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HYDROCHEMICAL FEATURES OF A GEOTHERMAL TEST WELL IN A VOLCANIC CALDERA, MT. PINATUBO, PHILIPPINES

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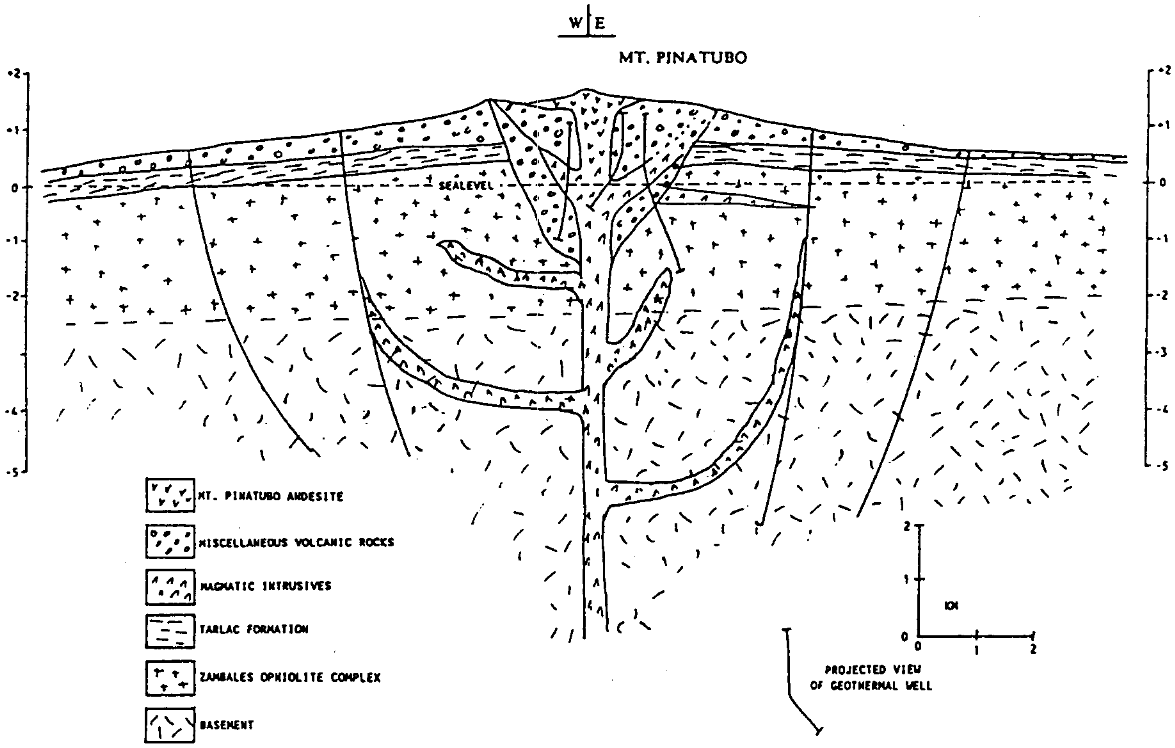
ABSTRACT

Mt. Pinatubo is one of several recent-age volcanoes along the west Luzon volcanic arc. A fumarole near the summit emits gases with magmatic characteristics. Several thermal springs on the east and west flanks yield various fluid types, including neutral chloride and bicarbonate. Three wellbores probed the Mt. Pinatubo caldera from elevations of +1230 through -1600 mRSL. Trajectories may be described as: central, crossing a boundary wall from the inside, and skirting a wall [probably] on the inside. Brine discharges indicate severe evapo-concentration effects accompanied by other phenomena. Severity of evapo-concentration indicates low fluid mobility near the wellbores. Large variations for ratios of component concentrations were observed, indicating negligible natural circulation (mixing). Implications about fluid movements and heat transfer processes are explored. Three components of steam can be quantified and all are significant; separate entry, adiabatic boiling, and boiling by rock heat.

<u>SETTING:</u> The West Luzon Volcanic Arc results from eastward subduction of the Manila Trench and includes a number of major stratovolcanoes of dominantly andesitic composition. Mt. Pinatubo is in western Luzon, north of Bataan peninsula, where the northwest Iba fracture (or graben) intersects the Arc. This region of Luzon has been built upon the Zambales Ophiolite Complex, part of the Eocene oceanic crust, along with overlying, unconformable marine, non-marine, and volcaniclastic sediments. These tilt eastward, forming the western margin of the Central Luzon Basin. Mt. Pinatubo (Figure 1) is locally the most prominent of several volcanic vents, mostly aligned along the north-trending volcanic axis. Initial volcanism began in late Pliocene and consists of andesitic to basaltic-andesitic lavas, tuffs, breccias, and lahars. Younger volcanics are dominantly dacitic ash-flow and ash-fall tuffs with minor andesitic-to-dacitic lavas and breccias.

GEOLOGIC CROSS-SECTION THROUGH MT. PINATUBO



SUMMARY OF INVESTIGATIONS: The Mt. Pinatubo area is considered a prospect for geothermal energy development. Three deep wells were drilled and tested in 1988-90, following geological, geophysical, and geochemical investigations. Wellhead elevations were 1098 to 1230 mASL. Wellfluids were obtained from depths of +100 to -1600 mRSL, and most were acidic, a feature recognized as indicating magmatic origins of some components. All wells yield fluids with excess enthalpy, partly due to separate steam discharges, but considerable boiling by rock heat is apparent for wells PIN-1 and PIN-3D. Downwell samples were obtained from static wellbores (PIN-2D and -3D), after, or between periods of discharge. These downwell compositions show uneven correspondences with the compositions of discharged fluids. Collectively, the variations among wellfluid compositions, and trends during production, indicate that fluid circulations are constrained. Some H_2O in wellfluids is suspected to be meteoric, but there are significant indications for the presence of magmatic components. No isotope data are available.

The wells had low permeabilities which, with magmatic associations, denies their participation with a general upflow of liquid from some deeper source. PIN-2D and -3D were the hottest wells (338 C @ -400 mRSL, and 330 C @ -1092 mRSL). They were located closest to the axis of magma movement during massive eruption events of Mt. Pinatubo. These rocks are hot precisely because they are not significantly involved with circulations of meteoric water. The other deep well, PIN-1, was the coolest (260 C @ -1400 mRSL). It discharged a large variety of fluid compositions. The vicinity of PIN-1 could be considered as an area where meteoric waters collect, moving generally downward, not up, as they enter a hydrothermal circulation system.

Features shared by the three wells and wellfluids are acidity, that makes them unworkably corrosive as resources for a geothermal power plant, and low mass productivity, which makes them uneconomic in an energy sense. Details of their fluid compositions show large contrasts among nominal fluids from separate wells and relatively enormous contrasts among discharges from individual wells at different times.

Both poor productivity and acidic character of the fluids relate to the nature of rocks penetrated by the wellbores. These are relatively fresh magmatic rocks, relatively protected from water-rock chemical action involving meteoric water. The discharged fluids are highly interesting because they expose a magmatic rock at its last stages of cooling and early stages of interaction with fluids from meteoric sources. In this sense, the fluids may be considered "rock-dominated", as evidenced by their acidity which derives from the magmatic volatiles associated with cooling, now in its last stages.

AN INTERPRETIVE APPROACH: Fluid samples from the three Pinatubo wells were not only distinct from one another in a compositional sense, but they also reflect the actions of physical processes and events that accompany well testing. Accordingly, chemical data may be applied to non-chemical questions about the reservoir structure, how the fluids are distributed within it, and how fluids mix, or are constrained from mixing. For these applications, data are handled according to statistical concepts or in regard to some mathematical principles which describe processes, such as heat transfer and evaporation. Since these wells did not deliver fluids in the ways that other commercial wells deliver fluids, the chemical data may be used for defining and describing the uncommon processes actually involved. This report will focus on PIN-3D as an example of how fluids are altered by testing in these uncommon environments.

The data treatments used here are not a complete set. They are provided to show how results and implications, from one interpretive step, may be combined with some outside fact, leading to a subsequent interpretive step, which develops into a series. The series is emphatically not presented as a pattern for reviewing other sets of resource data. Specifically, the circumstances of available data and the results of each interpretive step will make the review process a unique sequence of steps for each resource.

PIN-3D: was completed through the interval -260 to -1092 mRSL, near the caldera boundary, where it passes through dacitic rocks and multiple dikes. The well is deep enough to intercept the O'Donnell formation and Zambales Ophiolite Complex, but they were not reported. Perhaps dikes have hidden their presence, or the well is actually inside the caldera. Clearly, the fluids have strong magmatic connections.

Water loss and heat-up surveys indicate one production interval, a suspected intersection with Marunot fault, near -400 mRSL. Maximum measured temperature was 330°C at TD (-1092 mRSL) after a very short heat-up period. Temperature at -400 was 225°C. Static water level was at the wellhead (1098 mASL).

PIN-3D was discharged initially on 2-3 December 1989, but fluids appeared diluted with drilling and injection waters. The definitive test began 18 December 1989 and continued through 26 January 1990. An initial discharge rate near 4 kg/s diminished within two days. Final conditions in January were near 2.5 kg/s at 0.18 Mpag.

FLUID COMPOSITIONS: Thirty-three complete analyses of liquids and gases are available. Fluid pH on 2-3 December was near 7, but only 4.32 upon start-up 18 December, with most subsequent values in the range 3.2 to 3.7. Concentrations of brine components increased persistently during the testing and concentrations of several components, such as iron, magnesium, manganese, and calcium were relatively high compared to geothermal waters in other sites. Sulfate concentrations were relatively less than in the other PIN-wells.

Discharge fluids contained excess enthalpy that increased during the testing. This was interpreted as boiling due to additions of rock heat. Steam addition was also indicated by a chloride-enthalpy plot which incorporated an unusually concentrated sample, 158,000 ppm Cl. Two chloride concentrations among thirty-three samples exceeded 100,000 ppm, all others were less than 60,000 ppm.

A preliminary estimate of reservoir chloride concentration was obtained by establishing a linear regression between chloride concentration and measured (wellhead) enthalpy. Then, by assigning a reservoir enthalpy, a corresponding chloride concentration could be identified. The selected enthalpy corresponded to an early measurement of enthalpy, 1401 j/g, and indicated Cl_{res} = 10,320 ppm. That enthalpy value corresponds to a single-phase liquid at 310°C. This early enthalpy value may correspond to a "heat-contaminated" fluid. To the extent that 310°C overestimates the average initial temperature of the fluid mixture, the corresponding reservoir chloride concentration will be underestimated.

Discharged fluids showed a variety of concentrations and ranges of concentration ratios. Most of the concentration ranges are associated with increased boiling due to rock heat that increased during later stages of testing. The ranges of ratio values were less variable than for PIN-1, but perhaps that is due to the shorter period of testing and the much smaller amounts of fluids produced.

Five downhole liquid samples were collected from three different depths, -290, -450, and -770 mRSL, on 13-15 February 1990, after the main discharge test. The concentration range was narrow compared to the range for surface samples. For example, chloride concentrations were 15,600±612 ppm, without a clear trend with depth. These concentrations may represent some evapo-concentration related to rock heat boiling during the testing.

Ratios of concentrations among these five downwell samples defined a narrow range. For example, Cl/B = 38.0±2.3, (n = 5). All individual values are higher than 31 (of 33) surface samples, which average 25.4±4.6. The remaining two surface samples had Cl/B = 57.6±3.0, and were the samples with chloride concentrations of 107,000 and 158,000 ppm, referred to earlier. Clearly, reservoir fluids in the vicinity of PIN-3D are highly variable and interpretations must consider that analyses may represent mixtures with (initially) undefined proportions.

EVAPO-CONCENTRATION: The range of apparent concentrations is large, and, for most components, there are 33 data points, enough for reasonable statistics. Figure 2 shows sample concentrations of six components plotted versus days of testing (no compensation for steam losses). All concentrations show general increases, with variability becoming severe after day 20. The similarity of trends suggests continuous boiling from a limited volume of initial liquid, a concept which can be tested.

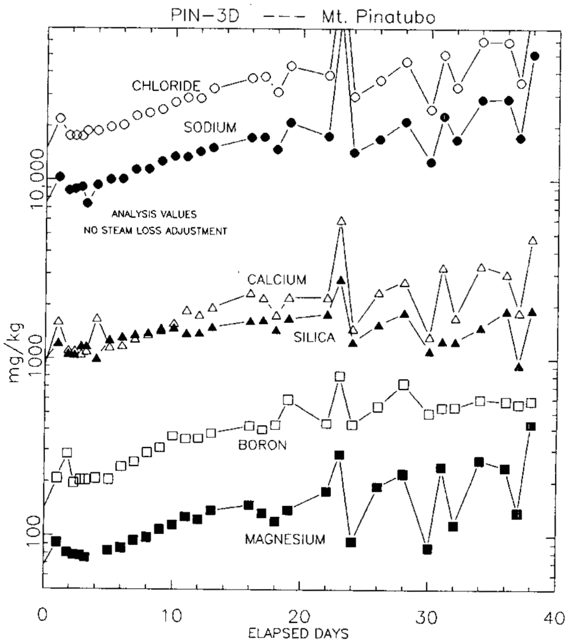


FIGURE 2: CONCENTRATIONS versus PRODUCTION DAYS

When two components (a and b) remain totally dissolved during evapo-concentrations, a graph of their changing concentrations, a versus b, will yield a straight line. The plotted line will be straight in either linear-by-linear graph axes or in logarithmic-by-logarithmic (log-log). In log-log plots, evapo-concentration yields lines with slope values $\delta\log(a)/\delta\log(b) \approx 1$. Hence, plotting several component pairs would yield a set of nearly parallel plots -- if concentration changes were due to evapo-concentration.

Figure 3 shows log-log plots for five components, each plotted versus chloride. Specific values for slopes are: sodium, 0.936; calcium, 0.953; silica, 0.413; boron, 1.099; magnesium, 0.942. The proximity of most slope values to the theoretical unity is strong evidence that evapo-concentration is a dominating process.

However, the differences from unity are more than could be justified by analytical errors if evapo-concentration were the only process operating. Thus, one must strongly suspect that other, non-conservative, processes are also reflected in the data. Slope values less than unity can be due to losses of the non-chloride component. For mid-range chloride concentrations, near 38,000 ppm, losses of initial sodium, calcium, silica, and magnesium are indicated as 4.7, 3.5, 36.0, and 4.3 weight percent, respectively. Loss can be readily suspected for the case for silica, slope 0.413. From a set of computed losses, one might even venture to identify the mineral, or minerals implied to be deposited.

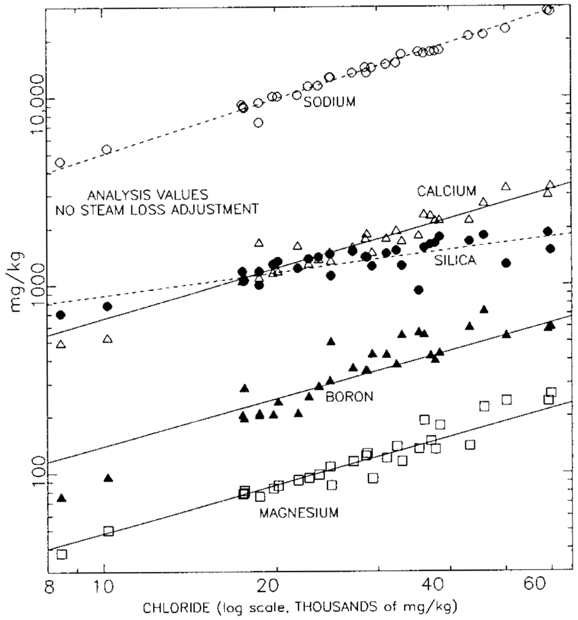


FIGURE 3: TEST FOR EVAPO-CONCENTRATION

The procedure above permits calculations to be made with mathematical, and definable, precision. However, the logical precision requires considering more issues. Specifically, the slope value for boron, about ten percent greater than unity, indicates a gain of about 7.8 weight percent, at a mid-range chloride concentration. This is more than analytical uncertainties and requires a relative addition of boron. Clearly, this requires addition of a distinct fluid which, by implication, also contains sodium, calcium, magnesium, etc. Consequently, the overall apparent "losses" may be due, instead, to the new fluid having lower values of Na/Cl ratios, etc. Since the computed losses, described earlier, explicitly consider evapo-concentration of one initial composition, results would be misleading to some degree. This point is considered later, where some resolution occurs.

Figure 4 shows an expanded view of the boron-chloride relationship with lines connecting sequential data. The first 17 to 20 days of data appear to show a dominating evapo-concentration effect. Subsequent data show scatter mainly above the trend, indicating irregular additions of a boron-rich composition. Whether that composition is relatively richer, or poorer in other components, including silica, requires additional investigation. Figure 4 does show that a simple evapo-concentration model is appropriate for about the first 20 days of data.

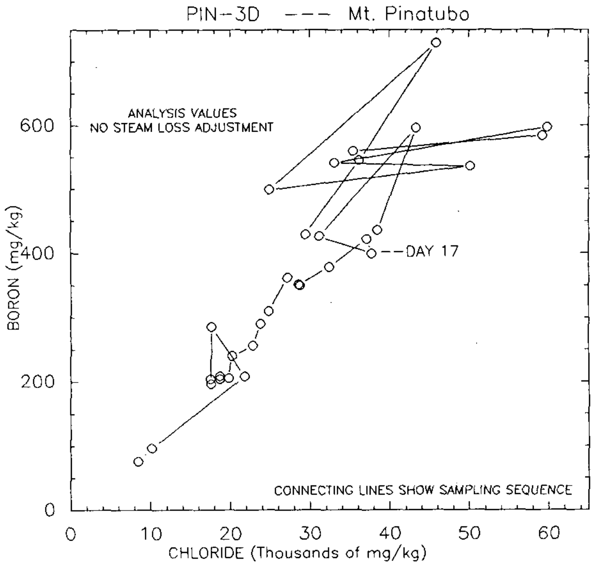


FIGURE 4: CHLORIDE versus BORON

BIAS IN THE QUARTZ GEOTHERMOMETER: Returning to the issue of silica, the effect of evapo-concentration is two-fold. Specifically, the computations for a quartz temperature would be biased. The computation initially proceeds by presuming only adiabatic formation of steam. Loss of additional steam, due to extra boiling related to additions of rock heat, would cause the adiabatic computation to overestimate the quartz temperature. Conversely, loss of silica by deposition, indicated by the low slope value in Figure 3, would tend to cause an underestimate of the true quartz temperature.

Using the apparent silica concentrations to determine pre-boiling (quartz) temperatures does appear mathematically successful for the first few days. Yet, results become increasingly unreasonable after the 5th day of testing. Calculated quartz temperatures range up to 367°C, which greatly exceeds the instrumentally measured wellbore temperatures. They also exceed the temperature of maximum silica solubility, showing that the adiabatic computation method is far outside its range of applicability. *[The specific model used does not include the diminishing solubility of silica above 340°C.]* Thus, despite the low value of silica slope, indicating more than one-third of initial silica is lost by deposition, the effects of evapo-concentration remain clearly potent.

Accordingly, only the earliest silica data may be considered as possibly representative of initial quartz temperatures, and these are somewhat ambiguous. Preliminary discharges on 2-3 December yielded quartz temperatures of 260C. That value is probably low, due to contamination by drilling and injection fluids, also indicated by pH values, near 7, that were never observed in subsequent testing. The value T_{qtz} = 295°C, based on silica concentration measurements for the second day of the extended testing, is reasonable. It may be compared to instrumental measurements of 304°C at -750 mRSL and 225°C at -400 mRSL. This estimate of T_{qtz} does not apply to fluids collected after the 20th day of testing, when irregular mixing became apparent. However, in the absence of other relevant data, it may be the most reasonable estimate.

ADIABATIC STEAM FRACTION AND INITIAL BRINE CONCENTRATIONS: Between a reservoir temperature of 295°C and the 140°C sampling temperature, adiabatic boiling yields about 36 weight percent steam. On the second day of testing, which appears to be the most representative of early conditions, the measured chloride concentration was about 17,600 ppm. This implies a reservoir basis of 11,264 ppm, about 9 percent greater than the estimate of 10,320 ppm, described earlier, based on a regression of chloride versus total discharge enthalpy, with a designated resource temperature of 310°C. Using 295°C in the earlier regression yields 10880 ppm chloride, which may be a better comparison for the two approaches and is only 3.5 percent smaller than the value based on quartz geothermometry.

NON-ADIABATIC STEAM FRACTIONS: Since the log-log plots with chloride indicated a prominent amount of boiling due to additions of rock heat, one may inquire whether the total fluid enthalpy also includes a component due to a separate entry of steam. A reasonable reference composition would be the 20th day of discharge, the last day before onset of irregular additions of undefined fluids. On that day, the chloride concentration reached 37,760 ppm, a factor of 3.35 times the initial reservoir concentration derived in the previous paragraph.

The adiabatic component of evapo-concentration, from 295°C, accounts for a concentration factor of about 1.56 for residual components, such as chloride. The remaining concentration effect, a factor of about 3.35/1.56 = 2.145, corresponds to boil-away of 53.4 percent of the initial liquid, occurring prior to its entering the wellbore, where the adiabatic boiling stage takes place. Enthalpy of a steam/water mixture, 53.4 percent steam at 295°C, would be 2085 j/g. This is much less than the measured enthalpy values at the surface on days 17 through 20, which average 2412±6 j/g, so, a separate steam entry appears operational.

Using 2756 j/g as the enthalpy of the separate steam entry (corresponding to 295°C), with the other, mixed-phase enthalpys, leads to an estimate for the mass fraction of total discharge represented by the separate steam; 48.7 weight percent. Thus, the energy content of PIN-3D fluids have three major inputs; adiabatic heat in initial liquid, rock heat in some steam from initial liquid, and a separate steam component. However, the steam-phase enthalpy value, used above, does not consider the presence of CO_2. Thus, the computed weight percent values must be considered approximate.

GASES An alternative model for steam development could involve boiling in a single feeder fracture, such that all the steam entering the wellbore derived from one initial liquid. The apparent "separate" steam entry would then be merely the effect of differential permeability for steam versus liquid moving through a common path. This alternative can be tested by considering the gas contents in steam and their relationship to the brine components, particularly chloride.

If all the steam were derived from boiling a single initial brine with steam and liquid entering the wellbore at a single common point, then CO_2 content, in the discharging mixture of steam and liquid, would decrease with increasing concentration of chloride. This effect would be prompt and severe. Boil-away of more than a few mass percent of initial liquid would severely purge gases from the residual liquids. Since brine concentrations increase by more than a factor of two between the second and 20th days of production, the nonadiabatic boil-away clearly has been severe. Associated steam production would be essentially gas-free.

However, if CO_2 is carried in steam that enters the wellbore at a different place than the brine (or brine-steam mixture) enters, then CO_2 content in the discharging mixture would not vary systematically with chloride concentration. A separate steam entry could carry substantial CO_2 to the sampled mixture at the surface, regardless of differential permeability effects, etc., in the fracture(s) where rock heat boiling occurs.

Figure 5 tests for correlations between CO_2 and chloride; an expanded replot of the sodium data is included for comparison. The plot shows CO_2 to be independent of the chloride concentration. Thus, a separate entry for CO_2 is indicated; by implication, it carries the requisite steam.

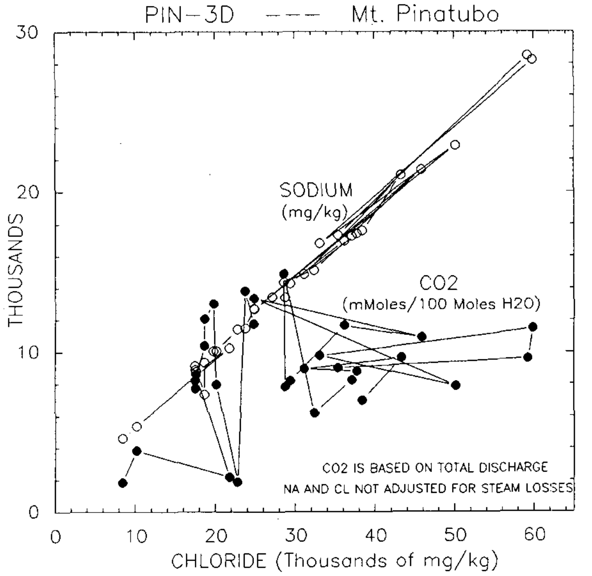


FIGURE 5: CHLORIDE versus SODIUM and CO2

This separate steam entry can also be deduced from the apparent concentrations of CO_2. From Figure 5, the average concentration appears near 10 moles CO_2 per 100 moles H_2O, on a basis of total discharge, about 20 weight percent. However, the solubility limit for CO_2 in water at the temperature and pressure of the PIN-3D production interval is only about 1.8 moles CO_2 per 100 moles H_2O, based on data from Ellis and Golding, (1966). Thus, a substantial vapor phase is indicated, prior to initiation of production. Since there seems no other source of CO_2 except the local rocks, a large magmatic component is indicated. This is in accord with the track of PIN-3D being inside the caldera.

Additional description of this vapor cap and its relationship with an equilibrium liquid phase could be explored. For example, the separate steam entry would be about 40 weight percent CO_2 if no CO_2 were carried by the liquid and its associated steam that issue from the feeder fracture where rock heat boiling occurs. This concentration is far outside normal industrial experience. It emphasizes, further, the magmatic character of the Mt. Pinatubo fluids. This kind of data would be returned to earlier computations, such as the steam enthalpy used for estimating weight percent of separate steam. By iterations, a complete set of internally consistent values may be obtained for most features of the resource.

MULTIPLE MINOR FLUID SOURCES: A minor multiplicity of gas sources is indicated by the imperfect correlation between CO_2 and H_2S shown in Figure 6. If both gases were derived only from a single source of uniform composition, then variations in concentrations would lie along a trend that extended to the graph origin (0,0). Most of the data does trend toward the origin, suggesting that a simple model, described above, has considerable validity. However, multiple offsets of data, above and below the trend toward (0,0), suggest that at least two other minor, distinct inputs are operational. Details in Figure 6 suggest these inputs were sporadic after the fourth day of testing.

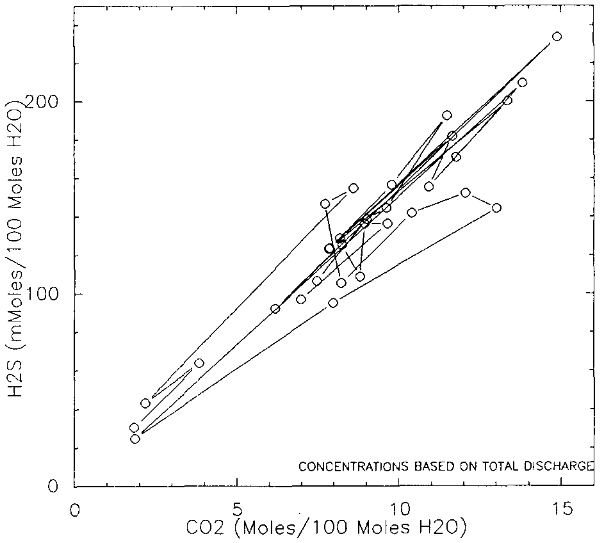


FIGURE 6: CO2 versus H2S

Similar small variations are shown by sodium in Figure 5. The trend lines between later data are parallel to earlier trend lines, but successively offset upwardly, in an *en echelon* pattern. This direction of offset indicates that new fluid input compositions have Na/Cl ratios that are larger than the ratio of the primary (initial) fluid. Returning to the earlier concepts about unit slope for log-log plots of evapo-concentration effects, this direction of offset in the log-log plot would cause the slope to exceed unity. Since the observed net result of all effects on sodium yields a slope value less than unity it may be concluded that three processes are operational; evapo-concentration is the major effect, deposition of sodium (and others) occurs in the rocks, possibly in conjunction with a much more severe deposition of silica tends to depress slope to less than unity, and new liquid compositions are added at irregular times. The new liquids have distinctive proportions of dissolved components.

IMPLICATIONS FOR RESERVOIR ENGINEERING: The small concentration shifts, noted as details in the ratios of Na/Cl, CO_2/H_2S, and Cl/B, may be viewed as deliveries from fractures that intersect the main feeder. Two major alternative mechanisms may be considered. One is the case where fluid from the auxiliary fracture enters the main feeder and mixes during an interval of time when both fluid components have negligible vapor development. Alternatively, the liquid in each fracture may be considered to be stagnant until the boiling front reaches the fracture intersection. Mixing occurs after boiling, and the first parcel of mixed fluid causes a step-change in the measured surface concentration, which is observed.

The concentration shifts, Figures 4, 5, and 6, have more of a step-change character, suggesting that little movement of fluids in fractures occurs prior to their becoming involved with the advancing, boiling front. Additionally, stagnant-until-boil is consistent with the large observed effects of evapo-concentration which requires a continually increasing surface area for heat transfer from rock to fluid.

Although no production interference tests were made in conjunction with the PIN-wells, this conclusion shows that such tests should be interpreted with caution. Most mathematical models of reservoirs carry assumptions about fluid compressibility and what initiates fluid movement. Standard parameters and implied assumptions should always be verified for relevance.

"INITIAL" RESERVOIR COMPOSITION AT PIN-3D:

Composition of reservoir liquid produced initially may be estimated from the chemical analyses of early samples, adjusted for adiabatic boiling based on temperatures in the range of 290 to 300C. The nominal composition is given in Table 1, which applies to the first few days of discharge. After about day 20, other fluid components affected the composition of discharged fluids. Due to undefined, non-adiabatic evapo-concentrations of these new inputs, "reservoir basis" compositions of them cannot be deduced with confidence. The ratios of components can be compared, early versus later production, but the later values must be interpreted as mixtures of liquids with undefined proportions.

TABLE 1: RESERVOIR LIQUID COMPOSITION
PIN-3D; First 20 Days, T = 295 C
(ppm by weight, gas-free)

Sodium	5483	Iron	69.7	Chloride	10940
Potassium	911	Magnesium	4.94	Sulfate	147
Calcium	691	Lithium	8.96	Fluoride	0.95
Silica	656	Rubidium	3.01	Bicarbonate	0.0
Boron	126	Cesium	1.37		
Manganese	98.9	Ammonium	1.05		

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REFERENCES

Fournier, R.O. and R.W. Potter, II, 1982, A revised and expanded silica (quartz) geothermometer: Geotherm. Res. Coun. Bul., November, p.3-12.

PNOC-EDC, 1990, Mt. Pinatubo resource assessment: PNOC-EDC Internal Report.

Ellis, A.J. and R.M. Golding, 1963, The solubility of carbon dioxide above 100°C in water and in sodium chloride solutions: Amer. Jour. Sci., v.261, p. 47-60.