 0.1 eq./liter (dashed lines); Abbreviations: R=Roosevelt Hot Springs; G= groundwater (mixing with R water, idealized, see text); r, g, are the same as R and G but on the generalized Langelier-Ludwig graph.

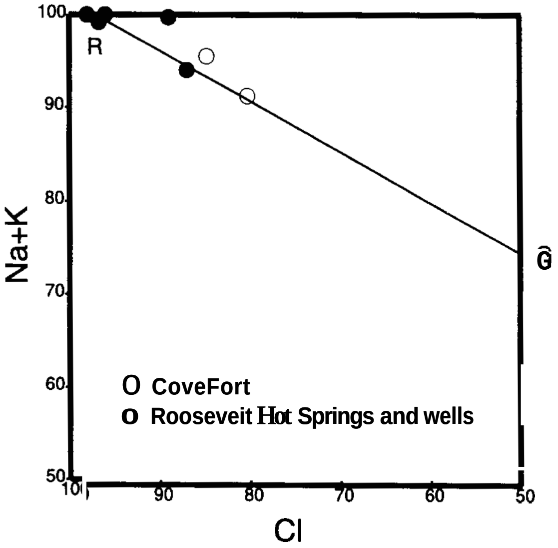

Figure 3

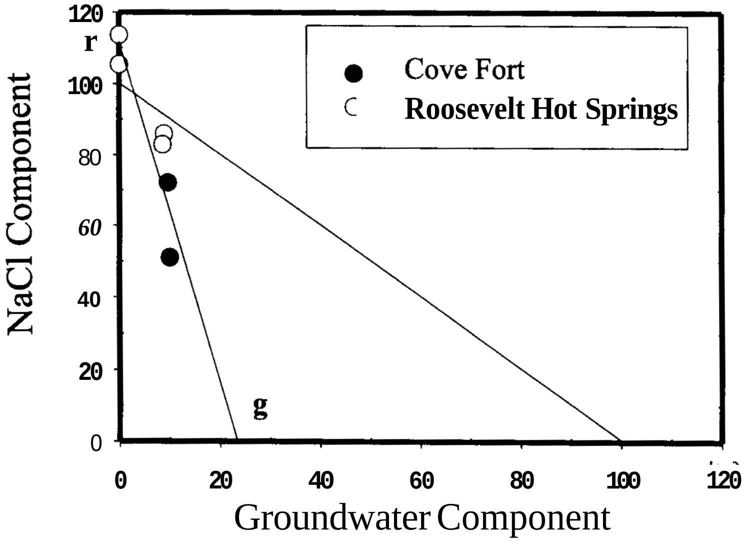

Figure 4

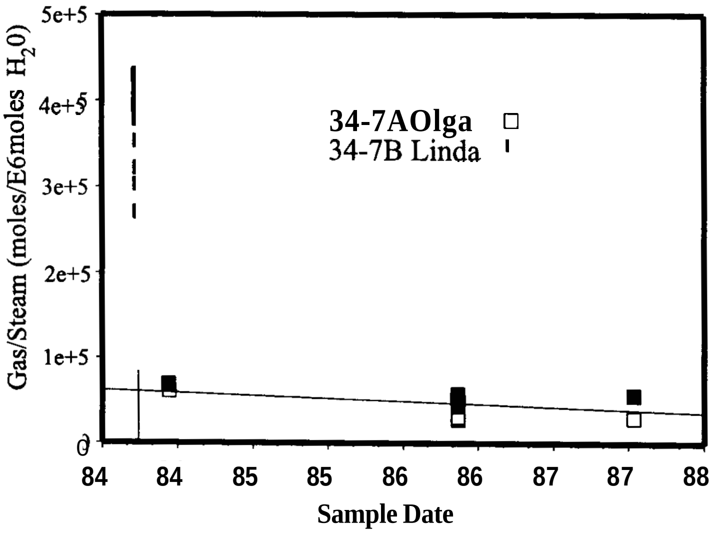

Figure 5