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An Update on the 3D Numerical Model of the Bacon-Manito Geothermal Field

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ABSTRACT

Since the start of the commercial operation of the Bacon-Manito geothermal field, continuous efforts have been exerted to develop a model that will reliably represent the field's response and evaluate its sustainable production capacity. A lumped parameter model was initially developed and used for resource management purposes. Eventually, a three-dimensional numerical model was developed using iTOUGH2 (Finsterle, 1997). A recent update in the numerical reservoir model has been carried out to simulate the response of the field since commercial operation and investigate the effects of added extraction from potential expansion areas. A major improvement in the model is the inclusion of non-condensable gases consistent with the high gas content measured in the production wells. The model has been manually calibrated against natural state temperatures and pressures. Further calibration was carried-out through matching of production history trends for enthalpy, pressure drawdown, and CO_2. Overall, acceptable matches were obtained for most of the wells.

1. INTRODUCTION

The Bacon-Manito (BacMan) Geothermal Production Field (BGPF) is one of the geothermal sites of Energy Development Corporation (EDC) covering ~19,100 has of contract area located 300 km southeast of Manila and situated in the boundary of Legaspi City, Bacon District of Sorsogon City, and the town of Manito, Albay in the Bicol Region (Figure 1). BacMan field lies within the Pocdol volcanic complex and part of the Bicol Volcanic Arc. It is divided into two main production areas: BacMan 1 within the Palayang Bayan Sector and BacMan 2 with 2 modular plants that is being supplied by Cawayan and Botong wells. The BacMan 1 turbine units have been commissioned in 1993 while Cawayan become operational a year after. The modular plant in Botong was later commissioned in 1998. Other expansion projects for future developments have been identified in 1992 which include Tanawon, Rangas and Kayabon area.

Figure 1. The Bacon-Manito Geothermal Project location site

Simulations, both analytical and numerical, have been carried out to investigate the field's response to different production strategy even before commercial operation had started. There were three studies that have been previously conducted to address this purpose. The first study was conducted by Castillo (1990) using CHARGR (Pritchett, 1980) as part of preliminary investigation on different schemes of production and injection. The second was a lumped parameter model (Fajardo, 2000) developed to determine response of field to additional mass extraction due to expansion projects and the effect of recharge. The recent project is part of a masters' thesis performed to generate different models of the field and analyze / compare sustainability of the BacMan field

(Austria, 2010). The extent of the calibration of the model and its complexity was dependent on the availability of quality data. Although, the generated model have been sufficient for their respective purposes, detailed calibration against natural state and history matching parameters have not been performed. In addition, expansion areas were not considered in the calibration and the effect of the different exploitation strategy in this respective area.

In line with the recent developments on the BacMan field, acquisition of the power plants and the need to efficiently and inexpensively assess the field's response to different management and exploitation schemes, a 3D numerical reservoir model has been developed. The study is a joint project with the University of Auckland that aims to provide the following main objectives: 1) validate and update results of earlier models, and 2) determine sustainable capacity of present installed power plants. It also incorporated in the simulation the effect of non-condensable gases on reservoir behavior. This recent model has utilized a rectangular mesh calibrated against 17 years of production data of the field. It had been simulated using TOUGH2 (Pruess, 1991) in PETRASIM (http://www.thunderheadeng.com/petrasim/) and AUTOUGH2 (Bullivant, et al., 1991) platforms. The results of the natural state and production history calibration will be presented in this report.

2. BACMAN FIELD OVERVIEW

In the succeeding paragraphs, several information regarding Bacon-Manito Geothermal Field were being presented. These have been used as basis in developing the model. It also served as guide in rock assignment for permeability distribution.

2.1 Geology and Stratigraphy

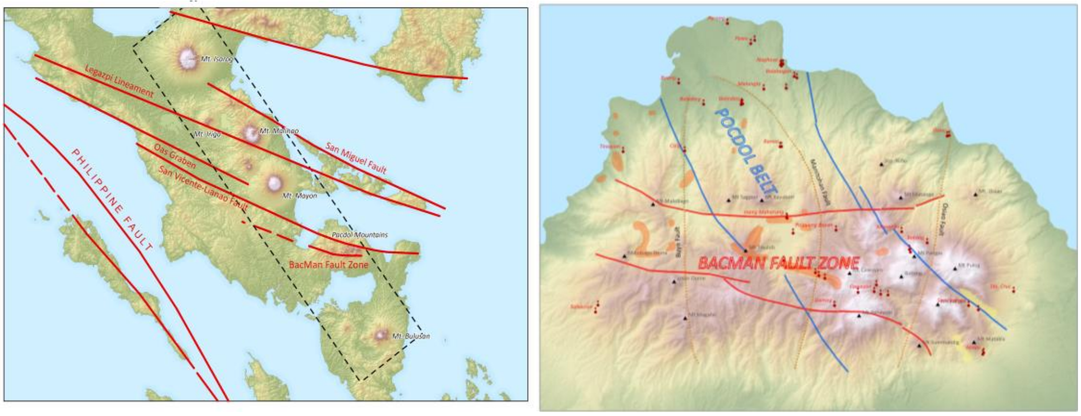


Figure 2. The SRTM image of Bicol Peninsula (Left). The San Vicente-Linao Fault (SVLF) manifests in the Pocdol Mountains as BacMan Fault Zone (Right) (after Braganza, 2011).

The BacMan field has been proven to be a geothermal area that is structurally controlled by fault system that is believed to be an extension of the San Vicente Linao Fault (SVLF) which is a splay of the Philippine fault (Figure 2). The local fault system is known as the BacMan Fault Zone (BFZ) (Dimabayao, 2012). The fault zone is characterized by broken volcanic terrain dissected by numerous faults (BGPF Resource Assessment 2012, 2013) and comprised mostly of WNW-ESE trending faults which control the fluid migration in the field. Although the SVLF trends NW-SE, the extension towards Pocdol were represented by E-W trending shears affected by the presence of the volcanic centers in the area (Dimabayao, 2012). These volcanic centers are part of the Bicol Volcanic Arc which is mainly overlain with Pocdol Volcanics.

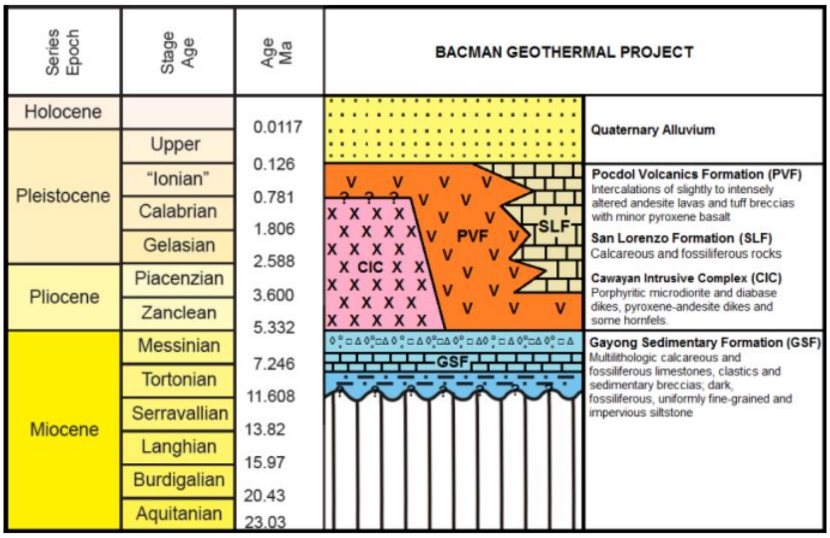


Figure 3. General stratigraphic column of BacMan field (after Santos and Dimabayao, 2011)

The Bacon-Manito sectors were underlain by andesitic, dactic, and basaltic lava flows and volcaniclastics (Castillo, 1990). Three major lithologic units shown in Figure 3 have been identified from the formations that have been generally encountered during drilling of wells in the BacMan area. The deepest and the oldest among these formations is the Gayong Sedimentary Formation (GSF) which is composed mainly of limestones, calcareous clastics and sedimentary breccias. The unconformably lying Pocdol Volcanics (PV) have been intersected by most wells and is composed of intensely altered andesite lavas and tuff with minor pyroxene basalt. The maximum thickness of this unit is estimated to be around 2000m. Another unit found in BacMan is the Cawayan Intrusive Complex present in some well's downhole data which consisted of porphyritic microdiorite, and andesite and diabase dikes with hornfels. (Dimabayao, 2012). Earlier data suggested that the Rangas intrusive found at surface is included in this unit while recently drilled wells have indicated the presence of another possible unit that is referred to as the San Lorenzo Formation (SLF) which is described to be consisted of calcareous and fossiliferous rocks.

2.2 Natural State Temperature and Pressure

Typically, as shown in Figure 4, conductive gradient can be observed along the cased off length of the wells and sudden convective flow at the openhole section. Some wells exhibit boiling profile while a nearly isothermal profile were measured that could be associated to downflowing of fluids. Temperature isoterms at different elevations have been generated based on interpreted natural state temperature profiles of drilled wells. The temperature distribution at -1000 mRSL which is shown in Figure 5, the hottest temperatures were concentrated to the eastern sector of Palayang Bayan in the vicinity of Mt. Pangas. Cooling trend of temperature can be seen towards the Inang Maharang area suggesting outflow conditions. The decrease in temperature towards the Cawayan wells is not as rapid compared to the Inang Maharang area thus the sector is interpreted to be within the peripheries of the upflow zone. Signatures of cooler fluid can be speculated to be originating from the northwest direction of the Masakrot area.

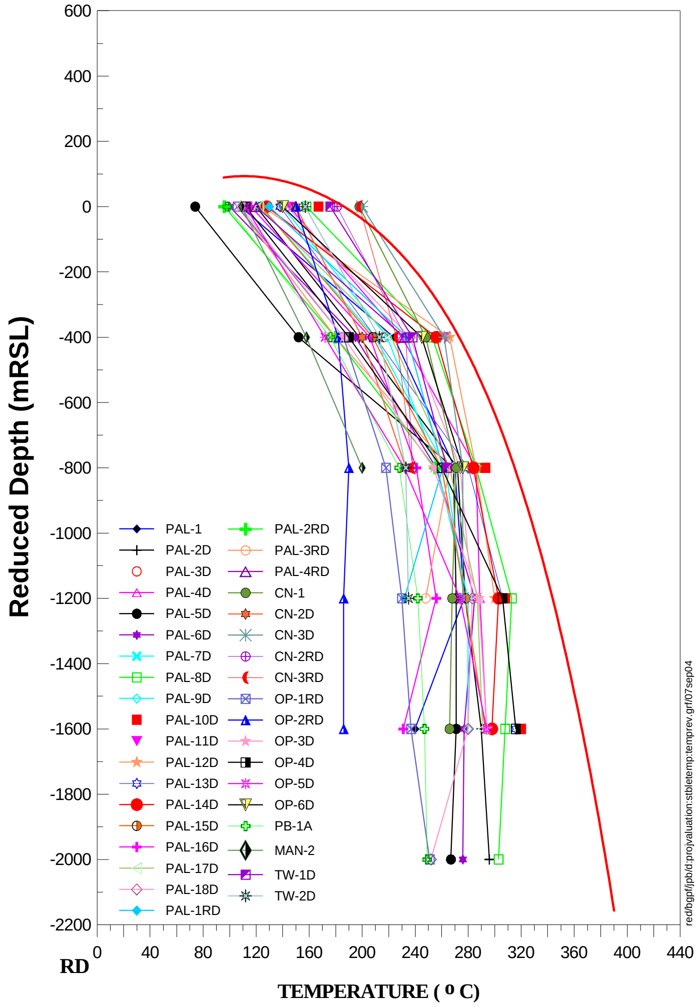


Figure 4. BacMan Stable Formation Temperatures (after Fajardo et al, 2004)

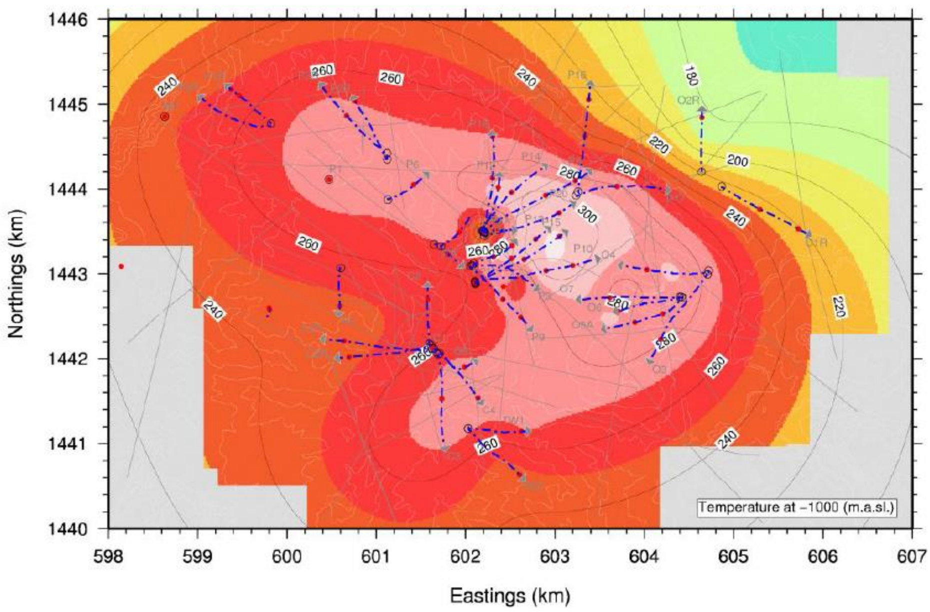


Figure 5. Temperature contours at -1000mRSL (after Austria, 2010)

The profiles for pressure decline towards the west\northwest confirm movement of temperature towards the Inang Maharang area. Overpressuring can be discern from the measurements of Botong wells which could possibly corroborate the existence of a geologic barrier isolating the area from Palayang Bayan. Another possible source of the over pressuring can be attributed to the presence of non-condensable gases dissolved in the liquid phase. BacMan wells' pressure values at controlled points showed a nearly hydrostatic condition. Average water level of the field is projected to stand at 0 to 200 mRSL. Most of the wells can be considered gassy that depressed the water level.

2.3 Permeability

Drilling results and well test analysis of drilled wells indicated that feedzones of BacMan wells are located between -300 mRSL and -2000 mRSL however majority of these feeds are found between -800 mRSL to -1700 mRSL as earlier reported (Fajardo, et al., 2004). These feedzones are commonly attributed to intersected faults and just minor percentages were linked with lithological contacts. Transmissivitiy values obtained from pressure transient analysis of these wells range from 0.5 to 42 dm, with higher kh commonly measured from Palayang Bayan and Cawayan wells. On the other hand, Botong wells exhibited very low kh values which reflected the formation have relatively lower permeability compared to the other two sectors. Mud damages during drilling were suspected to be one of the possible reasons for these low calculated kh values.

2.4 Initial Response to Production

During the early exploitation stage of BacMan, the field is operating at a total average capacity of 137 MWe supplied by wells coming from the Palayang Bayan, Cawayan and Botong sectors. The generation level is less than the available steam estimated from existing wells. Each sector has been observed to have different response with respect to production. Generally, increase in the average enthalpy has been measured for most Palayang Bayan wells. The highest value has been measured in PAL8D with a value of 2050+ kJ/kg enthalpy. However, decline in enthalpy had been observed in some wells at certain well pad. For the case of Cawayan wells, the output enthalpies of the Cawayan wells have been relatively stable with time. The slight increase at some period can be correlated with several factors such as pressure drawdown and scaling due to mineral deposition. Botong wells typically demonstrate discharge with high enthalpy two phase with high non-condensable gas content. Boiling and two-phase expansion were the prevailing processes in this sector.

Aside from enthalpy trends, slight drop in temperature have been observed to nearby wells when PAL1 had been utilized as a hot injection well. With this occurrence, injection strategy has been revised. Cooling was also recognized in the western section of the field due to continuous migration of cooler fluid from the Masakrot area but its effect on production is not the detrimental. Meanwhile, pressure drawdowns have varying degree across the field ranging from 0.07 to 4.3 MPag. The highest drawdown was noted in PAL-8D area while minimal drop was noted in the Cawayan sector. The values of pressure drop for Botong wells falls within this range.

2.5 Conceptual Model

The Bacon-Manito geothermal field is a liquid-dominated hydrothermal system. Its main upflow area had been established to be located beneath PAL-10D and OP-4D area associated with Mt. Pangas (Figure 5). This proposed system has been collaborated with several physical and geoscientific evidences, measurements, and trends observed in the field. Based on interpreted natural state temperature from KT surveys, the highest temperature was measured in PAL-10D which is targeted towards the Mt. Pangas volcanic center with a value of 326°C (Fajardo, et al., 2004) and would indicate the presence of the upflow. With respect to geochemical trends, the highest chloride concentration in the eastern Palayang Bayan sector which validate further the presence of the upflow (Castillo, 1990). Early MT data processing and modelling showed that a high resistivity body >50 ohm-m, beneath Palayang Bayan, Cawayan and Botong which was interpreted to be associated with this production zone (Los Banos, et al., 2000).

On the other hand, geologic evidence concerning the presence of youthful volcanic rocks from the Cawayan-Tanawon area point to possible second system having an upflow dominated by the one situated at Palayang Bayan (Castillo, 1990).

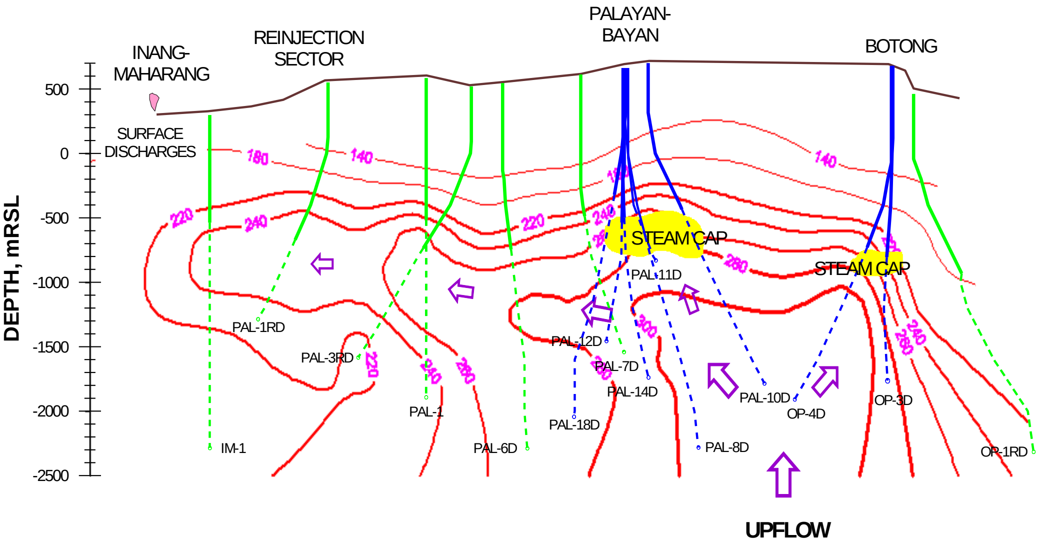


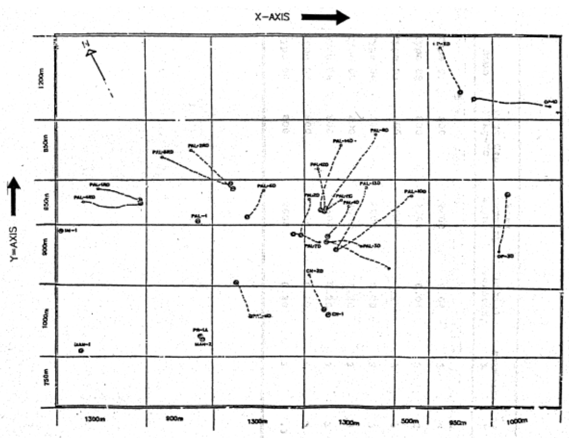
Figure 6. BacMan Conceptual Model (After Fajardo, et al., 1999)

From the Palayang Bayan upflow plume, the fluid moves out north-northwest towards the Inang Maharang area. Temperature distribution likewise supports this flow pattern as evident with the cooling trends into the northwest direction as shown in vertical slice Figure 6. Reversals in temperature were also observed on wells in this area which further prove that it is located in the outflow boundary of a resource. This preferential major outflow was claimed to be controlled by west-northwest and northwest-southeast trending faults (Ramos, 2002). This flow travel further north and as influenced by five major thermal springs located along the coast of the island as reported by Solis, et.al. (1994). There is also southeasterly migration of fluid into the Rangas area. This flow pattern, according to Ramos can be attributed to the Makabug, Botong and Dome faults. In addition to the major flow, there are also minor outflow in the direction of PAL-16D as marked by thermal inversion in measured temperature, surface thermal manifestations and outlined of resistivity surveys (Fajardo, et al., 2004). It was also highlighted that the unusually higher pressures among the OP wells could be attributed to a ‘geologic barrier’ between the Palayang Bayan area and Botong. This barrier somehow limits the migration of fluid between the two sectors.

3. EARLIER MODELS

There have been several numerical and analytical models that have been developed to study the possible response of the BacMan field during exploitation. The extent of the calibration of the proposed model was dependent on the availability of quality data which include steady state parameters (e.g. temperature and pressure) and production history of each well. The complexity of the generated model was likewise dependent on the time constraint the project had been conducted.

Prior to commercial operation of the BacMan power plant, a preliminary study (Castillo, 1990) had been carried out to perform a numerical simulation investigating the behavior of the reservoir under different schemes of recharge, production and injection. The model had covered an area of 40.24 km^2 with a thickness of 1.2 km consisting of 142 blocks distributed evenly into 3 layers as illustrated in Figure 7. The geological formation was represented using eight rock types wherein properties were adjusted using measured temperature and pressure of drilled wells. There were three production history scenarios that were carried out during the predictive simulation which was later on subjective into different recharge and injection strategy.



Name	Heat Cap. J/kg-°C	Rock Density kg/m^3	Porosity	k_x (X 10^{-15} m^2)	k_y (X 10^{-15} m^2)	K_z (X 10^{-15} m^2)
Type 01	800	2600	0.04	3	3	30
Type 02	800	2600	0.04	3	3	20
Type 03	800	2600	0.35	3	3	3
Type 04	800	2600	0.20	3	3	0.7
Type 05	800	2600	0.20	0.3	0.3	5
Type 06	800	2600	0.20	3	3	0.7
Type 07	800	2600	0.20	3	3	0.7
Type 08	800	2600	0.20	3	0.3	0.7

Figure 7. Preliminary BGPF Model (after Castillo, 1990)

Fajardo (2000), on the other hand, had formulated two analytical models of the BacMan reservoir calibrated respectively against two sets of pressure history data from two monitoring wells. In the study, the LUMPFIT (Axelsson and Arason, 1992), an automated simulator of pressure changes was utilized. Upon achieving satisfactory matches for the pressure trends, the behavior of the models under various production scenarios were determined without considering the effect of temperature. Results have shown that the model response is sensitive to the degree of mass extraction and the recharge constant.

In 2010, Austria has reported the results of the sustainability assessment conducted using three numerical models of varying complexity which included a lumped parameter model, a volumetric stored heat approach and a 3D reservoir model. The computational mesh for the 2008 3D model, shown in Figure 8, covered an area of 49,730 km^2 and thickness of 2400 m which is subdivided into 11 layers with 277 elements found in each layer. There are 12 rock types that were distributed in the model with properties optimized through inverse modeling. Its reliability was tested by comparison of simulated steady state temperature profiles and contours. Limited calibration was performed to match the well-by-well enthalpy trends and pressure drawdown of production wells during exploitation period. It only aimed to match mean enthalpy which was determined sufficient for its objective of validating field sustainability. In addition, the effect of non-condensable gas concentration was not considered. The study predicted minimal cooling despite the simulated 4 MPa drawdown over the 50 year period of exploitation.

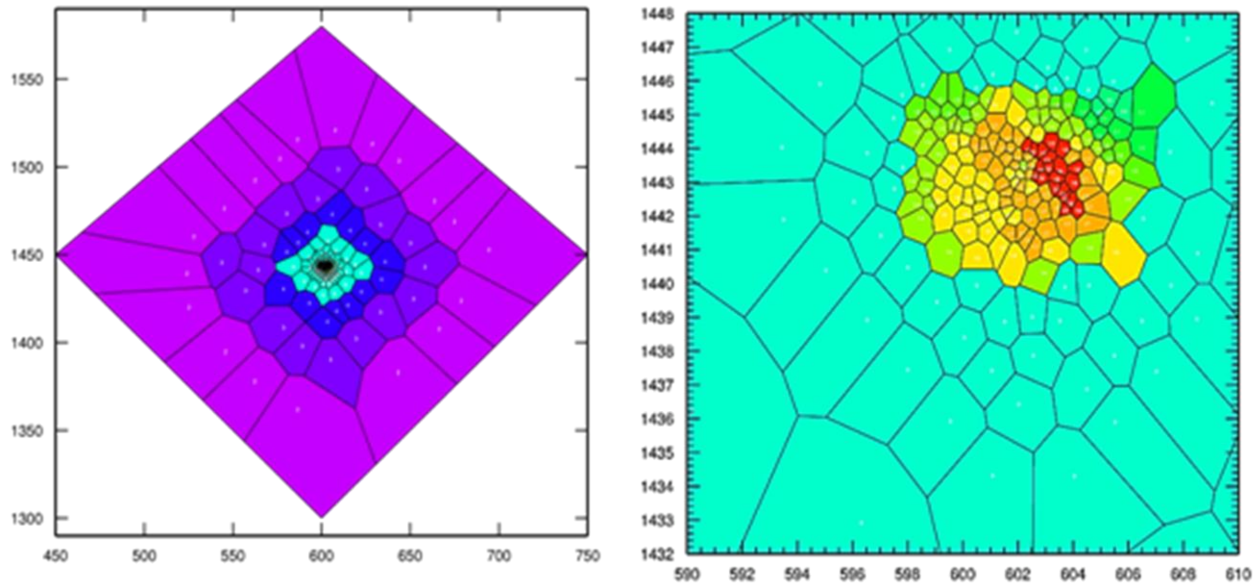


Figure 8. 2008 BGPF Numerical Model Computational Mesh (after Austria, 2010)

4. 2010 BGPF 3D MODEL

In line with the recent developments on the BacMan field, acquisition of the power plants and the need to efficiently and inexpensively assess the field's response to different management and exploitation schemes, another 3D numerical reservoir model has been developed. This project is a joint undertaking between Energy Development Corporation and the University of Auckland in New Zealand. It covered the natural state/pre-exploitation temperature and pressure matching, further enhancement during the production history matching for the enthalpy and pressure response of the field, and forecast simulation.

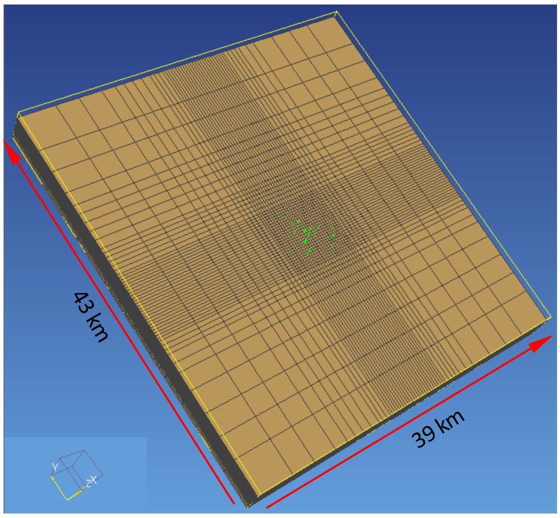


Figure 9. 2010 BGPF Model Grid

The BacMan 3D numerical model had been developed to an area of 1,677 km^2 (39 km x 43 km) and thickness of 4.5 km covering the main Palayang Bayan area and other nearby sectors (Figure 9). The model has 85,100 elements in a rectangular mesh distributed into 37 layers, of which 13 are inactive. It was oriented along the direction of the major fault zone the influence the flow migration as discussed on the conceptual model. The size of the model was made sufficiently large to minimize, if not completely eliminate boundary effects with finer block elements (300m x 300m) allocated in the central portion of the grid representing the production area to resolve sharing of well parameters. As illustrated in Figure 9, gradual increase in block dimensions was implemented towards the perimeter due to minor importance of the gradient and details in this area.

The topmost active layer, that is contoured based on water level and topography, is connected to a block which represents the atmospheric element assigned with 28°C and 1 atm while the basement have heat flux values of ~80mW/m^2 for the inner region while elsewhere have ~50mW/m^2. Aside from the heat source, a deep upflow for the convective system was represented by mass and heat at the bottom layer. The model initially has one mass and heat upflow source with mass of 83kg/s and enthalpy of 1350 kJ/kg.situated at the bottom of wells PAL-10D and OP-4D. As the matching progressed, another mass input source (as shown in Figure 10) have been defined near the Kayabon area with a mass flow of 25 kg/s and 1,350 kJ/kg. There are four fixed mass sinks at the northern coast of the concession area. Neither mass nor heat inputs have been defined along sides of the model. An important feature of the current model is the significant amount of non-condensable gas concentration included in the mass source input.

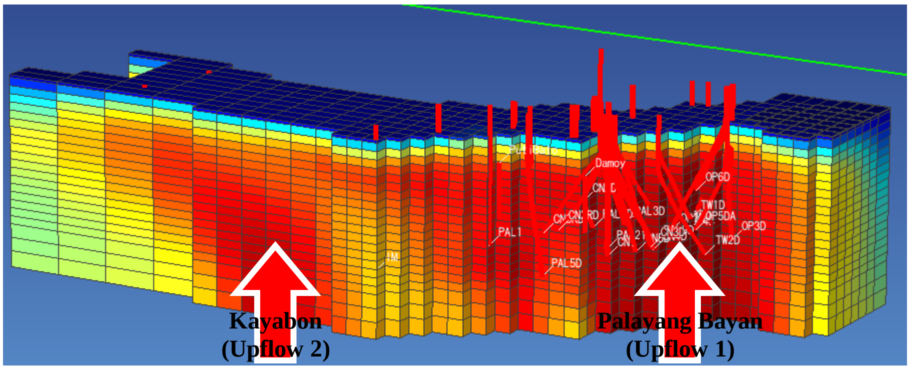


Figure 10. Simulated Upflow Location for 2010 BGPF Model

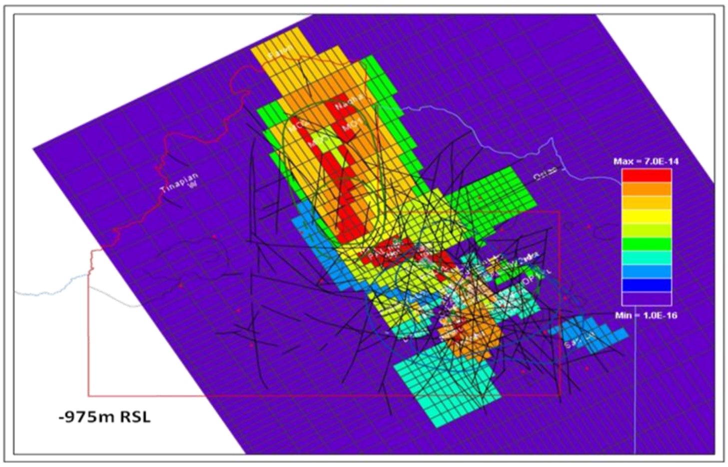


Figure 11.Permeability distribution at -975 mRSL of 2010 BGPF Model

The material distribution was configured following pertinent geological and geophysical features of the field. Most of the materials assigned have permeability values along the x- and y- direction although few anisotropic rocks have been utilized as needed. The ranged of horizontal permeability assigned was from 0.1 mD to 70 mD while the vertical permeability only ranged from 0.075 mD up to 6 mD. These values were obtained during the model calibration A sample permeability distribution is illustrated in Figure 11.

The simulation was implemented using TOUGH2 code in two different platforms. One is in Petrasim while the other is in AuTOUGH2. Calibration of the model was conducted in two stages - the natural state and production history - using these two TOUGH2 interfaces. Only manual calibration has been carried out for this project to obtain model parameters.

4.1 Natural State Modelling

As mentioned, the material distributions have been the result of the calibration of the model. The first stage is the natural state modeling which was performed using the Petrasim. The model has been calibrated against interpreted steady state temperature and pressure profiles for the drilled wells. The simulation time to achieve natural state condition has been set to 1.0E +15s or approximately 32 million years. Aside from permeability distribution, the mass source was also calibrated at this stage. The model suggested the need of two upflow in the system to match temperature in the northernmost part of the model as shown in Figure 12.

It seems that the three wells in the area would only reached its measured temperature if a mass source will be placed somewhere beneath Mt. Kayabon.

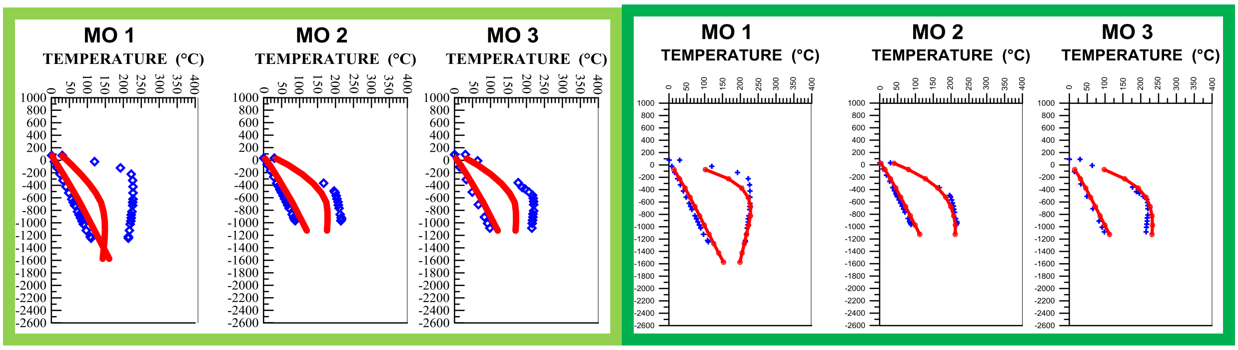


Figure 12. Comparison of simulated temperature for MO wells. Without a second source (left) With second source (right)

The results of the simulation have replicated the temperature contours (at -975 mRSL) as shown in Figure 13. This also depicts the fluid migration on the field as presented by the conceptual model. In the same figure, it can be seen that there is a major outflow of fluid in the northwest direction while a minor flow can be observed in the south of Cawayan.

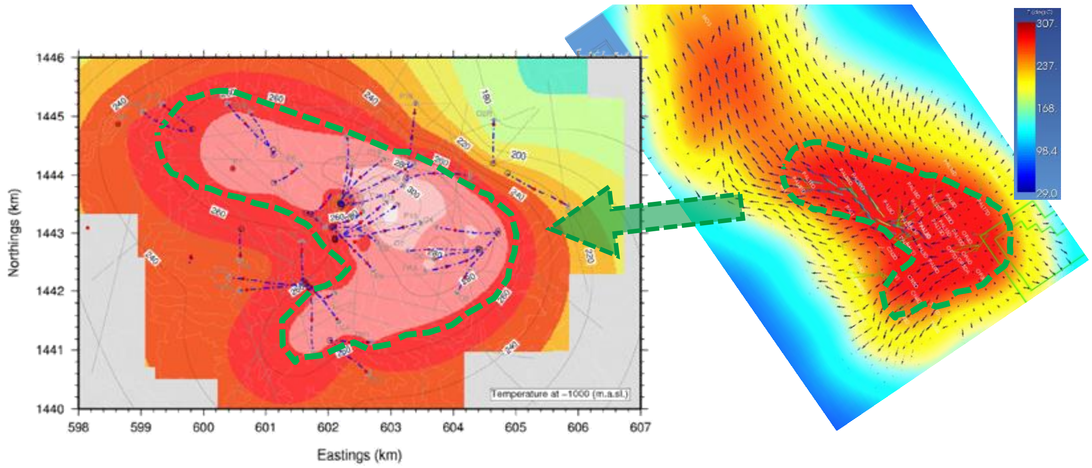


Figure 13. Comparison of Temperature Distribution @ -975 mRSL

4.2 Production History Matching

Upon achieving an acceptable match of the natural state parameters, the production history modeling have been performed and further calibrate the model. Due to the computational limitation of TOUGH2/Petrasim, the model input file was then migrated into AUTOUGH2 format. The model was calibrated against production enthalpy data from the 23 production wells during the 17 years operation of the field. There were only fewer data that have been used to calibrate for the pressure drawdown. Aside from these two parameters, the historical trends for the CO_2 have likewise been utilized as a parameter. Several significant permeability adjustments have been made to achieve reasonable match.

The model results were shown in Figures 14 to 17. It can be seen from the enthalpy plots (Figure 14) that relatively good matches have been attained for OP6D and PAL20D wells. Similarly, reasonable matches for pressure drawdown (Figure 15) have been simulated by the model. Some plots of simulated CO_2 trends (Figure 16) during production showed good agreement with the measured values. Fluid migration has also been monitored during production but was not calibrated. Illustrated in Figure 17 is the comparison between the flow pattern before and after 17 years of exploitation. It can be seen that significant recharge from the periphery of the field due to pressure difference.

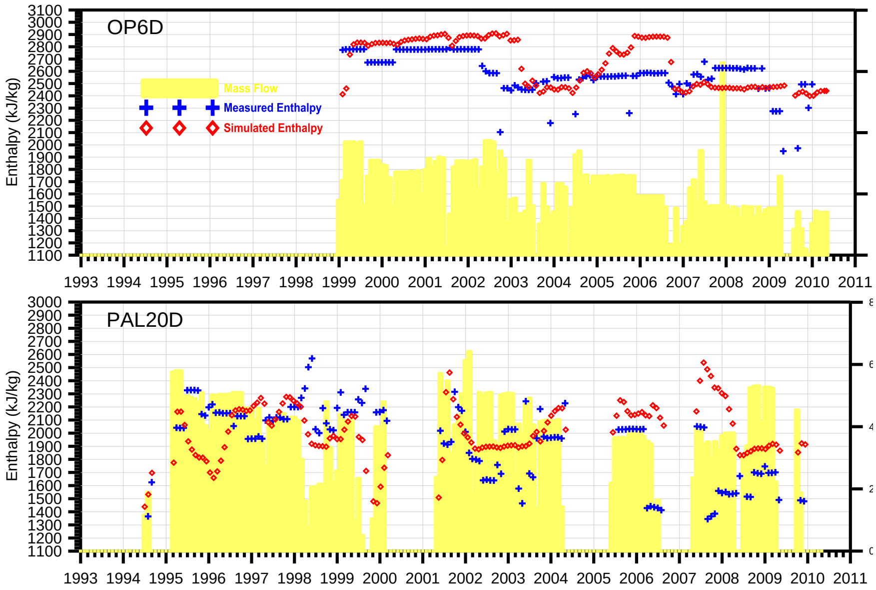


Figure 14. Simulated and measured enthalpy trends of OP6D and PAL20D

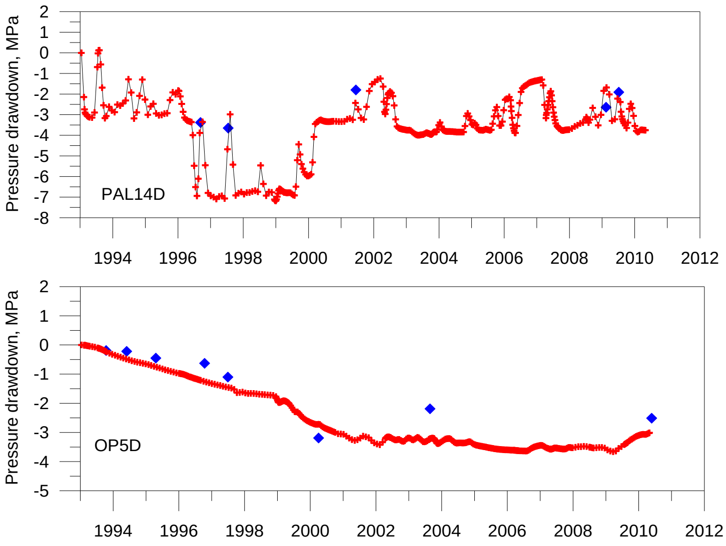


Figure 15. Comparison between simulated and measured pressure drawdown for PAL14D and OP5D

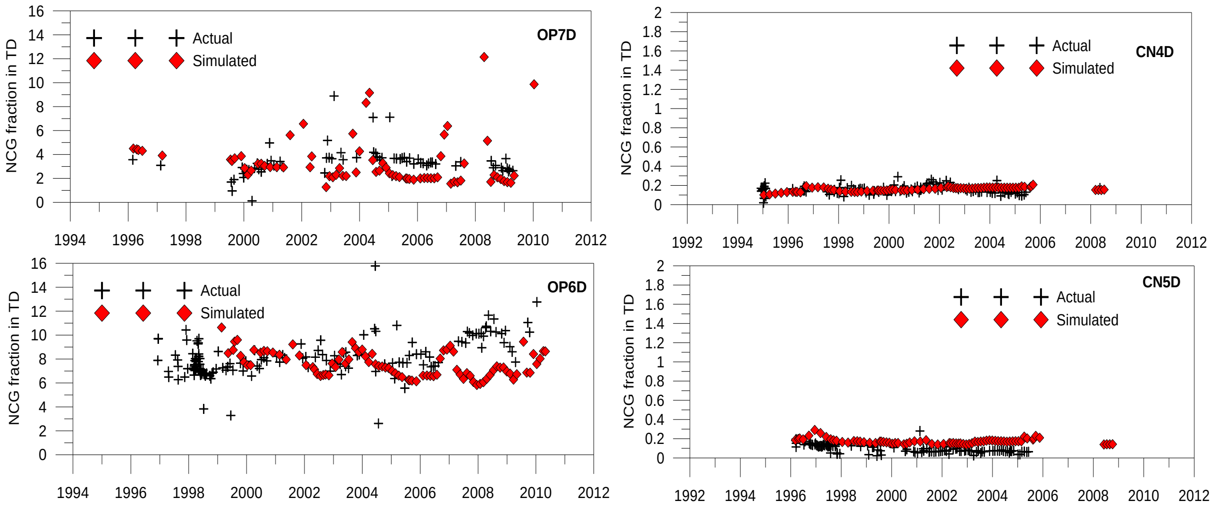


Figure 16. Simulated and measured CO_2 trends for OP (with high CO_2) and CN wells (with minimal CO_2) during production

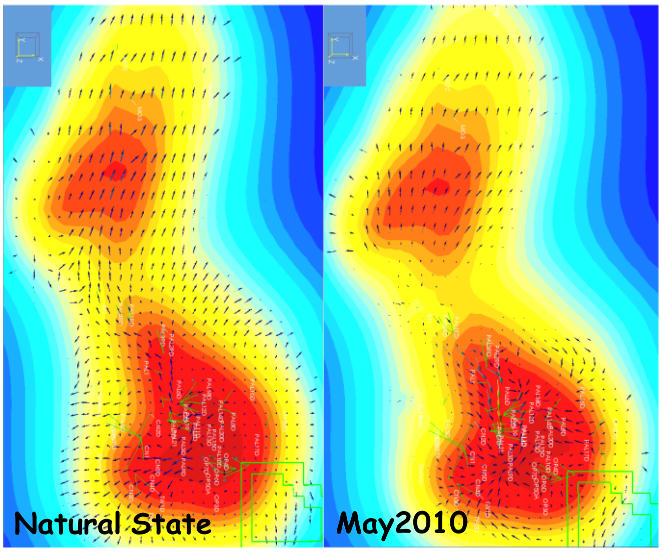


Figure 17. Comparison of Fluid migration after 17 years of production.

5. SUMMARY AND CONCLUSIONS

Significant efforts have been exerted in performing simulation studies for Bacon-Manito geothermal field. These studies usually aim to determine response to different production/injection schemes or investigate the sustainable capacity of the field. Numerical and analytical models have been developed to accomplish these objectives. There were three earlier simulation studies conducted for BacMan geothermal field. Calibration of models has been limited due to availability of quality data and the time period the project was conducted.

The 2010 3D reservoir model of BacMan has been developed in rectangular mesh that covered the areas for existing and future projects. The model had been calibrated using natural state parameters (temperature and pressure) of drilled wells and production data of 23 wells only. On the other hand, there were fewer data used for calibrating the observed pressure drawdown during production. Aside from the usual enthalpy and pressure drawdown trends utilized during production history matching, the historical trend for CO_2 during the exploitation period from the same wells was also used.

Acceptable matches have been achieved during the calibration of the model for both natural state and production history parameters. Permeability distribution and mass source inputs resulting from the calibration of the model has significant effect on the development of the field. Although fluid flow pattern have been monitored during the calibration, quantitative calibration have not been performed.

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REFERENCES

Austria, J.J.C.: Sustainable production Assessment of the Bacon-Manito Geothermal Reservoir, the Philippines. *Proceedings, World Geothermal Congress*, 25-29 May, Bali, Indonesia (2010).

Axelsson, G., and Arason, P.: *LUMPFIT: Automated simulation of pressure changes in hydrological reservoirs*. Version 3.1 user's Guide, Orkustofnun, Reykjavik, 32pp. (1992).

BGPF Resource Assessment 2012. Energy Development Corporation. Internal Report. Philippines (2013).

Braganza, J.S.: *Geology of Bacon-Manito Geothermal Resource*. Resource Assessment Update of Bacon-Manito Geothermal Project - Draft. Internal Report. Energy Development Corporation, Philippines (2011).

Bullivant, D.P., O'Sullivan, M.J., and Zuvoloski, G. A., Enhancements of the MULKOM geothermal simulator, *Proceedings, 13th New Zealand Geothermal Workshop*, University of Auckland, pp.175 – 182. (1991)Castillo, R. M.: *A Preliminary Numerical Simulation of the Bacon-Manito Geothermal Field*, UNDP – PNOC-EDC joint project. PHI/86/006 (1990).

Dimabayao, J.J.T.: Revisiting the Volcanic History of BacMan: Old and New Insights. *Unpublished Proceedings, 2012 Resource Management Meeting*, 19-20 July, Energy Development Corporation, Philippines (2012).

Fajardo, V. R.: Lumped Parameter model of the Bacon-Manito Geothermal Production Field Albay, Philippines. *Proceedings, World Geothermal Congress*, 28May-10June. Japan (2000).

Fajardo, V. R., Gerona, P.P., and Padua, D.O.: Reservoir Performance and Behavior of the Bacon-Manito Geothermal Production Field. *Proceedings, 24th Geothermal Reservoir Engineering Workshop.* Stanford University, Stanford, California, (1999)

Fajardo, V. R., Malate, R.C.M., and Sarmiento, Z.F.: *Update on the Evaluation of the Geothermal Reserves for the Bacon-Manito Geothermal Production Field*, Energy Development Corporation. Internal Report. Philippines (2004).

Finsterle, S.: iTOUGHs User's Guide, Version 3.1. LBNL-40040: lawrene Berkeley National Laboratory. Berkeley, California (1997).

Los Baños, C.F.L., Apuada, N.A., Layugan, D.B., Maneja, F.C., Olivar, R.E.R., and Rigor, D.M.: Magnetotelluric Survey at Bacon-Manito Geothermal Production Field, Southern Luzon, Philippines. PNOC-EDC Internal Report. Philippines (2000).

Pritchett, J.W.: *Numerical Techniques Employed in the MUSHRM and CHARGR Geothermal Reservoir Simulators*. Systems and Software Report, SSS-R-4681. (1980).

Pruess, K.: *TOUGH2: A general-purpose numerical simulator for the multiphase fluid and heat flow*. Lawrence Berkeley National Laboratory, Berkeley, California (1991).

Ramos, S.G.: Potential constraints to the development of the Rangas sector based on Petrologic Evaluation of the BacMan Geothermal field, Philippines. *Proceedings, 27th Geothermal Reservoir Engineering workshop,* SGP-TR-171. Stanford, California (2002).

Santos, B.N.E.A. and Dimabayao, J.J.T.: Paleoenvironment Reconstruction of the Gayong Sedimentary Formation, BacMan Geothermal Field, Philippines. *Proceedings, New Zealand Geothermal Workshop,* 21-23 November. AuckLand, New Zealand (2011).

Solis, R.P., Cabel, A.C., See, F.S., Ramos-Candelaria, M.N., Buenviaje, M.M., and Garcia, S.E.: *Bacon-Manito Geothermal Production Field exploitation baseline geochemistry data*. PNOC-EDC Geoscientific Department. Internal Report. Philippines (1994).