



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

## 3.0 DISTRIBUTION OF ACID ALTERATION

The acid alteration minerals in Cawayan are mainly recent deposits based on their fresh appearance, vein morphology, widespread distribution 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 this study, only the distribution of the fresh acid alteration will be discussed since they are likely 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-SD (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, anhydrite 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 disseminations. 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 thick shallow acid zone likely forms at relatively low temperatures, usually below 160°C (Fig 2).

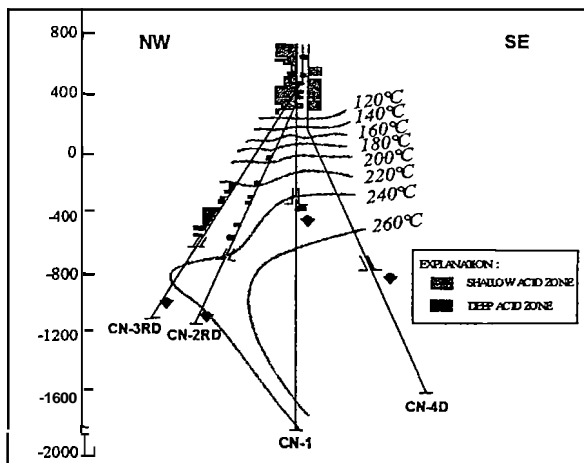


Figure 2. Acid alteration zonation and stable isotherms in wells CN-1, CN-2RD and CN-4D.

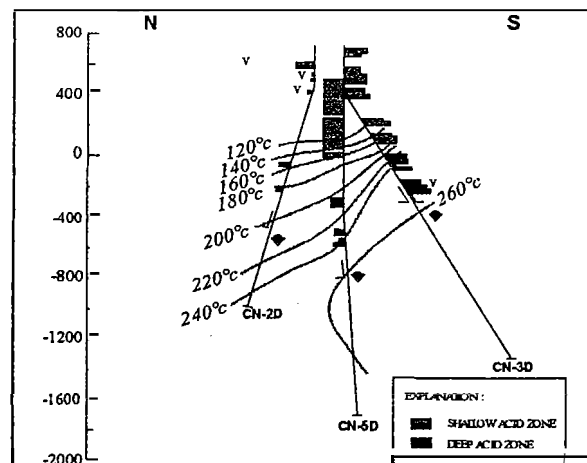


Figure 3. Acid alteration zonation and stable isotherms in wells CN-2D, CN-3D and CN-SD.

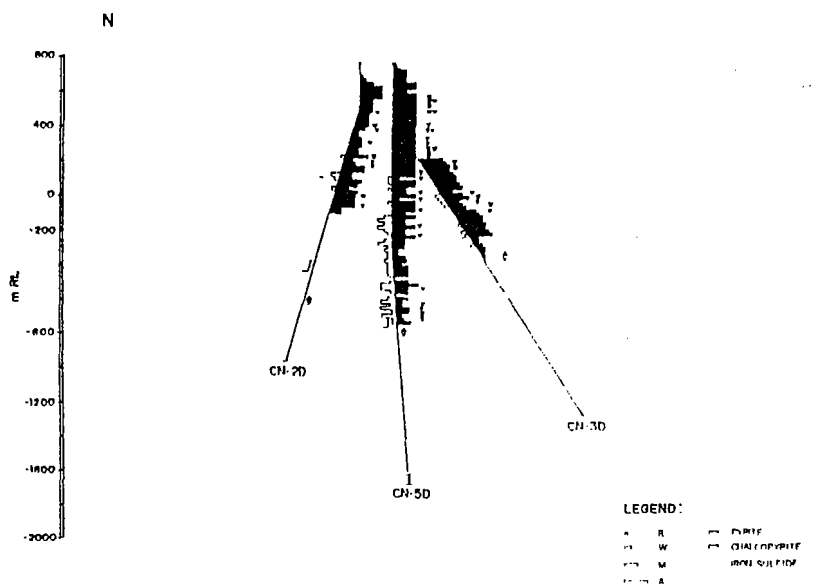


Figure 4. Sulfide minerals in wells CN-2D, CN-3D and CN-5D.

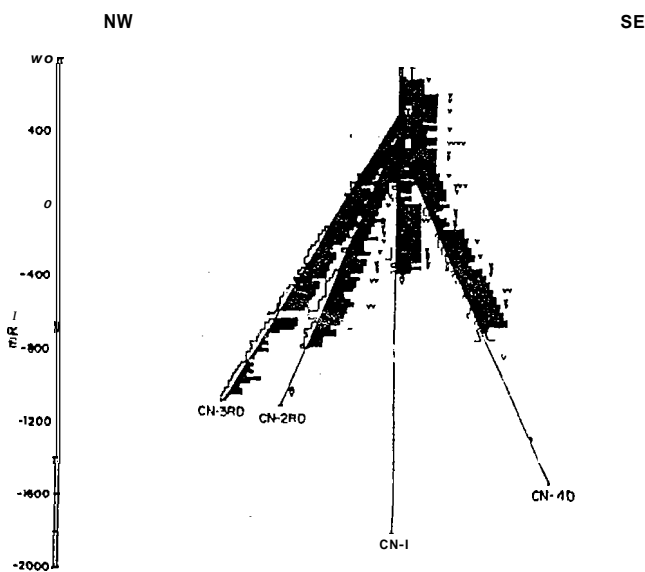


Figure 5. Sulfide minerals in wells CN-1, CN-4D, CN-2RD and CN-3RD.

### 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 diaspore and pyrophyllite with or without dickite and alunite. *Quam*, anhydrite, illite, pyrite and chalcopyrite also occur within this deep acid zone. Unlike the widespread and thick shallow acid zone, the deep acid zone exists in discrete, 20 m-thick layers, and the acid alteration minerals 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 diaspore within the thick zone in CN-3D at -160 down to -220 mRL (Fig. 3), and diaspore at -360 mRL in CN-3RD (Fig. 2). Chalcopyrite exists in rare to moderate amounts in all wells as coarse to fine-grained anhedral disseminations 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-5D, 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-5D and -800 mRL in CN-2RD. It is found in the entire sampled depths down to the blind drilled 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).

#### 4.0 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-SD, 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 +50 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-5D 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.

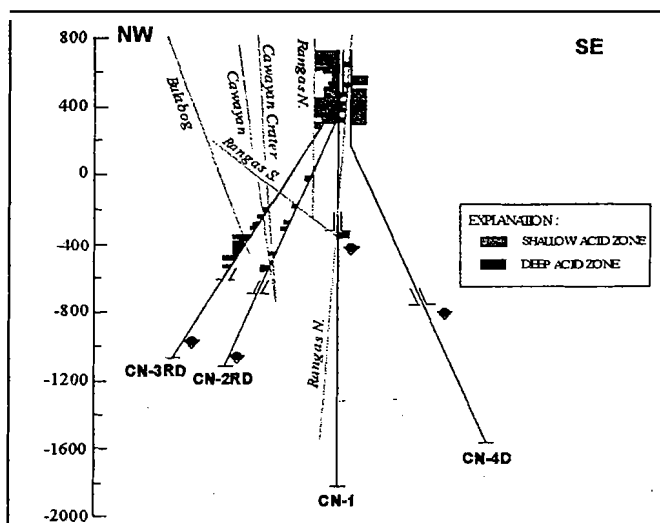


Figure 6. Structural correlation of acid alteration zones in wells CN-1, CN-4D, CN-2RD and CN-3RD.

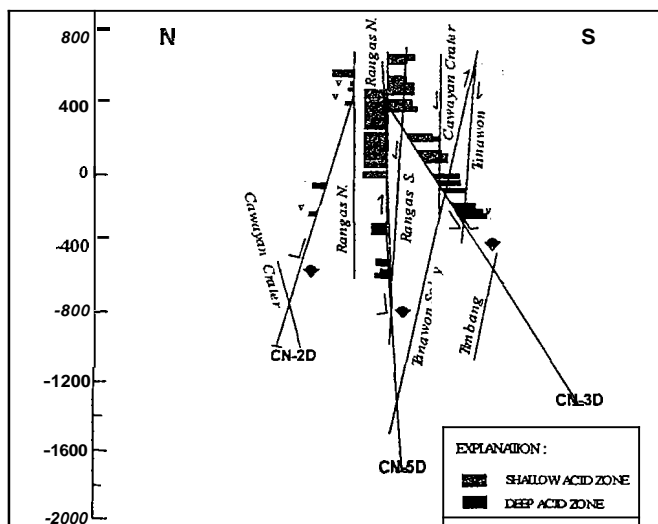


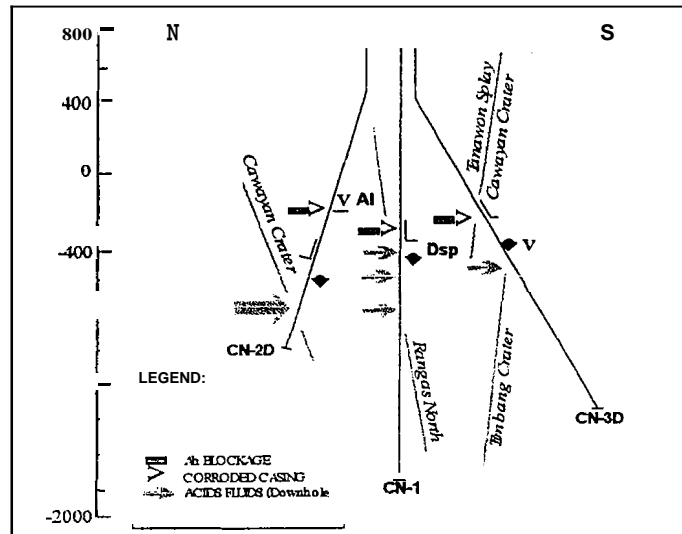
Figure 7. Structural correlation of acid alteration zones in wells CN-2D, CN-3D and CN-5D.

## 5.0 CORRELATION WITH ACID FLUID MFLAWS

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

mRL



In CN-2D, the corroded casing and anhydrite blockage exist at -248 mRL where alunite, illite and anhydrite 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 within the blind-drilled section and is associated with the Cawayan Crater. The acid fluid discharge of CN-2D was likely drawn mainly from this acid zone and constitutes the major production aquifer of the well.

In CN-3D, the corroded casing and anhydrite blockage were observed at -228 mRL coinciding with a diaspore-pyrophyllite-alunite-anhydrite alteration zone. Acid waters are likely 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, anhydrite, sulfur and opal blockages were observed at -818 mRL correlative to diaspore, pyrophyllite and vein anhydrite. 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 discharge 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-SD 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 likely 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.

## 6.0 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 which 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 + wairakite, 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 discharge 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**.

## 7.0 ORIGIN OF ACID FLUIDS

The vertical distribution pattern of hydrothermal alteration minerals in the Cawayan wells clearly suggests that acid **fluids** in this 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<sub>2</sub>S 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 likely surficial acid waters which migrated downward along vertical structures **as** attested **by** the restricted 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 diasporite 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-5D, 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 drilled by CN-3D and CN-4D in comparison to the areas drilled 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.

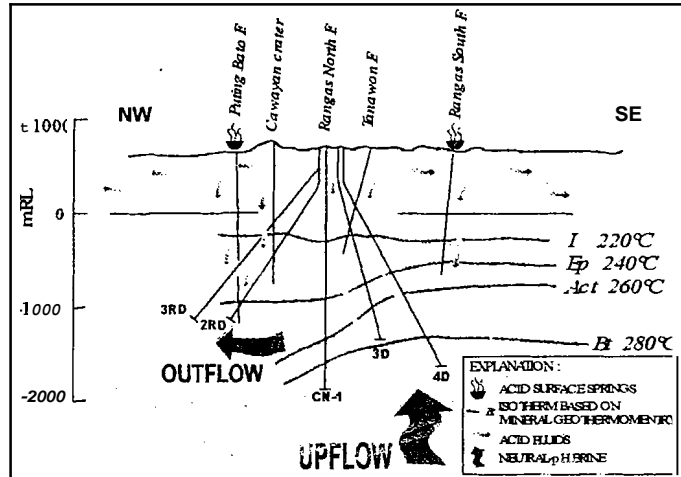


figure 9. Petrologic Model of Cawayan.

## 8.0 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 discharged 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 this 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 drilled 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 likely 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.

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