A NOVEL WAY OF USING GAS AND ENTHALPY DATA

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ABSTRACT

The carbon dioxide content of a geothermal well usually increases with increasing enthalpy of discharge.

A plot of carbon dioxide content (total discharge) versus % steam at inflow, calculated from Discharge enthalpy - water supply enthalpy (determined from the silica concentration) can be used to deduce the gas content of the water and steam inflows.

If the carbon dioxide is constant over a range of enthalpies the increasing enthalpy is probably due to heat transfer from the rocks. Used in conjunction with plots of chloride concentration in the deep water versus deep water temperature (from Silica concentration), dilution, boiling and heat transfer processes can be deduced.

The method is illustrated by data from Krafla and Tongonan.

INTRODUCTION

As fluids move towards a geothermal well various physical processes may occur. Heat may be lost or gained by adiabatic boiling, conductive transfer from the rock or mixing with hotter or cooler fluids. The concentration of chemicals in the fluid may also change by mixing with higher or lower mineralised fluids.

By monitoring a number of parameters it is possible to deduce the mechanism by which changes occur. These parameters are:-

a. Discharge enthalpy (H_{TD}) usually expressed in kJ/kg.
b. Deep water enthalpy (H_W) which is deduced from the silica concentration of samples, collected at the surface under atmospheric pressure and boiling point temperature, or from down the well at a depth where a single water phase exists, and the solubility of quartz.
c. Chloride concentration of the water discharged at the surface (Cl_A) at atmospheric pressure and boiling point.
d. Deep water chloride content (Cl_W) at the enthalpy H_W.
e. Chloride content of the total discharged fluid (steam + water), (Cl_{TD}).
f. Carbon dioxide content of the total discharged fluid $CO_{2,TD}$
g. % Steam at inflow (x).

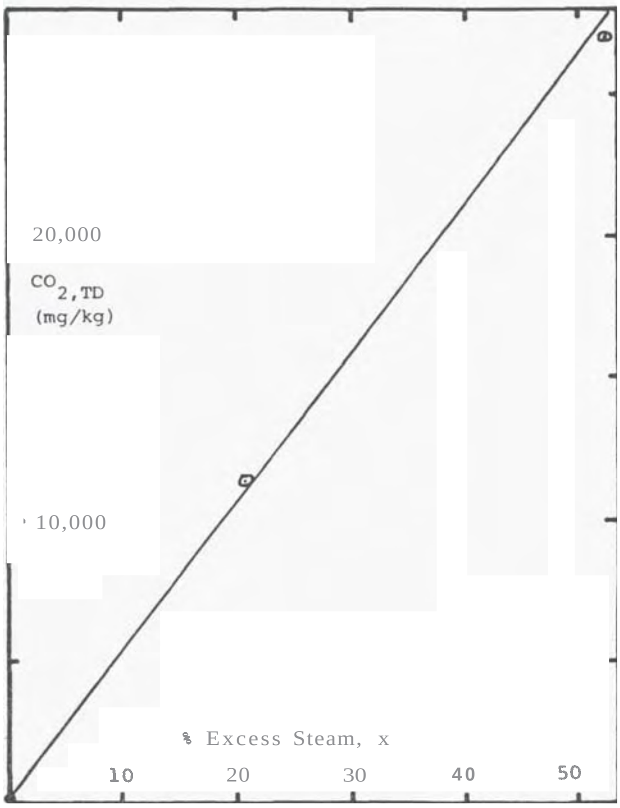

Fig. 1 CO_2 in total discharge/% Excess Steam plot for Krafla Well KJ-11.

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Table 1 - Changes in Physical and Chemical Parameters of a discharging Well due to Heat Transfer and Fluid Mixing Processes

Process[1]	Discharge Enthalpy H_{TD}	Deep water Enthalpy H_W	%[2] Steam x	Surface[3] Chloride Content Cl_A	Deep water Chloride Cl_W	Chloride in total discharge Cl_{TD}	CO_2 in total discharge $CO_{2,TD}$
A	NIL	-	+	NIL	+	NIL	NIL
B	-	-	Slight +	Slight +	+	+	-
C	+	NIL	+	+	+	NIL	NIL
D	-	-	NIL	-	NIL	NIL	NIL
E	+	+	NIL	+	NIL	NIL	NIL
F	-	-	NIL	-		-	-
G	-	-	NIL	-	-	-	+
H	+	+	NIL	4	-	-	-
I	+	+	NIL	4	-	-	+
J	-	-	NIL	4	+	+	-
K	-	+	NIL	4	+	+	+
L	+	+	NIL	+	+	+	-
M	+	+	NIL	+	+	+	+
N	+	NIL	+	+	NIL	-	+

Notes

1. A = Adiabatic boiling (all steam and water enters well)
   B = Adiabatic boiling (some steam does not enter well)
   C = Isothermal boiling by conductive heat gain
   D = Cooling by conductive heat loss
   E = Heating by conductive heat gain
   F = Addition of water (cooler, lower chloride, lower gas content)
   G = Addition of water (cooler, lower chloride, higher gas content)
   H = Addition of water (hotter, lower chloride, lower gas content)
   I = Addition of water (hotter, lower chloride, higher gas content)
   J = Addition of water (cooler, higher chloride, lower gas content)
   K = Addition of water (cooler, higher chloride, higher gas content)
   L = Addition of water (hotter, higher chloride, lower gas content)
   M = Addition of water (hotter, higher chloride, higher gas content)
   N = Addition of steam (usually higher gas content) in well

2. Calculated at inflow with saturated steam in equilibrium with water of enthalpy H_W and fluid of total enthalpy H_{TD}.

3. As analysed in water separated at atmospheric pressure and boiling point.

4. In these cases the change in enthalpy and the change in deep water chloride affect the surface chloride in opposite direction. Thus the surface chloride may either increase, decrease or do neither depending on which effect predominates.

The effect on these seven parameters of the various heat exchange and fluid mixing processes is shown in Table 1.

DEEP WATER ENTHALPY/DEEP WATER CHLORIDE PLOTS

Many workers e.g. Ellis and Mahon (1977), have used a deep water enthalpy/deep water chloride plot to deduce the subsurface mixing and heat transfer processes occurring in a geothermal system. Cl_D is usually plotted as the ordinate and H_W (sometimes expressed as T_{SiO_2} - the temperature at which the silica concentration is equal to the solubility of quartz) as the abscissa.

Most underground changes can be deduced by this approach.

e.g. (i) dilution by a colder, lower mineralised water (Process F or G) decreases H_W (or T_W) and Cl.

(ii) adiabatic boiling (Process A or B) decreases H_W (or T_W) and increases Cl_W.

DETECTION OF STEAM ADDITION AND DETERMINATION OF THE GAS COMPOSITION OF BOTH PHASES

This process (N in Table 1) is quite common in a geothermal well where there are two supply zones. Usually the shallow zone contains steam and the deep zone contains water. Discharging the well at differing wellhead pressures can cause a variation in the amounts of steam and water entering the well. A similar variation can also occur with time, e.g. prolonged discharge in an area of relatively low permeability can cause a draw–down of pressure, and the water level in the country drops to allow steam from shallow levels to enter the well.

At the surface the gas content of the total discharge can be measured. However the gas contents of the separate water and steam flows into the well are unknown.

Now,

$$xH_S + (1-x)H_W = 100H_{TD} \quad (1)$$

and

$$xCO_{2,S} + (1-x)CO_{2,W} = 100.CO_{2,TD} \quad (2)$$

where:– S, W are the values of the parameters in steam and water respectively.

x is the percentage steam present under saturated steam conditions with a water enthalpy $= H_W$, and the total fluid enthalpy $= H_{TD}$ calculated from equation (2).

$CO_{2,TD}$ is as defined in Table 1.

If equation (2) is obeyed a plot of $CO_{2,TD}$ versus x should be a straight line.

Also, $CO_{2,W} = CO_{2,TD}$ when $x = 0$

$CO_{2,S} = CO_{2,TD}$ when $x = 100$

Table 2 – Discharge data, Well KJ11, Krafla

Well	H_{TD} kJ/kg	H_W kJ/kg	$CO_{2,TD}$ mg/kg	% Steam (x)
KJ-11[1]	915	939	28	–0.4[4]
KJ-11[2]	1300	962	11300	20.4
KJ-11[3]	1900	1115	27000	52.1

Notes:
1. Producing from upper aquifer only
2. Producing from both aquifers
3. Producing mainly from lower aquifer after an attempt to shield off the upper part
4. Assumed to be zero for plotting purposes

Table 3 – Discharge Characteristics of Well 403 – Mahiao

Sample No.	T_W °C	H_{TD} kJ/kg	% Steam x	$CO_{2\,TD}$ mM/100M	CO_2/H_2S	$SO_{4,A}$ mg/kg	Cl_{TD} mg/kg
1	241.4	960	–4.8	888	164		3356
2		935		668	156	160	3700
3	248.7	975	–5.7	673	150	121	3918
4	250.6	1014	–4.2	632	129	108	4084
5	249	1042	–2.2	648	124	93	4271
6	250.8	1066	–1.4	567	113	83	4418
7	255.2	1147	2.1	526	108	68	4839
8	256.7	1203	5.1	455	94	72	5361
9	268.4	1272	5.9	441	87	44	5557
10	271.3	1323	8.3	470	86	42	5658
11	271.1	1372	11.4	530	94	34	5765
13	276.1	1469	16.1	511	114	30	5638
14	277.5	1392	10.8	405	68	31	6089
15	283.8	1416	10.5	407	72	32	6136
16	283.2	1416	10.7	407	69	32	6271
17	284.4	1459	13.2	458	74	30	5993
18	278.9	1402	11.1	421	76	23	6340
19	277.4	1373	9.7	381	74	18	6485
20	276.5	1268	3.2	273	70		6938
21	281.5	1323	5.2	307	72		6861
22	281.2	1357	7.5	333	70		6648
24	275.4	1269	3.62	294	67		6646
25	278	1283	3.69	310	69		6650
26	285	1439	11.7	436	72		6524
27	279.9	1437	12.7	386	65		6560
28	282.7	1443	12.6	401	67		6473

Data from two wells are examined by this method.

Example 1: Krafla, Well KJ11

Armannson et al. (1980) in a study of 'magmatic' gases in well fluids at Krafla geothermal field gave the data shown in Table 2.

Fig. 1 shows a plot of $CO_{2,TD}$ versus % steam (x) and the line drawn has the equation:-

$$CO_{2,TD} = 28 + 528x \quad (3)$$

Thus the CO_2 content in the steam entering from the lower zone is 52878 mg/kg and this would be the CO_2 content of the magmatic steam.

Example 2: Well 403, Mahaio, Leyte.

Table 3 shows measured and calculated data for Well 403 in the Mahaio geothermal field, Philippines.

Fig. 2 shows a plot of $CO_{2,TD}$ versus % Steam.

Table 3 and Fig. 2 show the following features:

a. The initial discharge has a high gas content, low water temperature, and even lower discharge enthalpy resulting in a negative value calculated for the percentaqe steam, a high CO_2/H_2S ratio and high sulphate concentration.

b. During discharge, T_W increases and the CO_2/H_2S ratio and SO_4 content decrease until relatively stable values are attained after sample 13. The CO_2 content also decreases from 888 millimoles per 100 moles in sample 1 to 441 in sample 9.

c. Samples 13 to 26 lie along a straight line in Fig. 2 that can be described by the following equation:

$$CO_{2,TD} = 223 + 17.5x \quad (4)$$

These features may be explained as follows:-

1. Cold water used in drilling and completion tests cooled off and diluted the geothermal fluid. This is supported by low values of Cl_W, not shown in Table 3.

2. The cold water also condensed some of the steam.

3. The oxygen in the injected water oxidised some of the H_2S to SO_4 resulting in a high CO_2/H_2S ratio in the cooled gas and a high sulphate content in the water phase.

4. During the initial discharge the gas had a lower enthalpy than the water phase so that H_{TD} was less than H_W.

5. The cooled gas and diluted water mixed with the unaltered geothermal fluid until they were completely removed by sample 14.

Table 4 - Discharge Characteristics of Well Okoy 10, 1981

File No.	Date	WHP MPag	T_W °C	H_{TD} kJ/kg	% Steam	$CO_{2,TD}$ mM/100M	Cl_{TD} mg/kg
1	22 Jan	0.389	255.4	965	-8.7	25.4	2837
2	29 Jan	0.469	261.2	1052	-5.3	41.0	3.353
3	5 Feb	0.517	259.3	1130	-0.1	48.2	3538
4	12 Feb	0.965	261	1128	-0.7	68.1	3688
6	26 Feb	0.614	261.7	1190	+2.8	69.6	3773
7	5 Mar	0.614	260.7	1208	+4.2	74.1	3751
8	12 Mar	0.689	260.6	1237	+6.0	94.9	3747
9	19 Mar	0.603	259.9	1274	+8.4	78.0	3700
10	30 Mar	0.600	260.9	1263	+7.5	67.9	3787
11	11 Apr	0.600	256.9	1283	+10.1	77.0	3799
12	20 Apr	1.38	261.5	1082	-3.6	60.0	4210
13	25 Apr	0.700	261.1	1231	+5.5	78.9	3995
14	2 May	0.915	262.2	1349	+12.4	83.9	3577
15	9 May	1.39	263.3	1135	-1.0	67.9	4178
16	16 May	1.39	262.7	1254	+6.4	98.1	3855
17	20 May	1.45	262.6	1207	+3.6	95.2	4099
18	23 May	1.37	259.9	1116	-1.1	80.5	420.1
19	26 May	1.49	264	1115	-2.4	102.3	3858

Notes: WHP = Wellhead pressure; other parameters are described earlier in the text.

6. The CO_2 content of the phases entering the well during the later discharge period was:

$CO_{2,W}$ = 223 mM/100M and $CO_{2,S}$ = 1973 mM/100M

As the percentage of steam increases $CO_{2,TD}$ also increases and Cl_{TD} decreases (see also Table 1). Thus a plot of $CO_{2,TD}$ versus Cl_{TD} should show an inverse relationship. Fig. 3 shows this plot for Well 403. The chloride content of the deep water was calculated to be 7000 mg/kg (from a plot of Cl_W versus H_W) and the chloride content of the steam is zero. Combining this chloride data with the gas data from Fig. 2 (point 6 above) the following equation can be derived.

$$CO_{2,TD} = -0.246\ Cl_{TD} + 1973 \qquad (5)$$

The plotted data in Fig. 3 lie close to this line supporting the validity of this approach.

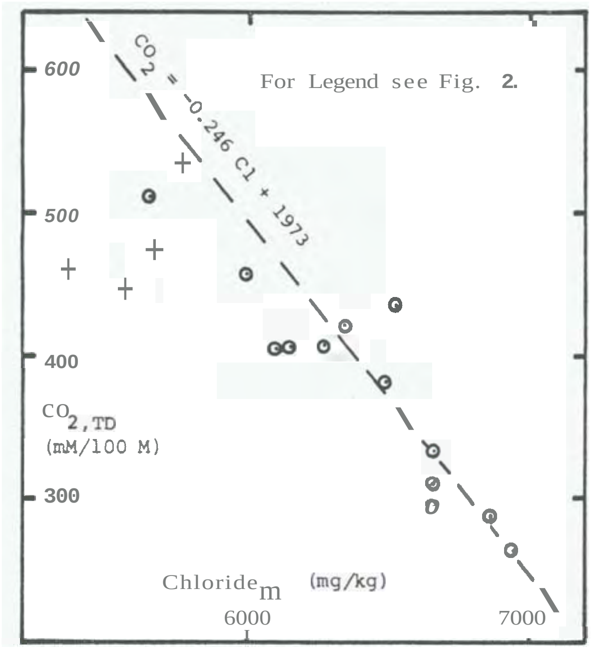
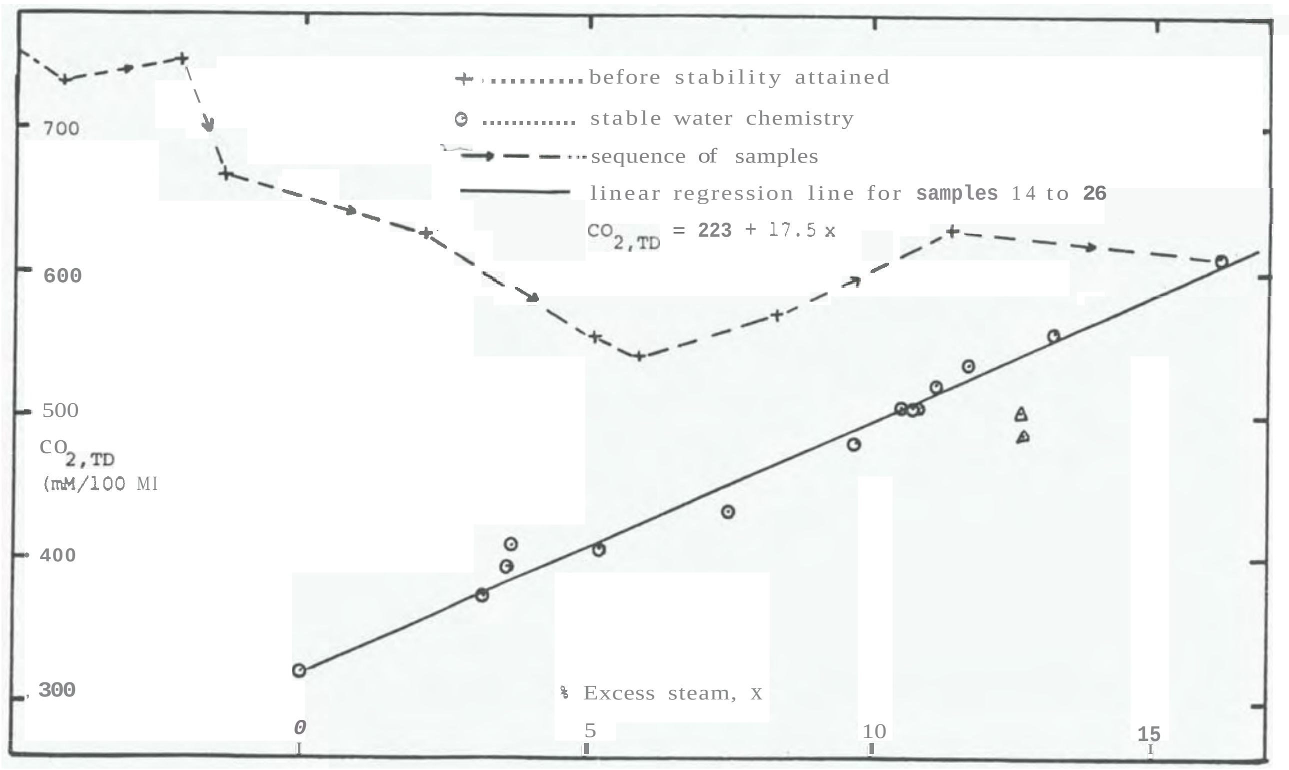


Fig.3 (above) CO_2 in total discharge v Chloride in total discharge. Well 403.

Fig. 2 (below) CO_2 in total discharge/% Excess Steam plot for Well 403.



CONSTANT GAS CONTENT WITH CHANGING ENTHALPY

If the enthalpy of a well discharge increases by extraction of heat from the rocks and not by steam addition the CO_2 content of the discharge should remain constant (Process C). Data from a number of wells have been examined. Examination of data from well 103, Mahiao (Ruaya, 1980) show that both steam addition and heat extraction from the rocks occur. As the wellhead pressure decreases the enthalpy and gas content increase and then the latter remains constant with further enthalpy changes.

Data from Well Okoy 10, S. Negros, Philippines are shown in Table 4. Fig. 4 is a plot of $CO_{2,TD}$ and % steam for Okoy 10.

The first samples are diluted and stability is reached in the chloride content by sample 6. The linear regression line for data points 6 to 19 is shown in Fig. 4 and indicates almost constant values of $CO_{2,TD}$.

This relationship would also occur if $T_W(H_W)$ decreased due to adiabatic steam separation (Process A, Table 1). However, in Process A the discharge enthalpy, H_{TD} would remain constant. The discharge enthalpy of Okoy 10 increases, e.g. in Fig. 4 B1 and A6 have discharge enthalpies of 1116 and 1349 kJ/kg and water enthalpies of 1134 and 1151 kJ/kg respectively.

If the excess heat is all extracted from the rocks the $CO_{2,TD}$ and Cl_{TD} should not vary. A plot of these parameters, Fig. 5 confirms this. Fig. 5 also indicates that the earlier discharge samples had low CO_2 and Cl contents.

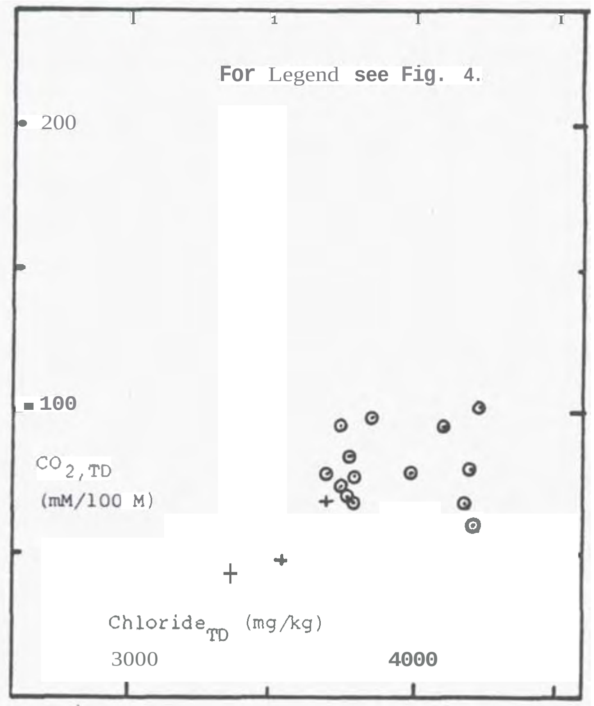
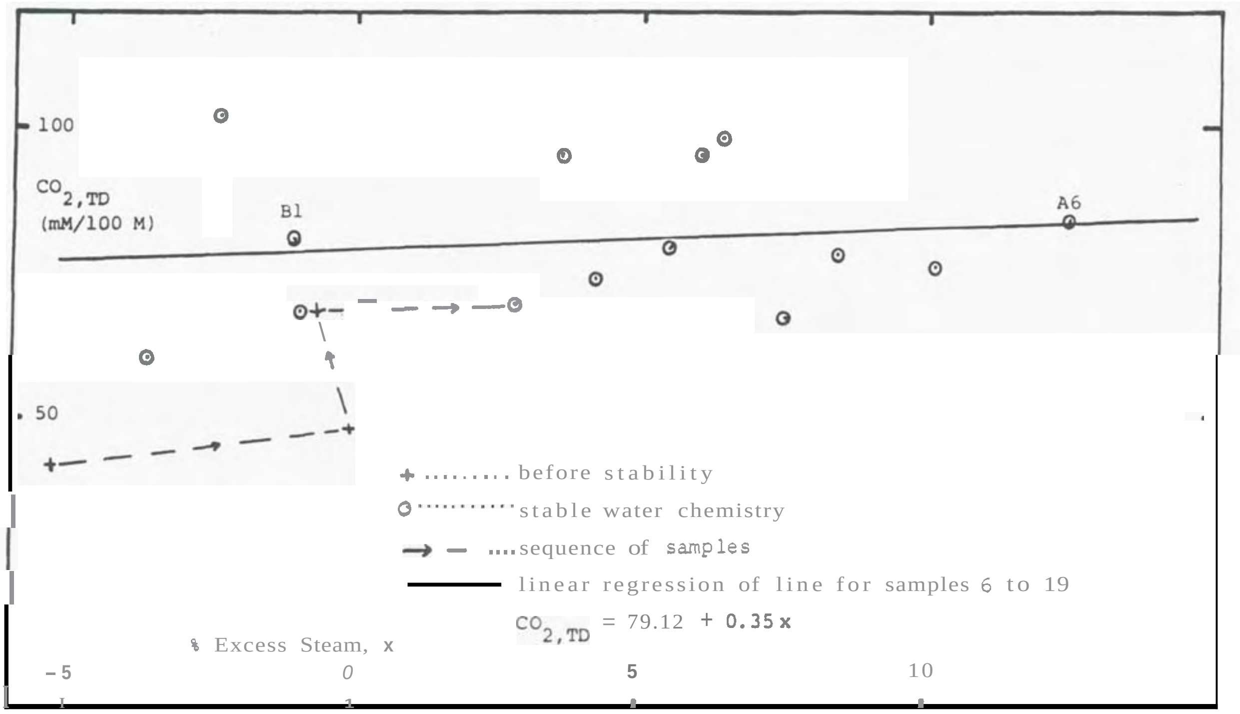


Fig. 5 (above) CO_2 in total discharge/chloride in total discharge plot. Well Okoy 10.

Fig. 4 (below) CO_2 in total discharge/% Excess Steam plot for Well Okoy 10.



CONCLUSION

A plot of carbon dioxide content of the total discharge of a well versus % steam at the inflow can be used to deduce whether increased enthalpy is due to (a) steam addition or (b) heat extraction from the rocks.

In case (a) $CO_{2,TD}$ is proportional to % steam. In case (b) $CO_{2,TD}$ is constant. If case (a) occurs the graph of $CO_{2,TD}$ versus % steam can be used to calculate the carbon dioxide content of the water phase, $CO_{2,W}$, and the carbon dioxide content of the steam phase, $CO_{2,S}$.

A plot of $CO_{2,TD}$ is inversely proportional to chloride content of the total discharge, Cl_{TD} in case (a). In case (b) both of these parameters are constant.

ACKNOWLEDGEMENTS

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