# THE APPLICATIONS OF NATURAL TRACERS IN GEOTHERMAL DEVELOPMENT: THE BULALO, PHILIPPINES EXPERIENCE

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**SUMMARY** - The Bulalo geothermal field, 70 km southeast of Manila, has been in production since 1979. Sampling of production fluid is regularly conducted to monitor reservoir response to exploitation. Natural tracers including chloride, natural tritium, and magnesium have proved useful in characterizing the types and pathways of fluids that enter the reservoir. Fluid characterization helps identify reservoir processes which in turn lead to efficient resource management. Chloride monitoring has been very useful in detecting injection breakthrough at Bulalo. Now, the western edgefield injectors are shut-in and new injectors are drilled farther west to prevent production losses due to injection breakthrough. Natural tritium is used to define the areas affected by natural groundwater influx, injectate dispersal and other surface waters such as drilling fluid Based on these data, casing programs were modified for development wells. Monitoring chemical by-products from acid stimulations i.e., magnesium provides an additional tool in identifying the permeable pathways and heterogeneities within the Bulalo reservoir.

## 1 INTRODUCTION

The Bulalo geothermal field, located about 70 km southeast of Manila, (Figure 1, inset) has been in production since 1979. Bulalo is one of two geothermal projects developed by National Power Corporation (NPC) of the Philippine Government and Philippine Geothermal, Inc. (PGI), a subsidiary of Union Oil Company of California (UNOCAL). The three 110 MW power plants have generated a cumulative total of 22,977 GWh of electricity as of July 1991. Bulalo now supplies about 13.5% of Luzon's energy requirements. Exploration began in 1973 with the discovery well, Bul-1 (Figure 1). Since then, 58 production wells and 21 injection wells were completed to a minimum depth of 655 m M.D. and a maximum depth of 3625 m M.D.

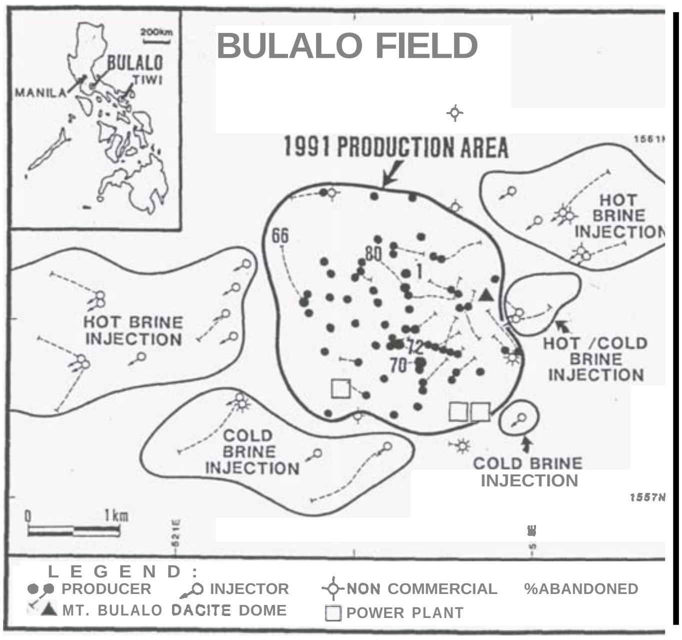


Figure 1- Map of well locations in the Bulalo geothermal field showing production and injection areas. Map of the Philippines is shown inset. Well numbers are posted at TD.

PGI conducts an extensive reservoir fluid geochemical monitoring program at Bulalo. This paper discusses the most important natural tracers used to characterize the types and detect pathways of fluids that enter the reservoir. Interpretation of these results is essential to efficient resource management.

### 1.1 Background

Figure 1 shows the location of production, injection, and other wells at Bulalo geothermal field. In the center is the production area and on the periphery are the injection areas. There are two injection systems at Bulalo, one for hot brine and the other far cold brine. The hot brine system is used to reinject separated brine at 175°C while the cold brine system reinjects cooling tower blowdown and sump water (Mosby, et. al, 1988).

### 1.2 Geochemical trends

Most production wells in the Bulalo field have calculated reservoir chloride (Cl) compositions of about 2500-3000 mg/kg and temperatures of 260-290°C. The areal distribution of reservoir Cl in 1990 is shown in Figure 2. Reservoir Cl compositions are low in the northwest and increase towards the center and the southeastern (SE) portion of the field. The SE has the highest reservoir Cl and is believed to be the *source* of the upwelling geothermal fluids. The tongue of high Cl in the west is caused by injection breakthrough from the western edgefield injectors. Similar to reservoir Cl, the highest concentrations of non-condensible gases (NCG) occur in SE Bulalo. Figure 3 shows a *cross* section from SW to SE and illustrates the probable pathways of geothermal fluid as it rises from the southwestern edge of Mt. Bulalo through intensely altered and fractured andesitic flows, tuffs and volcaniclastics along permeable faults (Clemente, 1987).

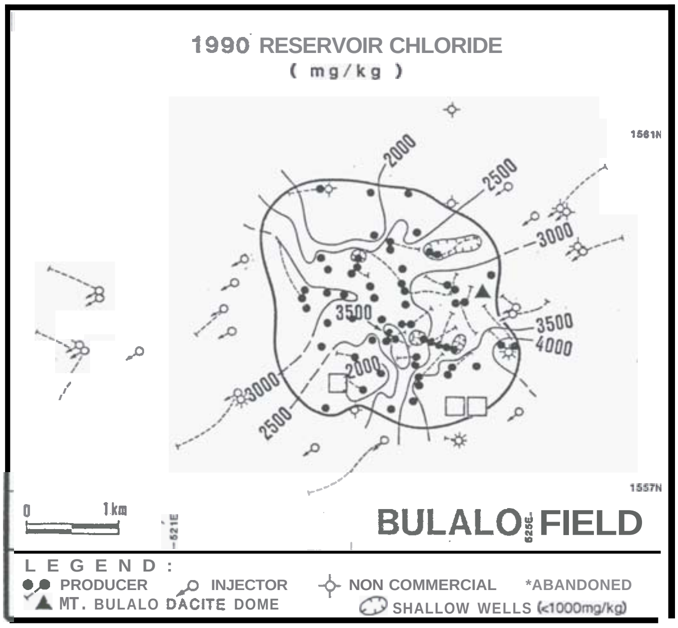


**Figure 2**- Map **of** 1990 reservoir chloride.

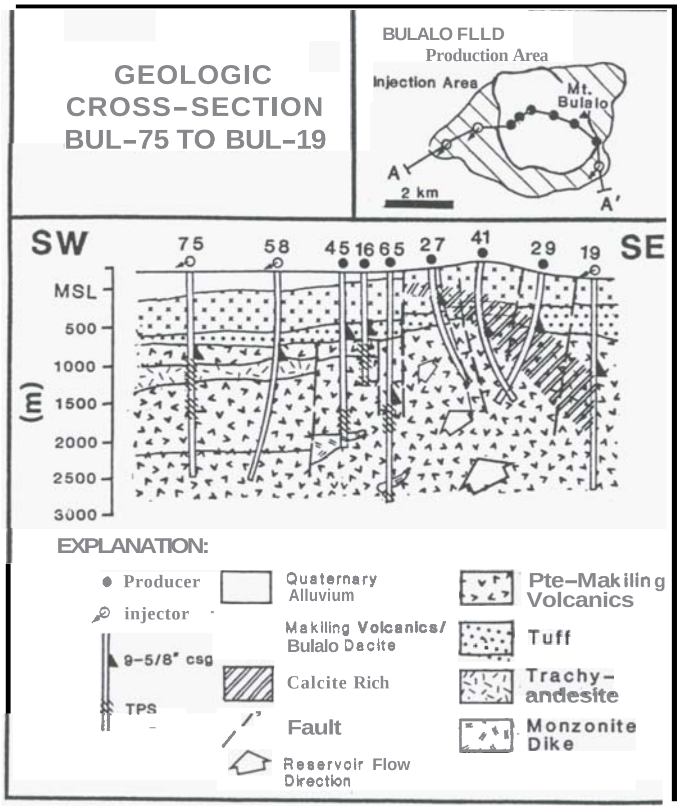


**Figure 3**- Cross-section from western to eastern portion of Bulalo field showing the stratigraphy, structures, and probable pathways of geothermal fluid.

## 2. METHODOLOGY

### 2.1 Sampling and Analysis

Chloride: There are several chemical constituents in geothermal well discharges which can be utilized for monitoring purposes, but Cl is the easiest to analyze. It is very soluble, unreactive once in solution, non-volatile, and responds rapidly to dilution and concentration processes. Processes such as injection breakthrough and cold water influx *can* be indicated by monitoring Cl in the well discharges during exploitation.

Samples from all production wells *are* collected from test separator waterlines at least three times a year and flowed into a condenser where they are cooled to 25°C. The separated brine samples provide the most reliable data since discharge enthalpy and separator pressure are simultaneously measured and from these the reservoir compositions *can* be calculated. Two-phase samples are collected more frequently (twice a month) using a mini-test separator and cooled by passing through a condenser. Cl is analyzed at the Bulalo Chemical Laboratory using an automatic Memotitrator with silver nitrate as titrant.

Tritium: Tritium is a radioactive isotope of hydrogen with a half-life of about 12.3 years. It is produced naturally by reactions of cosmic rays with nitrogen and oxygen in the atmosphere. Its natural abundance is about 5-10 atoms of tritium per $10^{18}$ atoms of hydrogen (5-10 tritium units or *TU)* but increased to more than 1000 TU and 50 TU in the northern and southern hemispheres, respectively due to thermonuclear testing (Truesdell and Hulston, 1990). Water out of contact with the atmosphere should contain undetectable tritium. Geothermal water is expected to contain very low tritium since it typically has been out of contact with the atmosphere for a long time. Therefore, the presence of tritium in geothermal well discharges indicates that young surface water is infiltrating the reservoir.

Two-phase samples were collected from 47 production wells between March 8 and 15,1989 for tritium analysis. Surface water samples from cooling tower blowdown, sumps, rivers, and rainwater were likewise collected. They were all analyzed by the Department of Scientific Industrial Research in New Zealand. Sample volume was reduced from 1 liter to 8-10 ml by an electrolytic process and tritium was measured using a liquid scintillation counter.

Magnesium: In high temperature geothermal reservoirs with neutral pH, Mg content is usually low. One of the reaction by-products of acid stimulation is Mg, probably in the form of chloride or fluoride complexes.

The post-acid stimulation fluid chemistry of well Bul-72 showed that anomalous concentrations of Mg (a "Mg spike") and other elements are produced by the interaction of the acid and reservoir rocks (Figure 4). This suggests the possibility that acid stimulation by-products might he detectable in production wells close to acid stimulation targets. If that is so, then acid jobs *can* be simultaneously used as a tracer test (Hoagland, 1989).

Pre-stimulation background samples were collected from Bul-70 and -80 and their monitor wells in July 1990. Two-phase samples were collected once a day for 3 days and were analyzed for Mg and pH. A two-stage acid job was performed at Bul-80 on August 8-10, 1990 and samples were collected from 17 nearby production wells for *2.5* months. Bul-70 on the other hand was acidized on August 31, 1990 and 16 wells were monitored for pH and Mg for 1.5 months. Sampling continued for 10 days after Bul-70 was first flowed back. Mg was analyzed at the Bulalo Chemical Laboratory using an atomic absorption spectrophotometer.

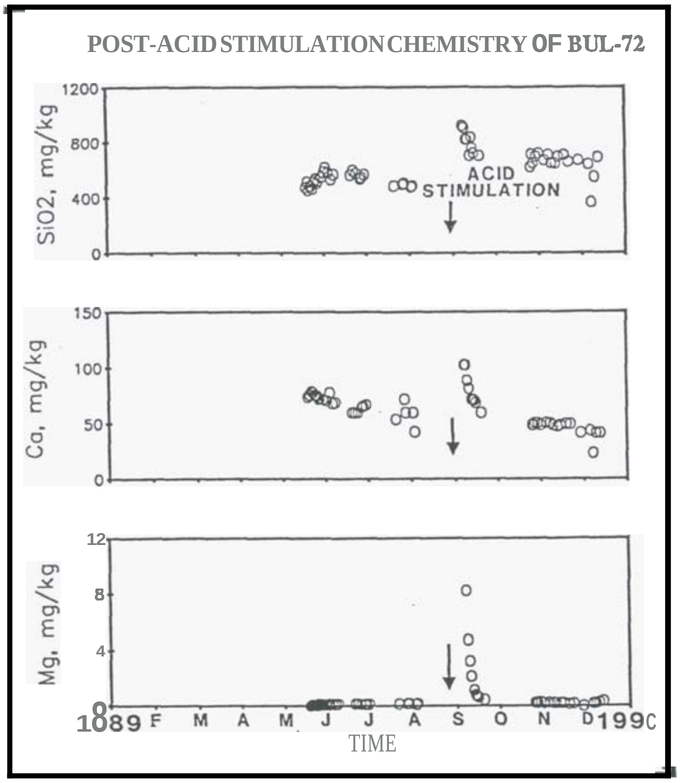


Figure 4- The post-acid stimulation chemistry of Bul-72.

## 3. RESULTS

Chloride: The western edgefield hot brine injectors have been operational since 1980. *An* increase in reservoir Cl was first noted at Bul-66 in 1986 and this continued into 1990 (Figure 5). A significant decline in discharge enthalpy and steam rate came later, in 1987. The steam decline rate of Bul-66 between 1989 and 1990 has been about **20% per year.** This is relatively higher than other wells in *the* vicinity. The fieldwide average decline rate is about 4.5% per year. Figure *6* shows the wells affected by injection breakthrough from the western edgefield injectors and the eastern hot/cold brine injectors.

Tritium: Sixteen wells showed anomalous tritium levels ranging from 0.09-0.3 TU. The magnitude of the anomalies is small compared to Tiwi which has a maximum of *1.9* TU. Surface waters contained tritium levels of 0.5-2.1 TU.

Magnesium: A Mg peak at Bul-72 appeared about *5* hours after acid injection with a magnitude of 72 mg/kg Figure 7). This is the fastest and largest tracer return among the monitor wells. Generally, the Bul-70 monitor wells showed lower Mg tracer velocities than did the Bul-80 monitor wells. Almost all monitor wells showed positive Mg returns except

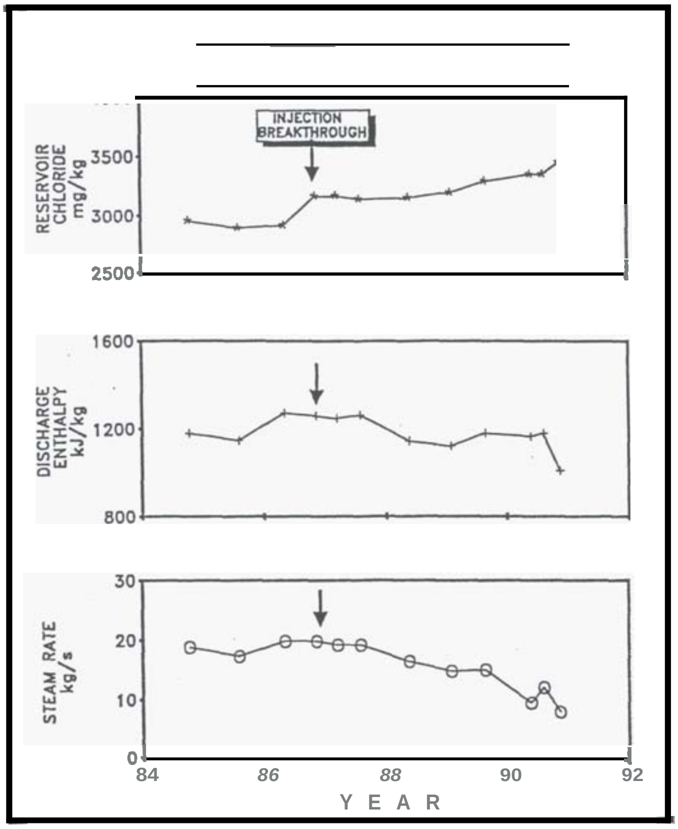


Figure 5- Plots of reservoir Cl, discharge enthalpy and steam rate of Bul-66.

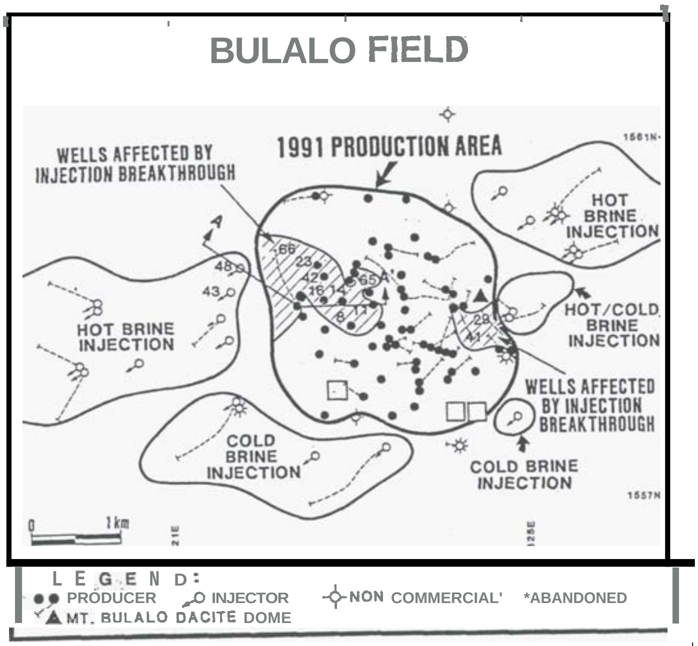


Figure 6- Map of Bulalo well locations showing areas affected by injection breakthrough.

Bul-1. *All* the monitor wells of Bul-80 showed Mg increases resulting from acid injection. The results are summarized in Table 1.

## 4. DISCUSSION

Chloride: Monitoring Cl in separated brine has been very useful in detecting reinjection returns to nearby production wells at Bulalo.

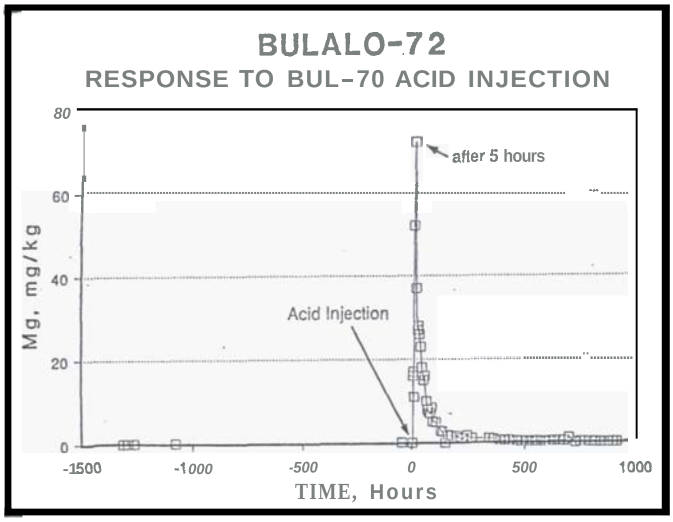


Figure 7- Plot of Bul-72 Mg tracer concentrations versus time in response to Bul-70 acid injection.

**Table 1 - Bul-80 and Bul-70 Magnesium Tracer Returns**

| BUL-80 MONITOR WELLS | PEAK ARRIVAL (Hours) | PEAK CONC. Mg,mg/kg | SPEED (m/hr) | BUL-70 MONITOR WELLS | PEAK ARRIVAL (Hours) | PEAK CONC. Mg,mg/kg | SPEED (m/hr) |
|---|---|---|---|---|---|---|---|
| Bul-11 | 6 | 0.4 | 72 | Bul-72 | 5 | 72 | 36 |
| Bul-28 | 7 | 0.6 | 124 | Bul-53 | 21 | 0.12 | 18 |
| Bul-3A | 9 | 025 | 41 | Bul-38 | 24 | 0.12 | 14 |
| Bul-09 | 9 | 0.5 | 90 | Bul-79 | 27 | 0.25 | 11 |
| Bul-08 | 10 | 0.5 | 74 | Bul-12 | 33 | 0.4 | 8 |
| Bul-71 | 15 | 0.3 | 14 | Bul-55 | 33 | 0.12 | 20 |
| Bul-06 | 19 | 0.45 | 20 | Bul-13 | 50 | 0.15 | 12 |
| Bul-01 | 23 | 0.4 | 8 | Bul-46 | 50 | 0.15 | 10 |
| Bul-20 | 23 | 0.4 | 23 | Bul-15 | 52 | 0.20 | 11 |
| Bul-23 | 23 | 0.45 | 33 | Bul-10 | 58 | 0.10 | 4 |
| Bul-65 | 23 | 0.25 | 9 | Bul-44 | 58 | 0.12 | 6 |
| Bul-07 | 24 | 0.4 | 22 | Bul-08 | 78 | 0.13 | 9 |
| Bul-13 | 24 | 0.45 | 19 | Bul-11 | 80 | 0.11 | 9 |
| Bul-64 | 25 | 0.4 | 12 | Bul-39 | 80 | 0.12 | 6 |
| Bul-14 | 26 | 0.15 | 22 | | | | |

Hot brine is more concentrated than the reservoir fluid because the steam phase has been separated from the liquid phase. The increase in reservoir Cl, followed by declines in discharge enthalpy and steam rates all suggest that the well is producing injected fluid. Fluids injected into Bul-48 and -43 probably migrate through a widespread tuff unit at about 670 m bsl (Figure 8). This tuff horizon forms the uppermost producing reservoir of Bulalo. Wells Bul-11, -14, -16, -23, and -42, which were affected by breakthrough in 1989 commonly produce from this horizon. Likewise, injection into the lower zone of Bul-48 has significantly worsened steam deliverability of nearby wells, particularly Bul-66. These wells intersected a common permeable zone at 1490 m bsl consisting of another thick tuff horizon situated in the downthrown block of the Makiling arcuate fault. The injectates travel in the deeper parts of the reservoir through faults related to the Makiling radial fault (*see* a, Figure 8) (Villadolid and Buban, 1991).

Realizing the consequences of injection breakthrough, we are currently changing the location of injectors at Bulalo. We stopped injecting in the western edgefield while new wells *are* drilled farther west. Injection at the two eastern hot/cold

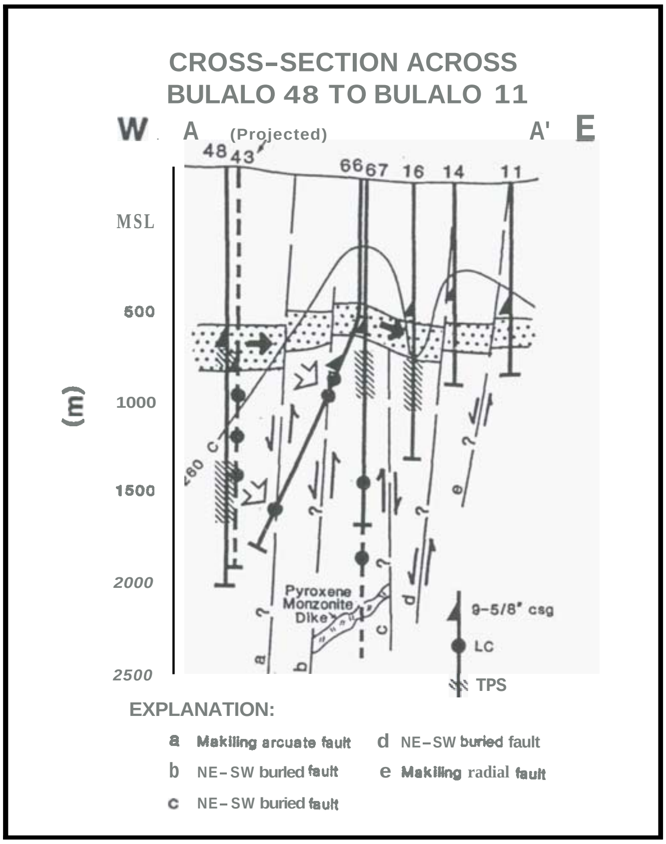


Figure 8- Cross-section A-A' through the western edgefield injection and production areas showing geologic structures, permeable zones and probable pathways of fluid from the western injectors.

brine injectors has been terminated to prevent production losses due to injection breakthrough.

Tritium: Four distinct anomalies were detected in the 1989. tritium survey results. These are the NE, NW, SE, and S anomalies shown in Figure 9.

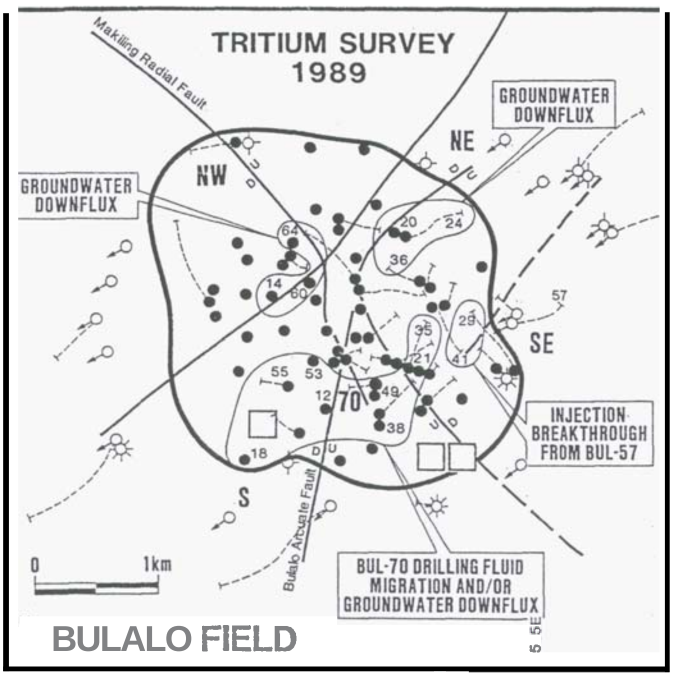


Figure 9- Map of 1989 tritium anomalies.

Tritium is plotted against the depth of first lost circulation in Figure 10. This shows that most wells that produce tritium in the NE and NW sectors have shallow production zones and are high enthalpy producers.

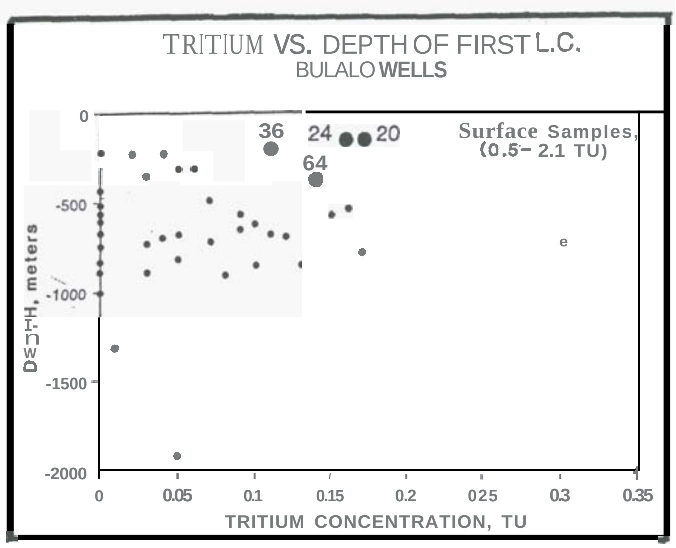


Figure 10- Relationship of tritium concentration with depth of first lost circulation.

The NE tritium anomaly is related to natural groundwater influx probably flowing along the Bulalo arcuate fault. Bul-20 and -24 have relatively higher decline rates. Bul-20 has been one of the highest tritium producers while Bul-24 is an "intermittent producer" and there are indications of downflux from this well going to Bul-20.

The NW tritium anomaly is also associated with natural groundwater influx. The wells responsible for this anomaly are located along the Makiling radial fault. The influx may originate from the slopes of Mt. Makiling and enters the reservoir at the intersection of two faults (Figure 9). The steam rate of Bul-64 is also declining from cold water influx. However, scaling is another possible reason for this well's decline.

The SE tritium anomaly is related to cold brine and condensate injection into Bul-57. Dilution events were noted at Bul-41 in 1987 which continued into 1988. Cold brine condensate were injected into Bul-57 during this time period.

The S tritium anomaly is related to two factors: 1) drilling of Bul-70 between December 1988 and February 1989, and 2) natural groundwater influx. During the first and second acid stimulation of Bul-70, permeable pathways were established from Bul-70 to the neighboring wells. The wells that contained tritium are also the wells that showed positive response to acid injection into Bul-70. This suggests that the tritium measured during the 1989 survey might have come from the drilling fluid. Natural groundwater infiltration to wells Bul-12, -21, -49, and -53 is also possible since their chemistries showed slight dilution prior to drilling Bul-70.

The results of the tritium survey have been valuable in deciding the location of make-up wells and in making field performance forecasts. In the new casing program, where a tritium anomaly exists, the shallow production zones of a well are cased off to prevent the risk of groundwater infiltration.

Magnesium: Figure 11 shows a contour map of Mg tracer arrival times for Bul-80 monitor wells. The wells that showed rapid returns are different distances from Bul-80 but showed small differences in their peak arrival times. This indicates that tracer returns are less dependent on distance from the tracer source than on flow path. Strobel (1989) defined a "permeability boundary" (Figure 11) at 590-1420 m bsl based on reservoir simulation work with relatively higher permeability to the west.

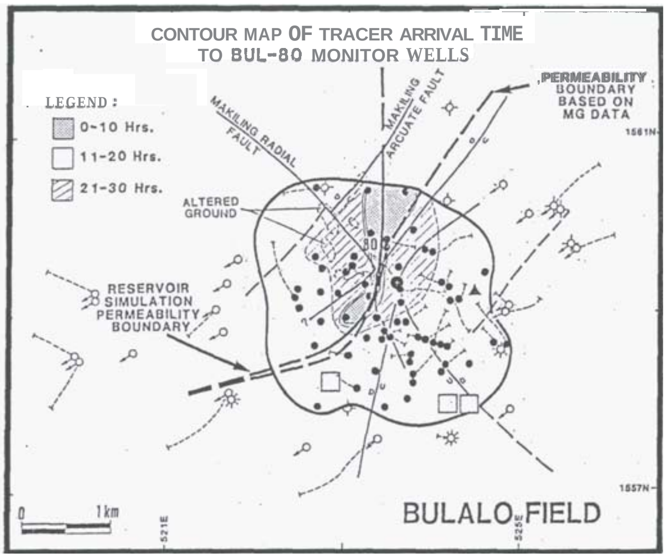


Figure 11- Contour map of Mg tracer arrival times of Bul-80 monitor wells.

The contour map showing response to the Bul-80 acid job shows that wells near the permeability boundary responded faster than wells on either side. Based on the results of Mg monitoring, the permeability boundary was revised; it now coincides with the mapped NE trending fault in Figure 11 (Villadolid and Golla, 1991).

The arrival times of Mg tracer to Bul-70 monitor wells were contoured in Figure 12. The largest and fastest Mg tracer return from Bul-70 to Bul-72 is probably because these two wells produce fiom the same horizon and are linked by permeable pathways related to the Makiling radial fault.

Generally, the western monitor wells exhibited faster response to acid stimulation compared to eastern monitor wells. It appears that secondary mineral deposition affects fluid movement in the eastern part of the field. Boiling of high NCG fluid probably caused extensive calcite deposition along the eastern and southeastern margins of the reservoir (Clemente, 1987). This probably explains the general differences in permeability between the eastern and western sides of Bulalo.

The technique of utilizing acid job by-products is an additional tool for identifying the permeable pathways and reservoir heterogeneities within the Bulalo reservoir. As a result of Mg monitoring, wells that showed strong fluid communication during acid jobs are being considered for an interference test study.

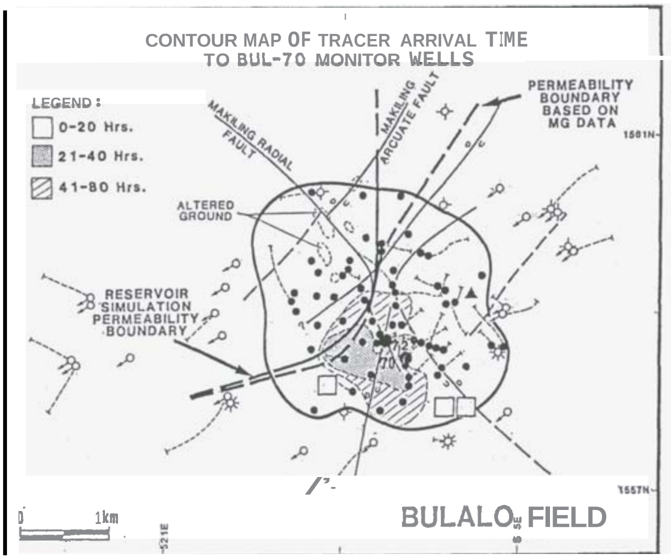


Figure 12- Contour map of Mg tracer arrival times of Bul-70 monitor wells.

## 5. CONCLUSIONS

Chloride is an important tracer in identifying areas affected, by injection breakthrough at Bulalo. Tritium has also proven; to be a useful tracer in studies of natural groundwater movement and other surface water such as drilling fluid and geothermal injectate breakthrough. Magnesium monitoring during acid jobs is a powerful tool to map permeable pathways within the reservoir and investigate interwell communication. Combining the knowledge gained from these tracers will increase our understanding of the reservoir mechanics and enable us to improve development strategy in the future.

## 6. ACKNOWLEDGEMENTS

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