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APPLICATIONS OF STABLE ISOTOPES IN HYDROLOGICAL STUDIES OF MT. APO GEOTHERMAL FIELD, PHILIPPINES

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ABSTRACT

The local precipitation in Mt. Apo is depleted of heavy isotopes owing to high elevation and landward location of the field. Rainwaters infiltrate the shallow grounds, circulate in short distances with almost no interaction with the host bed rocks, and effuse in the surface as cold springs. Lakes and rivers are affected by surface evaporation while the acid SO_4 springs are affected by both evaporation and steam-heating. Only the neutral-pH Cl springs have the signature of the deep thermal fluids. The parent fluids of the deep thermal brine contain Cl of 4,800 to 5,000 mg/kg, $\delta^{18}O$ of -4.62 to -4.13 ‰ and δ^2H of -60.0 to -57.8 ‰. Inside the Sandawa Collapse, boiling of the parent fluids resulted to a two-phase reservoir with lighter isotope contents. The thermal fluids laterally flow towards the west where they are affected by cooling and mixing of cold waters. Deep water recharge has $\delta^{18}O$ of -10.00 ‰ and δ^2H = -61.20 ‰which come from the upper slopes of Sandawa Collapse (1580-1700 mASL).

INTRODUCTION

Mt. Apo forms part of the north-south trending Quaternary volcanoes in South Central Mindanao, Philippines (Fig. 1). Surface exploration and drilling activities have proved the existence of a hydrothermal system in Mt. Apo which can be related with the volcanism of this andesitic terrain (e.g. Delfin et al, 1984).

As part of the hydrological study in Mt. Apo, water samples for isotopic and chemical analyses were collected at different sampling points. These include rainwaters at different elevations, rivers, lakes, cold springs, hot springs, well discharges and downhole waters. Collection of water samples followed the standard procedure set by PNOC-EDC. The water samples were analysed for their $\delta^{18}O$ and δ^2H composition; selected samples were analysed for δ^3H but were not presented in this paper. All isotope analyses for 1993 and 1994 were done at IAEA laboratory in Vienna, Austria while the 1984 samples were analysed at IGNS in Lower Hutt, New Zealand. All isotopic units in this report are expressed in per mille (‰) deviation from Vienna Standard Mean Oceanic Water (VSMOW).

THE LOCAL METEORIC WATER LINE

Five rainwater collection stations were installed at the northwestern flanks of Mt. Apo. The plot of $\delta^2H - \delta^{18}O$ of all the rainwater samples and the generated local meteoric water line (LMWL) are presented in Figure 2. After disregarding the data points which are suspected to be affected by evaporation and using the *a priori* slope of 8.0, the resulting equation of LMWL is:

$$\delta^2H = 8.0\,\delta^{18}O + 14.0, \qquad (n = 76;\ r^2 = 0.964)$$

The high deuterium excess reflects the isotopically depleted nature of the rainwaters in Mt. Apo. This characteristics is attributed to the high elevation and the landward location of the project area.

The relationship of the weighted mean of $\delta^{18}O$ and δ^2H in rainwaters and the elevation of the collection station is evaluated to determine the isotopic gradient, in this case about $\Delta\delta^{18}O$ = -0.20 ‰ and $\Delta\delta^2H$ = -1.51 ‰ per 100 m rise in elevation. Therefore, rainwaters at lower elevations have enriched isotopic composition and those at higher elevations have depleted isotopic contents.

THE SURFACE WATERS

Non-thermal Waters

The data points from cold springs, rivers and lakes are plotted in Figure 3a with LMWL. The cold springs with continuous flow are almost coincident with the trace of LMWL indicating that the waters originated mostly from local precipitation. On the other hand, the springs with ponded waters may have been exposed to surface evaporation causing isotopic enrichment. It is also interesting to note that the springs found at higher elevations are more depleted with heavy isotopes than those found at the lower elevations. Basing on the isotopic gradient of rainwaters, the waters effusing from the cold

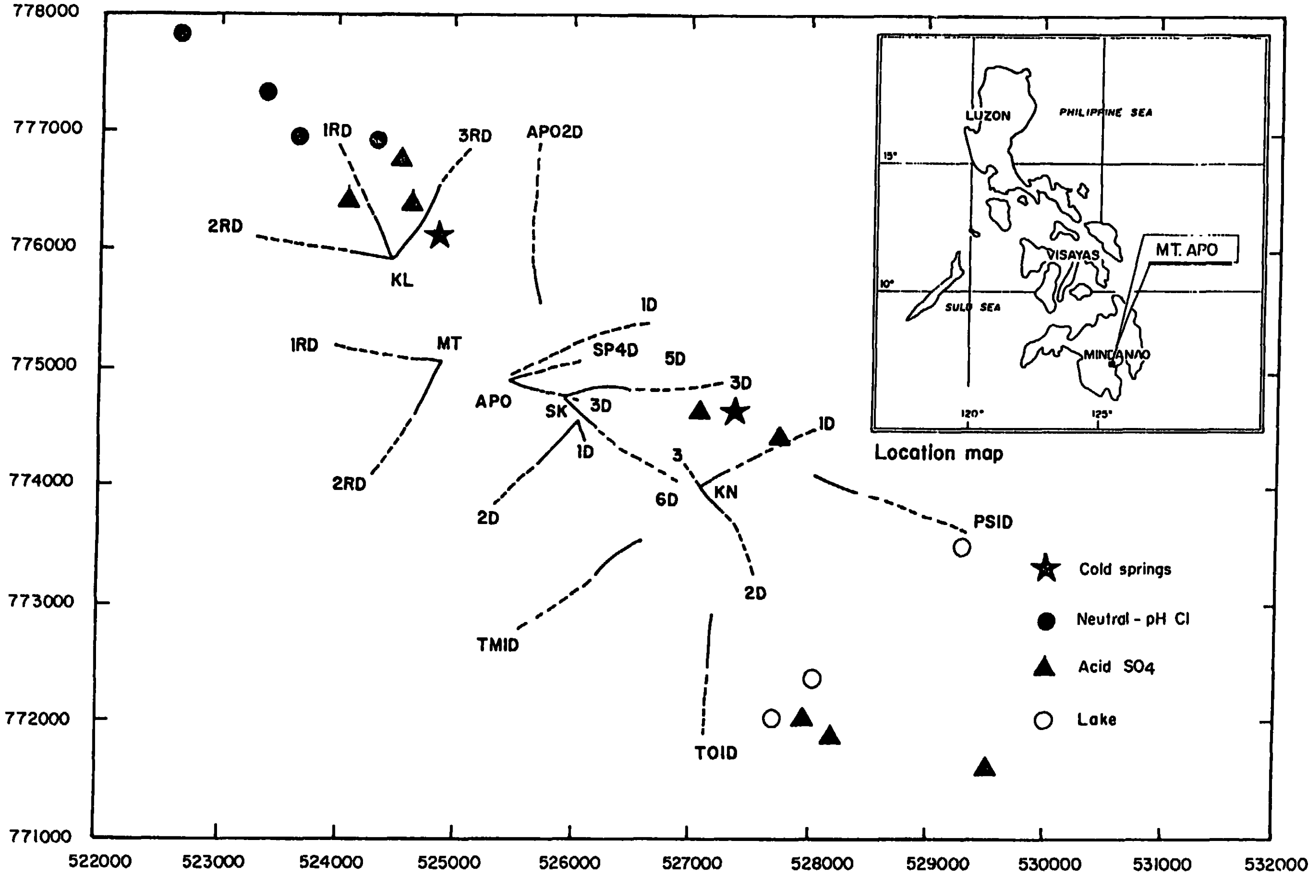

Figure 1: Map showing the general location of Mt. Apo geothermal field (inset), the welltracks drilled within the project area, and the location of cold and hot springs.

springs are thought to have originated in their vicinities. The rainwaters may have possibly circulated in shallow levels and travel in short distances, and not deep into the reservoir to interact with the bed rocks.

The rivers and creeks are also coincident with LMWL which established that the waters flowing as surface run-offs are largely coming from the local precipitation. The plots of the waters from lakes which has no inlet and outlet are shifted to the right of LMWL. The positive slopes which signify enrichment in both $\delta^{18}O$ and $\delta^{2}H$ indicate intense evaporation processes occurring in these lakes. On the other hand, Lake Venado, which has a water inlet, is slightly coincident with LMWL reflecting the continuous input of rainwaters into the lake.

Thermal Springs

The isotopic compositions of the thermal springs are shown in Figure 3b. All of the thermal springs which are classified as acid-SO_4 springs plotted close to LMWL. This trend suggests that the springs are mostly meteoric waters which were possibly heated by the ascending hot steam from deep reservoir. Among the acid-SO_4 springs, the samples from Agco boiling pool are the most enriched with heavy isotopes (see dashed line in Figure 3b). The same isotopic enrichment was observed in the thermal waters in the adjacent Lake Agco. The main reason for the isotopic enrichment in Agco could be the high evaporation rate occurring in the ponded waters of the boiling pool and the steaming lake.

All the data points of the neutral-pH Cl springs are shifted to the right of LMWL. This enrichment is interpreted to be the effects of mixing of the deep thermal waters with the shallow groundwaters. The regression line of these points intersects LMWL at $\delta^{18}O$ = -10.10 ‰ and $\delta^{2}H$ = -62.30 ‰ and this is the assumed isotopic composition of the meteoric recharge. Based on isotopic gradient of rainwaters, the water recharges of these springs are possibly coming from 1560 mASL. These recharges are interpreted to have penetrated deep into the thermal reservoir and interacted with the deep thermal brine, the reason for the positive shift in their isotopic composition.

Surface and Shallow Hydrology

Most of the input to the water budget comes from surface precipitation (Gat and Gonfiantini, 1981). Mt. Apo receives its water input from the heavy rainfall in the area which vary monthly from 80 mm at its lowest to 1200 mm at its highest level. The rainwaters in Mt. Apo were found to be depleted of heavy isotopes as evidenced by high deuterium excess of +14‰. There are two main reasons for this isotopic depletion: (i) Mt. Apo lies at high elevation; and (ii) the area lies inland of the Central Mindanao Cordillera. The stable isotopes in rainwaters follow the classic trend of isotopic depletion with increasing elevation. Calculations showed that the isotopic gradients are about -0.20 ‰ $\delta^{18}O$ and -1.51 ‰ $\delta^{2}H$ per increase of 100 m elevation.

Figure 4 presents the scheme of the surface and shallow groundwater hydrology. The arrows indicate the fluid flow and the numbers are the isotopic composition of waters at different sampling points. The rainfall at high elevation infiltrates the shallow levels after precipitation. The infiltrants circulate in the shallow grounds possibly within a very short residence time thus waters do not interact heavily with the bed rocks. This results to the similarity between the stable isotope of cold springs in the area and the rainwaters in their vicinities.

When the precipitated rainwaters are exposed to the atmosphere as run-offs or as ponded waters in lakes, they are affected by evaporation processes. The lighter isotopes are partitioned to the evaporated steam leaving isotope enriched waters in lakes.

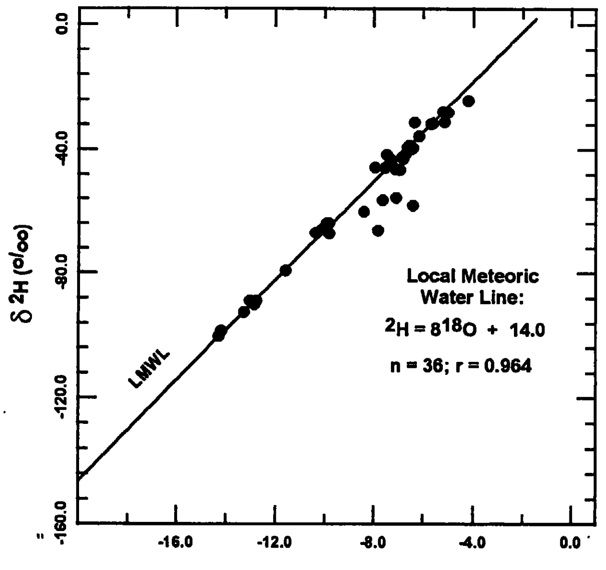

Figure 2: Plot of isotope composition of rainwaters in Mt. Apo geothermal field with the generated local meteoric water line (LMWL).

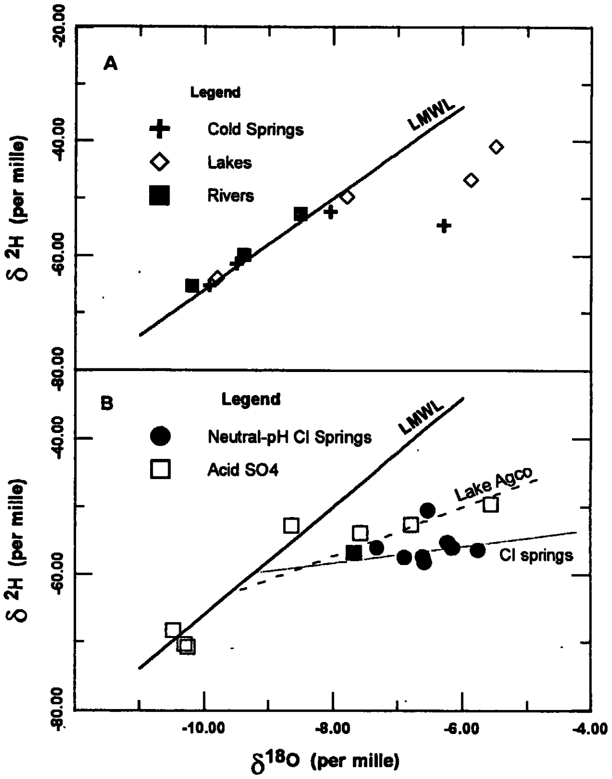

Figure 3: Isotope composition of waters from the cold and hot springs in Mt. Apo.

The acid SO_4 springs in both the southeast and northwest sides of Mt. Apo have isotopic composition similar with the rainwaters. These springs appear to have originated from heating of groundwaters by the hot ascending vapours of the deep thermal fluids. On the other hand, the neutral-pH Cl springs are shifted to the right of LMWL reflecting the contributions of the deep thermal brine into the spring waters.

GEOTHERMAL WATERS

Well Discharges

The reduced isotopic data of well discharges are plotted with LMWL in Figure 5b. The most shifted data come from Wells SK-6D and SK-3D which is about +6‰ from LMWL. The waters from Wells KN-1D, KN-2D, SK-5D and SP-4D clustered on the same region of the graph indicating homogeneity of their waters. The slight difference in their isotopic contents is probably related to the prevailing temperature in the wells. For instance, the waters from Well KN-1D with temperature of 310°C is slightly enriched with the heavy isotopes compared to the waters from SP-4D with temperature of 250°C. KN-3 has depleted $\delta^{2}H$ relative to other wells which can be explained by steam addition to the thermal fluids. Well SK-1D, a shallow well which discharged pure steam has enriched $\delta^{2}H$ but depleted $\delta^{18}O$.

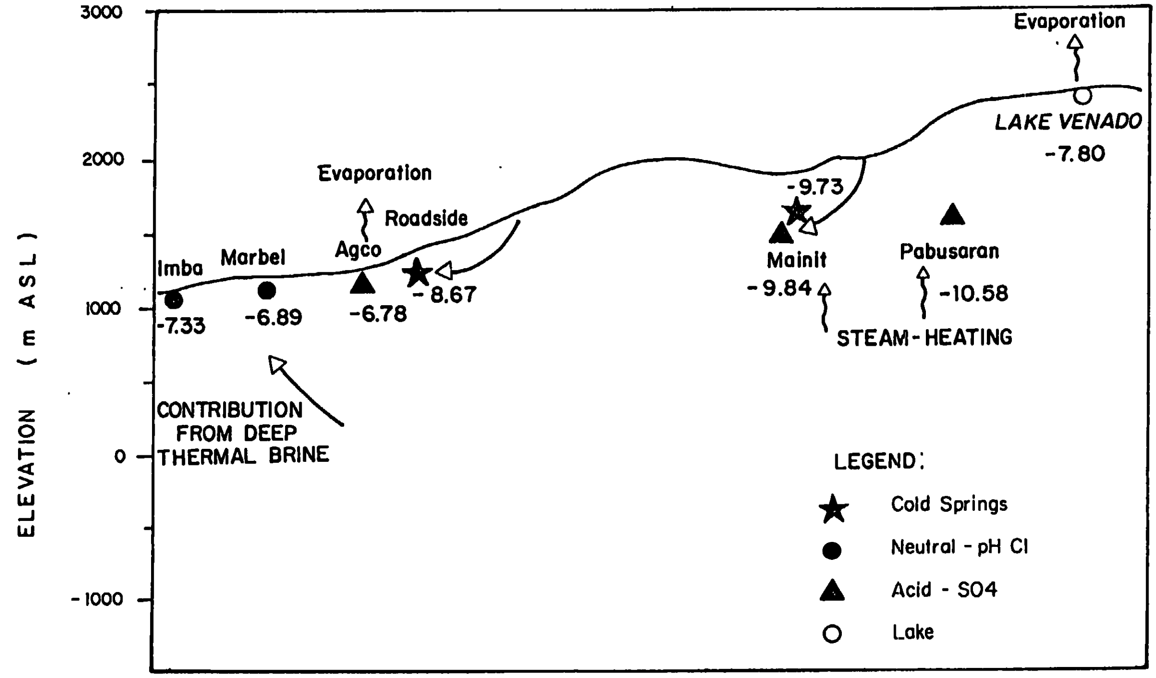

Figure 4: Schematic diagram showing the shallow and surface hydrology in Mt. Apo geothermal field. The arrows indicate path of fluid flow. The numbers are the $\delta^{18}O$ composition of water from each sampling station.

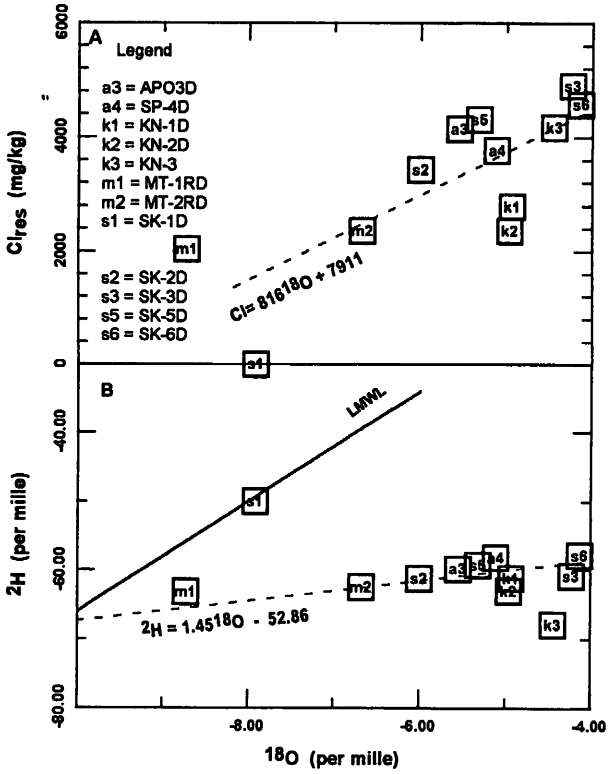

Figure 5: (A) Plot of $\delta^{18}O$ with Cl of waters from the wells; (B) Plot of isotopic composition of the waters from the well.

The distribution of the data points of deep geothermal waters and some Cl springs generate the following regression line:

$$\delta^2H = 0.19\ \delta^{18}O - 59.60$$

Its intersection with LMWL is about: $\delta^{18}O$ = -10.00‰ and δ^2H = 61.20‰. The possible source of the recharge rainwaters is at 1580 to 1700 mASL based on isotope gradient of rainwaters. This area in the field corresponds to the steep slopes of the Sandawa Collapse feature.

Figure 5a relates the stable isotope with Cl_{res} while Figure 6 shows the field trend of $\delta^{18}O_{res}$ across the Mt. Apo geothermal field. Wells SK-3D, SK-6D and KN-3 closely represent the parent fluids in the Mt. Apo reservoir which have $\delta^{18}O_{res}$ from -4.62‰ to -4.04‰, δ^2H_{res} from -59.89‰ to -57.99‰ and Cl_{res} of 4,800-5,000 mg/kg. Towards the west, $\delta^{18}O_{res}$ and Cl_{res} compositions decline paralleled by the drop in fluid temperature (PNOC-EDC, 1994). These trend altogether signify cooling and dilution processes towards the west. In the southeast, the fluids have also depleted isotopic composition but there is a marked increase in the steam fraction in the fluids. The depletion in δ^2H_{res} in the southeast is interpreted to be the effects of steam addition into the parent fluids.

Downhole Waters

The available data on the isotopic composition of downhole waters are plotted in Figure 7. Contour lines are constructed in order to segregate the isotopically enriched fluids from the isotopically depleted waters. The most enriched samples came from the bottom of the Well KN-3 ($\delta^{18}O$ = -4.40‰). Towards the west the isotopic composition of waters are uniform between -6.0 to -7.0‰. The configuration of the contour line is tongue-shaped which is interpreted to indicate the lateral flow of the thermal fluids. The waters from the bottom of the wells in the extreme west of the field have the most depleted isotopic composition suggesting interaction of the thermal fluids with cold waters.

Hydrology at Depths

The study on the stable isotope of waters have identified Wells SK-3D and SK-6D as the close representative of the parent fluids in Mt. Apo hydrothermal system. These are the same conclusions derived from geochemical and reservoir investigations (PNOC-EDC, 1994). The parent fluids have Cl concentration of 4,800 to 5,000 mg/kg, reservoir temperatures of 300 to 320°C, and the following isotopic composition: $\delta^{18}O$ = -4.62 to -4.04‰ and $\delta^{2}H$ = -59.90 to -58.00 ‰.

Figure 7 presents the scheme of fluid flow in the reservoir. Inside the Sandawa Collapse, there appears to be segregation of liquid and vapour phases of the fluids due to boiling. This process generated the high-enthalpy two-phase fluids which have slightly depleted $\delta^{2}H$. These are the fluids discharged by Wells KN-1D, KN-2D and KN-3. The pure steam phase is present in the discharge of Well SK-1D having $\delta^{18}O$ = -7.92‰ and $\delta^{2}H$= -50.00/₀₀.

Towards the west, the isotopic compositions of the waters are uniform; $\delta^{18}O$ ranges from -5.73 to -5.32‰. The uniformity of isotope composition could be directly related with the uniformity of the reservoir temperatures which are in the order of 250-280°C as well as with the uniform chemistry of the waters (PNOC-EDC, 1994). The direction indicated by the tongue-shaped $\delta^{18}O$ contour

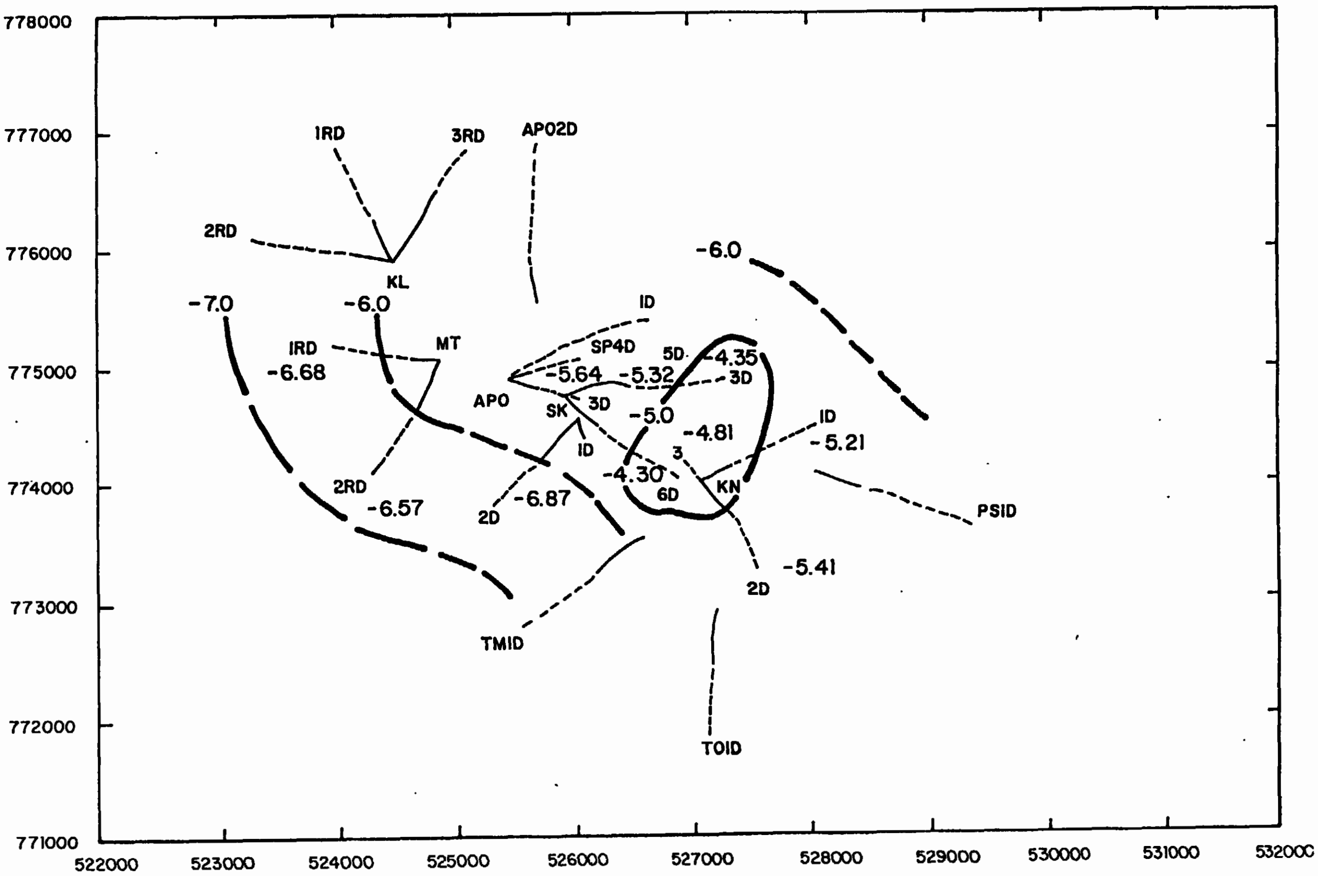

Figure 6: Distribution of $\delta^{18}O$ across Mt. Apo geothermal field. The most enriched region lies within Sandawa Collapse. The waters become depleted of heavy isotopes towards the northwest.

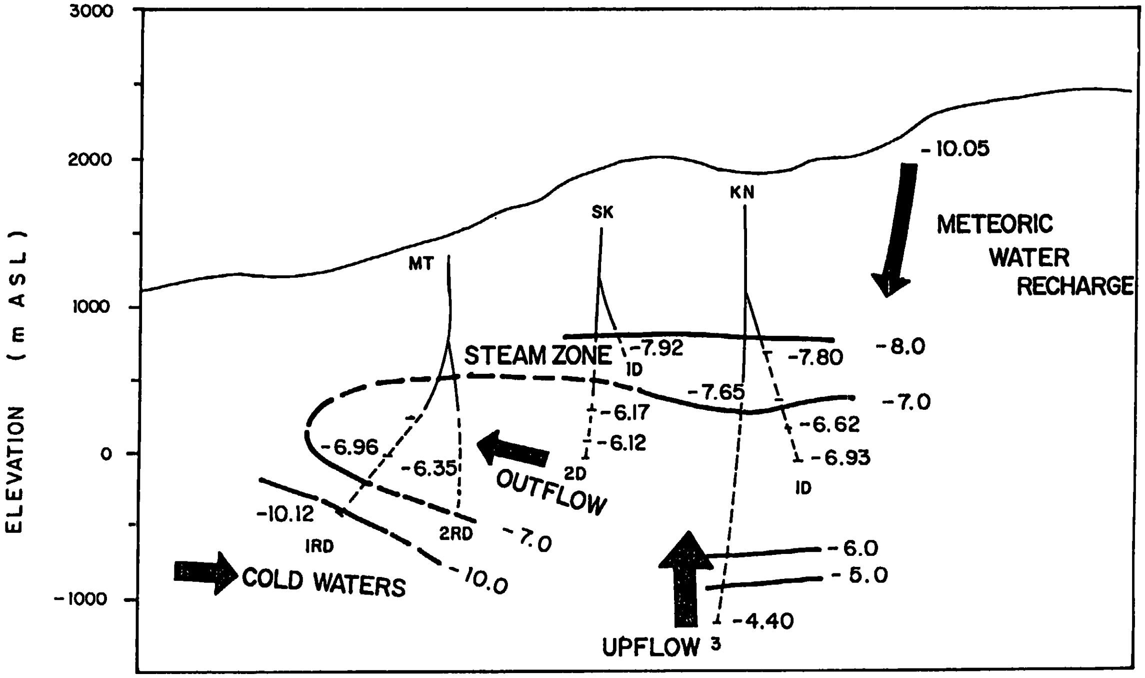

Figure 7: Schematic diagram showing the path of fluid flow at depths. Arrows indicate fluids flow. The iso- $\delta^{18}O$ contours are based on the isotope composition of downhole samples. Meteoric water recharges come from the slopes of Sandawa Collapse.

possibly indicate the path of fluid flow towards the northwest.

The waters from Wells MT-1RD and MT-2RD are the most isotopically depleted among the thermal brine. Geochemical data established that these waters are diluted thermal brine while downhole surveys indicated temperature inversions at the bottom sections of these wells (PNOC-EDC, 1994). Altogether, these suggest mixing of cold fluids with the thermal brine in the western sector of the field.

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