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## Reservoir Geochemistry of the Karaha - Telaga Bodas Prospect, Indonesia

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### Keywords

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### ABSTRACT

Karaha Telaga Bodas is a large, partially vapor-dominated geothermal system in western Java, Indonesia with temperatures up to 350°C. Chemical and isotopic analyses of liquids and gases discharged from deep geothermal wells indicate that the reservoir fluid has a relatively low salinity of 1-2 weight percent TDS and that the steam in the southern part of the field contains an appreciable magmatic component. Although wells drilled throughout the field are in pressure communication, the chemical analyses suggest that the reservoir liquid is poorly mixed. Variations in the chloride/boron ratios of the fluids, in particular, imply that the condensation of steam and gases may play an important role in controlling the chemistry of the reservoir liquids.

Gas geothermometers suggest that CO<sub>2</sub> and H<sub>2</sub> may be in chemical equilibrium but that the other gases (H<sub>2</sub>S, CH<sub>4</sub>, and NH<sub>3</sub>) are not. The apparent lack of equilibrium may be due to derivation of some gases from local sources. Organic-rich sediments represent a possible source of NH<sub>3</sub> and CH<sub>4</sub> whereas H<sub>2</sub>S and CO<sub>2</sub> may be magmatic in origin.

### Introduction

Karaha-Telaga Bodas is a recently discovered, high temperature partially vapor dominated geothermal system in western Java, Indonesia. The thermal activity appears to be associated with Kawah Galunggung, a 4000-year-old horseshoe-shaped crater located south of the geothermal field. Kawah Galunggung was the site of five volcanic eruptions between 1822 and 1984. During the 1990's, nine exploration and production wells and 19 temperature gradient coreholes were drilled by the Karaha Bodas Co. LLC to test and delineate the resource (Figure 1). The wells, which were drilled to depths of up to 3 km, encountered temperatures as high as 350°C. Pressure and temperature measurements demonstrate that the geothermal system consists

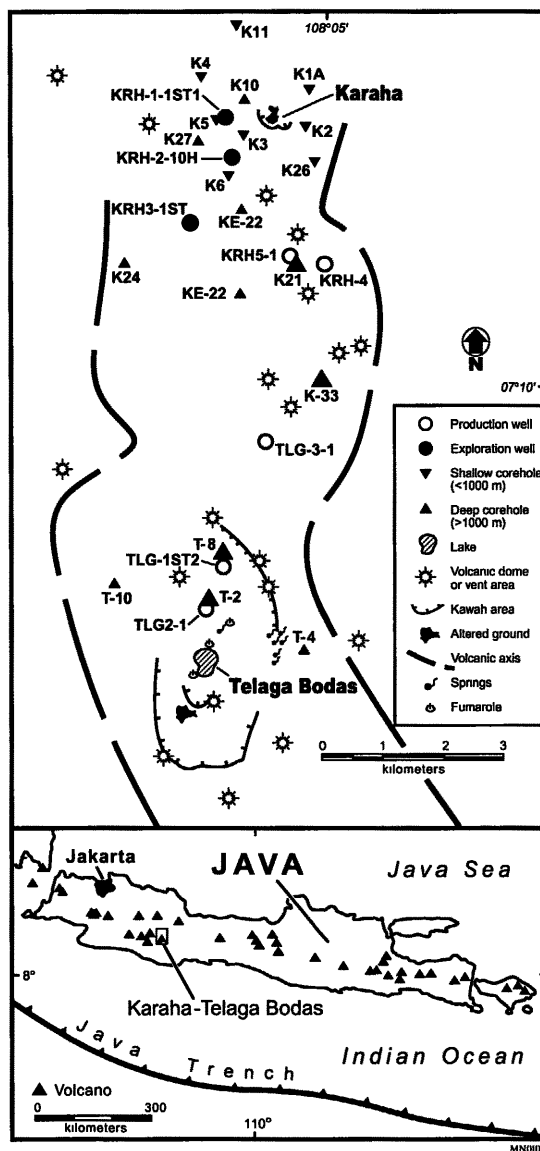


Figure 1. Location map of wells and thermal features at Karaha-Telaga Bodas.

of an upper condensate zone, an underlying vapor-dominated region that extends laterally for at least 10 km., and a deeper liquid-dominated resource with low to moderate salinities (Allis *et. al.*, 2000). Pressures within the vapor zone range from 30-60 bars. Surface manifestations occur at the northern and southern ends of the explored portions of the resource, with the greatest concentration being found at the southern end. Here, fumaroles and associated argillic alteration, an acidic lake (Telaga Bodas) and chloride-sulfate-bicarbonate springs, some of which discharge moderate to low pH waters (to < 2) are found. Surface manifestations at the northern end consist mainly of fumarolic activity and associated argillic alteration.

Detailed petrologic and fluid-inclusion studies have been conducted on core samples from two wells that reached temperatures of 288 and 321°C at depths of 1326 and 1383 m respectively (Moore *et. al.*, 2000). The rocks consist mainly of lava flows and pyroclastic deposits, although significant thicknesses of fine-grained organic-bearing sediments that appear to have formed in locally developed lakes, occur in some of the wells. The origin and characteristics of the faults and fractures that cut these rocks are described by Nemcock *et. al.* (2001a, b).

The vein assemblages in the caprock and reservoir document the transition from an early, extensive liquid dominated resource to the present vapor-dominated conditions. The early liquid-dominated regime is represented by an upper assemblage of calcite, chlorite, pyrite, and hematite, and a deeper, higher temperature propylitic assemblage of epidote, albite, actinolite, chlorite and minor biotite, talc, clinopyroxene, pyrite and quartz. The transition to the vapor-dominated regime was marked by the deposition of chalcedony and quartz during episodes of rapid decompressional boiling. The deposition of chalcedony may have coincided with a major volcanic eruption. Most liquid-rich fluid inclusions trapped in quartz yield homogenization temperatures of >250° to ~350°C and ice-melting temperatures

between -27°C (~24 wt % NaCl-CaCl<sub>2</sub> equiv) and -2°C (3.4 wt % NaCl equiv). These high salinities are unusual, and suggest that the fluids reflect the effects of boiling and/or the input of magmatic gases and liquids.

As the vapor-dominated regime developed, downward percolating condensate deposited anhydrite, pyrite, calcite and fluorite. Fluid inclusions record temperatures ranging from 300°C to the present-day values. Most contain low- to moderate- salinity liquids (<~5 wt % NaCl equiv), although halite saturated inclusions (31 wt % NaCl) are occasionally found. Halite and precipitates of Fe, Na, K, Ti, and Cl represent the youngest stage of hydrothermal alteration. These precipitates formed as the descending fluids and any remaining liquids boiled-off.

In this paper, we describe the chemistry and origins of the geothermal fluids currently circulating within the geothermal reservoir. Data was obtained on fluid samples from the wells during rig and flow tests, springs, Telaga Bodas (lake), and fumaroles.

## Reservoir Brine Chemistry

Weirbox brine samples were collected during rig tests while drilling and later during well flow tests. Samples from the rig tests show chemistries indicative of drilling water contamination, as do samples from some of the briefer flow tests. Table 1 presents the calculated reservoir liquids, corrected to downhole conditions (Truesdell & Singers, 1974). For the correction, an aquifer temperature was chosen that best matched both the quartz and Na-K-Ca geothermometers.

Samples from KRH 2-1 ST and K-33 likely reflect drilling water contamination because the samples were collected after only a few days of flow, the wells flowed weakly, the samples are comparatively dilute, and they are unsaturated with respect

Table 1. Reservoir chemistry and geothermometers.

Sample	Res stm frac	Na ppm	K ppm	Ca ppm	Mg ppm	Li ppm	B ppm	Si ppm	Cl ppm	SO <sub>4</sub> ppm	T-nkc °C	T-nkcm °C	T-qtz °C	T-anh °C
KRH 2-1ST	7%	424	52	3.7	0.31	0.72	33.0	348	534	128	228	227	223	300
KRH 3-1b	15%	497	96	2.6	0.018	1.68	43.4	541	826	58	268	268	267	unsat
KRH 4-1a	70%	1313	201	24.8	0.039	3.82	105.8	391	2247	29	248	247	233	260
KRH 4-1b	74%	1251	188	24.0	<0.0042	3.51	103.4	365	2107	27	245	245	227	262
KRH 4-1c	67%	1428	230	42.6	0.21	4.07	110.0	402	2450	22	247	247	236	255
KRH 5-1a	22%	2983	832	675	0.92	24.24	102.4	110	6909	20	272	271	143	220
KRH 5-1b	34%	2983	999	726	1.03	17.94	1.05	528	7014	14	285	285	264	232
KRH 5-1c	11%	3547	1069	929	2.31	19.56	129.4	70	8033	3.6	278	278	118	287
K-33a	25%	140	35	4.7	0.34	0.10	3.1	273	35	57	249	239	203	unsat
K-33b	25%	133	34	3.9	0.75	0.13	3.0	331	38	84	251	211	219	unsat
TLG 3-1a	85%	770	112	46.7	0.0094	0.26	165.1	502	1315	79	225	225	258	198
TLG 3-1b	88%	671	101	77.5	0.021	0.28	189.4	148	1223	79	218	218	161	183
TLG 3-1c	88%	769	120	143	0.025	0.35	143.6	186	1539	50	217	217	175	187
TLG 3-1d	87%	794	132	190	0.024	0.35	303.0	424	1660	45	219	218	241	186

Notes: T-nkc: Na-K-Ca geothermometer of Fournier and Truesdell (1973)  
 T-nkcm: Na-K-Ca geothermometer with the magnesium correction of Fournier and Potter (1979)  
 T-qtz: quartz geothermometer of Fournier and Potter (1982)  
 T-anh: temperature of anhydrite saturation

to anhydrite, a common reservoir mineral at Karaha. On the other hand, consistent cation and quartz geothermometer temperatures and low magnesium concentrations suggest that these waters have equilibrated, at least partially, at reservoir conditions.

A single sample collected early in the flow testing of KRH 3-1 (sample KRH 3-1a) shows saline and corrosive chemistry in comparison to later flow test samples. The well, which was originally drilled to 3077 m, is reported to have bridged at 2286 m after the first sample was collected. The later flow test sample appears to show signs of drilling water contamination, similar to that suggested for KRH 2-1 ST and K-33, after 2 days of flow.

The most striking feature of the brine chemistry is its diversity. Excluding the samples with suggestions of drilling water contamination, reservoir chloride concentrations range from 1600 to 8000 ppm. Chloride/boron ratios range from 2.4 to 20, and Cl/Li and Cl/F ratios range over an order of magnitude. A ternary plot of the relatively conservative alkali elements Rb, Li and Cs (Figure 2), as proposed by Giggenbach (1991), shows a reasonable grouping of wells with uncontaminated samples, KRH 4-1 and KRH 5-1. Even though these two wells show a large difference in reservoir chloride concentrations, the simi-

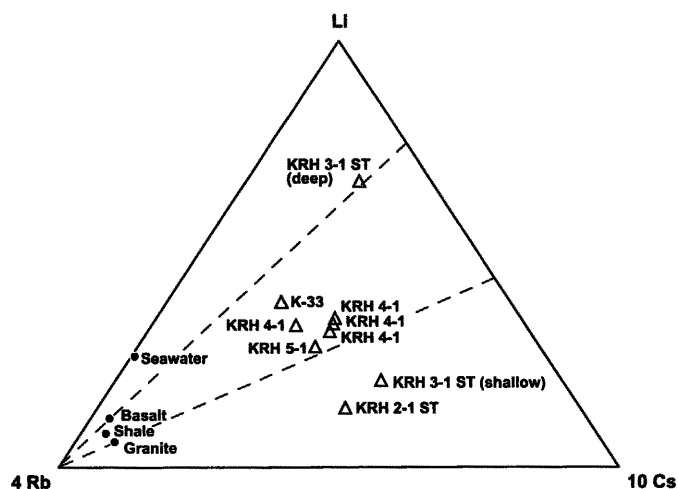


Figure 2. Relative concentrations of Rb, Li and Cs. JNM01010

ilarity in rare alkali elemental distribution suggests similar fluid origins. The samples show a similar amount of Rb loss relative to a silicic volcanic host rock.

A ternary of Li, Cl and B, also proposed by Giggenbach (1991), shows potential relationships between the reservoir waters (Figure 3). Most of the samples lie along a trend defined by the addition of low Cl/B steam, originating near the Cl/B trend defined by diorite. Waters with the composition of KRH 5-1 could give rise to other, more dilute brines by addition of low Cl/B steam. The composition of the anomalously saline and acidic KRH 3-1 sample (labeled “deep” in the figure) is consistent with the addition of high Cl/B steam to initial KRH 5-1 reservoir water.

KRH 5-1 yielded the highest geothermometer temperatures. The cation (Na-K-Ca) geothermometer gives temperatures as

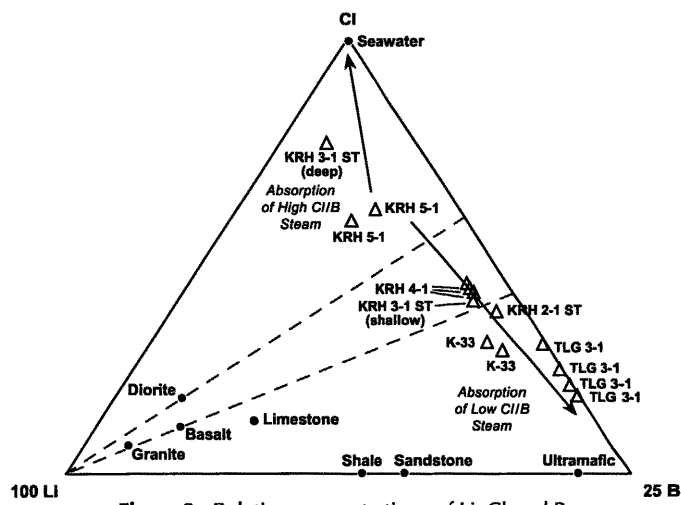


Figure 3. Relative concentrations of Li, Cl and B. JNM01011

high as 285°C, quartz as high as 264°C and anhydrite as high as 287°C. This correlates well with the 279°C maximum measured temperature of the well. The next hottest is KRH 3-1, with cation and quartz geothermometers yielding identical temperatures of 268°C, but with anhydrite undersaturated, yielding no temperature. This is somewhat higher than the 248°C maximum measured temperature in the bridged hole. The maximum temperature of the well before the bridge was 334°C, measured at the bottom of the hole.

KRH 4-1 samples give somewhat lower temperatures (245°C cation,  $\leq 236^\circ\text{C}$  quartz and 260°C anhydrite), as does KRH 2-1 ST and K-33. Maximum measured temperatures at feed zones in these wells are 265°C, 235°C and 256°C, all higher than the geothermometer temperatures for these wells. TLG 3-1, in the northern part of the system, gives nearly the lowest cation geothermometer temperatures (220°C). The combination of higher quartz ( $\leq 258^\circ\text{C}$ ) and lower anhydrite (190°C) temperatures suggest some evaporative concentration of the brine not accounted for in the standard excess steam correction. It is possible that the 220°C reservoir water mixed with higher temperature ( $\sim 240^\circ\text{C}$ ), and thus higher enthalpy, steam in the flowing wellbore. Temperature surveys show the well to be isothermal at 271°C below the casing shoe, suggesting that any 220°C reservoir water originates at shallow depths in the well.

## Stable Isotopes

Samples of steam and brine were collected during well flow tests and analyzed for oxygen and hydrogen isotopes ( $\delta^{18}\text{O}$  and  $\delta\text{D}$ ). In order to assess data quality, steam and brine analyses have been separately corrected to the content of the total discharge assuming the steam fraction of the flow test and isotopic equilibrium at separation conditions. For flow tests where both steam and brine samples were collected, this provides a quick way to assess the uncertainty in the combined analyses and flow test data, since isotopic equilibration at separation is very rapid. Corrections to brine analyses from well tests with greater than 90% steam fraction were found to produce erratic results, and

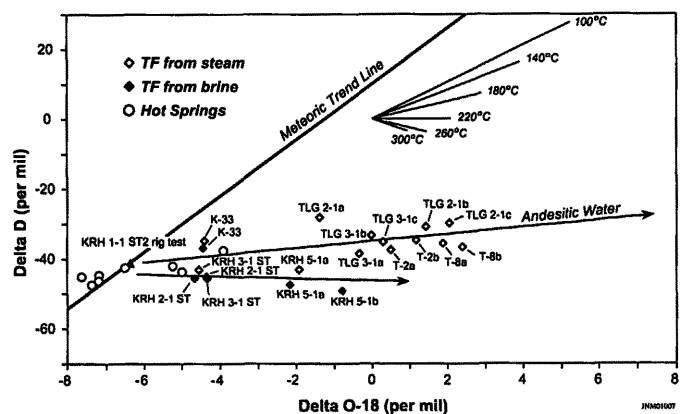


Figure 4. Stable isotope compositions of Karaha-Telaga Bodas fluids. Evaporation trends for temperatures of 100 to 300°C are shown in the upper right. TF = total flow.

have not been included. The results of these corrections and the analyses of selected hot springs are plotted in Figure 4 (overleaf).

Most of the hot spring samples cluster on the meteoric trend line between  $\delta D = -40\text{‰}$  and  $-50\text{‰}$ . Included here is a sample from a very brief KRH 1-1 ST2 rig test, which also plots on the meteoric trend line. This sample is probably representative of the drilling water. Corrected total discharge values for companion samples of brine and steam fall close together, showing that uncertainties in the analyses and flow test data are small. Successive flow test samples from the same well (labeled a, b, c, etc.) show a progressive migration away from meteoric water toward greater  $\delta^{18}O$ , indicative of decreasing drilling water contamination.

The stable isotopes of the well samples define two separate trends, one for the Telaga Bodas wells and one for Karaha wells. The Telaga Bodas wells, including core hole K-33, which lies on the boundary between the two field sectors, lie along a trend toward andesitic water, as defined by Giggenbach (1992). The Karaha wells appear to define a slightly divergent trend, toward an endmember water of lighter  $\delta D$ .

### Gas Chemistry

Gas samples were collected from separated steam during most of the well tests. Attempts to fit the gas data to conventional gas geothermometry grids largely ended in failure. The gases plotted at unreasonably high  $H_2S$  and HSH (hydrogen sulfide - hydrogen) temperatures, and showed significant scatter with Fischer-Tropsch and NAH (nitrogen-ammonia-hydrogen) geothermometers. The gases do, however, yield temperatures on a  $CO_2-H_2$  geothermometer grid (Figure 5). This geothermometer is similar to the  $CO_2/Ar - H_2/Ar$  ratio grid proposed by Giggenbach (1991) but uses the actual gas/steam ratio instead of its proxy, Ar. Samples group between the "equilibrated liquid" and "equilibrated vapor" boundaries, as might be expected for a vapor-dominated system. Geothermometer temperatures range between 225°C and 310°C, similar to measured temperatures in the wells. Wells located close to each other

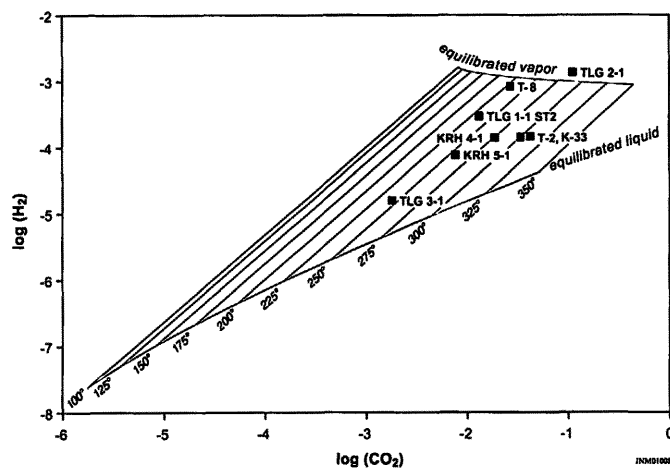


Figure 5.  $CO_2-H_2$  geothermometer grid.

give similar temperatures (e.g., T-8 and TLG 1-1 ST2; T-2 and TLG 2-1; KRH 4-1 and KRH 5-1). The application of the  $CO_2$  geothermometer is supported by the widespread occurrence of calcite in the reservoir.

Admittedly, the argument that these geothermometer temperatures are valid simply because the data fall on the prescribed grid is a circular one. The conformance of the gas data to this grid does suggest that, at least,  $CO_2$  and  $H_2$  are near chemical equilibrium in the reservoir, whereas it is clear that the other gases are not. Conformance to this grid also indicates that the oxidation state in the reservoir is near to RH -2.8, the RH value for which this particular grid is appropriate. This would suggest that the reservoir is a mature, rock-dominated system, as proposed by Giggenbach (1993). Hydrogen gas concentrations indicative of a less mature, fluid-dominated, and perhaps more "volcanic" system would be expected to fall below the grid.

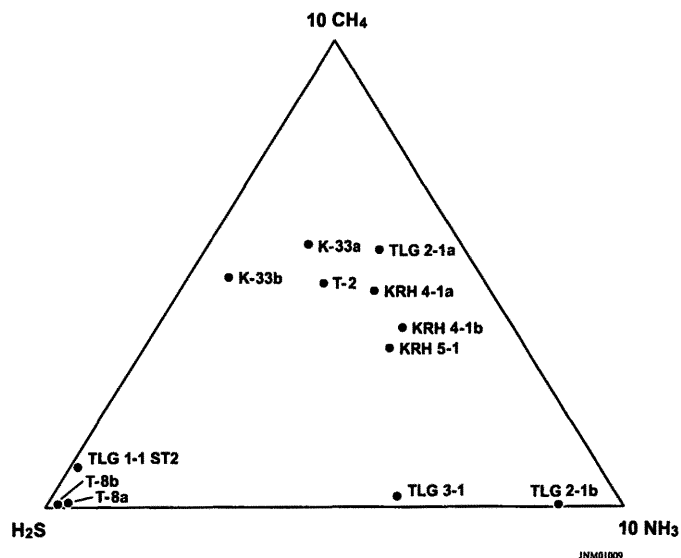


Figure 6. Relative concentrations of  $H_2S$ ,  $CH_4$  and  $NH_3$ .

The apparent lack of equilibration among certain gases suggests that they may, instead, be controlled by local sources. For CH<sub>4</sub> and NH<sub>3</sub>, the likely source would be the breakdown of organic matter in the reservoir rock. H<sub>2</sub>S is likely from a magmatic source since local temperatures are too high for H<sub>2</sub>S production by bacteria. Figure 6 is a ternary plot of the relative concentrations of H<sub>2</sub>S, CH<sub>4</sub>, and NH<sub>3</sub>. The gases show groupings similar to that observed on the CO<sub>2</sub>-H<sub>2</sub> geothermometer grid. T-8 and TLG 1-1 ST2 plot together in the H<sub>2</sub>S rich corner of the ternary, whereas T-2, TLG 2-1, KRH 4-1 and KRH 5-1 plot close to the CH<sub>4</sub> - NH<sub>3</sub> rich edge of the plot. Well TLG-3-1, with its very low CH<sub>4</sub> content plots in a unique position. Thus, the chemical diversity observed in the reservoir brine also appears to be reflected in the gas chemistry.

## Conclusions

The lack of homogeneity in brine and gas chemistry across the field suggests that the Karaha - Telaga Bodas reservoir is very poorly mixed. A central upflow, or series of upflows, that would feed gas and brine to the system, as found in liquid dominated systems, appears to be absent. Instead, the system seems to be composed of a series of "cells", where brine chemistry is dictated by the Cl and B content of convecting steam. Stable isotopes suggest that steam and brine in the southern, Telaga Bodas, part of the field contain a significant magmatic component, whereas this appears to be absent in the north. Gases in the north and south, while circulating long enough to come to chemical equilibrium with reactions involving H<sub>2</sub> and CO<sub>2</sub>, have nonetheless failed to achieve equilibrium with H<sub>2</sub>S and CH<sub>4</sub>. And, despite these indications of a short fluid residency time, the reservoir rock appears to control the oxidation state of the fluid. Taken together, the chemistry of the Karaha-Telaga Bodas reservoir suggests a most unusual geothermal system!

Future studies will undoubtedly help to clarify the origin and inner workings of this system, but at this stage it is intriguing to speculate on how such a system might operate. Pressure continuity across the field (Allis *et. al.*, 2000) suggests that while chemically distinct, these "cells" of unique chemistry are not isolated. Indications that the brine chemistry is largely derived from constituents carried by steam (i.e., Cl and B) suggest that convection and condensation of steam are intimately tied to the brine phase in the system. On the other hand, noncondensable gases appear to have a relatively short residency time. The sys-

tem seems to be a series of convecting steam cells, each evaporating from and condensing into local pockets of brine, and outflowing vigorously to the surface.

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