

THE BULALO GEOTHERMAL FIELD, PHILIPPINES: CONCEPTUAL MODEL OF A PROLIFIC GEOTHERMAL SYSTEM

G.U. Golla¹, F.V. Abrigo¹, B.O. Alarcon¹, P.A. Molling² and J.A. Stimac²

¹Philippine Geothermal, Inc., 12/F Citibank Tower, 8741 Paseo de Roxas, Makati City 1226, Philippines
²Unocal Geothermal Technology and Services, 1300 N. Dutton Ave., Santa Rosa, California 95401, U.S.A.

ABSTRACT

After two decades of study and monitoring, a mature conceptual model of the Bulalo geothermal reservoir has been developed which serves as the basis for ongoing numerical simulation. Bulalo is a hot, water-dominated, neutral-pH, low-chloride (2,800 mg/kg) system that rapidly evolved into a two-phase system upon exploitation. This geothermal system has a structurally controlled core of relatively high permeability surrounded by hot, lower permeability rocks. The core region sits astride the 500 ka-old Bulalo dacite dome, which probably is a manifestation of more widespread shallow intrusion. Hot, lower permeability rocks in the west, east and south and low-temperature rocks in the northeast and southwest bound this nearly circular production area. Wells inside the high permeability core have high steam production, low annual production decline rates and fairly constant well chemistry. Non-condensable gas (NCG) content is generally low (0.5 wt%) but the southeast portion of the field is characterized by 2-3 wt% NCG in steam. Southeast Bulalo is also distinguished by abundant calcite deposition that is thought to be responsible for the relatively low permeability in this part of the field. In plan view, the production area appears relatively small but a broad basal region of deep high-temperature (>260°C) surrounds and underlies the main production area. The top of reservoir is shallowest (150-300 m bsl¹) in the central core and deepens (21,200 m bsl) and broadens towards the edges. The geothermal system has a fairly well sealed reservoir top as indicated by the relative scarcity of surface thermal manifestations.

Geochemistry and high measured temperatures have delineated two upflow zones: a major Central upflow in the sweet spot and a

minor one in the southeast. Stable wellbore chemistry in these two upflow areas suggests vigorous basal recharge during production. The lateral reservoir boundaries are partially open, and deep outflows (>1,200 m bsl) have been identified in the south and relatively shallow for the north and west. These outflows are now avenues of recharge of moderate enthalpy dilute fluids.

1.0 INTRODUCTION

One of the oldest producing geothermal field in the country is Bulalo (a.k.a. Mak-Ban), which is about 60 aerial kilometers southwest of Manila. Exploration began at Bulalo in the early 1970s with surface mapping and sampling and electrical resistivity surveys. In November 1974, discovery well Bulalo-1 was successfully drilled. The first 55 MWe power plant was brought online in April 1979. The five-year turn-around from exploration drilling to power plant commercialization is one of the fastest geothermal development cases in the world. By 1984, the initial 330 MWe of baseload capacity was installed and put online. In 1994, 15.73 MWe of binary power plant was put online. An additional 80 MWe of capacity followed in 1996, bringing total installed capacity to 425.73 MWe today.

The Bulalo geothermal field lies within the Macolod Corridor, a 40-km 'rift-like' geologic zone that connects the northern end of the west-subducting Philippine Trench in the east and the southern portion of the east-subducting Manila Trench in the west (Figure 2). The Corridor is characterized by NE-trending normal faults that form horst and graben structures and NW-trending left-lateral strike-slip faults that appear to possibly bound them (Forster et al., 1990). Volcanoes in the Corridor are chemically distinct from those of the northern Bataan and southern

¹ bsl or below sea level

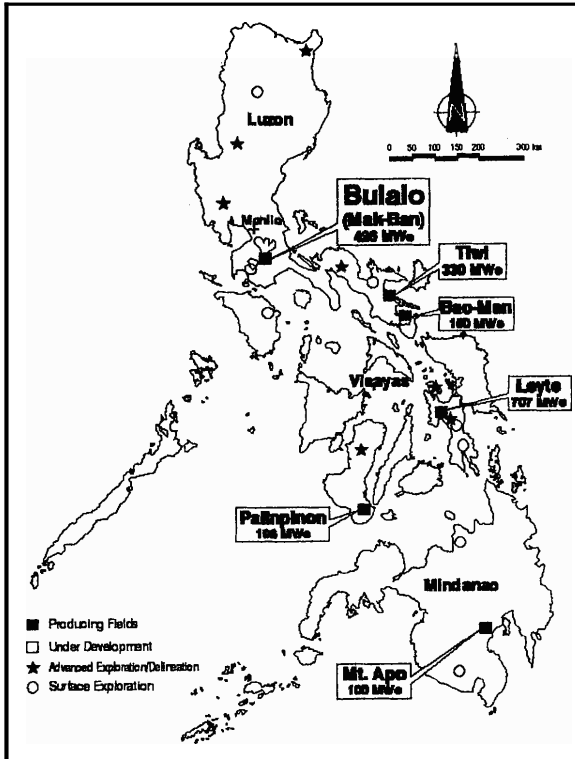


Figure 1. Map of the Philippines showing currently developed and producing geothermal fields.

Mindoro Volcanic Belts. Additionally, there are abundant NE-aligned basaltic scoria cones and maars and andesitic to dacitic domes immediately east of the Bulalo field (Figure 2). Maars and associated cones are postulated to be the surface manifestations of a basaltic dike swarm within the Corridor.

Clemente and Villadolid-Abrigo (1993) associated the development of the Bulalo geothermal system to two dacite domes: Mt. Bulalo (0.5 Ma) and Mt. Olila (1 Ma) (Figure 3). These dacite domes are found along the southeast flank of Mt. Makiling, a 2.7 Ma andesitic stratovolcano. Whole-rock geochemistry suggests a common magma source for these domes, indicating an extensive silicic plutonic complex at depth.

2.0 RESERVOIR FEATURES

2.1 Surface Thermal Manifestations

The Bulalo field is characterized by a general scarcity of surface thermal manifestations. The only surface thermal manifestations local to the system consist of

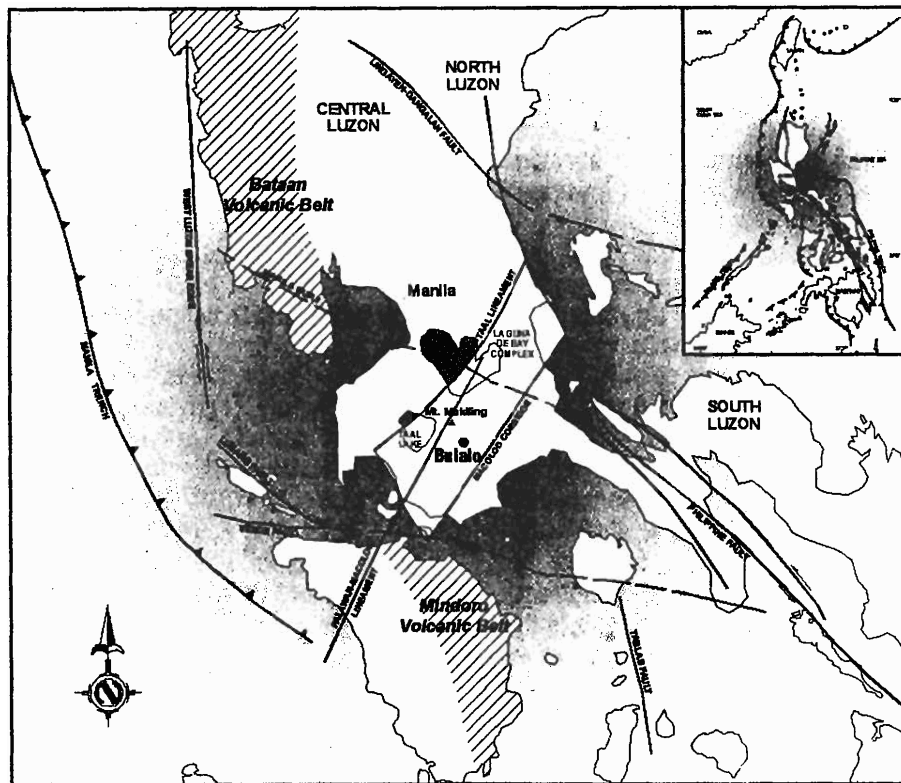


Figure 2. Map of the Philippines showing currently developed and producing geothermal fields.

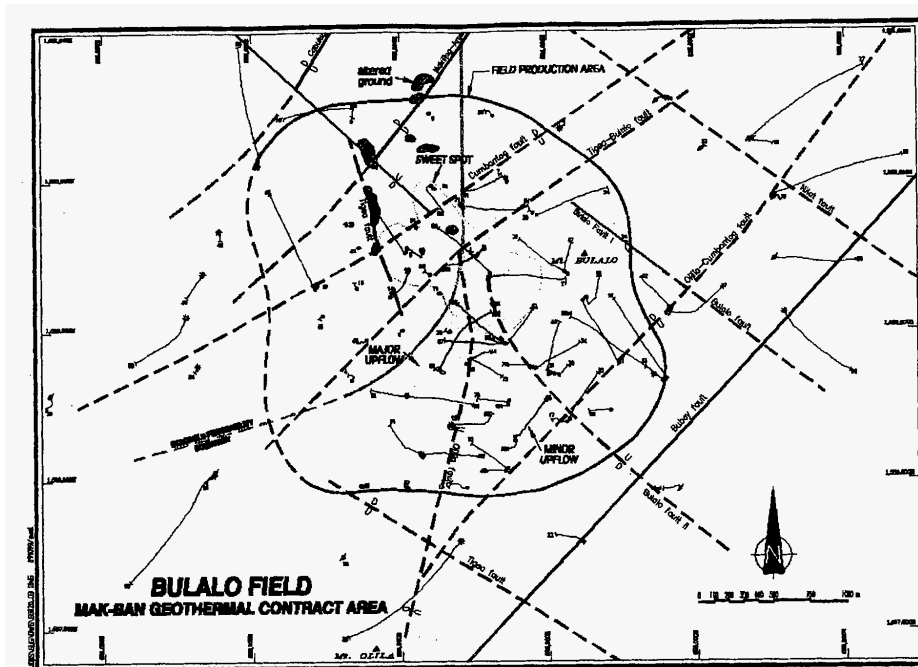


Figure 3. Plan view of the Bulalo (Mak-Ban) Geothermal Field showing the roughly circular 6.2 km² production area, the high permeability sweet spot and major and minor upflow areas. Also shown are major structures traversing the field.

small areas of weak fumaroles and warm altered ground that occur in the northern part of the production field. The Bulalo geothermal field is a low-elevation system located at the flanks of a stratovolcano. However, the apparent lack of thermal manifestations in Bulalo appears to benefit the resource. The absence of thermal features indicates that the system is well sealed along its upper margins. This is probably one of the reasons why Bulalo has maintained relatively high temperatures over its productive life, with little evidence of cool influx.

2.2 Host Rocks and Reservoir Configuration

Bulalo reservoir rocks are divided into three stratigraphic groups, namely: (1) surface rocks (including the Bulalo Dacite), (2) the Makiling Volcanics (MV) and (3) the Pre-Makiling Volcanics (PMV) (Clemente, 1987; Sigma, 1997; Buban, 1998; Golla, 1999). The PMV is estimated to be of Miocene to middle Pliocene age while the MV is late Pliocene to Pleistocene. Coarse-grained pyroxene monzonite and dacite dikes intrude both the MV and PMV. More extensive coarse-grained plutons have been encountered by the deepest wells in the west and southwest. These dikes suggest the presence of an underlying young intrusive that

likely provides the heat for the Bulalo geothermal system.

The MV is mostly composed of andesite lava and lesser lahars and pyroclastic flows from Mt. Makiling extending from near surface to -450 m bsl. The upper portion of the MV is locally altered to smectite, which appears to provide a low permeability cap to the geothermal reservoir.

The PMV is composed of andesite lavas and tuffs. These rocks, which are postulated to be the platform upon which Mt. Makiling laid its products (Clemente, 1987), and is the host of the producing reservoir. The Bulalo reservoir is generally found within the PMV at depths of 450-3,050 m bsl. So far, no reservoir bottom has been identified at Bulalo. The reservoir rocks are generally altered to a neutral pH calc-silicate assemblage of chlorite + illite + quartz ± epidote ± calcite ± wairakite ± pyrite. SOLVEQ modeling by Diomampo (1998) demonstrated that this mineral assemblage is in equilibrium with the chemistry of the wellbore discharge fluids, thus, indicating that it is a product of the current geothermal system.

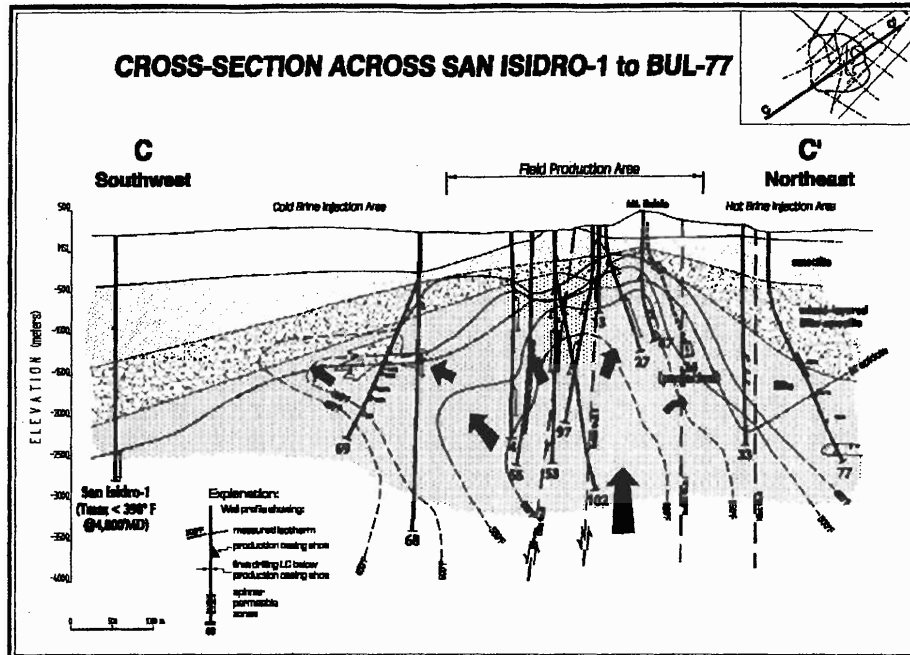


Figure 4. Southwest-northeast cross section showing clay zonation, first epidote, generalized fluid flow and deep outflow towards the southwest.

2.2.1 Clay alteration

Correlation of wellbore temperatures, rock mineralogy, and geophysical resistivity profiles identified a relatively shallow and thin smectite clay zone, the product of low-temperature ($\leq 120^{\circ}\text{C}$) alteration, capping the field's main production area. Within the field's production area, the smectite zone is commonly 150-300 m thick. Because of the well-sealed top, the system was forced to expand sideways through a porous volcanic tuff horizon thus forming the sombrero-shaped reservoir. The clay zone thickens on the margins of the field to ~600-1,200 m as shown in Figures 4, 5 and 6.

A deeper "transition" zone containing mix-layered smectite-illite, illite-smectite and chlorite-smectite, indicating a moderate-temperature (120° - 200°C) environment, generally follow the smectite trend. Where the smectite is thin (or thick), the transition zone is also relatively thin (or thick). The top of reservoir at Bulalo starts within the transition zone. In the east, the transition zone is very thick (~1,500 m) but still correlates well with the pre-production isotherms (Figure 6). In the northern portion of the production area, there is no transition from low- to moderate-temperature clays (Figure 5). However, there is a general agreement between the clay and measured isotherm trends even in northern Bulalo.

Illite clay, which is characteristic of high-temperature ($> 280^{\circ}\text{C}$) alteration, is dominant in the main reservoir section. However, lower temperature smectite and mix-layered smectite-illite sub-zones (or 'clay reversals') are found within the illite region (Figures 4 and 6). Some of these clay reversals may be relict products of low temperature alteration that have not equilibrated with the present day high-temperature fluids because of localized poor permeability. Others are probable imprints of either past or current cooler water recharge.

2.2.2 Epidote

Epidote is normally stable at temperatures $\geq 220^{\circ}\text{C}$, making it common in the high temperature liquid portions of many geothermal reservoir. In Bulalo, the shallowest occurrence of epidote (or first epidote) is a reliable indicator of the top of reservoir. During drilling, the combined presence of epidote, disappearance of smectite and flowline temperature of at least 80°C is used to determine the depth of production casing. Diomampo (1998) found that epidote is a good indicator of high permeability in Bulalo, as evidenced by the relative predominance of this mineral in the high permeability core of the field.

The occurrence of epidote in Bulalo generally matches the shape of the measured

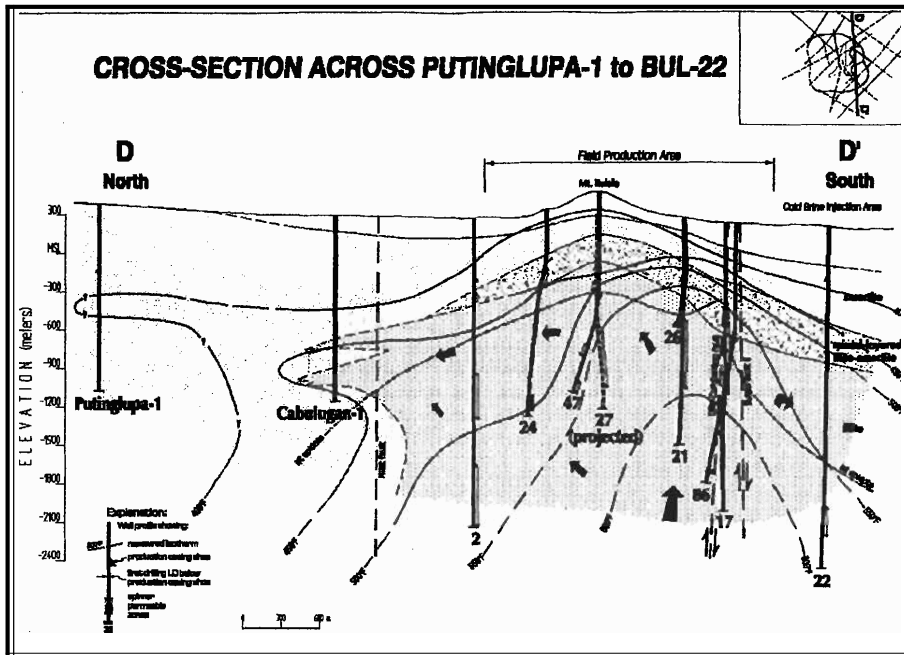


Figure 5. North-south cross section showing clay zonation, first epidote, generalized fluid flow and shallow outflow towards the north.

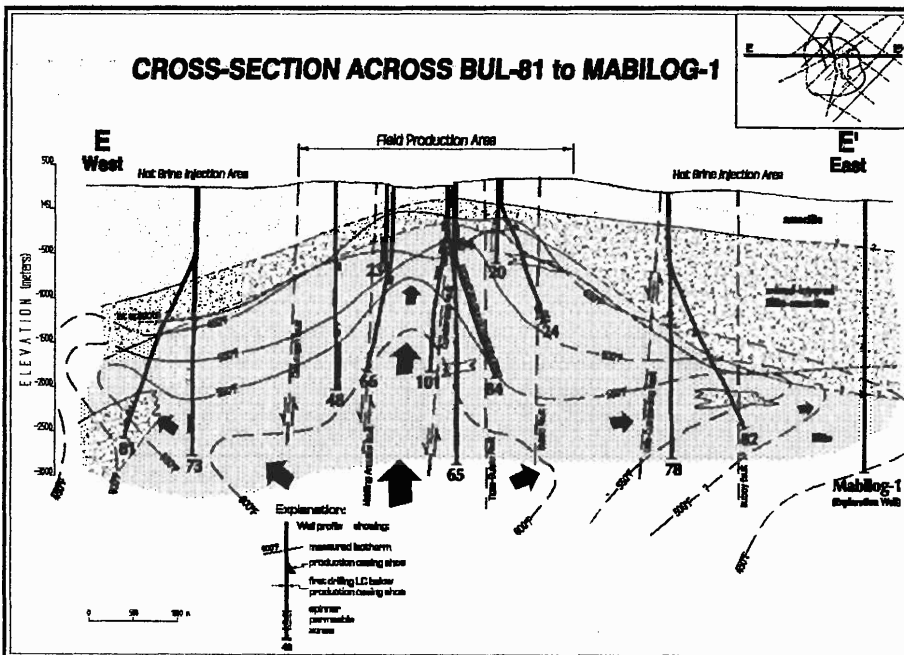


Figure 6. East-west cross section showing clay zonation, first epidote, generalized fluid flow and shallow outflow towards the west

isotherms, especially in the production area (Figures 4, 5 and 6). This is another indication that the current hydrothermal system is in equilibrium with identified hydrothermal alteration minerals. The deeper occurrence of first epidote in the south and southeast appears to be due to a greater abundance of carbon

dioxide in reservoir fluids. Along the periphery of the production area, deeper first epidote suggests that there may have been reservoir cooling along the outflow paths.

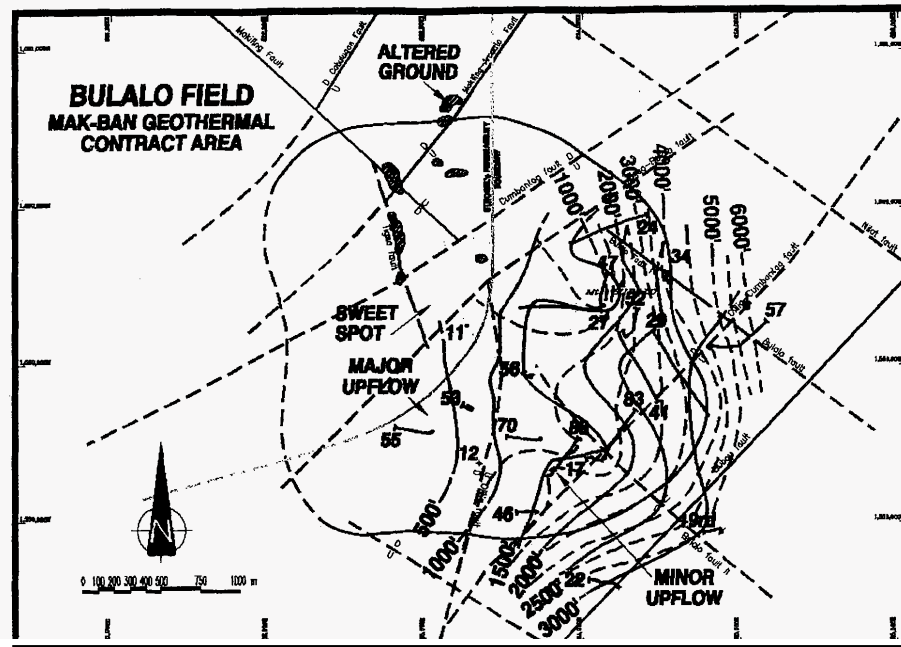


Figure 7. Plan view showing the thickness (solid lines) and bottom (dashed lines) of the calcite-rich horizon in high-NCG and low permeability southeast Bulalo.

2.2.3 Calcite in SE Bulalo

The high non-condensable gas (NCG) southeast Bulalo is characterized by abundant secondary calcite that extends deep into the reservoir (Clemente, 1987). Figure 7 is a plan view map showing the thickness and bottom of the calcite-rich horizon. Similar to the thickness contours, the bottom of the calcite horizon (dashed line) deepens towards the southeast. The calcite-rich zone is shallowest in the production area and deepens towards the reservoir edges. Outside the production area, the bottom of the calcite horizon is below 1,500 m bsl (Figure 7).

Clemente (1987) postulated that the calcite was deposited when ascending brine boiled as it encountered lower pressure at shallower levels. However, boiling should occur at far greater depths in gas-rich systems (i. e., southeast Bulalo) than in gas-poor systems (i. e., central Bulalo production area) (Nicholson, 1993). The deepening of the boiling point is caused by the increase of vapor pressure of the gas-rich fluid. This behavior is best shown by gas-rich edge wells where the bottom of the calcite horizon was encountered below 1,500m bsl (Figures 7).

Although it was postulated that the calcite in southeast Bulalo was precipitated due to boiling,

no bladed or platy calcite (indicative of boiling conditions during precipitation) has been encountered in samples analyzed to date. Most calcite appears either as replacement of phenocrysts and matrix of the host volcanic rocks or as open space filling in veins and cavities, and thus does not necessarily indicate boiling. Simmons and Christensen (1994) explained that replacement calcite is widespread and usually forms through hydrolysis reactions between calcium aluminosilicates and sub-boiling liquids that contain carbon dioxide. Platy or bladed calcite from boiling is formed over a restricted vertical interval (along faults and fractures) of a few hundred meters within the upflow zone through exsolution of carbon dioxide (Simmons and Christensen, 1994). Based on the extensive lateral and vertical distribution and absence of platy/bladed calcite, hydrolysis is probably the dominant process in southeast Bulalo.

This calcite apron in southeast Bulalo causes a loss in permeability. The deposition of calcite in open spaces and mineral micro-pores would be expected to retard the passage of fluids. Comparatively low permeability and poorly producing wells characterize southeast Bulalo.

2.3 Pathways, Barriers and Boundaries

Numerous NE-trending faults, parallel to the regional structural grain, and other NW- and north-trending structures pass through the field (Figure 3). Faults in the field are often zones of permeability at Bulalo; however, some faults actually act as barriers that prevent fluids from migrating from one sector to another. In many cases, faults appear to allow flow along strike but prevent flow.

Bulalo has a high permeability 'sweet spot' in the central portion of the field's production area (Figure 3). This sweet spot is an area where wells are producing ≥ 65 t/hr of steam, experience an annual decline rate of $\leq 4\%$, and where faults converge. The confluence of structures in this part of the field may have created an interconnected network of fractures and, consequently, high permeability. Similarly, the Cumbantog and Olila faults (in the north and south, respectively) appear to allow recharge back into the reservoir.

An interesting feature of the reservoir is the presence of an arcuate barrier, herein called the Strobel Permeability Boundary², which separates the northwest third with the rest of the field (Figure 3). During exploitation, wells west of the barrier generally have low steam fraction and possess lower enthalpy while wells east of the Boundary have high steam fraction and moderate to high enthalpy. Reservoir fluid entries west of the barrier tend to be confined to depths between 600-900 m bsl. There is no direct physical evidence that the barrier corresponds to a single fault or lithologic feature, but it is generally believed to be related to the possible northern extension of the Olila fault and the NE-trending Tigma-Bulalo fault (Figure 3). Recently, studies of the migration of tritium-rich meteoric waters appear to confirm the existence of this barrier. Other prominent barriers are the Olila-Cumbantog fault in the southeast, Tigma-Bulalo fault in the northeast and Bulalo 1 fault in the east. In the south, the Olila fault also serves as barrier because it prevents migration of fluids towards southeast Bulalo. The northwest boundary of the production area is delineated by the Cabulugan fault while the Buboy fault is the possible reservoir boundary in the southeast.

² Named after C.J. Strobel, a former Unocal reservoir engineer, who first postulated the barrier's existence.

2.4 Upflow

Clemente and Villadolid-Abrigo (1993) described the reservoir fluid at Bulalo as neutral-pH, dilute sodium chloride liquid with low total dissolved solids and NCG. Reservoir chloride (Cl_{res}), concentration ranges from about 2,100-3,500 mg/kg, which is low compared to other Philippine geothermal systems. Pre-exploitation chemistry indicates 0.7 wt% average total dissolved solids and 50.5 wt% average NCG. Chloride and NCG concentrations are highest in the SE, where an upflow was defined as described below. Surprisingly, and unlike all other commercial Philippine geothermal systems, no acid sulfate fluid has been identified in Bulalo.

Based on consistent trends in reservoir chloride and total flow NCG as function of depth, two upflows were determined in Bulalo (Molling and Abrigo, 1998). An arcuate primary Central upflow is located within the 'sweet spot' while a minor upflow was identified in the SE portion of the field (Figure 4). Both the Central and SE upflows possess the same basic chemistry, i.e., $\sim 2,800$ mg/kg Cl_{res} . The only difference between the two upflows is the amount of NCG in the produced steam: < 0.5 wt% in the central upflow and 2-3 wt% NCG in the SE upflow. Molling and Abrigo (1998) described the Central upflow as the primary source from which most pre-exploitation fluid chemistries have evolved. The minor SE upflow seems to supply the mass for highly-boiled fluids unique to the SE portion of the reservoir. It is generally thought that these two upflows join at depth.

2.5 Outflow and Recharge

The delineation of the outflow paths of the system has been made on temperature and pressure measurements in wells, resistivity signature and fluid geochemistry trends. The reservoir fluids initially outflowed towards the north, west and southwest (Figures 4, 5 and 6). Although isotherms have been extended towards well Mabilog-1 in the east, it may also be part of another system distinct from Bulalo (Figure 6). Low resistivity anomalies and temperature reversals and pressure behavior of Cabulugan-1 and Puting Lupa-1 confirm the presence of an outflow towards the north. The temperature reversals in outlying wells are evidences of the outflow towards the south and west. These outflow pathways are now avenues

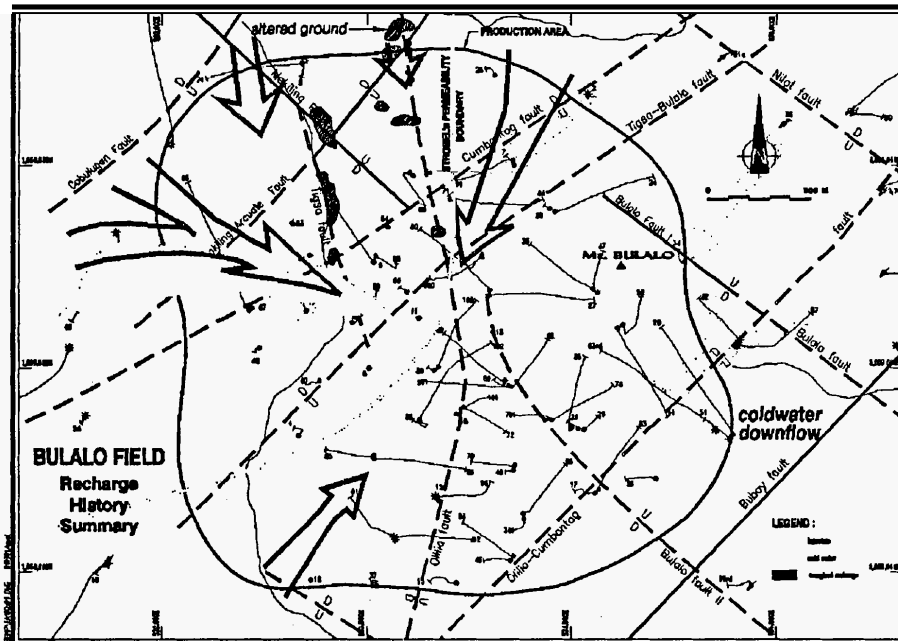


Figure 8. Recharge pathways in Bulalo based on geology, geochemistry and reservoir engineering data. Size of arrows define extent of recharge; injectate is shown as solid arrows; marginal recharge are the hollow arrows; the thin solid arrows in the southeast portion of the field represent meteoric recharge. Monitoring shows that what were once outflow pathways are now avenues of recharge.

of recharge, especially those in the north and west, based on geochemistry data. These fluid movements are parallel to the general orientation of the dominant structures in Mak-Ban.

Three types of recharge fluids, distinct from the Central and southeast upflows, are identified in Bulalo. These are marginal recharge, injectate and meteoric recharge (Abrigo et al., 2001) (Figure 8). These recharge fluids appear to be beneficial to the field in that they provide pressure support and have shown minimal detrimental effect on production.

Marginal recharge is moderate temperature ($T_{NKC} \sim 230^{\circ}\text{C}$), dilute (Cl_{res} 1,500-2,000 mg/kg) fluid that surrounded the production area during initial state (Abrigo et al., 2001). Influx and mixing of marginal recharge fluids with production has been detected in the west (610-1,050 m bsl), south (1,520-2,130 m bsl) and north (610-1,520 m bsl). Interestingly, the deep marginal recharge in the south enters the reservoir at nearly reservoir temperatures (T_{NKC} : 260°-290°C).

Injectate is typically high chloride (2,500-3,700 mg/kg), low NCG (<0.05 wt%) and cooler than reservoir water ($T_{measured}$ 190°-220°C) (Abrigo et al. 2001). Currently, injectate return to the production area is not a major source of recharge in Bulalo. Injection breakthrough was a major concern in the western production area. The original western edgefield injectors are well connected to the production area, and these injectors caused chemical and thermal breakthroughs during 1988-1991 (Sta. Maria et al., 1993; Wijaya and Molling, 1998). During this period, most western producers showed an increase in chloride and decrease in both NCG, and enthalpy. After shifting injection further west, it took about 1.5-2 years for the western producers to recover from chemical breakthrough (Abrigo and Molling, 1999). Aside from the west, minor injection breakthroughs were observed in the northeast and east (Figure 8). Thermal breakthrough was avoided by terminating injection in these other areas.

Natural influx of cold water into the reservoir has not been observed at Bulalo. However, downflows of cold water through casing leaks have occurred in recent years. In the southeast, meteoric recharge in Bulalo-51 in 1993 showed

up 2-3 years later in four nearby wells (Figure 8) (Abrigo et al., 2001). Workovers of wells with casing breaks arrested the spread of this cold water.

3.0 SUMMARY OF CONCEPTUAL MODEL

In plan view, the production area of the Bulalo geothermal field is roughly circular and appears relatively small at 6.2 km², but a broad base of deep high-temperature (>285°C) region surrounds and underlies the main production area. This configuration creates a "sombbrero-shaped" reservoir. The top of reservoir is shallowest (150-300 m bsl) in the central core and deepens (≥1,200 m bsl) and broadens towards the edges thus resulting in the sombrero configuration. This Bulalo geothermal system has a fairly well sealed reservoir top as indicated by the relative absence of surface thermal manifestations.

The internal structure of the Bulalo reservoir is largely dictated by faults. The intersection of faults in the interior of the geothermal field coincides with the central upflow and sweet spot. Other faults act as pathways for injectate and marginal recharge. Still others act as semi-permeable barriers as exemplified by the high NCG and high chloride brine portion in SE Bulalo. The NW boundary of the resource appears to be the Cabulugan fault while the Buboy fault is the possible SE boundary.

The overall thickness of the Bulalo field is not yet defined especially below the production area. The bottom of the reservoir appears to be at about (or even deeper than) 3,050 m bsl under the production area.

Geochemistry and measured high temperatures have delineated two upflow zones in Bulalo: a major upflow in the central part of the field and a minor one in the SE. A portion of the central upflow is coincident with the sweet spot, a sector of high steam deliverability and low decline rate. Constant wellbore chemistry in these two upflow areas suggests vigorous basal recharge over time. Partially open boundaries or deep (>1,520 m bsl) outflows have been identified in the S but relatively shallow for the W and N (-610 m bsl). These outflows are now avenues of recharge back into the reservoir.

ACKNOWLEDGMENTS

The authors would like to thank PGI and Unocal management for the support and permission to publish this paper. Reviews by Dave Rohrs, Gregg Nordquist, Wilson Clemente and Tom Powell helped finalize this paper.

REFERENCES

- Abrigo, F.V. and Molling, P.A. (1999). Recharge History of Bulalo. PGI memo, 7 pp.
- Abrigo, M.F.V., Molling, P.A. and Acuña, J.A. (2001). Geochemical Quantification of Recharge at the Bulalo Geothermal Field, Philippines, this volume.
- Buban, A.C. (1998). The Proposed Mak-Ban Geologic-Conceptual Model. PGI memo, 15 pp.
- Clemente, W.C. (1987). Petrographic Studies of the Bulalo Field. PGI memo, 31 pp.
- Clemente, W.C. and Villadolid-Abrigo, F.L. (1993). The Bulalo geothermal field, Philippines: Reservoir characteristics and response to production. *Geothermics*, Vol. 22, No. 5/6, pp. 381-394.
- Diomampo, G.P. (1998). Study of alteration mineralogy and fluid composition of the "Sweet" and "Sour" wells of Bulalo. PGI memo, 12 pp.
- Forster, H., Oles, D., Knittel, U., Defant, M.J. and Torres, R.C. (1990). The Macolod Corridor: A rift crossing the Philippine island arc. *Tectonophysics*, Vol. 183, pp. 265-271.
- Golla, G.U. (1999). Review of the structures, stratigraphy, hydrothermal alteration and geophysics of the Bulalo field: Implications to the conceptual model. PGI memo, 30 pp.
- Molling, P.A. and Abrigo, F.V. (1998). Analysis of upflow in the Bulalo reservoir: Implications for the conceptual model. PGI memo, 9 pp.
- Sigma Energy Technologies, Inc. (Sigma). (1997). The subsurface geology and hydrothermal alteration of the Mak-Ban geothermal field. Technical report for PGI, 31 pp.

Simmons, S.F. and Christensen, B.W. (1994). Origins of calcite in a boiling geothermal system. *American Journal of Science*, Vol. 294, pp. 361-400.

Sta. Maria, R. B., Villadolid-Abrigo, M.F., Sussman, D and Mogen, P.G. (1995). Development strategy for the Bulalo geothermal field, Philippines. *Proceedings of the 1995 World Geothermal Congress*, Vol. 3, pp. 1803-1805.

Wijaya, B.A. and Molling, P.A. (1999). Injection breakthrough in Western Bulalo. PGI memo, 11 pp.