MAGMATIC CONTRIBUTIONS TO PHILIPPINE HYDROTHERMAL SYSTEMS

MAYFLOR RAMOS-CANDELARIA, **DENNIS** R SANCHEZ and NOEL D SALONGA

PNOC-EDC Geothermal Division. Merritt Road, Fort Bonifacio, Makati, Philippines

ABSTRACT - The geochemical characteristics of known volcano-magmatic hydrothermal systems in the Philippines (Pinatubo, Biliran) are studied. Similar characteristics include solfataric activity with HCl bearing acid springs or mud pools at the summit or high elevations with S deposits formed where the hot waters mix with diluting cold waters. Isotopic compositions show positive $\delta^{18}O$ and $\delta^{2}H$ shifts and a magmatic water (or volcanic gas) - meteoric water mixing line, indicative that these are just condensed magmatic vapors with meteoric waters. Steam discharges have high gas (CO_2, H_2S) with non-reactive (N_2-He-Ar) gas compositions showing definite magmatic gas signatures with temperatures at depth greater than 300°C. Wells drilled towards or beneath these features encounter high temperatures at depth and discharge acid (pH 2-3) fluids with high gas contents. However, wells drilled away from the center of active acid gas input discharge neutral Cl fluids with significant concentrations of Mg, F, Ca and SO4 due to neutralization of an initially acidic fluids by water-rock interaction as the fluid migrates. In all other geothermal fields, neutral fluids also show distinct $\delta^{18}O$ and $\delta^{2}H$ shifts, which can be accounted for by mixing with magmatic water of similar composition to volcanic gases. Geochemical models for these types of systems are introduced and development strategies are suggested.

Key words: Philippines, Pinatubo, Biliran, Mt. Apo, magmatic, isotopes, gases, development

1. INTRODUCTION

Most Philippine high temperature geothermal systems are located in volcanic zones, with the emplacement of magma at shallow crustal depths serving as the heat source driving the system Therefore, it is reasonable to consider that the magma contributes components (gases, water) to the hydrothermal system, as it is unlikely that the exsolved acqueous phase remains constrained within the magma itself

We examined the physical and chemical characteristics of known "volcano-magmatic" systems in the Philippines to establish the signatures of magmatic fluids Classic among these, and possibly the most studied is the Pinatubo hydrothermal system, followed closely by the Biliran system. We then looked into the water and gas chemistry characteristics of known neutral Cl geothermal systems often considered to be meteoric water dominated (Craig, 1963) to determine if any magmatic signatures can still be recognized. We focused mainly on Palinpinon, Tongonan and Bacman data. We also introduced several conceptual geochemical models to explain observed geochemical data.

2. SIGNATURES OF ACTIVE MAGMATIC INPUTS

The Mt. Pinatubo volcano-magmatic hydrothermal system is possibly the most studied system of its kind in the Philippines. Before its catastrophic eruption in June 1991, PNOC had drilled three wells to probe the Pinatubo system in 1988 and 1989. All three of these wells have turned out acidic, with Pin-2D having weirbox pH of 2.40 (Ruaya et al., 1992). Obviosly, the fluids were more acidic than this at depth as reactions with the well casing and liner has partially neutralized the fluids resulting in the production of high amounts of Fe and Mn with the discharge.

The natural thermal features associated with the Pinatubo volcanism consist of hot and warm springs, solfataras, gas seepages and hydrothermally altered grounds. There is a pronounced gradation of the springs from the highlands to the lowlands; from the highly mineralized acid Cl-SO_4 springs at higher elevation to the mixed S04-HC03 springs at middle elevation and the distinctly CI-HC03 springs at low elevations. The presence of appreciable amounts of Cl in many highland springs (Mamot, Marunot, Pinatubo pool) suggests Cl is carried from depths as HCl and is directly related to active volcanism. This is also seen in the imbalance of the total cations and anions, indicative that Cl is carried from depths without its usual cation aggregates Na^+ and K^+, but with H^+ (Table 1). This is also demonstrated by the Biliran thermal discharges at Vulcan and Libtong, suggestive of the same phenomenon. For both the Pinatubo and Biliran highland springs, extensive S deposits are observed as the water cools and mixes with diluting river water.

Table 1. Cation-anion balance balance showing **excess** chloride and/or sulfate.

LOCATION	pH	ΣCATIONS (meq)	ΣANIONS (meq)
PINATUBO			
Pinatubo pool	1.01	591	1805
Pin-2D	2.32		189
BILIRAN			
Vulcan buubling pool	2.03	2.6	34.1
Libtong	3.01	0.8	3.8
Tenego	1.35	13.7	117.3
BN-3	2.60	110.8	221.0

Notes:
1. XCATIONS = $Li^+ + Na^+ + Ca^{+2} + Mg^{+2}$
2. ΣANIONS = $Cl^- + SO_4^{-2}$

In a Cl-HCO_3-SO_4 plot, there is a pronounced absence or lack of mature neutral Cl springs for these types of system (Fig. 1). The dominant anion in solution is SO4 with most springs at high elevation plotting at the SO4 apex. Mixed Cl-HCO_3-SO_4 springs appear in the periphery/lowlands of these systems, far from the high gas thermal upflows. This may suggest that the active acid system is limited and neutralization reactions by water-rock interactions give rise to more mature neutral fluids away from these primary regions

Stable isotope data show distinct **shift** in $\delta^{18}O$ and $\delta^{2}H$ (Fig. 2) of well waters relative to the LMWL. In fact for Pin2D, values are close to average values for high temperature volcanic gas in Japan ($\delta^{2}H = -25$, $\delta^{18}O = 6.6$ to 7.0). Similarly, Biliran well and thermal waters also show distinct positive $\delta^{2}H$ and $\delta^{18}O$ shifts suggestive of mixing with magmatic waters reaching up to 85% for the Volcan solfatara steam discharge.

These observations are in direct contrast to the popularly accepted concept introduced by Craig in 1963, where most geothermal waters are of meteoric origin and pronounced shifts only for $\delta^{18}O$ were attributed to water-rock interaction.

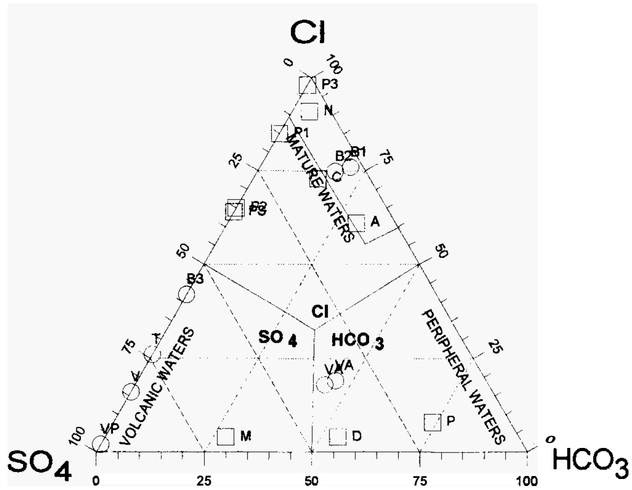

Fig. 1. Relative composition of Cl, HCO_3 and SO4 of Pinatubo and Biliran thernial waters showing the different water types. Legend: Pinatubo waters (□), Biliran waters (O); and for Pinatubo, Pin-1 (P1), Pin-2D (P2), Pin-3D (P3) and the thermal springs are identified as Nacolcol (N), Dagsa (D), Cuyucut (C), Asin (A), Marunot (M), Pajo (P); and for the Biliran waters, BN-I (B1), BN-2 (B2), BN-3 (B3), and the thermal springs are identified as Vulcan bubbling pool (VP), Vulcan warm spring (V), Tenego (T) Villavicenta (VA). Well names are affixed with a D for directional wells.

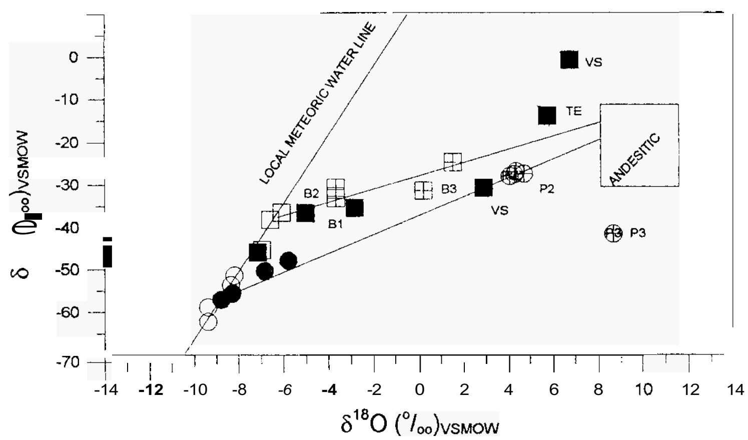

Fig. 2 Plot of δ^2H against $\delta^{18}O$ of Pinatubo and Biliran waters showing mixing of magmatic waters with meteoric waters. A linear regression lines are drawn passing through the Biliran meteoric (□) thermal (■) well samples (⊞) samples and intersecting the Giggenbach (1992) andesitic water box. Another linear regression line is drawn from the Pinatubo meteoric (O), thermal (●), and well (⊕) waters intersecting the Giggenbach (1992) andesitic water box. For these samples (VS) refers to the Vulcan solfatara steam samples and all other codes similar to Fig. 1.

Magmatic or andesitic gases have definite chemical signatures. Giggenbach (1992) introduced the use of the inert species N2-He-Ar to distinguish their origin (Fig. 3). In particular Pin-2D is coincident with the average White Island and the Japan high temperature volcanic gas (HTVG) composition. This is also true for the Biliran gas discharges (Fig. 3) where both the Vulcan Dako and Vulcan Gamay steam discharges plot close to the magmatic gas composition..

The water and gas chemistry data show that the hydrothermal fluids at Mt. Pinatubo have not attained chemical equilibrium with the host rocks. A conceptual geochemical model for the Mt. Pinatubo volcano-magmatic hydrothermal system is shown (Fig. 4). The temperature contours and approximate location of the two-phase zone are based on downhole measurements. Hot magmatic vapors rise through fractures, heating the volcanic rocks and condensing in shallow groundwaters, producing acidic waters that were tapped by Pin-2D, Pin-3D and Pin-1. The chemical signatures of the original magmatic vapors are largely retained in gas ratios and isotopic data obtained from discharges of wells Pin-2D and Pin-3D. Neutralization reactions of these acid waters with host rocks produced the mixed neutral SO_4-HCO_3-Cl springs of Mamot, Dangey, Pajo and Pula.

The thermal energy of the convecting magmatic vapor induces the formation of convective cells of largely metoric water origin on the periphery of the Mt. Pinatubo dome. At least two brine systems evolved. Although no wells were drilled in these regions, the outflow of this system is manifested by the Cl springs of Dagsa, Cuyucut and Nacolcol.

The Biliran system is similar to Pinatubo (Fig. 5) Although a high temperature acid magmatic core beneath the Volcan solfatara exists at depth, a neutral Cl environment has already evolved away from this region. Wells BNI and BN2 discharged neutral Cl fluids at temperatures ranging from 210°C-240°C proving the limited lateral extent of the high temperature acid Cl+SO4 environment. The discharge fluids have significant amounts of Mg, F, Ca and SO4 due to neutralization of an initially acidic fluid with the host rocks as the fluid migrates.

Giggenbach (1981) and more recently Amorsson et al. (1993) proposed that most of the gases and essentially all the anions in volcanic-hosted geothermal systems are derived from an underlying magmatic source, while the cations in solution are largely the product of primary neutralization and reduction reactions between the wall rock and the aggressive acid fluids (the latter resulting

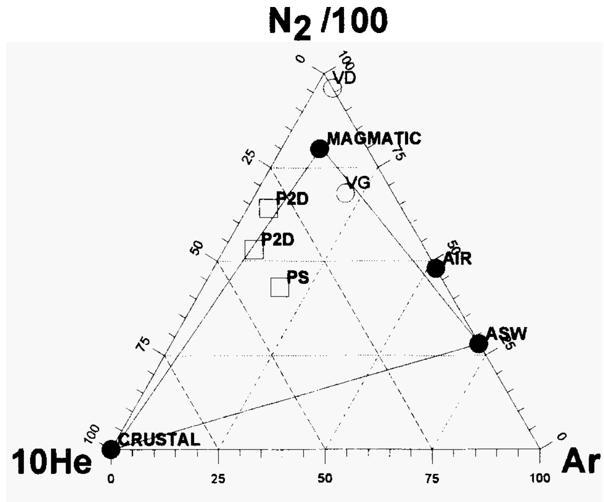

Fig 3 Relative composition of N_2, He and Ar values of Rnatubo and Biliran gas samples showing the ongin of the gases Legend Pinatubo steam samples (□), Biliran steam samples (O), with Rn-2D (P2D), Rnatubo solfatara (PS), Vulcan Dako (VD), Vulcan Gamay (VG)

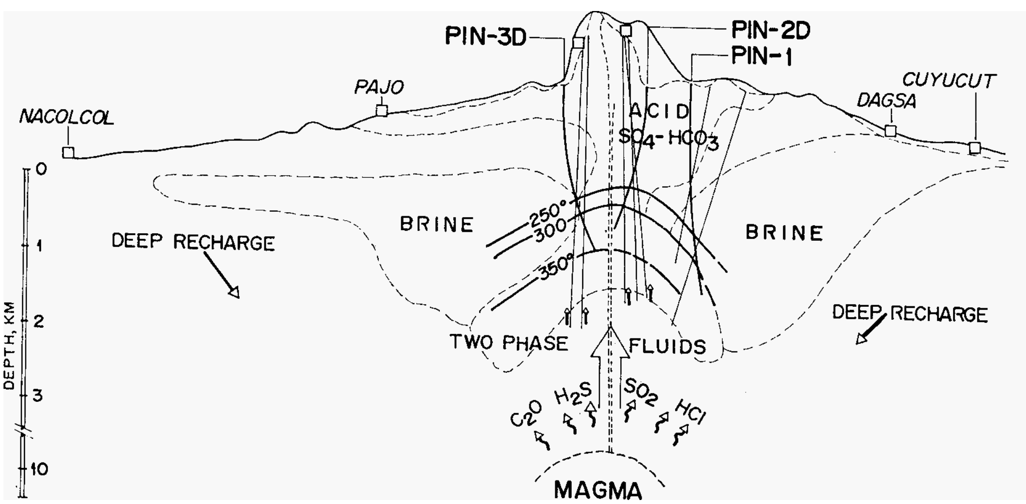

Fig. 4 A conceptual hydrogeochemical model of the Mt. Pinatubo geothermal system. Approximate locations of the temperature contours based on downhole measurements and distribution of fluids consistent with geochemical data are delineated.

during dissociation as the magmatic fluids cool upon ascent). This process as outlined below was termed as H+ ion metasomatism.

$$H^+ \Rightarrow \text{PRIMARY ROCK} \Rightarrow \text{SOLUTION} \Leftrightarrow \text{SECONDARY MINERAL} \quad (1)$$

3. NEUTRAL CHLORIDE GEOTHERMAL SYSTEMS

Neutral Cl geothermal systems in the Philippines have long been exploited and their geochemical characteristics well studied Alvis-Isisdro et al., 1993; D'Amore et al., 1993; Gerardo et al, 1993; Ruaya et al., 1994) These systems were previously believed to be dominated by meteoric waters (Craig, 1963). However, there is increasing evidence from stable isotopes showing a distinct δ^2H and $\delta^{18}O$ shift which can be easily explained by a component of magmatic water similar in composition to that of volcanic gas discharges mixing with the meteoric waters (Fig. 6). For these systems those exhibiting larger $\delta^{18}O$, δ^2H shifts have much higher CO_2 and H_2S concentrations and with gas compositions trending towards magmatic gas signatures and lie closer to the heat source. In contrast, those with lesser $\delta^{18}O$, δ^2H shifts have lower gas contents, temperatures and trends toward air saturated meteoric water signatures.

These trends in isotopic and gas compositions suggest that a component of magmatic water is entrained by meteoric dominated convection cells below drilled depths in Philippine geothermal systems as shown by %magmatic compositions of 40% for Tongonan, 20% for Palinpinon and about 50% for Bacon-Manit0 (Alvis-Isido et al, 1993; Gerardo et al., 1993; Ruaya, et al., 1994). The proximity of Philippine geothermal systems to recently active or to active volcanoes accounts for the strong magmatic signatures to the fluids, particularly where the fluids are acid.

4. MT APO GEOTHERMAL SYSTEM

The model for a volcano-magmatic system is also exhibited by the Mt. Apo geothermal system (Fig. 7) A magmatic vapor core is marked on the surface by the HCl emitting Apo solfatara. A highly degassed neutral Cl geothermal system has already evolved beneath the Marbel corridor as intersected by the SK, APO, MT and KL wells.

Magmatic volatiles (e.g. HCl, SO_2, CO_2) dissociate in solution producing aggressive acid fluids. The interactions of these fluids with the formation leave the rocks leached of cationic components and thus minerals like diaspore, pyrophylite, alunite and residual

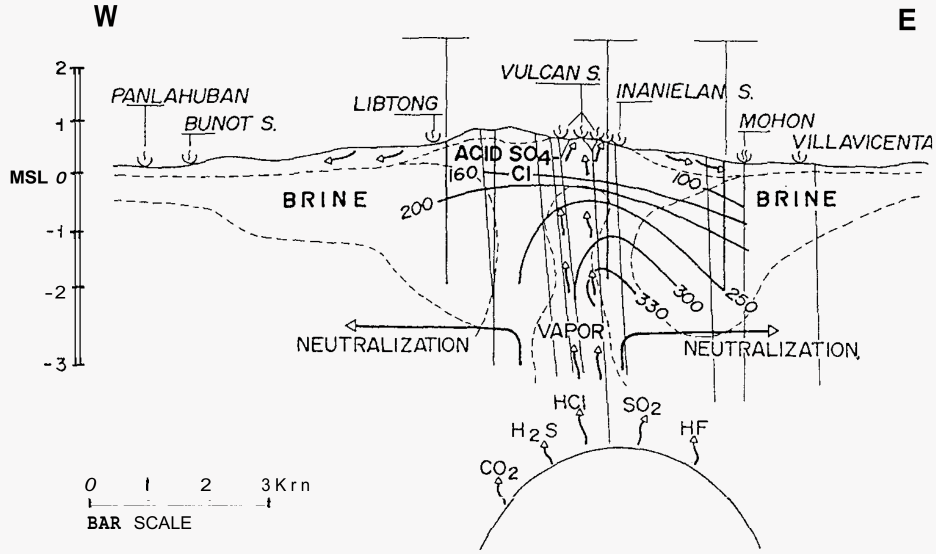

Fig. 5 A conceptual hydrogeochemical model of the Mt. Biliran geothermal system compatible with geochemical and downhole measurements.

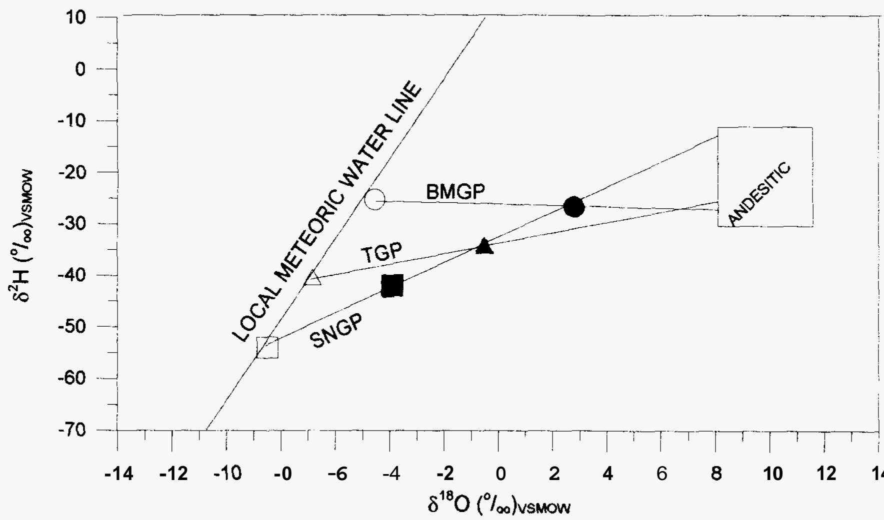

Fig 6 Plot of δ^2H against $\delta^{18}O$ of neutral Cl geothermal systems in the Philippines showing that the most enriched water (filled symbol) may be produced from mixing of local andesitic water with the local meteoric water (open symbol).

silica are formed. With the expulsion of H_2S gases from solution, the solubilities of Cu and Fe are greatly affected precipitating metallic sulfides like chalcopyrite, pyrite and bornite. Silicified and sulfide zones are formed on the rims of the cores of magmatic systems as intersected by well PS-ID. PS-ID discharged highly acidic (pH = 2.0) waters with highly mineralized chemistry from intensive rock dissolution.

Away from the Mt. Apo crater, a neutral Cl reservoir has evolved in the Marbel Corridor, with the low amounts of CO_2 and other gas species favoring the development of epidote in the reservoir. However the interphase region beneath the Sandawa collapse is rich in H_2SO_4 formed from the disproportionation of the magmatic gas SO_2 in water. At deep reservoir conditions the activity of the bisulfate ion is too low to initiate acid alteration. However, upon boiling (during the discharge testing of wells KN-ID, KN-2D and KN-3), the HSO_4^- readily dissociates into SO_4^{-2} and H^+ producing highly acidic fluids at the surface,

The mature neutral Cl waters in the Marbel corridor were encountered by the SK, APO, MT and KL wells. This parent fluid with temperatures from 300-310°C undergoes boiling with the separated steam accumulating in a shallow reservoir tapped by well SK-ID at temperatures of about 180-240°C.

5. DEVELOPMENT STRATEGIES

Pre-1992 exploitation drilling in the Philippines concentrated on targetting the heat upflow, believing that this is also the region of geothermal (mass or water) upflow. Regions with active HCl emitting solfataras near the summit (e.g. Pinatubo, Mt. Apo, Biliran) have all encountered magmatic acid fluids at greater depths. In most cases a neutral Cl rich region is always found farther away from this region. Thus, for development purposes the extent of the Cl-rich region should be firmly established, while the deep acid region is avoided or isolated. Steam-rich regions at the shallower portions of these reservoirs can also be targeted for production.

At Mt. Apo, the deep acid zone of well KN1D was isolated, and the production of the shallow steam rich zone was induced. Other development strategies considered for Apo include harnessing the acid sulfate fluids by controlling the well head separator pressures, modifications in surface equipment and mixing the produced brine from acid wells with neutral brines from nearby wells. Experiments

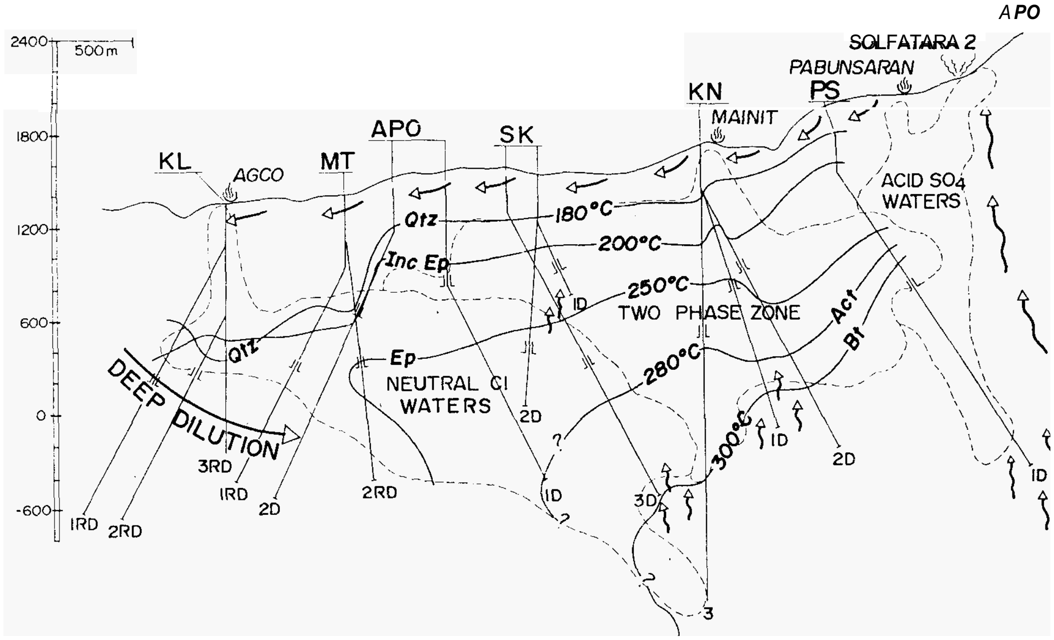

Fig. 7 **A conceptual hydrogeochemical** model **of the** Mt. **Apo geothermal system showing the distribution** of **the different** fluids based **on geochemical interpretations** with **lemperature contours** based **on the distribution of index minerals.**

on cathodic passivation in PS-ID are being considered to check if fluids from the well can effectively coat the casing and surface piping with FeS or other suitable metallic sulfide found in the discharge fluids **so** that the acid fluids can be utilized for production

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