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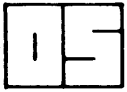
NATIONAL ENERGY AUTHORITY
GEOTHERMAL DIVISION

**Halldór Ármannsson
Gestur Gíslason
Trausti Hauksson**

**MAGMATIC GASES IN WELL FLUIDS AID
THE MAPPING OF THE FLOW PATTERN IN
A GEOTHERMAL SYSTEM**

OS81022/JHD13

Reykjavík, October 1981



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ABSTRACT

Gas composition and silica concentrations of well fluids are used in conjunction with pressure, temperature and enthalpy data to obtain a model of the drilled part of the Krafla geothermal field (Northeast Iceland).

A magma chamber has been located at 3-8 km depth under the field. Magmatic gases emanate from the chamber and travel via a channel reaching the surface at the Hveragil eruptive fissure. The composition of the gases is apparently modified on the way, in that sulphur, which presumably is in the form of sulphur dioxide to begin with, is removed on the way, and what remains is in the form of hydrogen sulphide at the end. It is suggested that the major removal mechanism is the deposition of pyrite and pyrrhotite during the passage of the gases through the hydrothermal system.

The hydrothermal system is divided into a lower part whose temperature exceeds 300°C and whose fluids are to a varying extent affected by the magmatic gases, and an upper part whose temperature is ca 200°C. This upper part is a run-off from the lower part but the magmatic effects have mostly disappeared there.

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MAGMATIC GASES IN WELL FLUIDS AID THE MAPPING OF THE FLOW PATTERN IN
A GEOTHERMAL SYSTEM

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INTRODUCTION

The Krafla high temperature geothermal field lies in the northern part of the neovolcanic zone in Iceland (Figure 1). Twelve wells have been drilled there with the aim of providing steam for a geothermal power plant. The field has been described by Stefánson (1981). The area has been hit by rifting. The current episode started in 1975 (Björnsson et al 1979) and has resulted in 17 major rifting events in seven of which eruptions have occurred. The centre of this activity is in the vicinity of Leirhnúkur (Fig.2). A magma chamber has been located at a depth of 3-8 km below the drilling area (Einarsson 1978), providing a source of heat and of magmatic gases. The positions of the wells relative to the plant, Mt Krafla and Leirhnúkur are shown in Figure 2. The depths of these wells vary between 1100 and 2200 m, and they draw water and steam from 300 to 2200 m depths. The physical and chemical properties of the well fluids vary greatly from well to well in spite of their relative proximities, but they are here divided into three distinct groups (Table 1).

Group I comprises relatively shallow wells, drawing a fluid from veins at depths above 1000 meters. Their inflow temperatures are 200-220°C; their measured temperatures and enthalpies correspond to quartz equilibrium temperatures (Table 1) and thus they are thought to tap a pure water phase. Gas contents are small but variable, diminishing westwards from Hveragil.

Groups II a and b comprise deep wells, whose inflow consists of a steam-water mixture at 300°- 340°C, as can be seen from the fact that silica enthalpies assuming single water phase and adiabatic flow do not correspond to measured enthalpies of total fluid. The group IIa

fluids are rich in gas, have caused blocking by iron-silica deposits and on occasions serious corrosion problems. Iron sulphide and silica deposits have not been observed in Group II b wells and ratios of water-insoluble to water-soluble gases (e.g. H_2/CO_2 , H_2/H_2S) are relatively low suggesting a fairly degassed state. The difference between Group I and Group II wells is thought to be due to the tapping of different aquifers. Several lines of evidence suggest, however, that there exists a single hydrothermal system, which can be divided into an upper and a lower part. An individual well may tap both parts.

Surface activity in the area is mostly connected with two fissure systems, the presently volcanically active Leirhnúkur system, and a series of fissures through Hveragil and Víti (Figure 2). The main eruptive fissure in Hveragil is close to the production area. Fumaroles and springs in its vicinity have been sampled for gases, analysis of which suggest that the most gas-rich upflow is close to the fissure itself, but gas concentrations decrease eastwards and westwards from it.

In this work the results of chemical analyses of well fluids are combined with those of physical measurements in wells to construct a model of the geothermal system in the present drilling area.

METHODS

Sampling

A Webre separator was used; gas, condensate and water fractions being collected into tightly sealed glass tubes. The water samples for the silica determination were immediately diluted with pre-measured volumes of distilled water in plastic bottles. The steam fraction was collected into a 40% sodium hydroxide solution in an evacuated flask.

Chemical Analysis

The hydrogen sulphide in the gas fraction was determined by titration with iodine in a Tutwiler burette. Combined carbon dioxide and hydrogen sulphide were determined in an Orsat apparatus by absorption in 60% potassium hydroxide, and carbon dioxide found by subtraction. Using the same apparatus, oxygen was determined by absorption in alkaline pyrogallol, combined hydrogen and methane by burning in oxygen, methane by absorption of the carbon dioxide formed in 60% potassium hydroxide, and the hydrogen content was found by subtraction (Kolthoff and Sandell 1952).

A glass electrode (Radiometer GK 2311 C) was used for the determination of pH in water and condensate fractions at room temperature, and for the titration of the same fractions from pH 8.20 to pH 3.80, to obtain their total carbon dioxide concentrations ($\text{CO}_2 + \text{HCO}_3^- + \text{CO}_3^{2-}$), after corrections for hydrogen sulphide and silica concentrations (see Ellis & Mahon 1977). Hydrogen sulphide in these fractions was determined by back-titration with sodium thiosulphate, after the addition of measured volumes of iodine solution to the samples, but by titration with mercuric acetate using dithizone indicator (Arnórsson 1969) in the steam fraction.

Silica was determined spectrophotometrically as the yellow β -molybdate complex, in prediluted samples of the water fractions after the oxidation of sulphide with iodine and the destruction of the excess iodine with sodium thiosulphate (Elísson 1969).

Chloride in the condensate from well KG-12 was determined indirectly by the atomic absorption determination of silver following the precipitation of silver chloride, all traces of sulphide being first removed by oxidation with hydrogen peroxide in nitric acid.

Radon was determined by counting α -radioactivity after purification of the gas. The isotopic determinations were done mass-spectrometrically by DSIR, New-Zealand (Hulston & Lyon 1979).

Gas/condensate ratio

A known volume of condensate was driven out of a tube by the gas, and the additional volume of condensate accompanying the gas measured. When gas contents were high, this ratio was calculated from the carbon dioxide concentrations in the steam, gas and condensate fractions.

Enthalpy, total flow and steam fraction

Critical lip pressure and water flow were measured and enthalpy, total flow and derived parameters calculated by the method of James (1962). For the superheated steam well KG-12 measurements of temperature and differential pressures over orifices as described by the American Society of Mechanical Engineers (1971) were employed.

Temperature and pressure

Downhole temperatures and pressures were measured with Amerada gauges (Geophysical Research Corporation 1974).

The isolation of lower part properties by calculation

As most of the deeper wells draw water from upper part veins as well as water and steam from lower part veins it is necessary to be able to distinguish between these types of veins. A calculation method developed for this purpose is presented in Fig. 3.

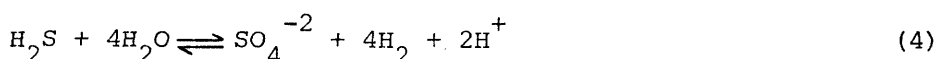
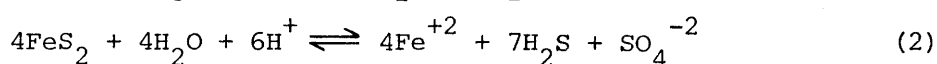
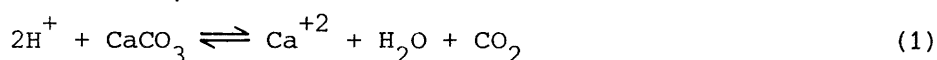
FACTORS GOVERNING GAS CONCENTRATIONS AND RATIOS

For sake of clarity the following two types of equilibria, generally established in geothermal water, are treated separately.

- 1) Equilibrium between gases on the one hand and water and minerals in the surrounding rock on the other.
- 2) Equilibrium distribution of gases between liquid and vapour phases.

The concentration of a gas in the water at a given temperature is controlled by the dissolution and deposition of minerals, depending on whether there is a sufficient amount of a specific mineral in the rock to maintain the equilibrium concentration. During rock alteration the mineral may be used up and the concentration of the gas in the water be controlled by other effects. After flashing and/or degassing of water has occurred, distribution equilibria between phases are soon re-established. All the gases considered concentrate preferentially in vapour compared with liquid phase. The order of their solubilities in the liquid phase is: $H_2S > CO_2 > N_2 > H_2$

The hydrogen/hydrogen sulphide, carbon dioxide/hydrogen sulphide and hydrogen/carbon dioxide ratios are thus decreased in the liquid phase, but increased in the vapour phase. The liquid phase becomes relatively depleted with respect to gases, and mineral water equilibria are disturbed. New equilibrium gas concentrations are approached at a given temperature and pressure, but the carbon dioxide and hydrogen sulphide concentrations may be limited by the amounts of carbonates and sulphur compounds in the rock. The concentration of carbon dioxide in single phase geothermal water in equilibrium with rock minerals has been shown to be controlled by temperature only (Arnórsson 1978). Calcite is thought to be the mineral controlling the carbon dioxide concentration, and pyrite and pyrrhotite the hydrogen sulphide concentration. The hydrogen concentration is probably dependent on the hydrogen sulphide concentration, or

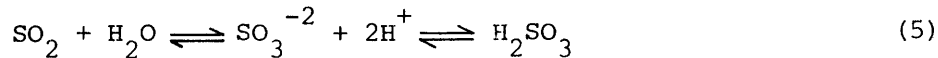


The following processes disturb the above equilibria:

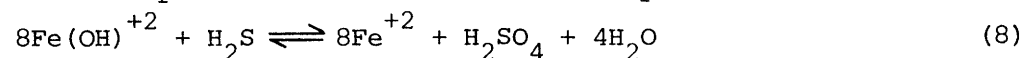
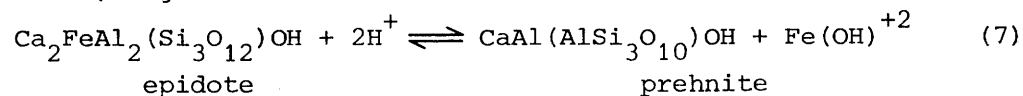
1. Liquid flow, which causes temperature changes.
2. Pressure drops, which cause flashing and degassing of water.
3. Degassing of magma, which causes gas concentration increases.

If rock temperature is different from that of a liquid flowing through, the gas concentrations will deviate from equilibrium concentrations until the new equilibrium is established. This will be reached by dissolution of gases from the rock if the liquid is undersaturated, but by a gas concentration decrease if it is supersaturated.

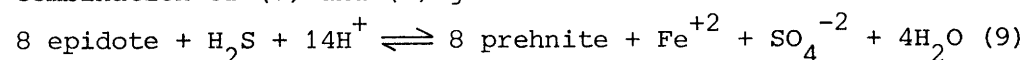
When intrusions occur and pressure drops in the magma at great depths, gases will escape, and may in turn cause gas increases and even supersaturation with respect to gases in the overlying geothermal system. The most important magmatic gases are carbon dioxide, sulphur dioxide, and water vapour (Gerlach 1979, 1980 a,b,c & d). Sulphur dioxide forms a strong acid upon dissolution in water, which may then disproportionate into sulphuric acid and hydrogen sulphate.



These products will react with divalent iron, which is abundant in reactive forms such as in basaltic glass, magnetite and pyroxene in Krafla rocks, and forms pyrite and pyrrhotite as described by equations (2) and (3). An additional source of divalent iron may be alteration minerals such as epidote and chlorite which upon acid attack may release trivalent iron, which then will be reduced to the divalent state, e.g.



Combination of (7) and (8) gives



Thus equilibria (2), (3) and (4) are affected and pyrite and pyrrhotite formed. Carbon dioxide is less soluble and less acidic in water than

is sulphur dioxide. It does not reduce epidote, but it affects the precipitation of carbonates, as described by equation (1). High temperatures reduce carbon dioxide uptake in the rock. Its flow through the geothermal system is however slowed down due to its water solubility.

RESULTS AND DISCUSSION

Two analyses of steam from fumaroles in Hveragil are presented in Table 2, along with the composition of a sample from a fumarole from the southeast slope of Mt Krafla. The locations are shown in Fig.2. As a reference the composition of a sample from position G-12, taken in 1950, is shown as well. Several old analyses suggest that the composition of fumarole steam in the area was fairly uniform and relatively unchanged from 1871 (Cristensen 1889) until the start of the current rifting episode in 1975 (Björnsson et al 1979). If we assume that the difference in composition between 1979 and 1950 represents the addition of a magmatic gas reaching the surface, the composition of this gas is: $\text{CO}_2 = 98.8\%$, $\text{H}_2\text{S} = 1.2\%$, $\text{H}_2 = 0\%$. Values for non-condensable gas concentrations in volcanic gases, adapted from Gerlach (1979, 1980 a,b,c & d) as well as the composition of this gas are shown in Table 3. If the gas emanating from the magma chamber is similar to these gases, then its composition has been modified a great deal by the time it reaches the surface. Other workers have found that carbon content of magmatic gases need not change significantly, while there may be large differences in sulphur, due to changes in SO_2 (see e.g. Nordlie 1971). Apparently substantial amounts of sulphur have been removed from the gas on its way to the surface. The observed formation of iron sulphide deposits in wells suggests that deposition as described by equations (2) and (3) is the major mechanism of sulphur removal. The mean hydrogen sulphide/sulphate mole ratio in the lower part of the system is 125, suggesting that sulphate is being used up relatively fast at the stage, whereas this ratio is 3.3 in the upper part, reflecting the addition of atmospheric oxygen, and the effect of redox reactions such as (4).

Calculations isolating lower part properties using the method described in Fig.3, have been performed for a large number of analyzed samples. The results for representative samples from each well are shown in Table 4. Gas concentrations of representative upper part samples can be seen in Table 1. There is a similarity between the lower part gas composition and that of the present Hveragil fumaroles (cf Table 2), which is unlike the pre-1975 composition of fumarole gas in the area (see above) and that of the gas from fumaroles on the south east slope of Mt Krafla (G-5, Table 2) which are thought to be relatively unaffected by present day magmatic activity. Thus a connection between the lower part of the drilled part of the geothermal system and the fumaroles in Hveragil is suggested. Furthermore, a plane through all important lower part water and steam veins intersects the surface at Hveragil. A plane so constructed is in Figs 4 and 5 used to provide a proper perspective for the comparison of measured and calculated lower part properties between individual wells. The vertical projection of this plane is shown in Fig.2.

Carbon dioxide concentrations of representative upper part samples are shown for each well in Fig.6 and H_2/CO_2 ratios in Fig.7 on a horizontal plane depicting well sites.

An attempt is made to construct a model of the flow in that part of the Krafla geothermal field which is under study. The main features of the model are:

- a) A channel extending from the magma chamber to the surface at Hveragil, through which magmatic gases flow.
- b) The division of the hydrothermal system into a hot ($t^\circ > 300^\circ C$) lower part, which is to a differing degree affected by the gases from the channel, and a cooler ($t^\circ = ca. 200^\circ C$) upper part which is a run-off from the lower part but where the magmatic effects have mostly disappeared. Use is made of the varying signs of magmatic gases in the fluids from different wells. To get a better picture of relative points, the positions of the most important water and steam veins are considered three-dimensionally. The following properties are compared to get an idea of the closeness of each important vein to the stream of magmatic gas:

- 1) The carbon dioxide and hydrogen sulphide concentrations of the fluid.
- 2) The extent of iron sulphide deposits.
- 3) The degassing state as revealed by the H_2/CO_2 ratio. As hydrogen takes part in some of the reactions which occur while the system is not at equilibrium (see e.g. equation (4)), the picture given by the H_2/CO_2 ratio may be obscured.
- 4) The concentration of radon-222 in the fluid.
- 5) The occurrence of hydrogen chloride, which is thought to be a magmatic gas (Table 3), in steam discharge.
- 6) The isotopic composition of the fluid.

These will be considered in turn:

1) The large amounts of carbon dioxide found in the lower part of the geothermal system (Fig.5a) cannot remain dissolved in water at the pressures and temperatures (Table 4) of the lower part veins. Thus boiling conditions are suggested to exist in the system. In drill cuttings from depths greater than 1000 m in Krafla wells only traces of carbonates have been found (Kristmannsdóttir 1978). It is therefore concluded that the carbonates cannot all be dissolved from the surrounding rock and that the carbon dioxide is largely of magmatic origin. If this is the case, well KG-10 is probably the one closest to the magma source, but carbon dioxide concentrations at given locations are probably to some extent modified by pressure and possibly rock temperatures. The hydrogen sulphide concentrations (Figure 5b) show a similar trend, but the low concentrations in the fluids of wells KJ-9 and KJ-11 suggest that some sulphur removal has occurred before the magmatic gases reach these wells. The decreasing carbon dioxide concentrations in the upper part (Fig.6) westwards away from Hveragil show that the magmatic gases are disappearing from the upper part due to degassing and/or precipitation and that this, indeed, is the direction of this flow.

2) Extensive iron sulphide deposits have been found in well KG-10 at depths below 1500 m, and it only takes the lower part of this well about three weeks to become completely blocked off by deposits. Similar deposits have been found in well KJ-7, but these are formed over a longer period, and it takes the lower part of this well 1-2 years to become blocked off. Upon start of flow, black discharges identified as ferrous sulphide were abundant in the discharge from these wells, and in the discharge from wells KJ-6 and KG-12.

Calcite deposits have been found in the upper part of well KJ-9, but no iron sulphide deposits. There have been no signs of deposit formation in well KJ-11. The formation of iron sulphide deposits in wells is believed to be due to disequilibrium in the inflowing fluid caused by the addition of magmatic gases. The resulting acidic fluid dissolves iron from the rock, which then will be deposited as sulphide (see equations (2) and (3)). Thus the extent of iron sulphide deposits in a well is taken to reflect closeness to magma, and therefore the fluids of well KG-10 and KJ-7 are thought to be more affected by magmatic gases than those of well KJ-11.

3) The apparent lack of hydrogen in the magmatic gas probably make its ratios unsuitable parameters to trace the progress of that gas. Where the system is in disequilibrium such as in well KG-10 the values will be relatively low, but after it has approached equilibrium hydrogen will disappear faster from the system than carbon dioxide due to its lower solubility in water. Thus the flow direction may be followed with the decrease of the H_2/CO_2 ratio. The low values for this ratio in wells KJ-9 and KJ-11 suggest that these wells receive the geothermal flow at a fairly late stage. The westwards flow away from Hveragil in the upper part is confirmed by values for this ratio (Fig.7).

4) During degassing of magma radon-222, which is constantly being formed as an intermediate in the uranium-238 series, will escape into the gas phase and thus be carried into the geothermal system. As its half life is 3.8 days, it will not stay for long in the system. However, a large concentration is observed in well KG-10 (Fig.5c, Table 4.) with decreasing concentrations through KJ-7, KW-1 and KJ-6, and the lowest ones in KJ-9 and KJ-11. In the upper part the radon concentration is constant at about 3.5 Bq/kg (Table 1) with no significant variation between wells. If it is assumed that this represents a background value for the area then all magmatic radon has disappeared when the flow reaches the upper part. Assuming that radioactive decay is the only mechanism of radon removal and that there is a direct fluid flow from well KG-10 into the upper part of the system, then the radon activity would be 7.5 Bq/kg after 20 days and 3.5 Bq/kg after 23 days. Complicating factors such as degassing are more likely to suggest longer than shorter residence times, but it seems safe to assume that the flow would take more than 20 days to travel from the lower part of well KG-10 into the upper part of the geothermal system.

5) Hydrogen chloride has been found in the discharge from the superheated steam well KG-12. This suggests closeness of unchanged magmatic gas.

6) Isotopic analyses (Hulston & Lyon 1979) show ^{34}S close to zero suggesting a magmatic origin. This is consistent with the results of Sakai et al (1980), Vinogradov et al (1974) and Torssänder (1979).

CONCLUSIONS

The Hveragil eruptive fissure extends right down to the magma chamber and acts as a channel for magmatic gases to the surface. The composition of these gases is modified on the way up, especially during their passage through the hydrothermal system. The present drilling area for the Krafla geothermal power plant is close to this channel and the fluids in the different wells are to a varying extent affected by magmatic gases. The lower part of the geothermal system is mostly in close contact with magmatic gases, whereas the cooler upper part is a run-off from the lower part. The equilibrium in the upper part is re-established, and magmatic effects have died away. A model of the flow in the system with some indications of the processes taking place is presented in Fig.8. It is concluded that what was classified as Group I in Table 1., are wells tapping exclusively the upper aquifer, but group II wells tap both or only the lower one. Group IIa wells are in close contact with magmatic gases, while group IIb wells (KJ-9 and KJ-11) are apparently further away from the main gas stream and therefore less affected by it.

The practical conclusion is that this drilling area is unsuitable for the purpose of providing suitable steam for the Krafla power plant. As the inlet pressure of the plant is 7 bar abs., the relatively cool group I wells are not suitable. There are problems of blocking by deposition and of corrosion connected with the use of steam from group IIa wells. Group IIb wells are relatively non-problematic, but to site such wells, the magmatic channel has to be very accurately located, and the drilling operation performed with great care to avoid contact with the channel. Therefore the drilling area has now been moved to the southeast slope of Mt Krafla where fumarolic steam seems less affected by magmatic gases.

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TABLE 1 Some properties of Krafla Wells

Group No.	Well No.	Producing zone depth(m)	Enthalpy of discharge (kJ/kg)	Silica ¹⁾ enthalpy of aquifers (kJ/kg)	Measured temp. of aquifers(°C)		CO ₂ mg/kg	H ₂ S mg/kg	H ₂ mg/kg	Rn Bq/kg	CO ₂ H ₂ S x10 ³	H ₂ CO ₂	δ ³⁴ S H ₂ S ‰	Deposits and/or Corrosion	
					upper	lower									
I	KW2	350-1180	825	916	193	-	268	54,8	0,33	3,0	4,9	6,0	1,2	+0,2	Blocked, probably by calcite
	KG8	585-1658	880	959	215	-	213	59,2	0,06	3,6	3,6	1,0	0,28	+0,8	
	KJ9 ²⁾	275-1100	885	1033	210	-	521	65,7	0,76	3,8	7,9	12	1,5		Calcite deposits
	KJ11 ³⁾	788-(1700)	915	939	205	-	67,3	43,5	0,02	1,5	1,5	0,46	0,30		
IIa	KW1	296-1140	1675	1081	220	300	2760	171	4,2	32	16	25	1,5		Blocked; reason unknown.
	KJ6	585-2000	1570	1145	210	320	9600	203	7,2	8,5	47	36	0,8	+0,3	Iron sulphide found in discharge
	KJ7	809-2165	2220	1125	220	340	37500	321	31,0	66	117	97	0,8	+0,5	Iron sulphide and silica deposits
	KG10	817-2100	1340	1023	190	340	48600	1100	12,1	100	44	11	0,2		Iron sulphide and silica deposits
IIb	KG12 ⁴⁾	1100-2222	> 2776		-	325	17100	1130	40,0	55	15	35	2,3		Iron sulphide in original discharge
	KJ9 ⁵⁾	1100-1245	1320	1237	210	300	7230	135	0,9	6,2	54	6,7	0,1	+0,7	Corrosion due to HC in steam discharge
	KJ11 ⁶⁾	788-2217	1300	962	205	340	11300	95	1,0	5,9	119	10	0,1		Calcite deposits
	KJ11 ⁷⁾	(788)-2217	1900	1115	205	340	27000	382	3,5	71	9,2	9,2	0,1		

- 1) Enthalpy of water phase in equilibrium with quartz, assuming adiabatic flow.
- 2) Before deepening operation.
- 3) Producing from upper aquifer only.
- 4) Dry steam from lower aquifer only, HCl = 115 mg/kg
- 5) After deepening operation.
- 6) Producing from both aquifers.
- 7) Producing mainly from lower aquifer after attempt to shield off upper part.

TABLE 2 Gas Composition of Steam from Fumaroles

Area	Sampling Location	Year	CO ₂ mg/kg	H ₂ S mg/kg	H ₂ mg/kg	CO ₂ /H ₂ S	H ₂ /H ₂ S x 10 ³	H ₂ /CO ₂ x 10 ³
	G-16	1979	112370	1729	64	65,0	37	0,6
Hveragil	G-12	1979	217870	3840	74	56,7	19	0,5
	G-12	1950	7360	1343	76	5,5	57	10,3
Mt Krafla S-E slope	G-5	1979	9315	695	55	13,4	79	5,9

TABLE 3. The Non-Condensable Gas Composition of Various Volcanic Gases (After Gerlach 1979, 1980 a,b,c & d)
 Compared with the Calculated Composition of Added Fumarolic Gas at Hveragil, Krafla, During
 Current Magmatic Activity.

Location	Year	Sample No.	Gas composition, excluding water, mass %										$\Sigma C/\Sigma S$			
			CO ₂	CO	H ₂	H ₂ S	SO ₂	S	COS	SO	HCl	ΣC		ΣS		
Nyiragongo, Lava Lake Zaire	1959	2	87,79	2,53	0,11	2,40	5,31	1,63	0,22				25,07	6,66	3,76	
Surtsey, Iceland	1965	24	48,70	2,19	1,83		36,64	7,47					3,15	14,22	25,79	0,55
Mt Etna, Sicily, Italy	1970	5	39,66	0,53	0,04	0,25	58,97	0,50		0,05			11,04	30,25	0,36	
Kilauea volcano Hawaii, U.S.A	1919	J-13	51,74	1,15	0,13	0,18	46,16	0,13					0,51	14,60	23,38	0,62
Erta 'Ale Lava Lake Afar, Ethiopia	1974	920	46,65	1,22	0,29	2,38	46,67	1,30					1,51	13,25	26,88	0,49
-- " --	1971	1154	55,21	1,54	0,22	2,22	38,55	2,18	0,08				17,32	23,59	0,73	
G-12, Hveragil, Krafla Iceland	1979	1056	98,8		0	1,2							26,94	1,13	23,8	

TABLE 4 Calculated Composition of Hot (lower) Aquifers

Well No	Sample No	Assumed temperatures of aquifers °C	cold	hot	Ratio of flow from hot aquifer to total flow	Discharge from hot aquifer kg/s	Pressure of hot aquifer bar.abs.	Enthalpy of discharge from hot aquifer kJ/kg	Steam fraction of hot aquifer fluid	Gas concentration				Gas ratio	
										CO ₂ mg/kg	H ₂ S mg/kg	H ₂ mg/kg	Rn Bq/kg	CO ₂ /H ₂ x 10 ³	H ₂ /CO ₂ x 10 ³
KW1	771161	220	300	0,6	3,2	86	2100	0,55	5100	451	12,4	34	11,3	27,5	2,4
KJ6	771034	210	320	0,64	9,6	113	1950	0,39	14700	290	10,9	17	50,3	37,6	0,7
KJ7	771086	220	340	0,8	7,4	146	2420	0,78	41000	346	34,1	83	118	98,6	0,8
KG10	771193	190	340	0,4	22	146	1930	0,33	91000	2200	21,0	233	41,3	9,5	0,2
KG12	791003	-	325	1,0	6,5	121	>2776	1,00	17100	1130	40,0	55	15,1	35,3	2,3
KJ9	771206	210	300	0,83	25	86	1410	0,05	9200	163	0,27	5,7	56,4	1,7	0,03
KJ11	771083	205	340	0,33	14	146	2140	0,52	30300	186	2,7	11	163	14,5	0,1
KJ11	791044	205	340	0,75	6,8	146	2260	0,62	35700	494	4,8		73,7	9,7	0,1

FIGURE CAPTIONS

Figure 1. The Neovolcanic Zone in Iceland, Including Known High Temperature Geothermal Fields (After Stefánsson 1981).

Figure 2. The Krafla Area. Map Showing Eruptive Fissures, Craters and Faults, and Locations of Wells and Fumarole Sampling Locations.

Figure 3. The Isolation of Lower Part Properties by Calculation.

Symbols: m:mass flow; T:temperature; H:enthalpy; Y:vapour fraction; C:concentration of chemical constituent;

SiO₂: concentration of silica; $\phi(T), \theta(T)$: functions of T.

Subscripts: 0:of total flow; 1:of upper part flow; 2:of lower part flow; V:of vapour phase; L:of liquid phase.

Assumptions: $1 = m_1 + m_2$ (1); $H_0 = H_1 m_1 + H_2 m_2$ (2); $C_0 = C_1 m_1 + C_2 m_2$ (3);

SiO₂ V = 0 (4); SiO₂ L = $\phi(T)$ (5); H_L = $\theta_L(T)$ (6) H_V = $\theta_V(T)$ (7)

Thus

$$H_0 = m_1 \theta_L(T_1) + \{ \theta_L(T_2) (1 - Y_2) + \theta_V(T_2) Y_2 \} m_2 \quad (8);$$

$$\text{SiO}_2 \text{ L} (1 - Y_0) = \phi(T_1) m_1 + \phi(T_2) (1 - Y_2) m_2 \quad (9).$$

T₁ and T₂ have been measured, so equations (1), (8) and (9) can be solved to obtain the three unknowns m₁, m₂ and Y₂.

H₁ and C₁ are generally known with reasonable certainty, so H₂ and C₂ can be obtained from equations (2) and (3).

Figure 4. Flow and Steam Fraction of Lower Aquifer, Measured shortly after Starting the Wells and with Wellhead Pressures between 6 and 12 bar abs.

Figure 5. Gas Composition of Lower Part Fluids.

Figure 6. Carbon Dioxide Concentration (mg/kg) in the Upper Part of the Krafla Geothermal System.

Figure 7. H₂/CO₂ Ratio (wt/wt) x (10³) in the Deep Water of the Upper Part of the Krafla Geothermal System.

Figure 8. Schematic Picture, Showing the Flow Pattern in the Krafla Geothermal Field.

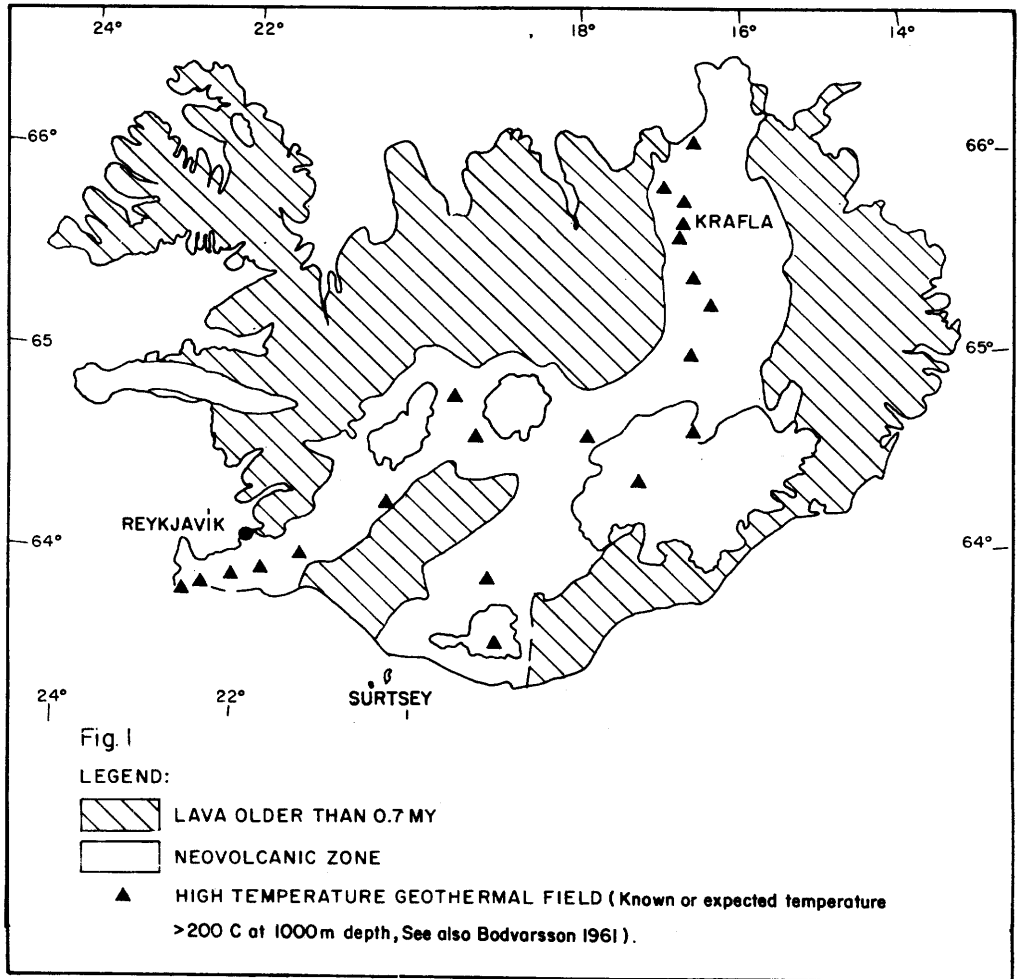








Fig. 2.

LEGEND:

-  Fault (bars on downthrown side)
-  Eruptive fissure (post-glacial)
-  Eruptive crater
a. post-glacial
b. older
-  Well
-  Fumarole
-  Plane, shown in figs. 4 and 5 (Inclination 12°, intersects surface at Hveragil)

0 200 400 600 800 1000m

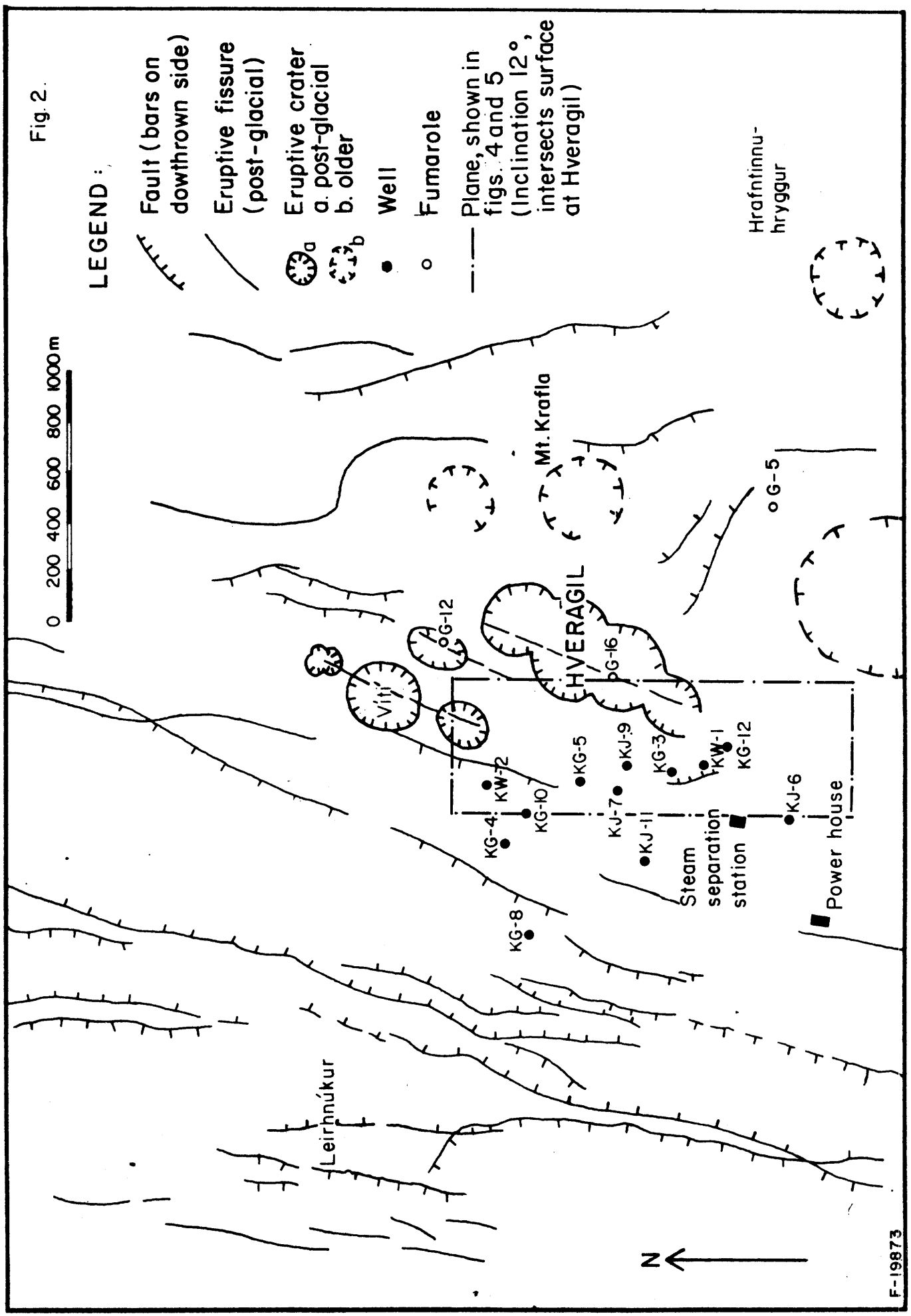
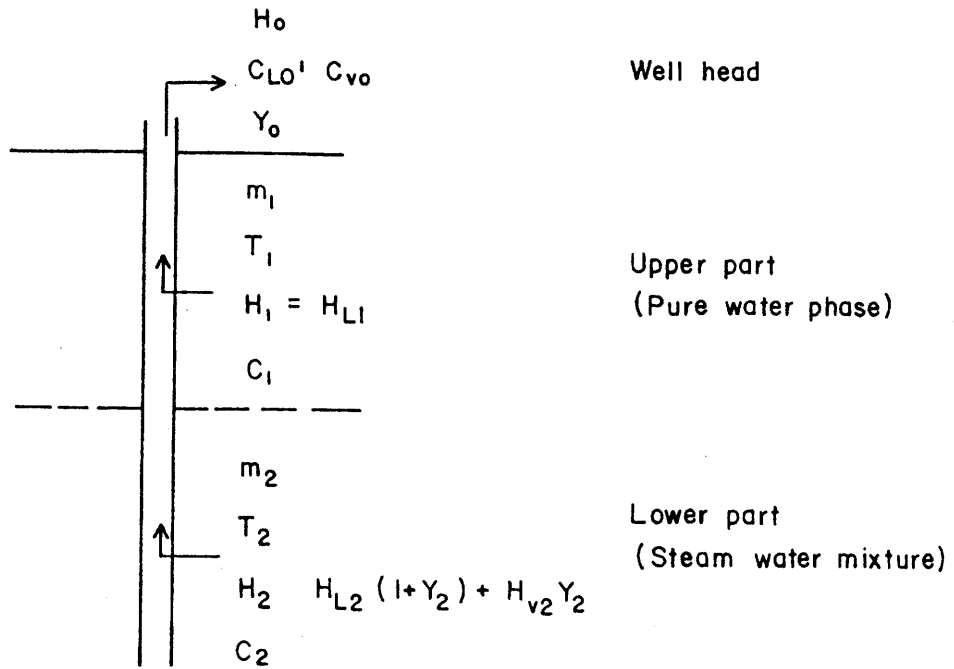


Fig. 3



A KRAFLA
BOREHOLE
A SCHEMATIC
DIAGRAM

Figure 4.

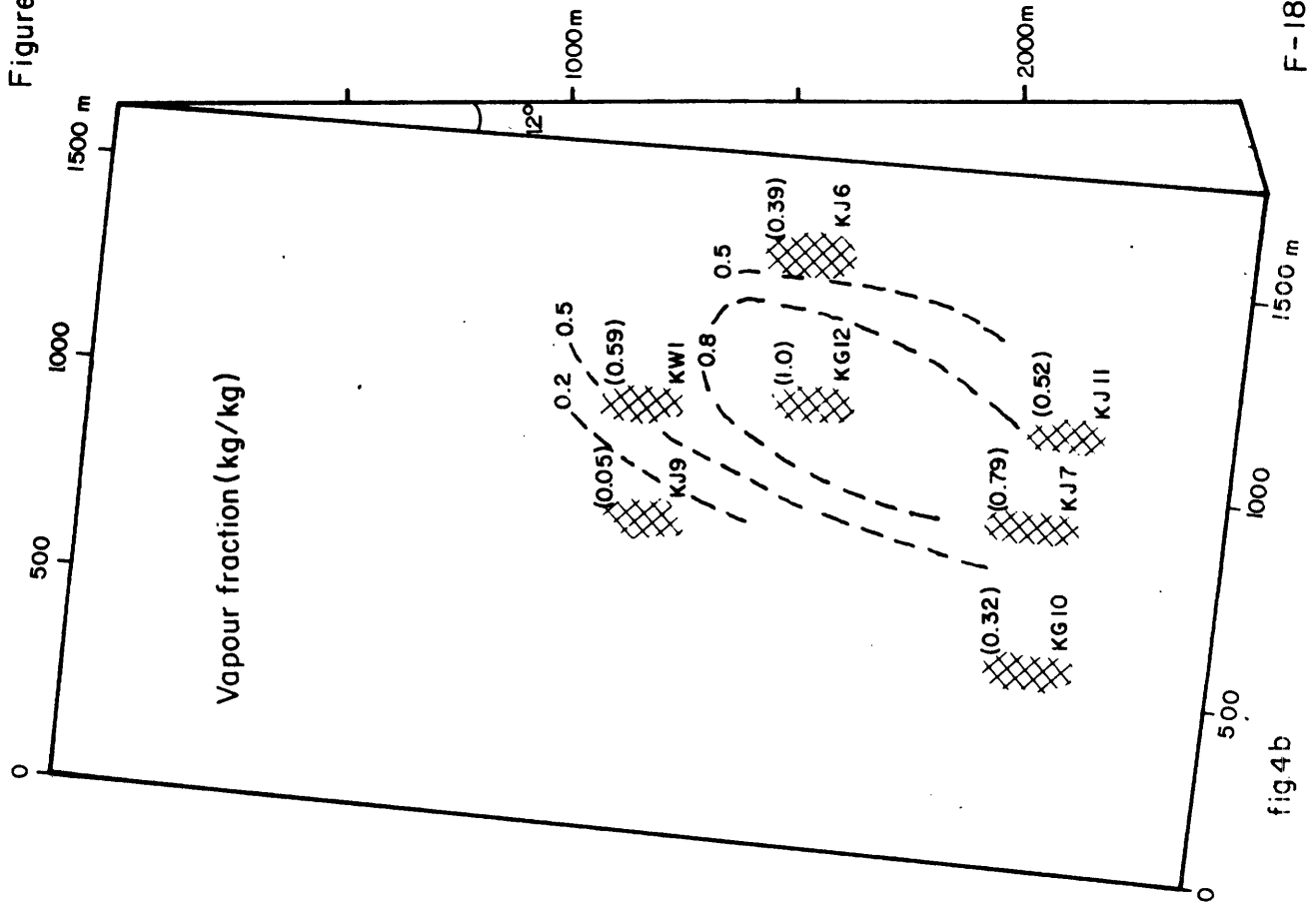


fig 4b

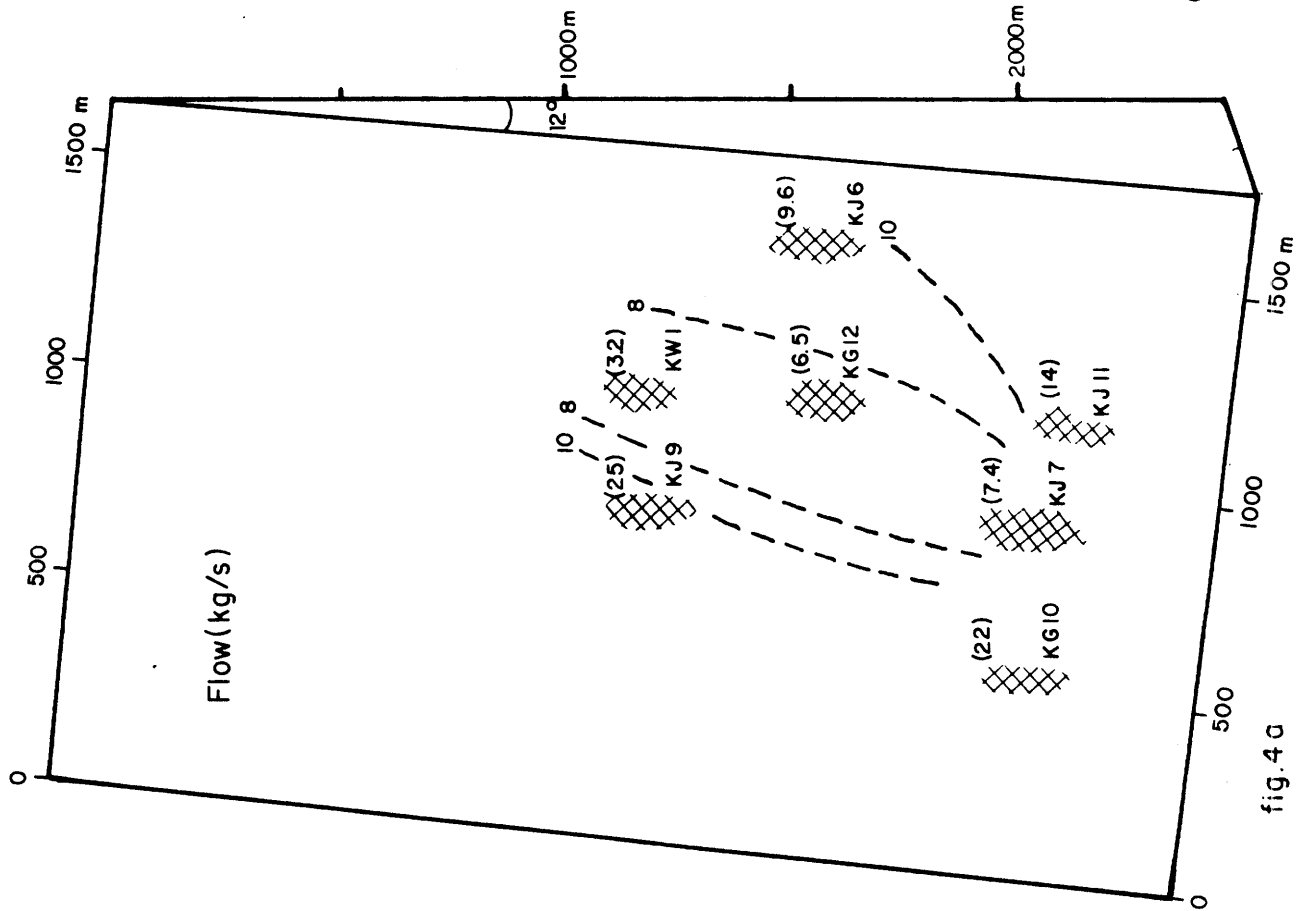


fig. 4a

Fig. 5

