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INTERPRETATION OF FLUID CHEMISTRY FROM THE PLTG-1 EXPLORATORY DRILL HOLE, PLATANARES, HONDURAS

A.H. Truesdell[1], M.L. Stallard[1], P.E. Trujillo[2], D. Counce[2], C.J. Janik[1], T.L. Winnett[1], F. Goff[2], and L. Shevenell[2]

[1]U.S. Geological Survey, Menlo Park, Calif. 94025
[2]Los Alamos National Laboratory, Los Alamos, New Mexico 87545

ABSTRACT

Water and steam samples were taken from the discharge of the Platanares PLTG-1 exploratory well over a range of separation pressures. The analyses of these samples have been used to calculate the enthalpy and composition of the fluid feeding the well. Comparison with spring analyses suggests that boiling occurs between the aquifer and the surface and that carbonates and silica precipitate. Geothermometers indicate that a deeper, hotter reservoir exists in the system and that residence time in the aquifer feeding the well is relatively short.

INTRODUCTION

The PLTG-1 exploratory drill hole in the Platanares, Honduras, geothermal field was tested on February 24, 1987, after flowing at full discharge for 8 days. During the test, samples of water and steam were collected using a mini-separator at a series of line pressures controlled by a throttling valve. The main purpose of these collections was to characterize the fluid encountered from 625 to 640 m depth. These analyses have been used to calculate the aquifer fluid composition and enthalpy, to apply new gas geothermometers limited to well discharges, and to calculate geothermometer temperatures from fluid compositions less affected by near-surface reactions and reequilibration. Although this shallow aquifer fluid yielded little new information about conditions deeper in the system, it supported interpretations based on Platanares spring analyses (Goff et al., 1986; 1987) and allowed us to test various calculation methods previously used only on much higher temperature fluids.

SAMPLING

A 10-m horizontal 3-inch pipe was connected between the wellhead and a silencer with a gate valve at 5 m and sampling ports at 1 m and 9 m from the wellhead. These dimensions were based in a general way on the experiments on Wairakei, New Zealand, wells made by Mahon (1964) but greatly scaled down for the smaller well diameter and lower temperature fluids of the Platanares well. Single-stage stainless-steel centrifugal miniseparators, with internal dimensions of 5 cm diameter and 15 cm height, were equipped with both thermocouples and pressure gauges. The

separators were well-insulated and attached to each port on the discharge pipe by short 1-inch diameter pipes. Using the separators, water and steam samples were collected during a short time period (but not simultaneously) from the high-pressure and low-pressure ports with initial measured separation pressures (temperatures) of 3.27 bars g. (145.0°C) and 0.759 bars g. (116.2°C) and later of 2.07 bars g. (132.7°C) and 1.09 bars g. (121.3°C) by adjusting the gate valve. Conditions were allowed to stabilize before each sampling. In the absence of a barometer, atmospheric pressure (at 700 m a.s.l.) was assumed to be 0.975 bars (U.S. Standard Atmosphere, 1962). The two lower temperature and pressure measurements agreed with those obtained from steam tables (Keenan et al., 1969) but the higher temperatures (132.7° and 145°C) were 1.5° and 0.9°C, respectively, lower than calculated from the measured pressures. The pressure gauges were not calibrated and may have been affected by the high temperatures; we therefore used the measured temperatures in the calculations. Water and steam samples were passed through stainless-steel coils in water baths and collected in the usual manner. Samples were also collected from the weirbox at 91.5°C. The analyses of these samples and hot-spring fluids from Platanares are given in Tables 1 and 2.

ENTHALPY OF THE AQUIFER FLUID

Downhole-temperature measurements with a Kuster tool indicated 160°C for the aquifer temperature (Goff et al., this volume). The depth to the aquifer (625 m) was much greater than the minimum depth of boiling of 160°C fluid (54.3 m), so it can be assumed that only liquid was present and the fluid enthalpy was 675 j/g. Nevertheless, the sampling setup allowed an independent measurement of the aquifer fluid enthalpy by the use of the gas method described by Mahon (1966). Similar methods based on salt concentrations were tested but it was expected that necessarily small changes in the water fraction would make only small changes in salt concentrations and the method would be inaccurate. This proved to be the case, but the gas method worked very well. Because this method is little known and is complementary to the extensively used critical lip pressure method (James, 1964), it is described here in detail.

Because distribution of steam and water in a discharge pipe is nonhomogenous, it is not possible to collect a representative sample of the total fluid without a large production separator. It is possible, however, to collect separate representative samples of water and steam using a miniseparator provided the fluid in the separator is at the pressure of the pipe and does not lose heat. From the conservation of mass, the total fluid composition (on a weight or molar basis) of a steam-water mixture moving along a pipe must be the same at all points even though the pressure, temperature, and phase proportions may differ. Thus for steam samples collected at conditions A and B.

$$\left(\frac{CO_2}{\text{total fluid}}\right)_A = \left(\frac{CO_2}{\text{total fluid}}\right)_B \quad (1)$$

and (for each sample)

$$\frac{CO_2}{\text{total fluid}} = \frac{\%CO_2,\text{dry gas}}{100}$$

$$\times \frac{\text{total gas}}{\text{steam}} \times \frac{\text{steam}}{\text{total fluid}} \quad (2)$$

and

$$\frac{\text{steam}}{\text{total fluid}} = \frac{H - H_L}{H_V - H_L}, \quad (3)$$

where H is the aquifer fluid enthalpy and H_V and H_L are the enthalpies of vapor and liquid at the separation conditions. Substituting these equations into equation (1) and setting the measurable quantities to an intermediate quantity G,

$$G = \frac{\%CO_2(A) \times G/S(A)}{\%CO_2(B) \times G/S(B)} \cdot \frac{H_V^B - H_L^B}{H_V^A - H_L^A}, \quad (4)$$

we can solve for the aquifer enthalpy

$$H = \frac{G \times H_L(A) - H_L(B)}{G - 1}. \quad (5)$$

Using this equation and pairs of analyses (numbered 1-4 in order of decreasing separation temperature; data in Tables 2 and 3) we obtain the following enthalpies and temperatures for the aquifer fluid.

1 - 2	566.8	j/g	(135°C)
1 - 3	659.5	j/g	(156°C)
1 - 4	653.0	j/g	(155°C)
2 - 3	797.4	j/g	(188°C)
2 - 4	666.3	j/g	(158°C)
3 - 4	650.9	j/g	(154°C)

The 1 - 2 and 2 - 3 analysis pairs have the smallest differences in gas/steam ratio and are therefore the least accurate. The other pairs average 657.4±7.0 (1 s.d.) j/g and 155.8°C.

The temperature calculated by the gas method is about 4°C lower than that measured downhole. This difference is probably within the combined error limits of both methods and may not be meaningful. It suggests, however, that the produced fluid may not originate entirely from the deepest (160°C) zone but may have a minor contribution from cooler fluid.

Similar equations were developed for nonvolatile salt constituents but the results for this well were disappointing because only small differences in concentration resulted from the small changes in residual liquid fraction. For the separated samples the liquid fraction varied from 0.98 to 0.92; including weirbox samples increased this range to 0.88, still only a 10% total difference. Since the usual accuracy of water analysis is ±5% the calculation was not workable. In contrast, the steam fraction and the gas/steam ratio varied by 3.6 times and the analytical accuracy was probably about ±10%.

AQUIFER FLUID COMPOSITION

Once the aquifer fluid enthalpy has been calculated it is simple to calculate the aquifer fluid composition. Usually this calculation is made from a single analysis of a weirbox sample separated at atmospheric pressure and from a steam sample collected at higher pressure (Henley et al., 1984). In our study we had analyses of samples separated at a range of pressures so we could determine the effect of separation pressure on the consistency of the calculated aquifer composition. The general formula for calculating aquifer concentrations based on a material balance is $C_{aq} = C_V y + C_L(1-y)$, where y is the steam fraction (equation 3) and C_V and C_L are concentrations in the vapor and liquid phases. For nonvolatile salts the second term is sufficient and for gases, the first. Values of the steam fractions are given in Table 3. The results of the calculations (expressed for all species in milligrams per kilogram of total fluid) are given in Table 4. Only NH_3 and H_2S appear to be present in significant quantities in both liquid and vapor. Ammonia was analyzed in both phases but H_2S was analyzed in the gas only. The total NH_3 concentrations are very consistent, but apparently H_2S partitioning in these samples was not at equilibrium because analytical values of H_2S in steam combined with calculated values of H_2S in liquid do not give consistent results. The consistency of the calculated aquifer composition provides a check on the accuracy of the calculations and the analyses.

COMPARISONS OF WELL AND SPRING ANALYSES

The spring-water compositions (Table 1) may be compared to the aquifer fluid composition (Table 4) to indicate processes occurring during ascent to the surface. Only nonvolatile species can be compared as the steam/water ratio is unknown for spring fluids. The traditional conservative elements, Cl and B, have average concentration increases of 1.15 times compared to the factor of 1.12 calculated for boiling and steam loss based on the aquifer enthalpy of 657.4 j/g (from the gas method) and the average spring temperature. If the 160°C measured downhole temperature is used instead, the calculated ratio is 1.13, only slightly different. Other constituent concentrations show similar increases with Na (1.11) and Li (1.13) closer to calculated values. Within the accuracy of the analyses and

calculations, Li, Na, K, F, Cl, B, and HCO_3 appear conservative, with significant loss during ascent of Mg, Ca, Sr, SiO_2, CO_3, and total HCO_3. Only SO_4 gained significantly, although it was expected that HCO_3 would increase through reaction of CO_2 with rock. Similar differences were described by Fournier (1981) for well and spring samples at Yellowstone.

The observed differences in conservative element concentrations suggest that ascending fluids cool by boiling alone (with negligible dilution or conductive cooling). The decreases in Ca, Mg, Sr, and CO_3 are presumably due to the precipitation of carbonates as a result of boiling; the increase in SO_4, to oxidation of H_2S in and around the hot-spring pools. The added SO_4 did not affect SO_4 isotope temperatures, but the changes in SiO_2 and Ca affected chemical geothermometers, as discussed below.

GEOTHERMOMETER TEMPERATURE INDICATIONS

In theory, geothermometer reactions allow the estimation of temperatures in geothermal reservoirs where fluids remain long enough to equilibrate. In practice, unless collected directly from the reservoir, geothermometers generally show some degree of reequilibration or other alteration during fluid ascent and do not exactly indicate reservoir temperatures. Many of these reactions are particularly severe near the surface where temperature gradients are usually steepest. For this reason it may be quite advantageous to collect fluid from intermediate depths. This was a possible benefit of the PLTG-1 drill hole. On the other hand, the existence of permeability at intermediate depth and temperature may indicate the presence of an intermediate reservoir in which reequilibration may occur. For these reasons it is of interest to compare geothermometer temperatures from spring and well fluids (Table 5).

In general, spring and well waters indicate similar temperatures. Silica temperatures average 5-10°C higher in the well samples, suggesting that some precipitation of quartz or chalcedony occurs during passage to the surface. Amorphous silica is undersaturated at all sample collection temperatures and cannot have precipitated during ascent.

Cation temperatures have been affected differently. Minor reequilibration of Na and K at lower temperatures does occur but the indicated temperature decrease is only about 3-5°C. Na-K-Ca temperatures, however, are higher for the spring samples, the reverse of the change in other geothermometers. This must result from the removal of Ca by precipitation of carbonates (and perhaps fluorite) due to boiling, CO_2 loss, and increase in pH. (Aragonite scaling occurred in the well.) The average Ca concentration in

spring samples is 1.5 mg/kg lower than that of the calculated aquifer fluid (Tables 1, 4). Sulfate isotope temperatures corrected for the effect of boiling are essentially identical for spring and well samples.

The fact that spring and well samples yield similar high temperatures supports the existence of a higher temperature reservoir deeper in the system. No calculated temperature corresponds with temperatures encountered in the well and the differences that exist in geothermometer temperatures are small, which suggest that the permeability encountered in the well is not part of a major lower temperature reservoir and that reequilibration in and above the sampled zone is minor.

NEW GAS GEOTHERMOMETERS

Application of the gas geothermometer methods of Giggenbach (1980) and D'Amore and coworkers (e.g., D'Amore and Celati, 1983) require total fluid gas concentrations and cannot be applied to gas analyses from springs where the steam/water ratio is unknown. Fluid from the Platanares well can be used in these calculations because it is unlikely that steam separation occurred before it entered the well. Three geothermometer reactions were tested: methane breakdown, ammonia breakdown, and pyrite-magnetite-H_2S. The results show a wide range of temperatures from 175° to 275°C and generally indicate only liquid in the reservoir. Geothermometer calculations involving H_2S show apparent gas-depleted waters. The inconsistent total fluid concentrations of H_2S (Table 4) suggest that equilibrium distribution of H_2S between water and steam may not have occurred. Perhaps for this reason and perhaps because gas compositions were altered after leaving the deeper reservoir, the results of these gas geothermometers were scattered and disappointing. They do agree with other geothermometers in generally indicating the existence of a higher temperature reservoir.

SUMMARY

Despite the moderate temperature (160°C) encountered in the Platanares PLTG-1 exploratory well, it has considerably advanced our knowledge of the system. In addition to geological, petrological, and physical insights (see accompanying papers), its fluid chemistry has revealed information about deeper conditions and indicated reactions occurring at shallow depths. Fluid chemistry of the well discharge appears to be dominated by reactions in a deeper, hotter reservoir and little affected by residence in the aquifer encountered by the well. Detailed gas and water analyses have been used to calculate aquifer enthalpy and composition. The calculation of fluid enthalpy from gas analyses was very satisfactory and deserves wider application.

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Table 1. Composition of water samples from boiling hot springs and the exploratory drill hole at Platanares, Honduras.

Site	Temp.	pH	Li	Na	K	Mg	Ca	Sr	F	Cl	HCO_3	CO_3	ΣHCO_3	SO_4	SiO_2	B	NH_4	D/H	^{18}O	^{18}O (SO_4)
PL-1	99.5	8.75	4.04	310	38	0.06	2.5	0.35	12.4	36.7	78.1	206	490	225	288	16.7	10.4	-41.6	-6.14	0.33
PL-2	99.3	8.75	3.50	291	33	0.07	3.2	0.39	12.9	35.4	215	132	479	215	290	16.4	11.7	-42.8	-6.03	--
PL-3	100.1	8.75	3.85	305	36	0.04	3.0	0.33	12.7	33.4	171	168	507	238	277	15.5	13	-42.4	-6.17	0.12
PL-5	96.0	8.30	3.56	289	18	0.06	1.2	0.05	12.3	36.0	154	142	438	239	305	16.0	11.9	-41.6	-6.03	--
PL-7	98.5	8.75	3.53	311	26	0.08	3.8	0.32	12.6	34.4	171	154	479	245	236	16.0	9.5	-42.1	-6.12	0.14
PL-8	98.6	8.75	3.72	299	37	0.04	1.0	0.45	12.9	34.0	68.3	202	472	246	233	16.4	8.0	-42.7	-6.00	-0.02
PL-17	98.2	9.47	3.80	304	40	<.1	1.1	0.40	13.0	34.5	35.4	229	493	249	242	17.1	2.7	--	--	-0.4
PL-20	95.0	9.27	4.10	317	41	<.1	1.4	0.23	13.0	34.8	199	188	575	240	283	17.0	3.3	-44.4	-6.26	-0.12
PL-22	98.4	9.50	4.00	333	37	<.1	1.3	0.26	13.2	35.9	28	251	530	248	292	17.2	4.3	-46.5	-6.21	--
PL-23	95.0	8.52	3.70	305	35	0.3	8.9	0.48	12.4	33.5	276	139	554	231	156	16.1	8.1	-41.0	-6.44	--
PL-24	99.0	9.44	3.60	291	34	<.1	1.3	0.24	13.1	34.4	64.7	209	483	236	278	16.8	4.2	-43.2	-6.20	-0.29
PL-26	98.7	9.60	3.90	311	37	<.1	2.4	0.32	13.3	35.9	18.3	247	512	242	296	17.0	3.3	-43.1	-5.93	--
PL-27	99.0	9.56	3.70	303	35	0.1	6.5	0.35	13.3	34.4	32.9	238	509	240	282	19.4	3.6	-43.4	-6.02	--
PL-28	98.0	9.38	3.40	285	19	<.1	5.0	0.03	13.1	34.9	91.5	187	466	235	313	18.1	4.2	-42.2	-5.94	-0.2
PL-36	98.3	8.70	3.50	305	29	<.1	2.2	0.28	13.3	33.7	80.5	203	487	251	251	16.9	4.5	-44.9	-5.93	-0.25
Avgs.	98.1		3.73	304	35	0.06	2.0	0.34	12.9	34.8	112	193	498	239	276	16.7	6.9	-43.0	-6.10	-0.08
	±1.5		±.2	±12	±4	±.02	±1.0	±.08	±.3	±1.0	±80	±40	±35	±10	±26	±0.7	±3.7	±1.5	±.15	±.24
PLTG-1	91.5	8.88	3.97	320	40	0.22	3.3	0.22	13.0	34.3	123	202	527	222	300	16.5	7.4	--	--	--
PLTG-1	91.5	9.04	3.89	311	35	0.26	3.3	0.25	13.3	34.8	106	215	536	220	295	16.5	8	--	-5.81	--
PLTG-1	91.5	8.71	3.95	319	31	0.22	3.8	0.42	13.5	35.1	0	218	436	228	304	17.0	8.5	--	--	--
PLTG-1	116.2	8.84	3.45	292	36	0.18	3.6	0.36	11.9	32.2	94	202	498	220	273	15.6	14.5	-48.0	-6.32	0.0
PLTG-1	121.8	8.86	3.61	289	29	0.2	4.8	0.38	12.1	32.8	104	197	498	213	280	15.2	13.1	--	-6.35	0.0
PLTG-1	134.7	8.76	3.53	283	27	0.18	3.4	0.40	12.1	30.9	108	200	508	213	275	15.0	16	--	--	--
PLTG-1	145.9	8.47	3.37	280	34	0.22	4.8	0.46	10.8	30.5	227	144	515	223	345	14.8	20.8	-47.8	-6.60	0.1

Notes:

Spring samples PL-1 to PL-8 were collected in May 1985; spring samples PL-17 to PL-36 were collected in February 1986; the well samples were collected in February 1987.
Units are °C, pH units, mg/kg, and per mil SMOW.
ΣHCO_3 is $HCO_3 + (2 \times CO_3)$.
Average of spring analyses exclude outliers >2 s.d. from the mean.

Table 2. Gas analyses of steam from hot springs and the exploration drill hole at Platanares, Honduras.

Site	Temp.	CO_2	H_2S	H_2	CH_4	N_2	NH_3	O_2	Ar	He	T(D-P)	^{13}C (CO_2)
PL-1	99.5	81.62	2.59	0.0309	0.318	0.93	14.5	0.0062	0.0237	0.00005	230	-10.8
PL-1	99.5	82.02	3.01	0.0344	0.216	1.17	13.5	0.0036	0.0276	0.0	238	-10.8
PL-3	100.1	88.66	1.56	0.0165	0.341	3.55	5.82	0.0	0.0901	0.0	205	-10.0
PL-17	--	72.11	2.86	0.024	0.546	7.15	17.0	0.078	0.171	0.0	223	-12.2
PLnr22	98.4	90.97	0.17	0.034	1.26	6.29	0.01	1.02	0.151	0.0011	185	-8.46
PL-23	--	75.8	11.0	0.01	0.161	6.11	6.18	0.56	0.141	0.0	228	-12.8
PL-27	98.5	85.55	2.13	0.029	0.762	3.4	7.95	0.0	0.082	0.0006	217	-10.0
PL-28	98.3	87.99	1.63	0.042	0.196	2.9	7.09	0.03	0.07	0.0	234	-9.79
PL-36	98.3	82.06	1.94	0.012	0.124	4.88	10.7	0.11	0.115	0.0	210	-12.9
PLTG-1	116.0	89.47	1.61	0.0607	1.44	2.01	5.34	0.0	0.037	0.0014	225	-9.78
PLTG-1	121.3	91.08	1.31	0.0541	1.41	1.87	4.23	0.0	0.035	0.0014	219	-9.02
PLTG-1	132.7	91.11	1.25	0.0787	1.6	2.15	3.79	0.0	0.039	0.0016	227	-9.00
PLTG-1	145.0	92.95	1.02	0.0856	1.74	2.37	1.78	0.0	0.043	0.0017	226	-8.51

Notes:
Units are °C, mole %, per mil PDB.
T(D-P), D'Amore and Panichi (1980);
  well avg. 224±4°C; spring avg. 219±17°C.

Table 3. Data used in calculations of aquifer fluid and enthalpy composition.

Separation Temperature	Gas/Steam (molal)	Steam Fraction
91.5*	---	0.120
116.0	0.00315	0.0771
121.3	0.00427	0.0673
132.7	0.00515	0.0460
145.0	0.0114	0.0219

*weirbox

Table 4. Calculated aquifer composition (all in mg/kg of total fluid).

A. NONVOLATILE SPECIES

	Li	Na	K	Mg	Ca	Sr	F	Cl	SO₄	SiO₂	B	HCO₃**	CO₃**	ΣHCO₃
	3.30	274	30.3	0.19	3.5	0.33	11.3	30.2	201	271	14.5	97.6	185	468
	±0.09	±5	±3.7	±0.02	±0.7	±0.1	±0.4	±0.5	±8	±24	±0.2	±8	±5	±9
Spring/ aquifer	1.13	1.11	1.16	0.30	0.57	1.03	1.14	1.15	1.19	1.02	1.15	1.15	1.04	1.06

(The table with column headers $Li, Na, K, Mg, Ca, Sr, F, Cl, SO_4, SiO_2, B, HCO_3^{**}, CO_3^{**}, \Sigma HCO_3$)

B. WATER-INSOLUBLE GASES

CO₂	H₂	CH₄	N₂	Ar	He
609	0.022	3.76	8.90	0.235	0.001
±57	±.003	±0.25	±0.51	±0.01	±0.00006

($CO_2, H_2, CH_4, N_2, Ar, He$)

C. SPECIES IN BOTH STEAM AND WATER

Sep. temp. °C	NH₃(V)	NH₃(L)	NH₃(T)	H₂S(V)	H₂S(L)*	H₂S(T)
145.0	4.4	20.3	24.7	5.1	0.5	5.6
132.7	9.2	15.2	24.4	6.1	0.2	6.3
121.3	12.5	12.2	24.7	7.7	0.2	7.9
116.0	13.5	13.3	26.8	8.2	0.1	8.3
Average			25.1±1			7.0±1.3

($NH_3(V), NH_3(L), NH_3(T), H_2S(V), H_2S(L)*, H_2S(T)$)

Notes:

*H_2S in water was not analyzed. Values shown are calculated from solubility data (Henley et al., 1984).
**Two extreme values were not averaged.

Table 5. Geothermometer temperatures (in °C) for (near) boiling hot-spring and exploration-well waters from Platanares, Honduras

Site	Temp.	TQA	TQC	TCH	T13	TNK (1)	TNK (2)	δ¹⁸O(SO₄) a	δ¹⁸O(SO₄) b
PL-1	99.5	192	207	189	225	211	235	248	220
PL-2	99.3	193	208	190	216	201	228	---	---
PL-3	100	190	204	186	220	206	232	253	224
PL-5	96	195	212	194	190	142	179	---	---
PL-7	98.5	180	192	172	197	169	202	254	224
PL-8	98.6	179	191	171	235	212	236	261	229
PL-17	98.2	181	194	174	239	219	242	272	236
PL-20	95	191	206	188	236	217	240	261	228
PL-22	98.4	193	208	190	227	199	226	---	---
PL-23	95	156	164	139	207	203	229	---	---
PL-24	99	190	204	186	228	205	231	268	233
PL-26	98.7	194	209	192	224	207	232	---	---
PL-27	99	191	205	187	211	204	230	---	---
PL-28	98	197	214	197	180	148	185	267	232
PL-36	98.3	184	196	177	210	182	212	269	234
Averages		189	204	185	219	195	223	261	229
		±6	±7	±8	±15	±24	±19	±8	±5
PLTG-1	91.5	194	210	193	224	213	237	---	---
PLTG-1	91.5	193	209	191	217	201	227	---	---
PLTG-1	91.5	195	212	194	207	184	215	---	---
PLTG-1	116	191	203	184	220	211	236	252	233
PLTG-1	121.3	193	205	187	204	188	217	251	234
PLTG-1	132.7	194	203	185	204	183	213	---	---
PLTG-1	145	210	222	206	215	209	234	243	231
Averages		197	209	196	213	198	226	249	233
		±8	±7	±6	±8	±13	±10	±5	±2

Notes:

TQA	= Quartz saturation adiabatic cooling
TQC	= Quartz saturation conductive cooling
TCH	= Chalcedony saturation (conductive)
T13	= Na-K-Ca using β = 1/3
TNK(1)	= Na/K (Truesdell, 1976)
TNK(2)	= Na/K (Fournier, 1979)
δ¹⁸O(SO₄)	= SO₄ isotope; a = no steam loss;
	b = springs: continuous steam loss
	wells: single-stage steam loss