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ORIGIN OF ACID FLUIDS IN THE CAWAYAN SECTOR BACMAN GEOTHERMAL PRODUCTION FIELD

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ABSTRACT

A shallow acid assemblage of sulfur and kaolinite +/- alunite, dickite and pyrophyllite dominates the hydrothermal alteration in the seven wells in Cawayan from surface down to 0 mRL. These zones range in thickness from 20 to 220 m. Thts shallow acid zone formed at temperatures ≤ 160°C. Below 0 mRL down to -600 mRL, a deep acid zone of diaspore and pyrophyllite +/- alunite and dickite appear in thin, discrete zones which coincide with measured temperatures between 180-250°C. Neutral-pH alteration of epidote, calcite, chlorite and illite prevail at deeper levels. Actinolite veins and biotite at -1300 mRL suggest temperatures of about 280°C whtch are consistent with measured stable temperatures

The dominance of acid alteration in the shallow portions of Cawayan indlcate its surficial origin from the oxidation of H_2S. These fluid descended through highly permeable structures to levels as deep as -1000mRL. Its incursion resulted in mineral blockages and casing corrosion in CN-1. CN-2D and CN-3D. In contrast, the prevalence of neutral-pH alteration at deeper levels of the Cawayan reservoir shows that a neutral type of fluid circulates at these depths. This brine upflows beneath CN-3D and CN-4D and flows laterally towards the CN-2D/ 2RD/3RD sector.

As a consequence of this study, future production wells should be dnlled in the CN-3D/4D sector to tap the upflowing, hot, neutral brine. Structures which channel acid fluids should be avoided or intersected above the production casing shoe which should be set below -600 mRL.

INTRODUCTION

The Cawayan sector is located in the Bacon-Manit0 Geothermal Production Field in Southern Luzon (Fig. 1). It is presently supplying steam to a 20 MWe Modular Power Plant commissioned in 1994. Less than a year after commssioning, some of the production wells in this sector have already suffered casing corrosion and anhydnte blockage deposition due to acid fluids. This paper therefore aims to establish the nature of these acid fluids in Cawayan through a study of the acid hydrothermal alteration in the wells. their subsurface distribution and their correlation with acid fluid inflows. Fot future production wells in this sector. ways to avoid or isolate these acid fluids are recommended.

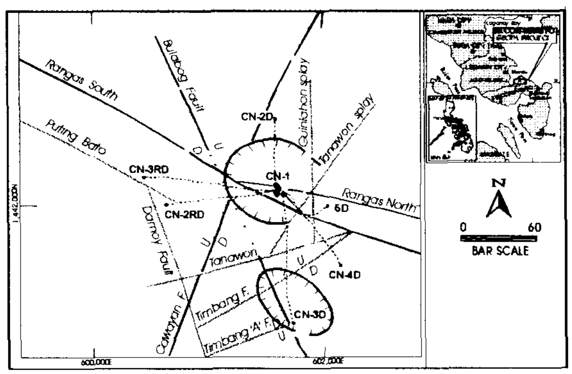

Figure 1. Location map of Cawayan sector, BacMan.

GENERAL GEOLOGY

The Cawayan sector is located within a volcanic depression called the Cawayan Crater which hosts a number of acid sulfate springs producing widespread

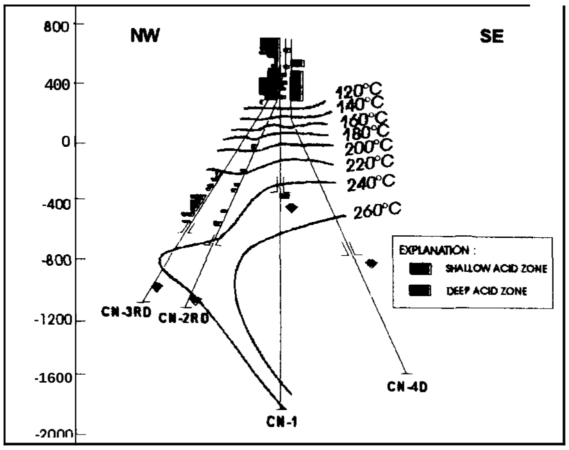

Figure 2. Acid alteration zonation and stable isotherms in wells CN-1, CN-2RD and CN-4D.

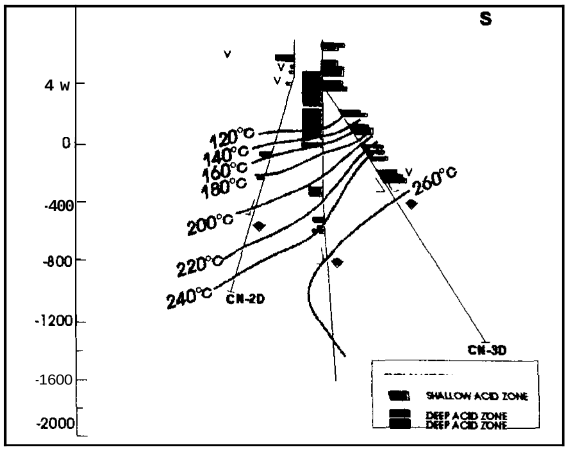

Figure 3. Acid alteration zonation and stable isotherms in wells CN-2D, CN-3D and CN-SD.

surface alteration. It is underlain by Plio-Pleistocene (?) Pocdol Volcanics composed of two-pyroxene andesitic breccias which are intruded intermittently by andesite and microdiorite Qkes of the Cawayan Intrusive Complex. The area is transected by permeable northwest- and northeast-trending structures through which hydrothermal fluids are presently circulating.

DISTRIBUTION OF ACID T TION

The acid alteration minerals in Cawayan are mainly recent deposits based on their fresh appearance, vein morphology, widespread Qstribution and abundance. Some relict acid alteration are occasionally observed coexisting with fresh acid minerals. Their relict nature can be discerned through their corroded margins and pitted surfaces. In tlus study, only the Qstribution of the fresh acid alteration will be discussed since they are llkely deposited by presently circulating acid fluids.

The acid alteration minerals in Cawayan can be divided into two major vertical zones: a shallow acid and a deep acid zone.

Shallow Acid Zone

The shallow acid zone, defined by the presence of sulfur or kaolinite, is delineated from surface down to +300 mRL in CN-1, CN-4D, CN-2RD and CN-3RD (Fig. 2) and down to +100 mRL in CN-2D, CN-3D and CN-5D (Fig. 3). Most of the rocks in this zone are completely altered to an acid assemblage of alunite, sulfur, kaolinite, pyrophyllite and dickite. These acid alteration minerals occur in abundant to moderate amounts and are associated with opal, cristobalite, quartz, pyrite, anhydnte and gypsum. The silica minerals opal, cristobalite, and tridymite only occur from the surface down to +500 mRL and transforms into crystalline quartz below +500 mRL. Kaolinite is the common surficial clay while pyrophyllite first appears as shallow as +560 mRL in CN-4D and slightly deeper at +260 mRL in CN-5D. Dickite was likewise noted at +260 mRL in both CN-2D and CN-3D. Weak vein counterparts of these minerals are present as sulfur between +540 down to +420 mRL in CN-2D and +480 down to +380 mRL in CN-1; and alunite at +60 down to 0 mRL. Pyrite is generally present in moderate to abundant amounts as replacement and Qsseminations. It is conspicuous as weak to moderate veins in CN-3D, rare to weak in CN-2D (Fig. 4), and generally rare in CN-4D (Fig. 5). Based on stable isotherms, this tluck shallow acid zone likely forms at relatively low temperatures, usually below 160°C (Fig 2).

Deep Acid Zone

The deep acid zone is characterized by the presence of diaspore. This zone starts from 0 mRL and extends down to -600 mRL. The deep acid alteration suite usually consists of Qaspore and prophyllite with or without Qclate and alunite. Quartz, anhydrite, illite, pyrite and chalcopyrite also occur within this deep acid zone. Unlike the widespread and tluck shallow acid zone, the deep acid zone exists in Qscrete, 20 m-thick layers, and the acid

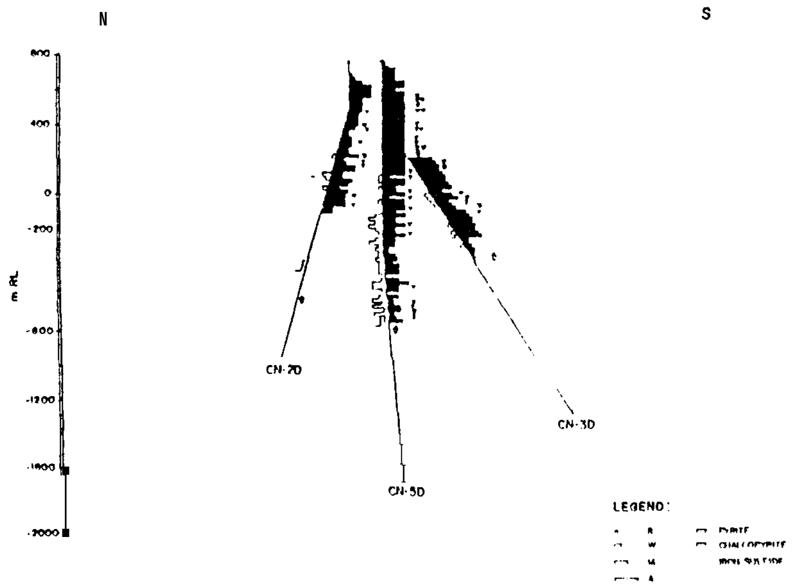

Figure 4. Sulfide minerals in wells CN-2D, CN-3D and CN-5D.

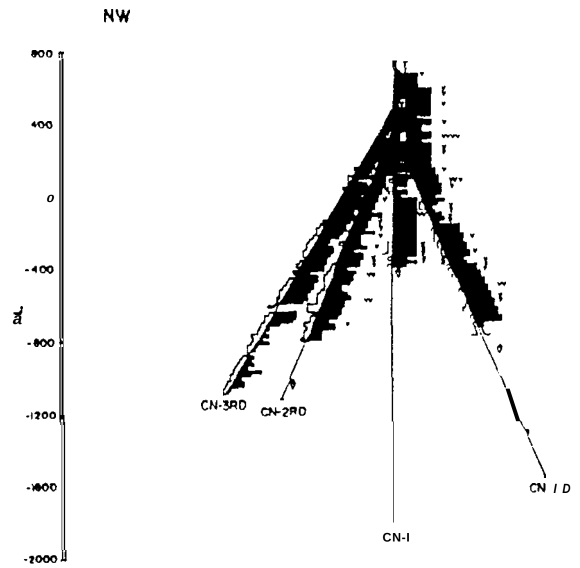

***Figure 5.** Sulfide minerals in wells CN-1D, CN-4D, CN-2RD and CN-3RD.*

alteration nunerals occur in weak to moderate amounts. Weak vein forms of acid minerals are found in three wells: alunite at -200 mRL in CN-2D, both alunite and Qaspore within the thick zone in CN-3D at -160 down to -220 mRL (Fig. 3), and Qaspore at -360 Mrl in CN-3RD (Fig. 2). Chalcopyrite exists in rare to moderate amounts in all wells as coarse to fine-grained anhedral Qsseminations in matrix, as inclusions in magnetite and rarely, associated with magnetite and pyrite. It occurs in rare to weak amounts in CN-1, CN-2D and CN-3D while it is ubiquitous in weak to moderate amounts in CN-4D, CN-SD, CN-2RD and CN-3RD (Figs. 4 and 5). Similar to the shallow acid zone, pyrite is present both as moderate to abundant alteration mineral as well as generally rare veins within the sampled depths above the point of blind drilling at -140 mRL in CN-2D, -720 mRL in CN-4D, -780 mRL in CN-SD and -800 mRL in CN-2RD. It is found in the entire sampled depths down to the blind dnlled depth in CN-1 and CN-3D. Using the stable isotherms, this deep acid zone lies between 180°C and 250°C (Figs. 2 and 3).

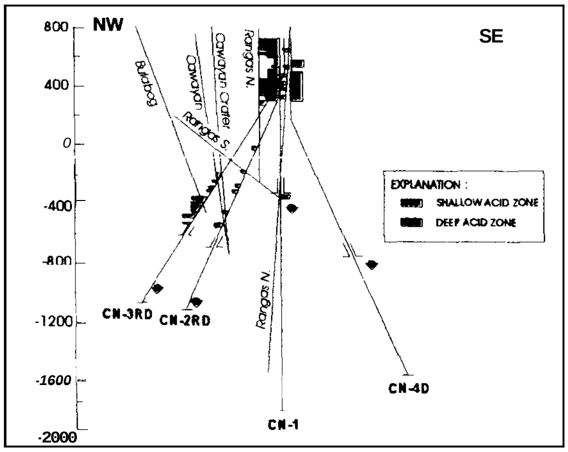

Figure 6. Structural correlation of acid alteration zones in wells CN-I, CN-4D, CN-2RD and CN-3RD.

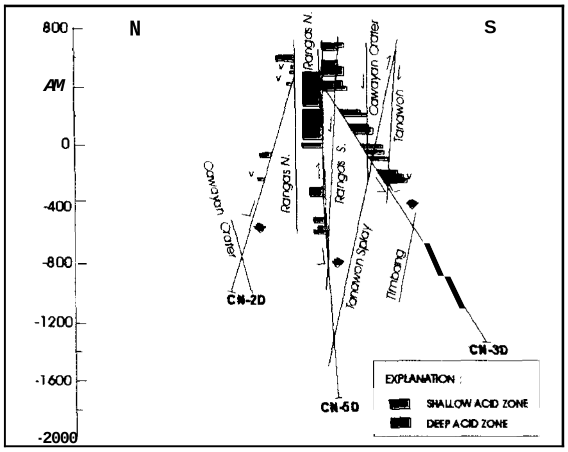

Figure 7. Strucfural correlation of acid alteration zones in wells CN-2D, CN-3D and CN-SD.

CORRELATION WITH STRUCTURES

Most shallow acid alteration minerals in Cawayan wells can be correlated structurally. Both the thick zones above +100 mRL in wells CN-3D, CN-4D, CN-5D, CN-2RD and CN-3RD and the thin, discrete zones in wells CN-1 and CN-2D can be all attributed to Rangas North (Figs. 6 and 7). On the other hand, the thin acid zone at +250 mRL in CN-3D is correlated to Rangas South (Fig. 7).

Most of the deep acid alteration zones are likewise associated to structures. Weak to moderate amount of acid zone at -500 mRL and at -560 down to -580 mRL in CN-5D is probably deposited through Rangas South (Fig. 7). Cawayan Crater and Tanawon Splay are possibly related to the thin, discrete but abundant acid zone at +80 down to -60 mRL, and to the thick abundant zone below -140 mRL in CN-3D (Fig. 7). The intersections of Cawayan Fault and Cawayan Crater with CN-3RD below -200 mRL, and with CN-2RD below -500 mRL also yielded thin, rare to weak amount of acid zone (Fig. 7). Bulabog, on the other hand, coincided with thin, discrete weak to moderate amount of acid zone below -300 mRL in CN-3RD (Fig. 6). Rangas South's intersection in CN-2RD at -180 mRL yielded weak amount of acid minerals (Fig. 6). In contrast, its intersection with CN-3RD is devoid of acid alteration. Both weak amount of thin acid zones at -20 mRL of CN-2RD and at -350 mRL in CN-1 is correlative to Rangas North (Fig. 6). Some of the the deep acid zones, however, cannot be attributed to structures. These are: the two thin acid zones in weak to moderate amounts at -40 mRL and at -200 mRL in CN-2D; the 40-m thick acid zone in moderate amount at -280 down to -320 mRL in CN-SD and; the two thin weak acid zone at -280 mRL and at -320 mRL in CN-2RD. No structure nor deep acid zone below +100 mRL down to point of blind drilling is observed in CN-4D.

CORRELATION WITH ACID FLUID INFLOWS

The association of an acid alteration zone with acid fluid inflows confirms the recentness of the acid alteration. In Cawayan, most of the deep acid alteration zones are correlative with either acid feeds, corroded production casings or anhydrite blockages (Fig. 8). This correlation indicates that the deep acid alteration zone has been deposited by present-day acid fluids. On the other hand, no casing corrosion has been reported yet within the depths of the shallow acid alteration zone. The three-string casings of the wells in Cawayan most likely delayed the attack of acid fluids on the production casing at shallow levels.

Among the seven wells, the production casings in three production wells have already suffered corrosion by acid fluids. In CN-1, the casing corrosion at -287 mRL is correlative with a deep acid alteration zone composed of diaspore, quartz, pyrite, illite and anhydrite. An anhydnte blockage was subsequently deposited at this depth when upflowing neutral fluids mixed with the acid-sulfate waters probably during discharge (See, 1996). The structure which llkely channels the acid fluids in this

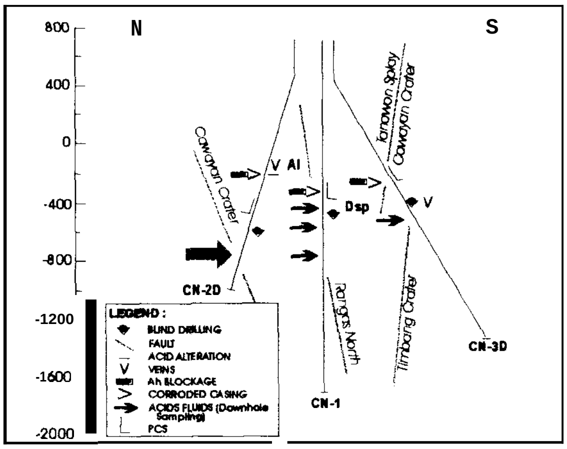

Figure 8. Acid alteration and structural correlation of acid inflows in Cawayan wells.

well at -287 mRL is the Rangas North fault. Based on downhole sampling, this fault still conducts acid waters in CN-1 at -418 to -468 mRL, and possibly till -668 mRL. Despite these acid feeds the Qscharge fluid pH of the well is neutral.

In CN-2D, the corroded casing and anhydrite blockage exist at -248 mRL where alunite, illite and anhydnte are observed. No mapped fault has been correlated to this shallow acid feed in CN-2D. A deeper acid feed exists at -734 to -778 mRL as indicated by downhole sampling. This acid zone lies witlun the blind-dnlled section and is associated with the Cawayan Crater. The acid fluid Qscharge of CN-2D was ldcely drawn mainly from tlus acid zone and constitutes the major production aquifer of the well.

In CN-3D, the corroded casing and anhydnte blockage were observed at -228 mRL coinciding with a diaspore-pyrophyllite-alunite-anhydrite alteration zone. Acid waters are ldcely being channeled by the structures Tanawon Splay and Cawayan Crater. Within the blind-drilled section of the well, another acid feed was detected at -518 mRL by downhole sampling. The fault correlative to this deeper acid zone is Timbang Crater. Like CN-1, the discharge fluids of CN-3D remained neutral in spite of the presence of acid feeds.

In CN-2RD, anhydnte, sulfur and opal blockages were observed at -818 mRL correlative to Qaspore. pyrophyllite and vein anhydnte. The possible structural conduit at this depth is Puting Bato. A deeper acid feed zone exists at -1043 mRL based on downhole water chemistry and is correlative to Damoy fault. No acid alteration minerals were observed at this zone because of blind drilling. The resulting acidic Qscharge fluid of CN-2RD was likely due to these structural conduits.

Thus, based on the presence of deep acid alteration zones, acid fluids were also likely encountered by CN-5D and CN-3RD. In CN-SD, the deep acid alteration suite consisting of diaspore, pyrophyllite and dickite suggests that acid feeds are presently flowing along Rangas South at *-500* mRL and at -560 to -580 mRL. In CN-3RD, the deep acid alteration zone consisting of vein diaspore at -400 mRL indicates that acid fluids are flowing along Bulabog fault. Acidic waters are also llkely present along Cawayan fault based on its association with deep acid alteration in CN-3RD at -200 mRL, and in CN-2RD at *-500* mRL.

RELATION WITH NEUTRAL-pH ALTERATION

In Cawayan, acid alteration is abundant and widespread from surface down to 0 mRL. Rocks at these shallow levels are almost completely altered to the shallow acid assemblage of alunite, sulfur and kaolinite. Neutral-pH alteration occurs in lesser amounts at these depths. The assemblage consists of smectite, vermiculite, calcite and silica. The predominance of acid alteration over the neutral-pH types suggests that the hydrothermal fluids presently flowing at these shallow levels are mainly acidic.

Below 0 mRL, acid alteration no longer abounds. The dominant hydrothermal alteration is already of the neutral-pH type. The suite is composed mainly of chlorite, illite-smectite, illite, epidote, calcite, actinolite and biotite. The predicted temperature of the first occurrences of the minerals nearly coincides with the measured stable temperature. For instance, in the CN-2RD/CN-3RD sector, the Occurrence of moderate illite + subhedral epidote wluch has a predicted temperature of 220°C and of abundant illite + epidote which has a predicted temperature of 240°C duplicate the measured stable temperature at -200 mRL and below -900 mRL, respectively. Likewise, the occurrences of illite + wairalute, epidote and actinolite in CN-5D have all the same predicted and measured temperatures of 220°, 240° and 260°C, respectively, at similar depths. The occurrence of abundant epidote + weak actinolite veins which has a predicted temperature of 260°C and of moderate actinolite + rare biotite veins which has a predicted temperature of 280°C in CN-1/ CN-4D below -900 mRL are both within the >260°C measured stable temperature contour. Hence, the progradational trend of these neutral-pH alteration minerals is consistent with present reservoir temperatures strongly suggesting that they are recent deposits. The neutral-pH Qscharge of all Cawayan wells, except CN-2D and CN-2RD, further confirm that the widespread neutral-pH alteration at levels below 0 mRL are formed by present-day neutral brine.

In contrast to the widespread acid zone at shallow levels, acid alteration occur in weak to moderate amounts below 0 mRL. In addition, they exist only in discrete, 20 m-thick zones. Their restricted distribution and their close association with faults indicate that these deep acid alteration zones are presently formed by acid fluids flowing along faults. The deepest level of acid alteration observed is -580 mRL in CN-5D correlative to Rangas South.

ORIGIN OF ACID FLUIDS

The vertical distribution pattern of hydrothermal alteration minerals in the Cawayan wells clearly suggests that acid fluids in tlus sector are of surficial origin as previously postulated (Robinson et al., 1987 in Solis et al., 1994; Reyes, 1987). Fresh, thick acid alteration zones which are widespread above 0 mRL are clear evidence that acid fluids are presently circulating at shallow levels of the reservoir. These shallow acid fluids are produced by the oxidation of H_2S gases upon mixing with groundwaters (Solis et al., 1994).

Though acid fluid inflows exist below 0 mRL down to levels as deep as -1000 mRL, no deep acidic source is considered in Cawayan mainly due to the predominance of neutral-pH alteration at deeper levels of the reservoir (below 0 mRL), and the neutral-pH discharge of all Cawayan wells drilled deeper than -1000 mRL. These observations strongly point that neutral waters, and not acid fluids, exist at deeper parts of the Cawayan reservoir.

Thus, acid fluids below 0 mRL are most ldcely surficial acid waters wluch migrated downward along vertical structures as attested by the restricted

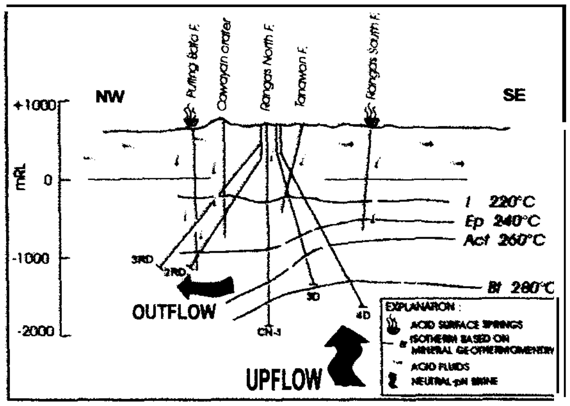

Figure 9. Petrologic Model of Cawayan.

distribution of acid alteration at depths below 0 mRL. These shallow acid fluids deposit alunite, sulfur and kaolinite at shallow levels where temperatures are less than 160°C. As they descend to deeper levels where temperatures exceed 180°C, they form a higher temperature acid alteration suite of diaspore and pyrophyllite with or without dickite and alunite.

Through interaction with surrounding rocks, these surficial acid fluids become neutralized as they percolate downward along faults. Hence, acid fluids are no longer detected below -1000 mRL. In CN-SD, for instance, Rangas South likely channels acid fluids down to -580 mRL as suggested by the presence of deep acid alteration minerals. At -1570 mRL, the same structure already conducts neutral brine in CN-1 based on its neutral-pH discharge.

Within the deep portions of the Cawayan reservoir, therefore, only neutral-pH fluids are presently circulating. Based on mineral contours, hotter temperatures likely exist in the sectors dnlled by CN-3D and CN-4D in comparison to the areas dnlled by CN-2D, CN-2RD and CN-3RD. The first appearances of illite, wairakite, epidote, actinolite and biotite are all relatively shallower in CN-3D and CN-4D in comparison to CN-1, CN-2D, CN-SD, CN-2RD and CN-3RD. This alteration trend agrees with stable isotherms which likewise show higher temperatures in CN-3D and CN-4D and declining temperatures towards CN-2D area. A deep lateral flow of hot (240°C) fluids is apparent across CN-2RD and CN-3RD, possibly originating from CN-4D/CN-3D sectors. Based on these mineralogic and isothermal trends. hot neutral brine with temperatures of ~260-280°C are apparently upflowing in the vicinity of CN-3D and CN-4D. These hot neutral fluids flow northward to CN-1/ CN-2D sector, and westward to CN-2RD/CN-3RD area. Based on the above discussion, a petrologic model of the Cawayan sector is shown in Figure 9.

IMPLICATIONS ON FIELD DEVELOPMENT

Potential Acid Feeds

Results of this study confirm that deep neutral brine exists in Cawayan sector but surficial acid waters descend along most of the structures down to depths of -1000 mRL. Faults which channel these descending acid fluids include Cawayan Crater, Rangas North, Rangas South, Cawayan, Damoy, Timbang Crater, Bulabog and Tanawon Splay. Below -1000 mRL, these structures already channel neutral brine.

Rangas South fault likely channels acid fluids along its intercept in CN-5D at -500 to -920 mRL. CN-5D Qscharged neutral-pH fluids possibly drawn from its major aquifer at -1700 mRL correlative with Guinlajon Splay. However, this well has a potential acid fluid inflow just below its PCS at -780 mRL along the Rangas South fault intersection. Fortunately, its corrosion-resistant casing can withstand the attack of acid fluids flowing along Rangas South above the PCS.

CN-4D also discharged neutral-pH fluids derived from its major aquifer at -1500 mRL associated with Timbang fault. Based on the absence of deep acid alteration minerals along its length, no acid fluids were intersected by tlus well below 0 mRL. Hence, CN-4D has no risk of casing corrosion nor acid fluid inflow below its PCS.

Reinjection wells CN-2RD and CN-3RD both have high risks of casing corrosion. Apart from discharging acid fluids likely channeled by Damoy fault at -1000 mRL, CN-2RD possibly also encountered acid fluids above its PCS, flowing along Rangas South, Cawayan and Cawayan Crater. Well CN-3RD, on the other hand, encountered neutral-pH fluids along its Puting Bato intercept at -1070 mRL. However, it likely intersected acid fluids above its PCS along its intercepts with Cawayan, Cawayan Crater and Bulabog.

Future Drilling

In the event that replacement production wells need to be dnlled in Cawayan sector, the following measures are recommended:

1) Target the well(s) preferably towards the southeast in the vicinity of CN-3D/CN-4D where hot, neutral brine are llkely upflowing.

2) Drill deeper than -600 mRL to ensure that neutral-pH fluids will be encountered.

3) Avoid intersecting faults which channel acid fluids, especially above -600 mRL.

4) If such acid channels cannot be avoided, kick-off at shallow depths in order to intersect these acid structures above the anchor casing shoe (ACS).

5) Use corrosion-resistant casing if the acid channels will be encountered below the ACS.

NOW

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