KAWAH KAMOJANG GEOTHERMAL FIELD, WEST JAVA

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ABSTRACT

Kawah Kamojang geothermal field occupies an area of 14 km2 beneath the upper slopes of the Gandapura volcanic complex. The hydrothermally active area covers a small area along the eastern side, and includes fumaroles and steam heated sulphate springs containing negligible chloride concentrations typically associated with a vapour dominated system. However, the initial nine wells drilled to 500-1500 m revealed the presence of a superficial layer of warm to hot sulphate water down to about 700 m, underlain by a low density fluid (0.085 $g.cm^{3}$), consisting of sodium bicarbonate/sulphate water of groundwater origin, into which neutral chloride water mixes locally up to undefined levels. The low density is ascribed to the presence of gas which rises continually through the system and lifts the chloride water from a widespread deeper layer.

INTRODUCTION

Kawah Kamojang geothermal field is located 42 km south-east from Bandung at an altitude of 1650 m on a large volcano complex of which Gunung Masigit (2249 m) is the highest peak and Gunung Guntur the youngest volcano. The volcanism migrated from Gandapura volcano, at the western end, east-south-east to Guntur which was active last in 1847. The hydrothermally active area of Kawah Kamojang occupies a depression on the south western flank of Gandapura, but at depth the hot area extends into an older caldera which is partly buried by lava flows from Gandapura and contains the village of Pateungteung.

Following a reconnaissance of hydrothermal areas in West Java in 1971, Kawah Kamojang was recommended for exploration and possible development as a source of geothermal energy for electrical power generation. This proceeded as a Colombo Plan project by joint agencies of the Governments of New Zealand and Indonesia, under the technical direction of Geothermal Energy New Zealand Ltd,

Preliminary superficial studies indicated that the field was of the "vapour dominated" type. The account presented in this paper related more particularly to data obtained from the initial wells drilled before conditions underground were significantly changed by the effects of large scale production of steam. It is believed that this was the first occasion on which data of comparable detail were obtained in a field of this type.

GEOLOGY

Gandapura forms part of a chain of volcanoes extending north and north-east from Papandayan to G. Sanggar and to Pasir Jawa which forms the western rim of the Pangkalan Caldera. Because weathered volcanic ash forms a mantle up to 20 m thick and exposures are few, and thick forest also covers the north-eastern half of the field, mapping was based largely on air photo study and field identification of lavas where possible.

Gandapura and the older lavas of the Guntur complex are composed of pyroxene andesite, the most comn lava in the area. Parts of the complex have collapsed on the north and south-east sides. Masigit and Batusun cones lie within the northern collapsed area, and north from these young cones a fan shaped pyroclastic flow deposit (Ciharus Tuff) extends across the Elos Valley and east over the plain of Leles. The young cone of Guntur is located at the head of the south-eastern collapsed area, and on it a number of young lava flows, the last dated 1840, extend down the south-eastern slopes to the warm springs of Cipanas at the base. These youngest lavas are labradorite basalt.

About 1 km west of the summit of Gandapura a north-south fault with downthrow to the west defines the eastern boundary of Kawah Kamojang hydrothermal area, which occupies a strip <0.5 km wide crossed by three faults striking south-east to intersect N-S fault. Two sets of faults which strike south-east and between north and north-east appear to dominate the structure of the Gandapura-Guntur complex. An important member of the latter set is the Kendang Fault, which extends north-east for 15 km from the summit of G. Kendang to the southern end of Pr. Jawa. Its prominent scarp faces south-east, but it has no visible extent north-east of Pr. Jawa. If the fault is present there, it is covered by the Gandapura lavas. It appears to be of structural and volcanic significance, and therefore likely to extend into the

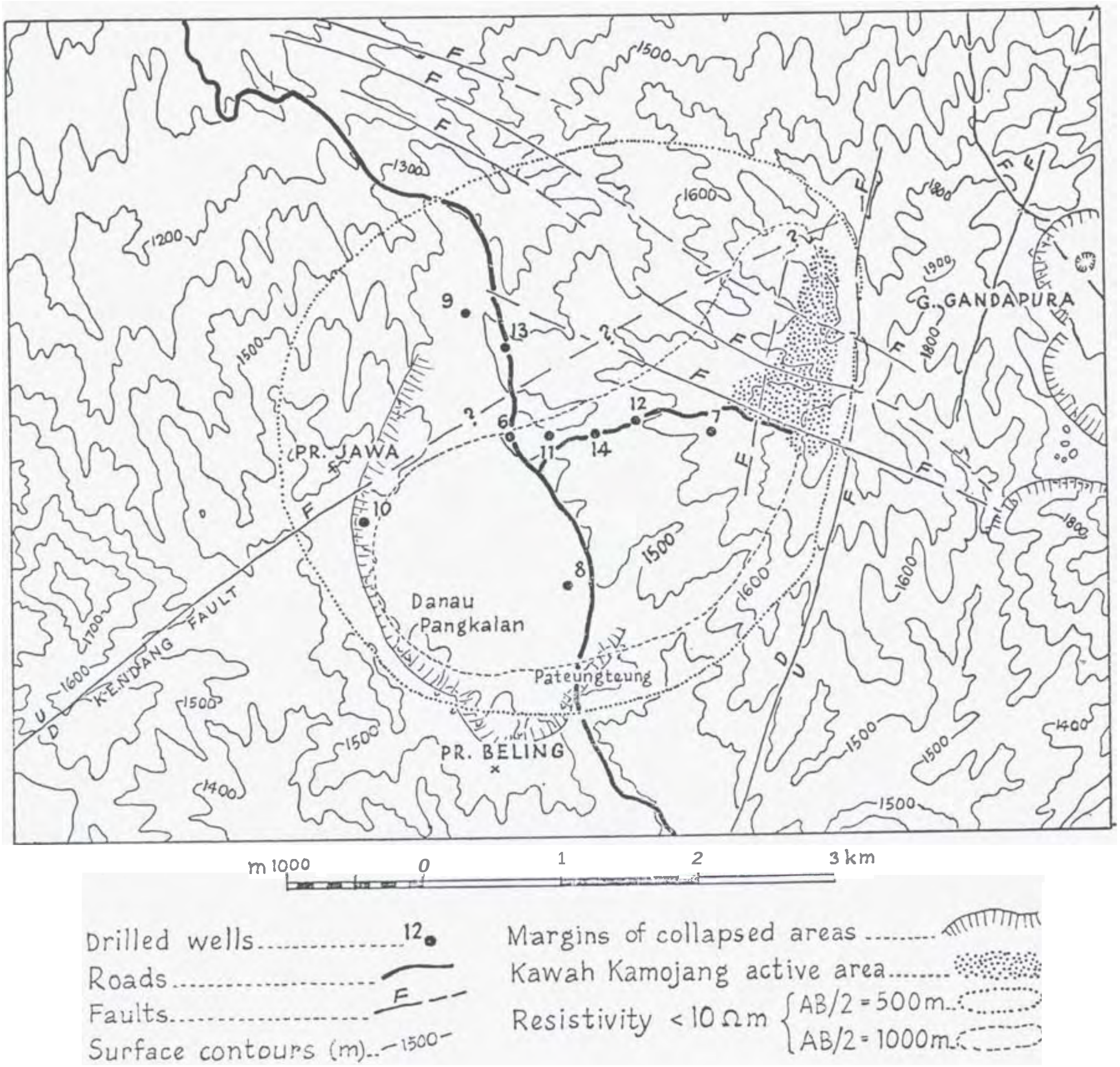

Figure 1. Kawah Kamojang Geothermal Field

Kawah Kamojang area, as shown also by Stehn (1929).

The veneer of volcanic ash around the southern and western margins of the Pangkalan depression masks its character, but it is here considered to be a caldera, possibly of complex form. Its visible diameter is 2-2.5 km, though the extent of its north-east extension beneath the Gandapura lavas is not known. In the south-eastern part of the caldera, tuffs and two pyroxene andesite flows from Gandapura are interbedded with siltstone and mud to a depth of 217 m in Well No. 8, indicating the existence of a lake or swampy conditions during much of its life.

KAWAH KAMOJANG GEOTHERMAL FIELD

The hydrothermal activity consists of fumaroles, mudpots and hot springs, scattered over an area <500 m wide and 1200 m long from south to north, intersected by faults referred to above. The most significant features are two hot lakes, Kawah Manuk (150 m x 80 m) and Kawah Bercek (200 m x 75 m), which contain muddy water and are surrounded by mud pools, small steam heated pools, and hydrothermally altered ground. Temperatures of many surface waters lie between 93°C and 94.5°C close to the local boiling point of 94.5°C, and a number of major fumaroles discharge large volumes of superheated steam.

Most of the hot surface water is very acid (pH~2) and contains high concentrations of sulphate (1000-2000 ppm) but very low concentrations of chloride (<5 ppm). Isotopic evidence suggests that the water is local meteoric water which has been heated by steam containing hydrogen sulphide, which oxidises to sulphuric acid to give the waters a low pH and high sulphate concentration.

Two kilometres south of the main activity are two warm springs of temperatures 38°C and 49°C. Considerable gas ebullition occurs from the warm waters but no odour of hydrogen sulphide or other sulphur gases is apparent. The major cations and anions in the waters, which are neutral, are sodium, calcium, sulphate and bicarbonate. The analysis of one of these springs is shown in Table 1.

The composition of hot and cold waters in an area of ±60 km2 encompassing Kamojang and the flanks of the complex indicate that there is no hot sodium chloride water reaching the surface in this zone. Chloride concentrations are rarely above 5 ppm although higher chloride waters (≈20 ppm) are present some kilometres south of Kamojang and also at Madjalaya, the nearest cold water sink to the area, some 14 km NW of Kamojang.

Gases present in the steam discharged from the fumaroles consist of carbon dioxide (≈90% by volume), hydrogen sulphide, methane, hydrogen, nitrogen, and ammonia. Isotopic analyses of the steam (D/H, $^{16}O/^{18}O$) suggest that it is derived from local meteoric water while gas geothermometry indicates deep temperatures greater than 230°C. Analysis of the steam discharged from the shallow Well 3 suggests that deep gas concentrations could be of the order of 2% by weight.

The general chemistry of the surface features, particularly the general acidity of the surface waters, the high sulphate concentrations and the absence of chloride suggests that Kamojang is a vapour dominated system, at least at shallow depths.

GEOPHYSICAL SURVEYS

The extent of the Kawah Kamojang geothermal field at depth was explored by measurements of apparent resistivity along traverses using Schlumberger arrays with AB/2=500 m and AB/2=1000 m (Hochstein, 1976). The areas with resistivities less than 10 ohm m outlined by both sets of traverses are shown in Fig. 1. In general the eastern boundary is determined by the N-S fault and the southern and south-western boundaries by the margin of the Pangkalan Caldera. The north-western boundary in the shallower survey coincides approximately with the projection of the Kendang fault, but that of the deeper survey extends farther to the north-west to enclose a total area of 14 km2 with resistivity less than 10 ohm m.

EXPLORATORY AND DEVELOPMENT DRILLING

(a) Shallower Wells

Because of rugged topography and thick forest cover in the northern third of the area, five sites for exploratory wells to depths of ±600 m were selected to test the extent of the remainder of the reservoir. Beneath the superficial ash and tuff, all encountered pyroxene andesite lavas from Gandapura to depths ranging from 125 m to 295 m. Hydrothermal alteration was absent or minimal in the upper part but increased towards the base where high temperatures were encountered. Exceptions were Well 7, drilled close to the hydrothermally active area, and Well 10, drilled at a point not

TABLE 1 Analysis of waters from Kawah Kamojang, Indonesia
Concentrations in ppm in waters at particular levels

Well or Spring	Depth of Sampling m	pH (20°C)	Li	Na	K	Ca	Mg	Fe	Cl	SO_4	SiO_2	HCO_3	B	NH_3
South Kamojang Spring	surface	7.0	<0.1	47	16	73	27	0.6	5	74	200	836	1.4	0.2
6	160	3.6	-	155	24	<1.0	<0.1		<2	430	260	70		
6	500	6.8	0.75	100	10	<1.0	<0.1		t2	290	415	60	-	-
6	600	7.0	-	92	13	<1.0	<0.1	-	<2	200	425	-	-	-
7	500	8.0	0.35	148	6.7	11.6	0.1	0.15	10	120	375	207	10	0.2
8	350	8.2	-	630	27	8.1	29	2.0	26	1175	75	435	4.2	-
8	550	8.6	2.2	606	20	16.1	14.5	6.0	30	1425	105	-	5.3	
8	600	7.1	0.7	622	15	32.0	4.8	6.0	13	1400	195	342	4.7	
9	320	7.1	1.1	217	45	24	29	0	6	42	190	606	1.6.	
9	550	6.4	0.85	347	8	1.3	4.8	1.5	5	109	390	590	7.1	
9	700	8.0	0.2	218	39	1.8	0.2	0.6	6	101	385	630	7.0	
10	400	7.2	0.3	89	17	143	3	3	12	432	150	155	0.4	
10	550	8.0	1.3	81	16	99	6.5	4	12	332	190	140	0.4	
10	730	6.7	0.3	79	16.5	67	8.1	0	14	260	225	109	0.2	
11	surface discharge	6.8	1.2	154	42	13			428	53	>400	70	41	
13	surface discharge	7.9	5	1150	139	25	<1.0	·	1305	479	>400	195	74	

reached by the Gandapura lavas. Pemeability was commonly present in the unaltered upper levels of the pyroxene lava, but absent in the lower altered part where joints and fractures were sealed by silica or calcite.

At deeper 1evels hydrothermal alteration was marked in underlying andesite lavas, breccias and tuffs of varying composition, except in Well 8 where the temperatures were generally lower. Well 10, drilled in the fracture zone of the Kendang Fault, passes through strongly altered rock, though temperatures appear to have decreased. Temperature profi1es in the wel1s consisted essentially of linear thermal gradients between points where hot fluids circulate through joints or fissures. Permeability was low in the hot zones except where major fissures were encountered. Along a south-east profile through Wells 9-6-8, isotherms reach their highest level in Well 6. On a north-east profile through Wells 10-6-7, they converge to the surface regularly towards Well 7.

Water and steam samples were collected from the surface discharges of Wells 6 and 7, and from different selected depths in Wells 6-10. Analyses of selected samples are shown in Table 1 together with the depths of collection. When Wells 6 and 7 were initially discharged some water was included in the discharges even though the discharge enthalpies were high (>2000 Kj/Kg). Water was collected from the discharges using a minicyclone steam/water separator.

The composition of the water at Kamojang at intermediate depths (160-700 m) is very similar to that of the south Kamojang springs (cf Table 1). Major constituents are sodium, calcium, sulphate, bicarbonate and silica. The waters are near neutral and contain a maximum of 30 ppm chloride (Well 7). Water collected from just below water level in Well 6, at 160 m, has a pH of 3.6. Whereas calcite and anhydrite are commonly detected in cores taken below water level, they are absent in cores taken from near the apparent water level. Acid conditions in this zone apparently prohibit the formation of these minerals.

The composition of waters discharged from Wells 6 and 7 both initially and later are similar to those sampled from down the wells. Although the discharges are mainly steam, some of the water residing in the formations is entrained in the discharges.

Calcium and magnesium concentrations in the lower temperature well waters (140-180°C) are appreciable but much lower in the higher temperature waters (200-240°C). This trend follows the decreasing solubility of calcium and magnesium sulphates and bicarbonates with increasing temperature. Similarly, magnesium remains at very low levels in higher temperature water by equilibrium with minerals such as chlorite and montmorillonite. In the highest temperature waters sodium should predominate as the major cation in bicarbonate/sulphate waters.

The water appears to have attained temperature equilibrium with the confining rock and minerals, particularly the higher temperature water. Silica concentrations in the waters approximate to those expected from the solution of quartz from the rocks at the measured temperatures. Similarly, the concentrations of sodium and potassium in solution and equivalent Na/K atomic ratios suggest temperature equi1ibrium between the feldspar phases in the rock and the hot water.

The gas composition of steam discharged from Wells 6 and 7, the local fumaroles, and the shallow Well 3, are very similar. Carbon dioxide is the predominant gas, making up over 90% by volume of the gases present and 1.5-2% by weight of the vapour phase. Hydrogen sulphide varies from 3-4% by volume and residual gases consisting of nitrogen, hydrogen, methane and ammonia are present at low concentrations. Gas collects at the well head of some of the nonproducing wells. The composition of this gas is very similar to that present in Wells 6 and 7.

(b) Deeper Wells

Four sites for 1500 m wells (Nos. 11-14) were selected in the central area and were drilled respectively to depths of 1026.7 m, 1100 m, 1272 m, and **1000** m. Each well was tested, and 12 and 13 were deepened to 1506 m and 1500 m respectively and tested again, before drilling proceeded at the next site. Tests included cold water injection followed by measurements of temperature and pressure profiles at intervals of 2, 4, 8, **16,** 30-32 days and, finally, discharge measurements. Wells **11** and 14 were good producers and were not deepened, but 12 and 13 were poor producers before and after deepening.

As stated above, the Gandapura pyroxene andesite lavas underlying the superficial ash and tuff were little altered, except near the base and in Well 7 where hydrothermal alteration extends to the surface. The underlying lavas in the deeper wells include basaltic andesite and basalt, indicating a change with time to less basic lavas, and are interbedded with tuff and breccia. They are strongly altered and it was not possible to make detailed correlations through the wells. P.R.L. Browne (personal communication) identified alteration by two distinct fluids, one sulphate rich associated with the formation of anhydrite, and the other neutral causing deposition of wairakite and calcite. In core from 601-602 m in Well 7, he noted a vein of anhydrite cut by a later vein of wairakite and calcite, suggesting that the neutral fluid was the later of the two.

Anhydrite is most extensively developed and to shallowest level in Well 10. Possibly the acid sulphate waters were associated with an earlier fumarolic stage of the Pangkalan caldera and the neutral waters with the later eruptive phase of Gandapura.

Two of the deeper production wells (11 and 13) encountered neutral pH sodium chloride water at depths below 900 m. The interface zone between the upper bicarbonate/sulphate water and the lower chloride water in each well has temperatures between 200 and 220°C. Higher temperatures (up to 244°C) occur at shallower depths and again below the interface zone. There is insufficient chemical evidence to outline in detail the upper limits of the chloride water throughout the system. The absence of chloride in Well 12, the deepest well in the general locality, suggests that the interface is belled up in places, which possibly represent zones of high heat and gas flow associated with fissures.

Table 1 shows the analyses of waters collected from Wells 11 and 13. In many respects the composition of the waters is typical of neutral sodium chloride waters found in water dominated geothermal systems like Wairakei, N.Z. and Ahuachapan, El Salvador. Rather high concentrations of sulphate and bicarbonate suggest some admixture of the sodium sulphate bicarbonate water occurring at shallow levels in the system with the neutral sodium chloride water. An alternative explanation could be a relatively low water temperature, particularly in the case of Well 13.

The similarity in the Cl/B ratios in waters of the two wells suggest that a sodium chloride water reservoir with some apparent chemical homogeneity occurs over a relatively large area. The undiluted deep chloride concentration is difficult to estimate on present information. The values of 428 and 1305 ppm in the surface discharges of Wells 11 and 13 respectively are probably high for atmospheric discharge samples. The enthalpies of both wells are extremely high, indicating that evaporation of water present in the respective discharges would be considerable.

The gas concentrations in the deeper wells at Kamojang (11-14) vary from about 1% to 2% by weight. The CO_2/H_2S molecular ratio commonly lies in the range 20 to 40 and a typical analysis of the gases present, excluding water vapour, is CO_2, 90-95%; H_2S, 4-10%; H_2, 0.04-0.06%; N_2, 0.5-0.6%; CH_4, 0.03-0.07%; (percentage by weight). Ammonia concentrations in the steam range from 1 to 6 ppm.

Most producing wells at Kamojang have high discharge enthalpies and produce only small amounts of water, though at higher well head pressures more water is entrained, particularly when the wells are initially opened. Well 11, for example, can be discharged over a pressure range of 1 to 30 kg/cm^2. At high discharge pressures (28 kg/cm^2) the water content of the discharge, during one series of tests, ranged from less than 1% wt up to 5% wt. As pressures were reduced, the average wetness of the well decreased to 0.5 to 2% wt. The water contained in the discharge of Well 11 comes primarily from the bottom of the sodium bicarbonate sulphate layer. Occasionally, however, some of the deeper sodium chloride water is entrained.

TEMPERATURES

Temperatures in the shallower wells 6-10 increased to the bottom, with the maximum temperature pf 230°C measured in Well 6. In the deeper wells the maximum temperature was 245°C in Well 11 located only about 300 m from 6, and was measured at the bottom while the well was shut in after discharging. The other three wells exhibited temperature inversions within zones in which some permeability had been encountered, though these were gradually decreasing during the heating up period. In Well 12 after a period of discharge the inversion had disappeared and the maximum temperature had increased to 239°C, and 17 days later to 244°C. During further discharge the temperature at the same level had decreased to 199°C, presumably due to flashing and gas release induced by reduction in pressure because of low permeability.

Well 13 showed greatly reduced temperature and maintenance of a temperature inversion during discharge, also related to low permeability. The higher temperature zone above the inversion was measured within the cased section of the well.

PRESSURES

The pressure profiles produced interesting results. In the shallow wells 6-10, cased to 300 m, free water levels were measured in 8 and 10, but in the other three were depressed by shut in wellhead pressures of steam and gas and were estimated by projecting the graphs of pressure vs depth in the water columns to zero pressure. The results are plotted in Fig. 2, which shows the water levels to lie within a limited depth range independent of depth drilled.

In the deeper wells, cased to 700 m through the sealed lower levels of the pyroxene andesite into the underlying hot zone, water was also present but at much deeper levels and further depressed by pressures of the shut in gas and steam. During the heating up period of each well, water level gradually rose and stabilised. Free water levels were estimated as for the shallow wells and are also plotted in Fig. 2, which shows that they decline consistently with depth drilled.

The interpretation adopted here is that the stabilised pressure measured at the bottom of each well is equal to the sum of the wellhead pressure and the weights of the columns of gas, steam and water, and is balanced by the pressure in the country at the same level. In Fig. 3 stabilised well bottom pressures have been plotted against depth. The wells fall clearly into two categories. The shallow wells show a linear relationship, with a vertical pressure gradient equivalent to saturation by a fluid of density 1.15 g cm^{-3} (line 1), or, more realistically, of density 0.98 g cm^{-3} if Well 10 be excluded (line 2), as it is the only well in which the water level does not lie within the Gandapura pyroxene andesite.

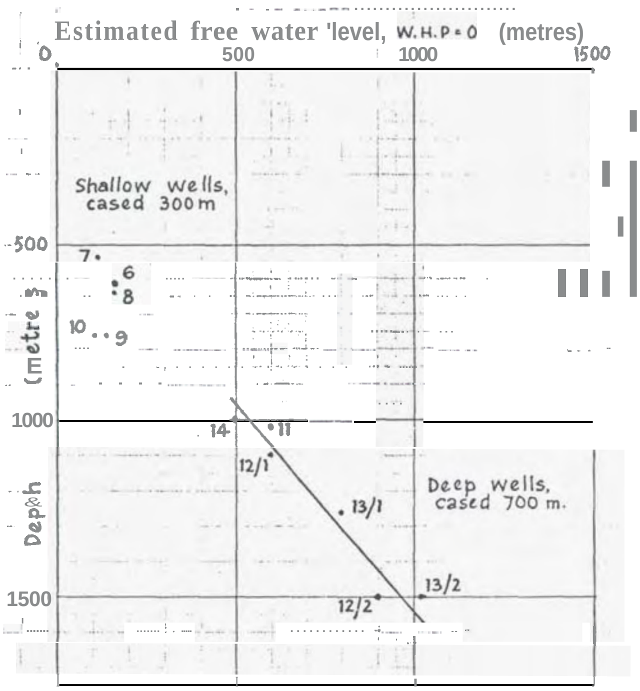

Fig. 2. Relation between static water levels and depths drilled in shallow and deep zones

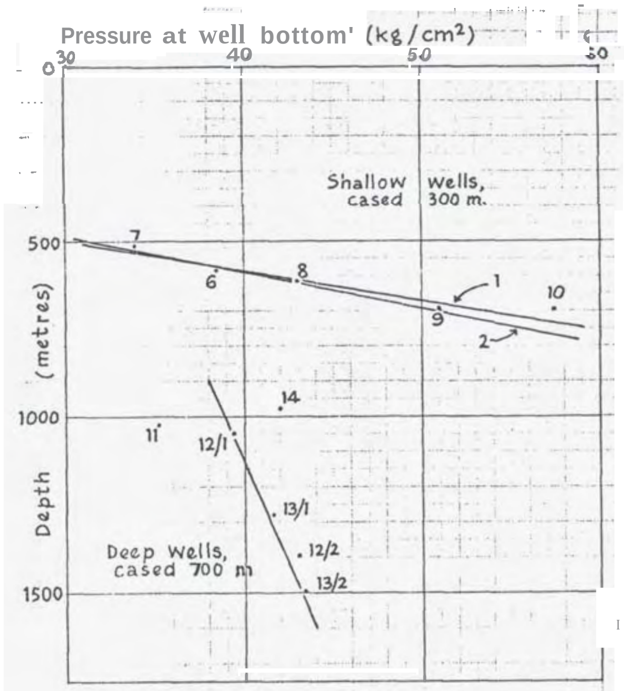

Fig. 3. Relation between pressures and depths in shallow and deep zones

The deep wells also show a linear relationship between pressure and depth, but equivalent to saturation by a medium of density only 0.085 g cm^{-3} (line 3). Well 14 was subjected to casing damage and repair, and was not fully stabilised before it was discharged, so the true density is probably a little higher than 0.085 g cm^{-3}. Line 3 if projected upwards intersects line 2 close to Well 7, suggesting a direct communication of that well, located on the margin of the active area, with the lower hot zone intersected by the deeper wells.

DISCUSSION

Initial reconnaissance of the Kawah Kamojang geothermal field suggested the presence of a typical vapour dominated system similar to The Geysers in the U.S.A. and Lardarello in Italy. The initial drilling revealed the existence of slightly higher temperatures and pressures than those assumed for the ideal system. The deeper drilling proved the existence of still higher temperatures (245°C) and pressures (>40 kg/cm2), together with the presence of chloride waters and the existence of a considerably higher vertical pressure gradient than the ideal assumption, suggesting the presence of a low density fluid rather than steam and/or gas alone.

On the evidence of hydrothermal alteration in the wells, the hot water surface is at a depth of 150-200 m over a wide area, and beneath this deposits of calcite, anhydrite and occasionally pyrrhotite are widespread. Amorphous silica forms a secondary hydrothermal mineral between 600 m and 700 m, and secondary quartz is widespread below about 800 m. Kaolinite present at depths of 300-400 m suggests the earlier presence of more acid waters, almost certainly as a temporary phase before rock/water interaction neutralised the acidity of the solution.

Mahon et al (1980) discussed the significance of the Kamojang chemistry in relation to the non-condensible gases, particularly CO_2 present in the system. Chemical evidence obtained from downhole samples before and after the discharge of some wells tends to suggest the continuous presence of sodium/bicarbonate/sulphate water down to the depth of the chloride water. This would be consistent with the presence of a low density mixture in which water is presumably a continuous phase in a frothy mixture. The water is of ground-water origin, heated by the ascending gas and steam rising from the deeper chloride water. The irregularity in levels to which the chloride water rises is likely to be related to the distribution of fissures through which it rises by gas lift. The occurrence of the bicarbonate/sulphate water in springs and streams on the flanks of the Gandapura complex show that there is a steady flux, the surplus steam and gas escaping from the Kawah Kamojang hot area. Recorded changes in superficial activity, often noted to be related to local earthquakes, suggest that either the latter maintain the discharge or alternatively are caused by release of occasional accumulations of gas pressure.

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