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Mak-Ban Geothermal Field, Philippines: 30 Years of Commercial Operation

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ABSTRACT

The Makiling-Banahaw (Mak-Ban, also known as Bulalo) geothermal field was the second geothermal resource (after the Tiwi Field) developed by Chevron Geothermal Philippine Holdings, Inc. (CGPHI) under a service contract executed in 1971 with the National Power Corporation. The deep discovery well, Bul-1, was drilled in 1974. Commercial production began in 1979 with the operation of the first two 55MWe generating units. Capacity was increased to 220MWe in 1980 and then to 330MWe in 1984, with the six 55MWe units installed in three power plants. Six binary bottoming-cycle plants totaling 15.73MWe were installed in early 1994 followed by two 20MWe steam turbine units in 1995 and a further two 20MWe units in 1996, bringing installed capacity to 425.73MWe. In 2004-05, four units were rehabilitated bringing the current fieldwide installed capacity to 458.53MWe. However, the present plan is to base-load Mak-Ban at 402MWe with 40MWe on stand-by, plus the binary plants.

To date, 113 wells have been drilled to measured depths ranging from 655m to 3,625m to support the production and injection capacity requirements. A total of 69 production wells presently provide steam to eight separation stations, while 23 injection wells provide the injection capacity for separated brine and power plant condensate re-injection. Generation in recent years has been affected by steam supply limitations, power plant availability and the introduction of a competitive wholesale electricity spot market (WESM) resulting in decreased generation and operational concerns when the units were used as load following rather than base load plants, but this situation has improved in 2008.

Mak-Ban is a remarkable example of a stable, relatively problem-free geothermal reservoir, based on its performance during these 30 years. During the first few years, reservoir pressures drew down rapidly resulting in the expansion of the two-phase zone with increased discharge enthalpy and steam flash as the main effect on production. More recently, however, the reservoir has been affected by marginal recharge, injectate and meteoric water. The main effect of these fluids is seen in a decrease in average steam flash which was greater than 50% up to 2001 and is about 43% in 2008. Technical and operational measures have been taken to mitigate the effects of these various fluids on the resource and on generation.

In the last 30 years, the Mak-Ban field operation has generated a total of 61,827 GWh of electricity saving the government from importing 114.67 million barrels of oil equivalent (MBOE). This high level of generation has been supported by an area of only ~7 km2, for a production density level of about ~57MWe/km2, with only modest declines. This is a very high density when compared to geothermal fields worldwide. The recent drilling program has accessed hotter, high pressure reserves deeper into the reservoir and the results are very encouraging. CGPHI therefore looks forward to many years of continued operation of this excellent geothermal resource.

1. INTRODUCTION

The Philippine Geothermal Inc. was a wholly-owned subsidiary of Union Oil of California until August 2005 when Chevron acquired it. PGI signed a Service Contract Agreement with the National Power Corporation on September 10, 1971 and was awarded the rights to explore and develop geothermal resources in two contract areas: the Tiwi Geothermal Contract Area under P.D. 739 in 1971 and the Mak-Ban Geothermal Service Contract Area under P.D. 1111 in 1974. The Mak-Ban (Makiling-Banahaw, also known as Bulalo) geothermal field is located in the island of Luzon, about 70 km southeast of Manila. The service contract area covered 1575 km^2 where eleven prospect areas were explored, out of which PGI successfully delineated and commercialized the Mak-Ban Geothermal Field, starting in 1974 with the deep discovery well, Bul-1.

2. FIELD DESCRIPTION

2.1 General Geology

The Mak-Ban Field is located in the Macolod Corridor, a 40-km “rift-like feature” that traverses the SW portion of the Luzon Island, (Forster et al., 1990; Pubellier et al., 2000; Aquino, 2004) separating the northern “Bataan” and southern “Mindoro” arc segments (Defant et al., 1988). Regional faults in the Macolod Corridor trend predominantly NE-SW, NW-SE and N-S and the main structures that control the Mak-Ban geothermal reservoir also trend NE-SW, NW-SE (Figure 1) although some N-S faults are also mapped (Golla et al., 2001; Aquino, 2004). Aquino (2004) stressed that NE and N-trending faults are the best targets for permeability because they are most likely extensional and the recent drilling campaign seems to verify this. Bulalo is about 1000’ above sea level but has accumulated approximately 5000’ of volcanic rocks in the past 500,000 years consistent with the tectonic setting being locally extensional and facilitating rapid deposition of volcanic and sedimentary units in the fault-bounded basin. No sedimentary basement has been encountered in Bulalo to maximum drilled depths of 11,000 feet, but some deep wells have encountered intrusive rocks. Evidence for continuing volcanism includes reported $^{40}Ar/^{39}Ar$ ages of < 22,000 years on hornblende separates from the Bulalo and Olila dacite domes (Stimac, 2003).

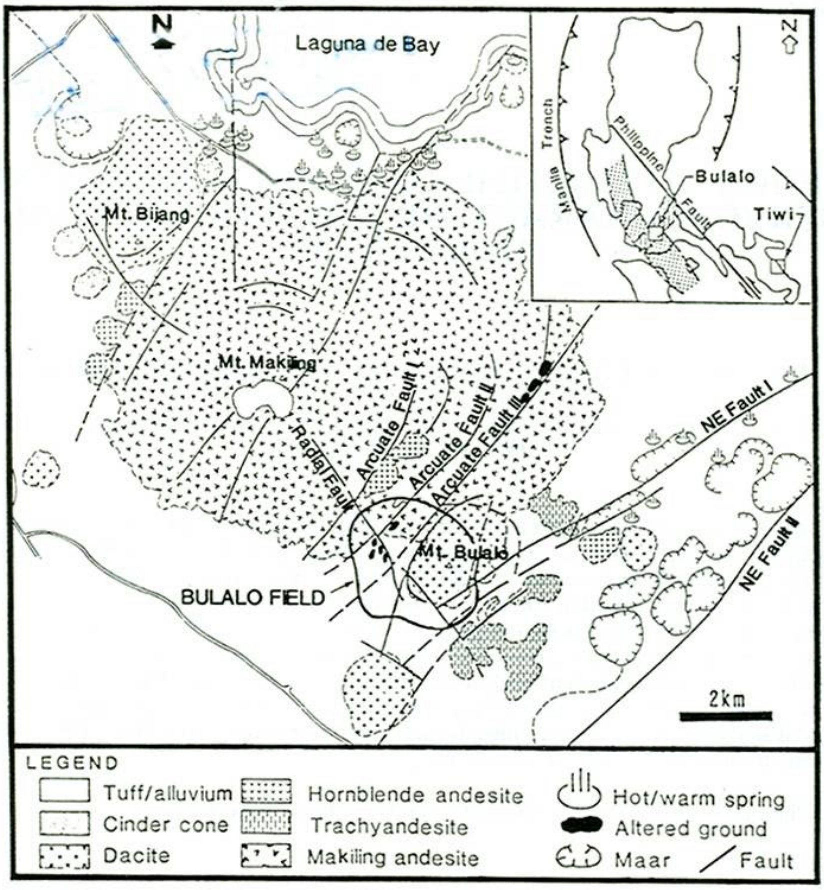

Figure 1: Geologic map of the Makiling Area. Inset shows tectonic setting of Luzon. Stippled areas in the inset are the Bataan and Mindoro arc; hatched area is the Macolod corridor (from Clemente et al. 1993).

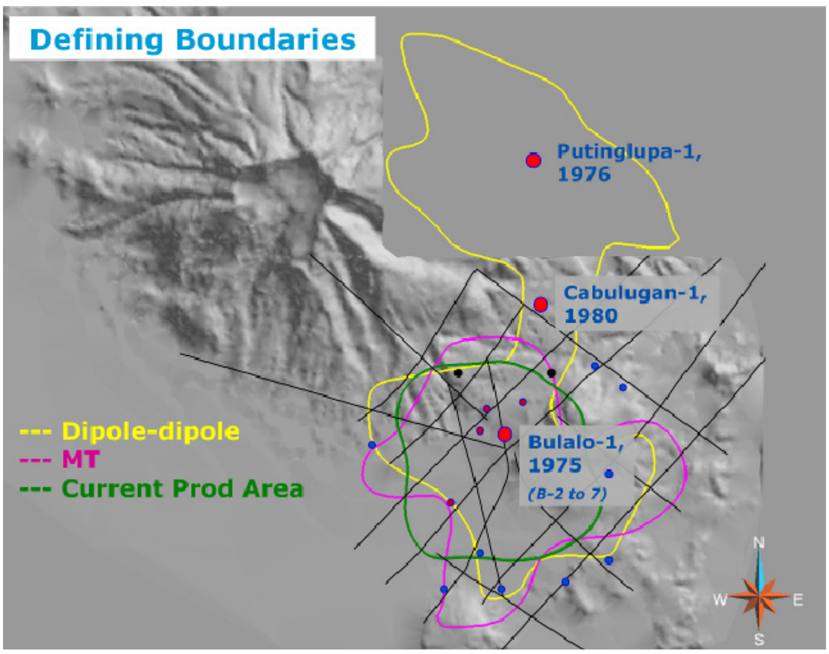

Figure 2: Resistivity anomalies in Mak-Ban. The Mak-Ban production area is outlined in green and roughly coincides with the dipole-dipole anomaly (yellow) and the MT anomaly (pink).

The hydrothermal system developed at Bulalo is associated with two dacitic domes (Mt. Bulalo and Mt. Olila) present on the SE flank of Mt. Makiling (Figure 2). The geothermal system has a well-sealed reservoir cap, so only minor surface thermal manifestations are found in the immediate area. An extensive near-surface hydrothermal clay alteration was identified through electrical resistivity surveys in 1972 and serendipitously, the discovery well Bul-1 was right in the middle of it. Figure 2 also show that the resistivity anomaly roughly coincides with the current production area. The dipole-dipole data suggest an extension of the clay alteration about 6 km to the north along the eastern flank of Mt. Makiling (Clemente and Villadolid-Abrigo, 1993) but for Mak-Ban, the MT anomaly is proving to be the better indicator.

2.1 Conceptual Model <Heading 2 Style>

Mak-ban is a fracture-controlled, hot, liquid-dominated, neutral-pH, system that rapidly developed a two-phase zone upon exploitation. The reservoir fluids have relatively low chloride (2800 mg/kg) and low gas (<0.5 wt%) concentrations compared to other Philippine geothermal systems (Abrigo et al., 2006) In plan view, the production area is only about 6-7 km^2 but a broad basal region of deep high temperature (>260^{0}C) surrounds and underlies the main production area allowing the highly permeable core to draw upon hot recharge from lower permeability rocks on its margins (Clemente and Villadolid, 1993; Golla et al., 2001). The top of the reservoir occurs between 100 m (328') and 1250 m (4100") below sea level. It is shallowest near the center, deepening gradually to the west and north, and deepening abruptly to the east and south (Clemente and Villadolid-Abrigo, 1993). A porous volcanic tuff unit provides an important fluid flowpath at the reservoir top, especially on the western side of the main production zone (Figure 3). SE Bulalo has a rather thick calcite–rich horizon which, based on the extensive lateral and vertical distribution and the absence of platy/bladed calcite, was formed by hydrolysis reactions between calcium alumino-silicates and sub-boiling liquids that contain carbon dioxide (Golla et al., 2001, Simmons and Christensen, 1994).

Geochemistry, combined with measured temperatures, has delineated a major upflow in the high-permeability central part of the field and a minor upflow in the SE. Wells inside this high permeability core have high temperatures, high team production, low annual production decline rates and fairly constant well chemistry suggesting basal recharge over time (Molling and Abrigo, 1999). In the initial state, partially open boundaries or shallow and deep outflows were identified on the N, S and W. After exploitation, those same boundaries are now regarded as the pathways of recharge to the reservoir. Recharge to the reservoir as a response to exploitation includes marginal or peripheral fluids, injection returns and meteoric water. Peripheral fluids are believed to be a mixture of basal recharge, which was modified through boiling along its upflow and outflow paths, and marginal fluids. As exploitation draws down the pressure in the reservoir, these fluids return as recharge through the outflow paths (Figure 4). In Figure 4, altered ground related to leakage from the system is shown in yellow, faults that act as semi-permeable barriers are highlighted in orange and areas of upflow are shown in magenta. Areas of marginal recharge and their assumed temperatures at initial state are outlined by the blue areas. The gray area encloses a region with measured temperatures > 600 º F. Wells in the solid red circles have historical NKC geothermometer temperatures > 590 º F. The purple line delimits the high gas SE sector: > 1.5% NCG in steam (Stimac et al., 2006).

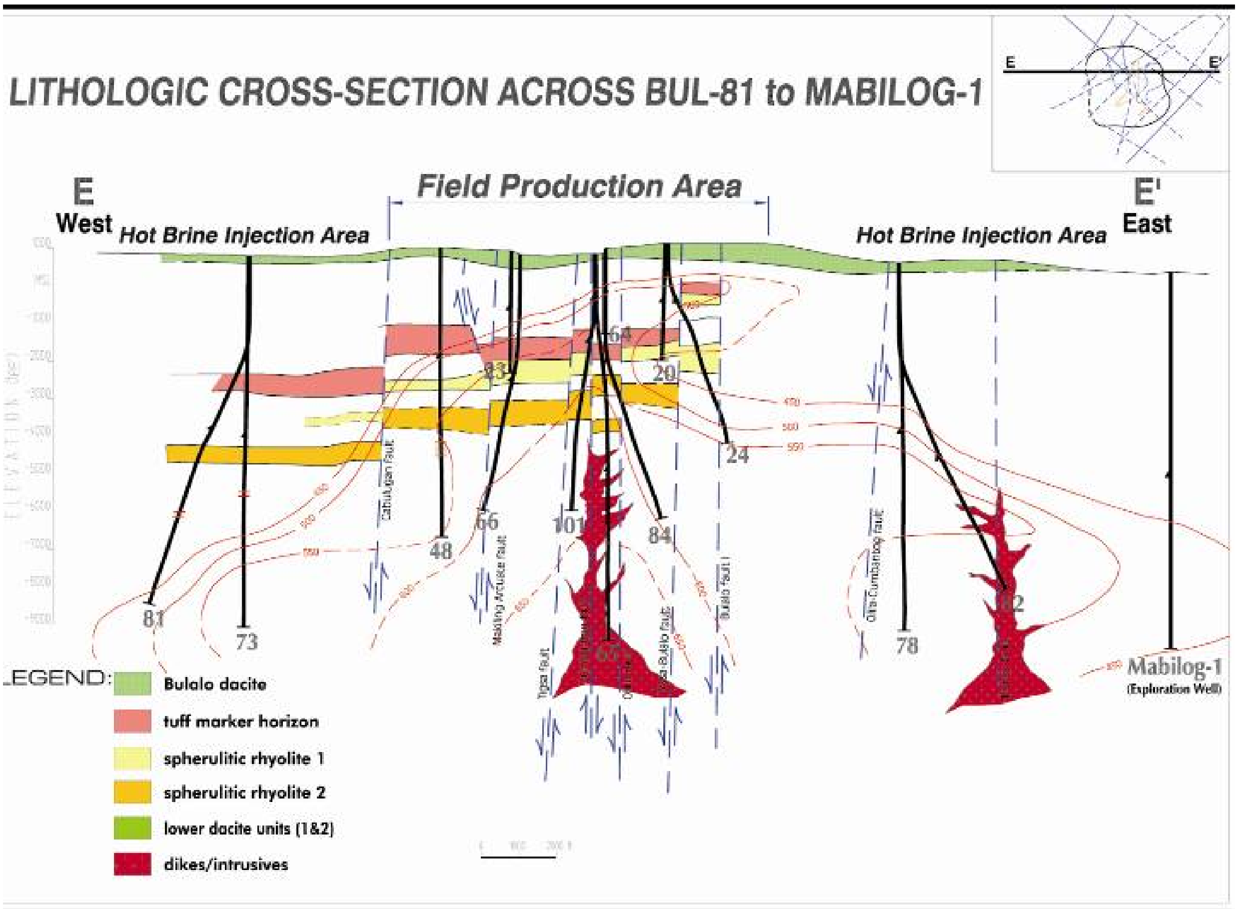

Figure 3: West-east cross section through the Bulalo field showing lithology, faults and isotherms. Note the broad basal region of high temperature rocks supporting the production from a small are in the surface.

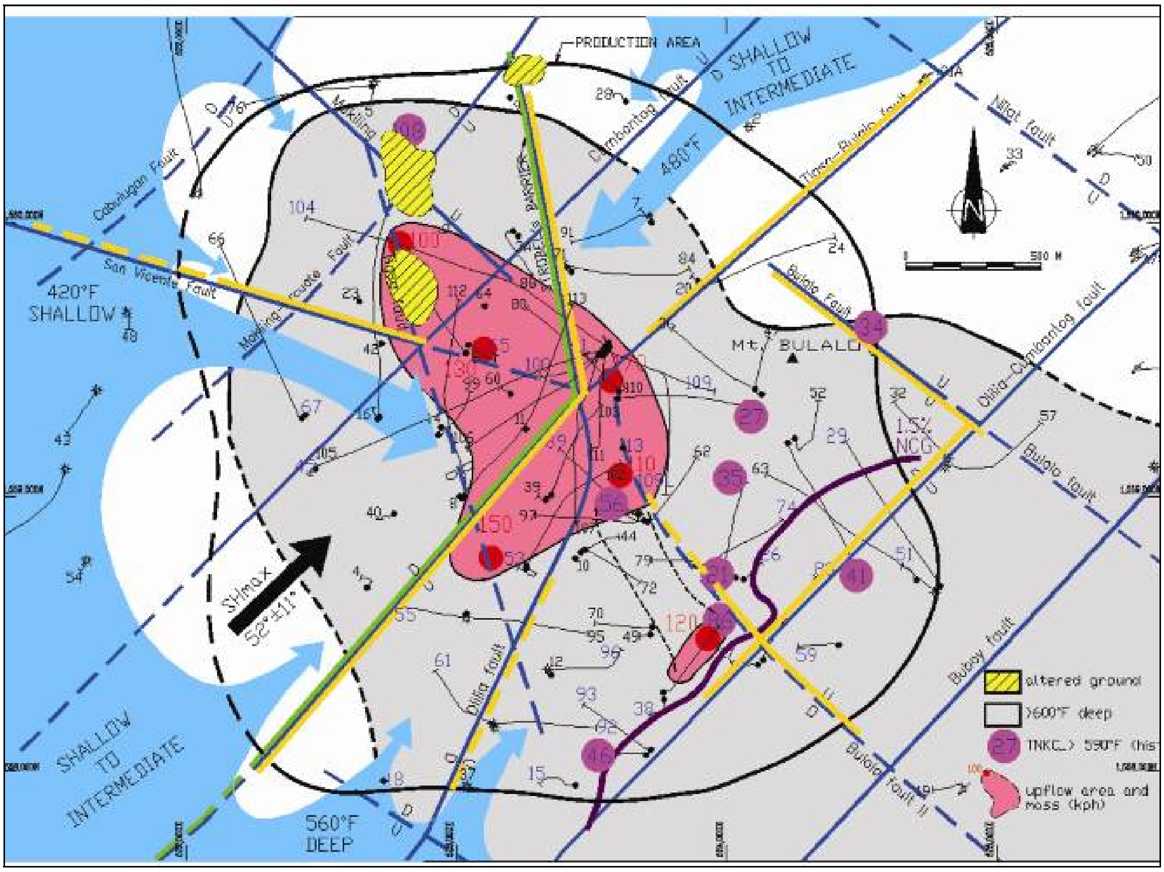

Figure 4: Summary of key conceptual model elements.

A geomechanics study determined that the maximum horizontal stress is oriented NE as interpreted from drilling induced fractures in borehole image logs from the sweet spot area (GMI Report, 2002). Injectate flowpaths interpreted from tracer test results are parallel to the direction of maximum horizontal stress, indicating that fluids preferentially flow along faults or distributed fractures that are critically stressed (Figure 5). However, reservoir and geochemical monitoring indicate that thermal degradation from injection breakthrough is not a danger to the production area.

3. DEVELOPMENT HISTORY

The discovery well (Bulalo-1) was drilled in 1974, and commercial production began in 1979 with an installed plant capacity of 110 MWe. This was increased to 220 MWe in 1980, and 330 MWe in 1984 (Sussman, et al., 1993). Binary units totaling 15.73 MWe were installed in early 1994, and two 20 MWe generating units were added in 1995 (Units 7 and 8) and another two units in 1996 (Units 9 and 10), bringing installed capacity to 425.73 MWe. In 2004-2005, Units 1-4 were rehabilitated and their generation capacity was increased to 63.2 MWe each. The installed capacity of Mak-Ban is now 458.53 MWe and this includes 15.73 MWe of binary units' capacity and the 40 MW of the standby units of Plant D (Figure 6) Presently, the Steam Gathering System (SGS) consists of eight separation facilities, 11 km of steam lines, 63 km of two-phase lines and 17 km of injection lines.

As of 2005, 113 wells have been drilled throughout the field. Of these, 69 wells provide the current steam requirements, 23 wells are used for brine and condensate injection, while the remaining wells are inactive, plugged and abandoned, or unproductive. Thus, 80% of the wells ever drilled in Bulalo are still in service (including the discovery well Bul-1 which still produces about 55 kph of dry steam), demonstrating an outstanding 35-year history of well targeting efficiency and completion durability. The deepest well has a measured depth of 3,625 m (11,890') while the shallowest is 655 m (2,148'); average well depth is about 2214 m (7353'). Average steam and brine flow rates are 14 and 16 kg/s (114 and 128 klbs/hr), respectively.

4. RESERVOIR PERFORMANCE

4.1 Production and Injection History

In the last 30 years, the Mak-Ban field operation has generated a total of 61,827 GWh of electricity saving the government from importing 114.67 million barrels of oil equivalent (MBOE). From 2003 to 2005 production was curtailed due to operational (rehabilitation of Units 1-4) and commercial factors. Makeup drilling and "banked steam" subsequently resulted in record generation for 2007.

Initially fieldwide average flash was below 50% but after a few years of pressure drawdown, the flash increased to 50-60%, where it remained stable until 2001. The reservoir responded well to the substantial capacity and load increases during the 1980's and 1990's. Decline rates have remained reasonable throughout the history of the field. As the shallow portions of the reservoir were drawn down, make-up drilling productivity has been sustained by adopting larger-diameter well completions (13⅜" production casing) starting in the 1980's, and by drilling deeper to tap hotter, higher-pressure targets. In recent years the shallow pressure drawdown has drawn in cooler marginal fluids and has decreased field flash to 43%. But despite the marginal recharge problem, overall decline rates remain moderate and the field is likely to sustain excellent performance for decades to come.

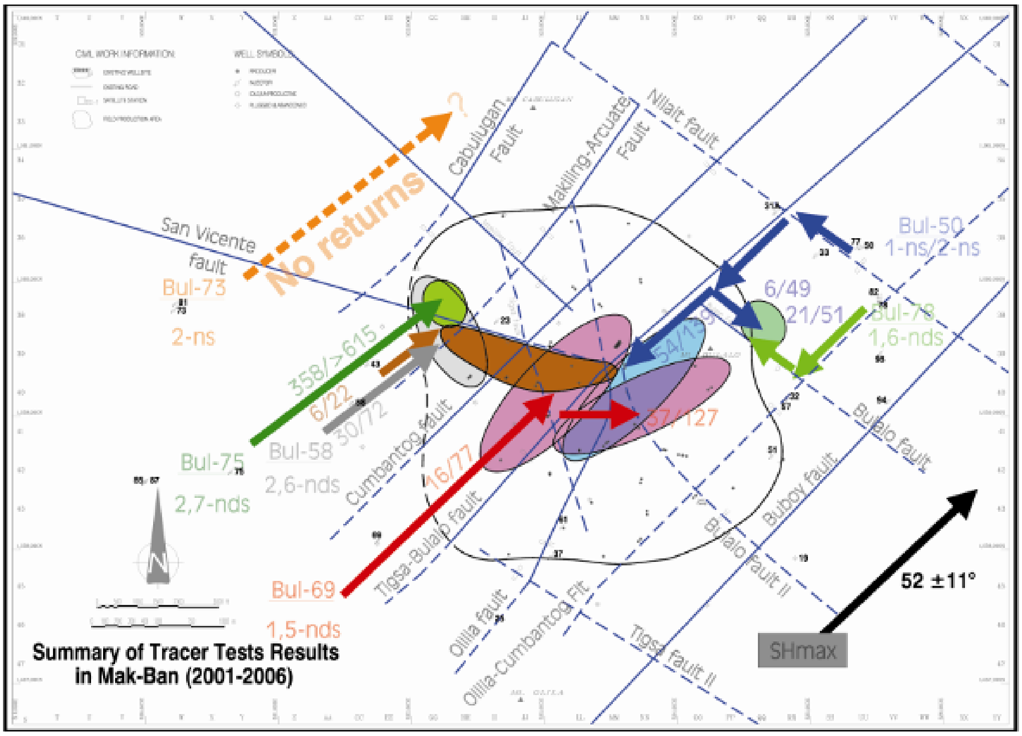

Figure 5: Summary of tracer tests conducted in Bulalo over a six-year period. The color-coded areas show regions where returns were noted for each tracer.

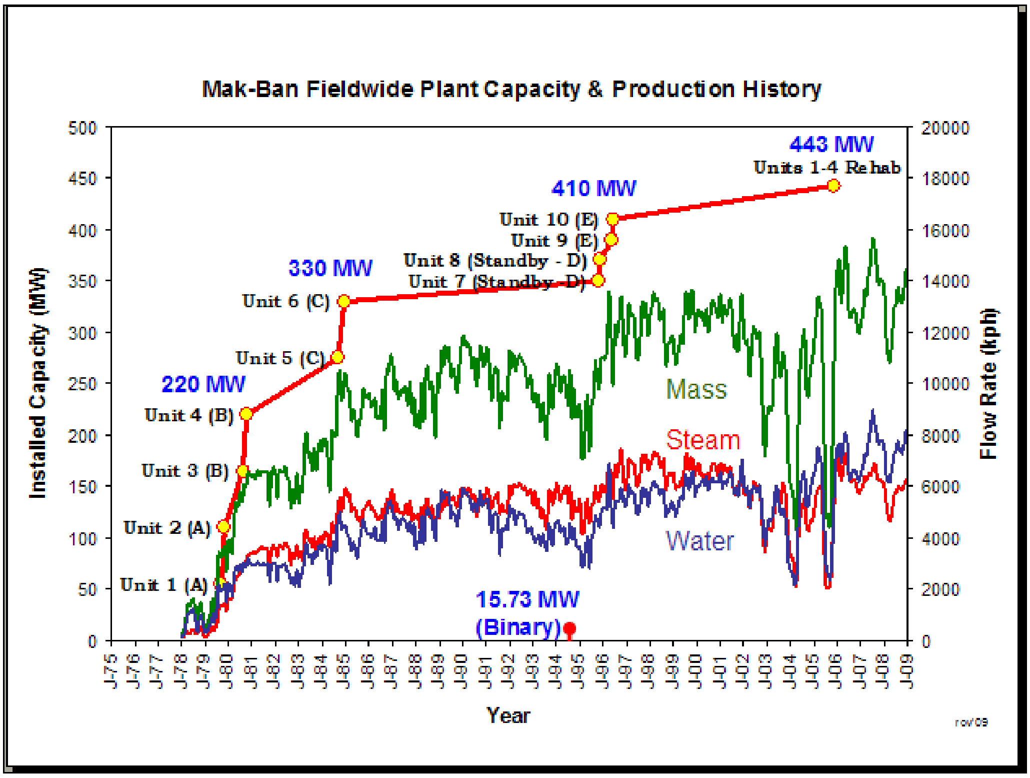

Figure 6: Development through time of the installed power plant capacity in Mak-Ban totaling 458.73 MWe by 2008. Production history is also shown.

Commercial-scale geothermal brine injection in the Philippines was pioneered at Bulalo (Sta. Maria and Villadolid-Abrigo, 1993; Golla et al., 2001). Brine injection was initially focused on edgefield sites immediately west and east of the production area, but by 1987 cooling due to injection returns was noted in a number of western production wells, so additional injection capacity was developed 2 to 3 km west of the production area, where permeability was found in the reservoir outflow plumes. Geochemical and tracer data indicate slow, manageable injection returns from these outfield injectors.

4.2 Reservoir Processes

After 30 years of operation, the Mak-Ban Field has experienced a number of significant reservoir changes.

As a consequence of fluid withdrawal, reservoir pressure and liquid level have declined resulting in the expansion of the two-phase zone. Figure 7 illustrates the dominant fluid processes controlling the cooling and fluid migration in wells, based on analysis of geochemical and production monitoring data. The dark blue area is characterized by inflow of cool marginal recharge (119-229^{0}C). The light blue areas in the west, SW and NE are affected by hotter marginal recharge, mostly at temperatures of ~230^{0}C, and as hot as 290^{0}C in the SW. The yellow area in the NW is characterized by rapid boiling with slow marginal recharge. The pink area in the east is characterized by cool temperatures due to sustained boiling at shallow depths. Injection breakthrough at the periphery of the production area in the east is indicated by the orange area. Southeast brine (a reservoir brine that has been enriched due to in-situ boiling) production is represented by light green in the south and southeastern part of the field. This area is characterized by rapid boiling with low recharge. The brine is believed to migrate towards areas of lower pressures after boiling. The dark green area is where mixed fluids consisting of upflow and SE brine are being produced (Abrigo, et al., 2006).

4.3 Marginal Fluids

The extent of the challenge of marginal recharge influx to the Mak-Ban geothermal field was established through reservoir surveillance. Thermal breakthrough following injection breakthrough was mitigated by moving injectors farther away (Sta. Maria and Villadolid-Abrigo, 1993) or by controlling the injection rates in edgefield injectors. Cold water downflows from casing breaks were mitigated by well workovers: installing scab liners or by a secondary tie-back recompletion. The potential entry of cooler marginal recharge in new wells was preempted by isolating the unwanted zones during drilling. Currently, procedures to isolate unwanted zones of marginal fluids in existing wells are being considered and will be tried in selected wells.

5. EXTERNAL INFLUENCES

5.1 Community Engagement

Mak-Ban is perhaps the world's most extreme example of people living in an operating geothermal field. Attracted largely by jobs and other opportunities associated with the field's development and operation, the resident population within the developed field area exploded tenfold from about 1,500 in 1979 to about 15,000 by 1996. Many houses have been built adjacent to well pads and right next to pipelines, in some cases even incorporating geothermal facilities as structural or decorative architectural elements. This pattern creates numerous health, safety and environmental concerns that must be addressed when planning and carrying out operations, maintenance and project work. In many cases, relocation of people or facilities is required. The foundation for preventing and mitigating such problems is an intensive community relations program that emphasizes constant engagement with local people and their elected representatives. Ideally, such large numbers of people should not be allowed to take up residence inside a geothermal field, but the Mak-Ban experience has shown that intelligent, sensitive and extensive community relations efforts can produce an outcome that is overall a significant net benefit to the residents.

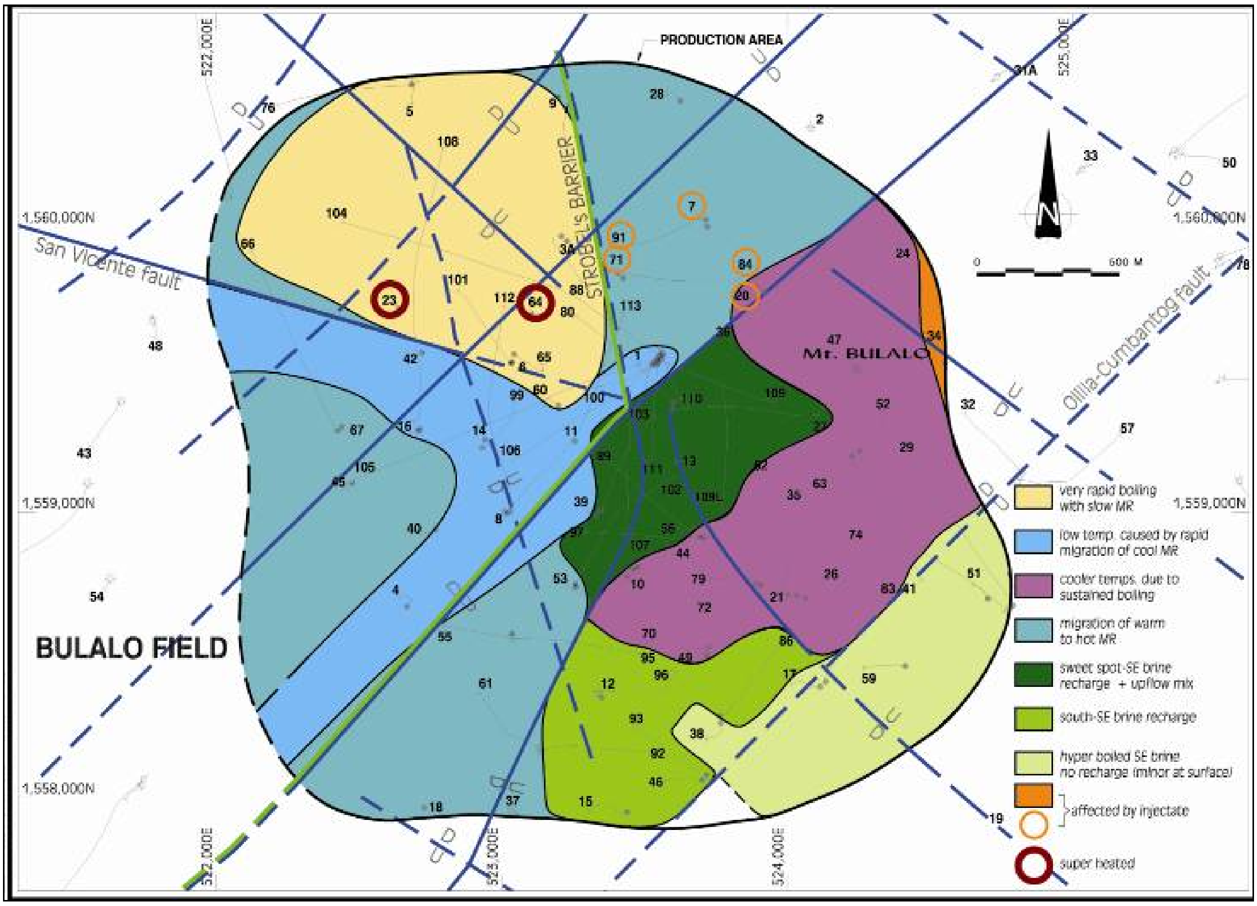

Figure 7: Plan view map of the major geochemical processes in the Mak-Ban field controlling cooling and fluid migration in the wells.

5.2 Others

In December 2008 President Gloria Macapagal-Arroyo signed into law a major Renewable Energy Bill, designed to promote development of new and existing renewable energy resources, including geothermal. The Philippines geothermal community, including Chevron, has enthusiastically supported the RE bill and looks forward to new growth in geothermal capacity and production as the bill is implemented. As of this writing, the Implementing Rules and Regulations for the bill have just been approved, with the support of the geothermal community.

The introduction of the Wholesale Electricity Spot Market in 2006 has forced frequent load curtailments, leading to some operational challenges because Mak-Ban's facilities were designed to operate as baseload.

6. MAK-BAN GEOTHERMAL FIELD: ANOTHER 30 YEARS

The Mak-Ban geothermal resource has turned in an excellent 30-year performance, with modest decline rates and few significant reservoir problems, and we believe this quality of performance can be sustained for decades to come. We can foresee a number of possible approaches that could promote future resource sustainment:

- Continued optimization of plants to minimize steam consumption and maximize generation. This may include additional binary capacity.
- Mitigating the cooling effects of marginal recharge, for example by devising well completions (or recompletions) that exclude the cool aquifers.
- Better understanding of the extent and properties of the deeper parts of the reservoir, so that the high pressures and temperatures there can be tapped to compensate for depletion and cooling of the shallower reservoir.
- Creation of an Enhanced Geothermal System southeast of the existing field, to mine the untapped heat resource that exists in this low permeability sector.

7. CONCLUSIONS

Mak-Ban has been a well-behaved geothermal field for the past 30 years. The successful operation of the field is attributed to sound reservoir management and effective partnership with the customer, the community and other business partners.

For both new wells and existing wells, a major reservoir concern for Mak-Ban is mitigating the effects of the influx of cooler marginal fluids with higher field extraction rates. Engineers and scientists are evaluating several approaches to the problem with a view towards sustaining the remarkable performance of the Mak-Ban field for decades to come.

8. ACKNOWLEDGEMENT

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