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Factors Controlling Reservoir Permeability at the Leyte Geothermal Field, Philippines

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ABSTRACT

Reservoir permeability at the Leyte geothermal field is highly influenced by the left-lateral movement of the Philippine Fault System. Deep wells are designed and drilled primarily to target near vertical fault structures of known permeability, and casing designs consider the calculated intercepts of these faults. Studies on microtectonics of specific areas indicate that most permeable structures coincide with areas under extensional regime while faults with limited permeability are located in areas under compression. Since the Philippine fault branches into three major traces in the area, these faults also define the boundaries of the exploitable resource in Tongonan and Mahanagdong. The West and Central Fault Lines delimit the permeability west of the resource, while the extent of the permeability to the east is yet to be completely defined. This model is supported by studies on the anatomy of volcanoes in strike-slip fault systems that suggest higher permeability east of the identified sigmoid bounded by the West and Central Fault Lines.

Previous studies of the Philippine Fault reveal an average movement rate of about 1.9-2.5 cm/yr based on kinematic models by Barrier et al., (1991) and 2.0 cm/yr from fault displacement measurements (Aurelio, 1992). Microseismic monitoring also indicates an average of 2 tectonic events per day, and there are even more events along the Philippine Trench located on the east. Records of tectonic earthquakes since the initial production in 1983 and the expansion in 1997 indicate that there are no major earth movements in the area that can be directly correlated to the geothermal production.

However, the permeability near wellbores is affected by different natural and production-related factors that results to varying degrees of permeability changes. The changing in-situ permeability characteristics of the faults transected by the wells in Tongonan may be attributed to the continuous movement along the Philippine Fault and from the different physical and chemical processes affecting the reservoir due to continuous steam production. Based on old and recently drilled wells, there appears to be an enhancement of permeability in some faults, and this may initially be attributed primarily to tectonic processes and secondary to change in reservoir phases. The different stress regime in the field is likewise re-evaluated to determine how the regional stress affects the local fault movement.

1. INTRODUCTION

Initial interpretations of recent fault data sets confirm previous studies on the presence of extensional and compressional local stress regimes at the Leyte Geothermal Field (LGF). As the field is exploited, pressure drawdown in the geothermal reservoir have indicated that even areas known to have been under compressional stress regimes have turned out to be permeable based on recent well drilling data. These areas are north of Upper Mahiao and east-southeast of Mahanagdong.

The type of lithology is also a factor in the overall permeability of the reservoir. The presence of ultramafic basement complex in central Bao valley southwest of the Central Fault Line renders the area impermeable, while the extensive deposit of the Mahanagdong claystone limits permeability west of Upper Mahiao and west of Mahanagdong. The extent of the claystone deposits is controlled by the Central Fault Line (CFL) and other major faults in the sector.

Different factors that play a role in the overall permeability of the geothermal reservoir in the Tongonan and Mahanagdong, and these factors will be presented in the following sections. Preliminary interpretations on the long-term changes on permeability due to exploitation of the geothermal reservoir are presented based on recent drilling and reservoir data.

2. THE PHILIPPINE FAULT IN NORTHERN LEYTE

The Tongonan and Mahanagdong reservoirs in LGF are located at the center of the northern trace of the Philippine Fault System in the island of Leyte (Figure 1). The state of stress of the Philippine Fault has been characterized by the coexistence of compressional and extensional zones (Aurelio et al, 1993). Compressional sites have been observed in the proximity of strike-slip faults while extensional areas occur near normal faults. However, due to the complexity of the different local faults in LGF, this assumption that faults under extensional regime are permeable and faults under compression are impermeable does not always hold true. And this can be observed in northern Upper Mahiao and eastern Mahanagdong areas.

As described by previous authors, the physiographic features are particularly spectacular in LGF because the Philippine Fault System, which spreads into three major traces in central Leyte, dissects volcanoes of quaternary ages (Dequesnoy, et al., 1994). These volcanic cones are the direct evidences of the left-lateral movement of the fault which yielded a minimum slip rate of 19 mm/year (Aurelio, 1992). The individual parallel faults at LGF, in a band of as much as 3 km wide, are complimented by conjugate faults oriented northeast-southwest. These faults structures, as well as the intersection of the dense network of faults, have created an inter-connected permeable conduit in LGF from one sector to another. And this is the main source of permeability of the geothermal reservoir.

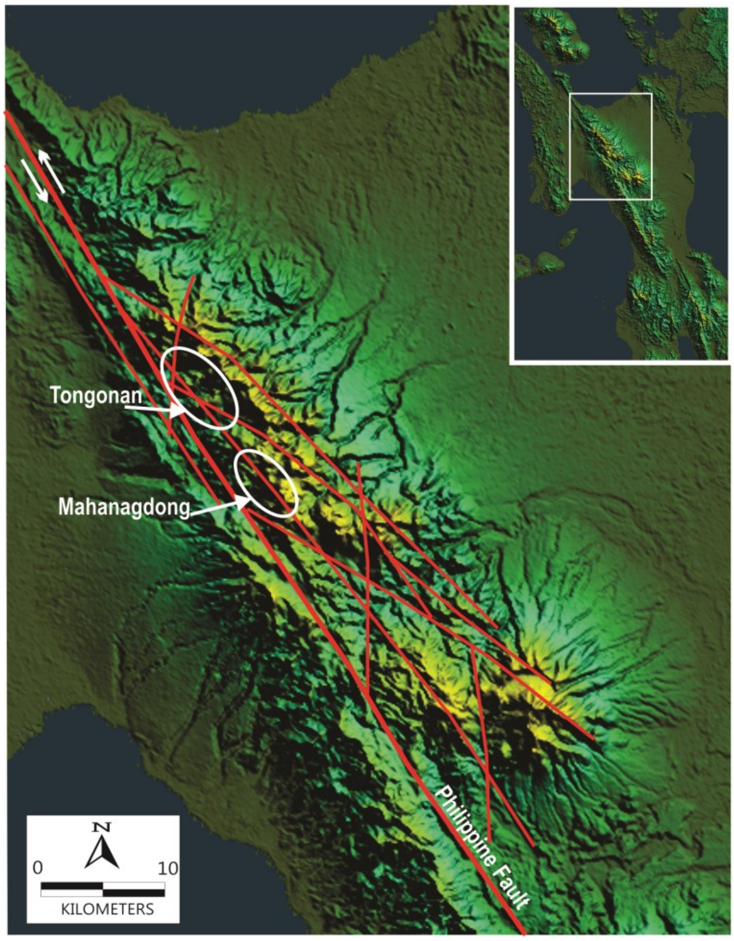

Figure 1: Location map of Tongonan and Mahanagdong Geothermal Fields in Northern Leyte. Also shown are the traces of the Philippine fault and some major faults.

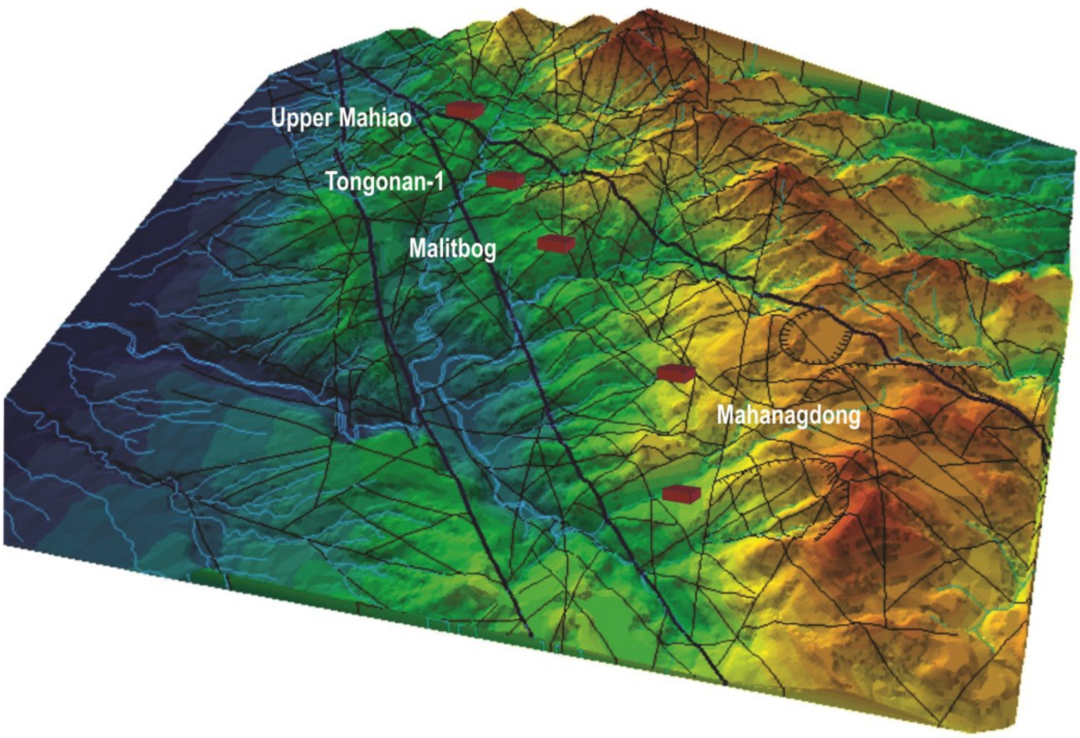

Figure 2: 3D image of the Leyte Geothermal Field showing major and minor faults. Also shown is the location of the power plants.

3. SUBSURFACE LITHOGICAL PERMEABILITY

All the geothermal wells at Tongonan and Mahanagdong produce from the lower section of Mamban Formation (MF) and within the sedimentary breccia of the Mahiao Sedimentary Complex (MSC). These formations extensively exist east of the CFL. The formations in LGF are briefly discussed in the following section in order of relative age from Youngest to Oldest.

3.1 Bao Volcanics (BV)

BV overlies almost all of the Leyte Geothermal Field. It is composed of slightly weathered hornblende/oxyhornblende andesite lavas and glass tuffs with an average thickness of 30 meters in Upper Mahiao and 200 meters in Malitbog. Based on the K-Ar age of representative samples from Upper Mahiao done by Wood in 1980 and 1983, BV has an age ranging from 0 My to 2.9-3.4 My. Considering the wide range of the K-Ar age, Delfin et al (1995) proposed a late Early Pliocene to Pleistocene age for BV. Figure 3A shows the surface distribution of BV across the field.

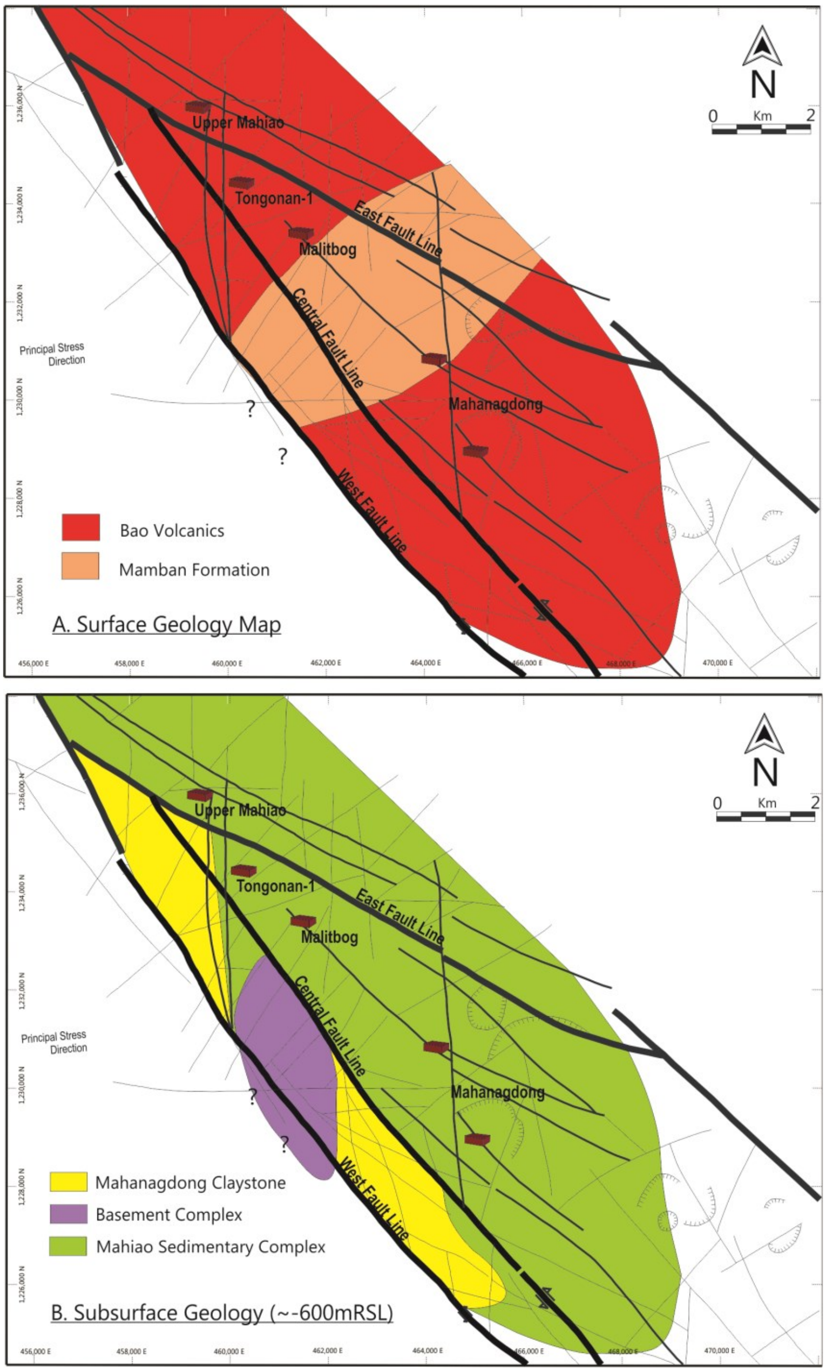

Figure 3: Simplified surface geologic map (A) and subsurface geology distribution (B) in the Leyte Geothermal Field.

3.2 Mamban Formation (MF)

MF is a thick sequence of predominantly biotite-bearing hornblende-pyroxene andesite lavas, hyaloclastites and tuff breccias (Delfin et al., 1995). These volcanic units are occasionally interbedded with lenses of claystone, siltstone, sandstone and fossiliferous limestone implying that it was water-laid. Most geothermal wells that were drilled through these lenses have not encountered losses, and there are wells in Upper Mahiao where these zones coincide with the abundant build-up of smectite clay materials. Hence, there may be minor matrix permeability within these clastic lenses but not enough to contribute to the total permeability of the wells. However, in Malitbog and Bao valley areas, there is substantial evidence from tracer studies that the shallow section of MF within the volcanic breccias has inter-formational permeability at around -200 mRSL. This is not very evident in other parts of the field. Gan in 1981 gave a Late-Miocene-Pliocene age for MF based on the paleontological analysis of core samples in Mamban. Shown on Figure 3A is the surface distribution of the MF.

3.3 Diorite Intrusives

Dioritic intrusives intersect the Mahiao Sedimentary Complex (MSC) at deeper levels. The contact of these intrusive bodies with the MSC has been the source of minor permeability in wells especially in the Upper Mahiao sector. Recent deep drilling in this sector further indicates the presence of a massive diorite pluton where several hundreds of meters of microdiorites were observed. Alteration mineralogy indicates very high temperature of more than 300°C with associated minerals such as actinolite, biotite and hornfels.

3.4 Mahiao Sedimentary Complex (MSC)

The MSC is the thickest formation encountered by wells at LGF, with at least 1100-1400 meters of thickness. This unit, which was originally regarded as an intrusive body by earlier authors, is actually a sedimentary breccia/conglomerate containing fragments of altered microdiorite, quartz monzodiorite, and minor volcanics (PNOC-EDC, 1990). Clasts are boulder in sizes that are set in a fine-grained arenaceous to argillaceous groundmass (Delfin et al., 1995). Within the conglomeratic unit, minor interbeds of sandstone, siltstone and claystone exist and these interbeds usually mark the contact of MSC with that of MF. There is no direct evidence of the intergranular permeability of MSC since most of the target permeable faults overlap with the lithological contacts. However, considering the nature of deposition and the argillaceous to calcareous nature of the matrix, there may be minor matrix permeability within the MSC that contributes to the overall reservoir permeability. MSC has a probable Early Miocene based on correlation with other units in the region (Delfin et.al., 1995). Figure 3B shows the spatial distribution of the MSC while Figure 4 shows its relationship with MF and BV.

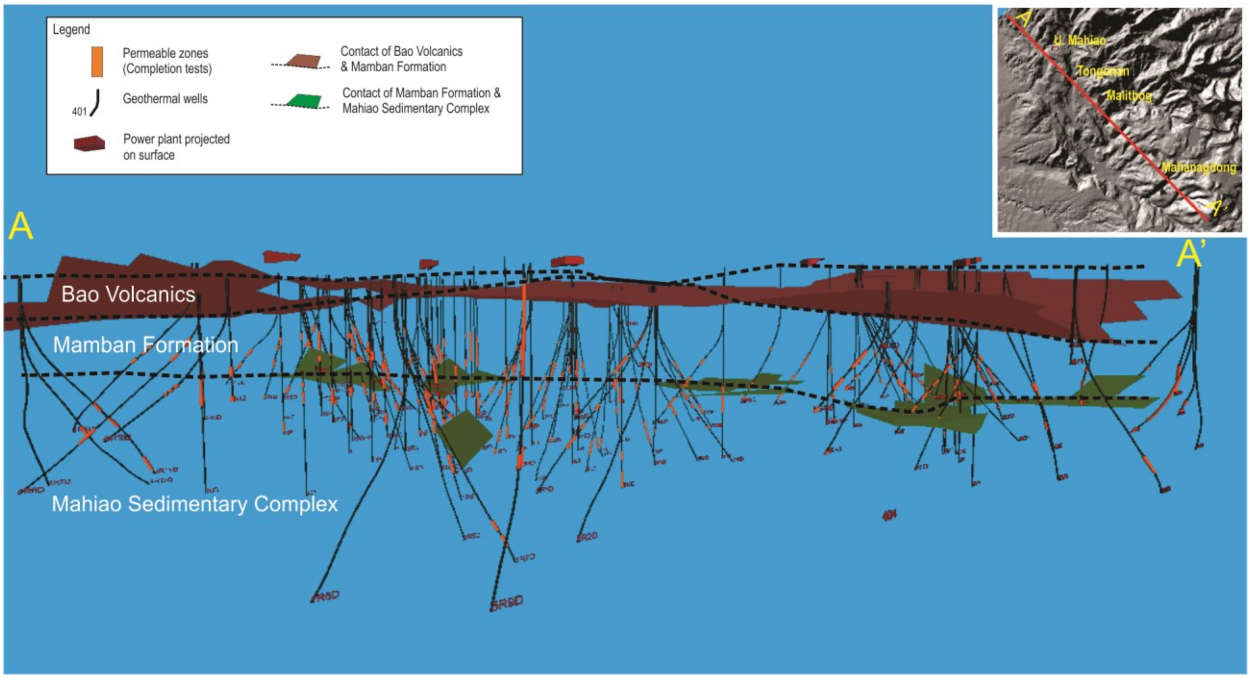

Figure 4: Cross section across Tongonan and Mahanagdong geothermal reservoir showing subsurface lithology. Other formations are offset from the section line and are not shown.

3.5 Mahanagdong Claystone

The Mahanagdong Claystone (MC) was drilled through by wells west of the Central Fault Line in Upper Mahiao, Lower Mahiao, and Mahanagdong areas. MC is a thick sequence of predominantly fine clastics of claystone, siltstone and sandstone, with minor occurrences of conglomerate, limestone and chert (Delfin et. al., 1995). The claystone member consists of finely laminated clay minerals and carbonaceous material with angular silt-size fragments of quartz, feldspar, calcite and pyrite. Production and injection wells in Upper Mahiao and Mahanagdong penetrated through this formation. The limited permeability in the wells was attributed to the fine-grained composition of the claystone that renders it as an aquitard (Delfin et al., 1995).

3.6 Basement Complex

The pre-tertiary ultramafic complex in LGF is composed mainly of serpentinite and accessory magnetite, with overlying sheared units composed of serpentinized peridotite, hornblende diorite, hornblende, and minor hornfels, schists and gneisses. These overlying rocks occur as a chaotic mixture without any discernible matrix and are interpreted as basement slivers which are upthrusted and emplaced at shallow levels (Delfin et al., 1995). Selected injection and development wells in Malitbog and

Mahanagdong encountered this formation and have proven to be impermeable despite evidences of shearing and extensive deformation based on cuttings obtained from drilling.

As shown in Figure 4, the contacts of the different formations do not show a distinct zone of permeability. Rather, the major well permeability are distributed within the MF and MSC, and controlled by faults.

4. PERMEABILITY CONTROLS FROM FAULTS

The permeability of geothermal wells at LGF is mostly controlled by local fault structures that are under the influence of the major branches of the Philippine Fault system (Figure 2). The complex fault network is composed of strike slip and secondary normal faults that is interpreted in terms of a Simple Shear deformation (Aurelio et al., 1993). The left-lateral faults forming angles of about 20^{o} with the principal strike-slips would correspond to Synthetic Riedel Shears while the right-lateral ones (80^{o} with the principal strike axis) would represent Antithetic Riedel Shears. The West Fault Line (WFL) was regarded before as the western boundary of the shear zone. Based on recent well information and microtectonic analysis, however, a different model is proposed suggesting that the western boundary of the shear zone is the Central Fault Line (CFL) while the eastern boundary goes beyond the East Fault Line (EFL).

A more recent volcano-tectonic analysis identifies a sigmoid feature where reverse faults were observed on its concave side and normal faults on its convex side (Lagmay 2002). A sigmoid feature was identified to exist in the field and coincides with the Mahiao West Fault in its northern trace and extends farther south of Lake Danao on its southern trace. Further northwest of this sigmoid, there still exists permeability based on evidences from recently drilled wells and microtectonic analyses. Hence, although the eastern permeable boundary in the upper segment of the sigmoid is defined by permeable normal fault, it does not necessarily follow that the upper western concave is also impermeable. The mobile condition of the block northeast of the CFL implies that faults within that block have permeability, no matter how limited, due to the left-lateral movement of the Philippine Fault. More recent movement along the Philippine Fault may have also influenced the current permeable condition of the faults in northern Upper Mahiao.

As shown in Figure 5A, all the wells in the field have intersected multiple faults at the shallow or deeper sections of the borehole. The length of the fault intercepts are based on the detailed well logs and evidences of its first occurrence as indicated by shearing, gouges, and veins and marked by increased alteration. It is possible that the entire length of the fault may be related to a single or multiple permeable zones as identified through well completion tests. Most if not all of the identified permeable zones are correlated to the intercepts of the faults (Figure 5B).

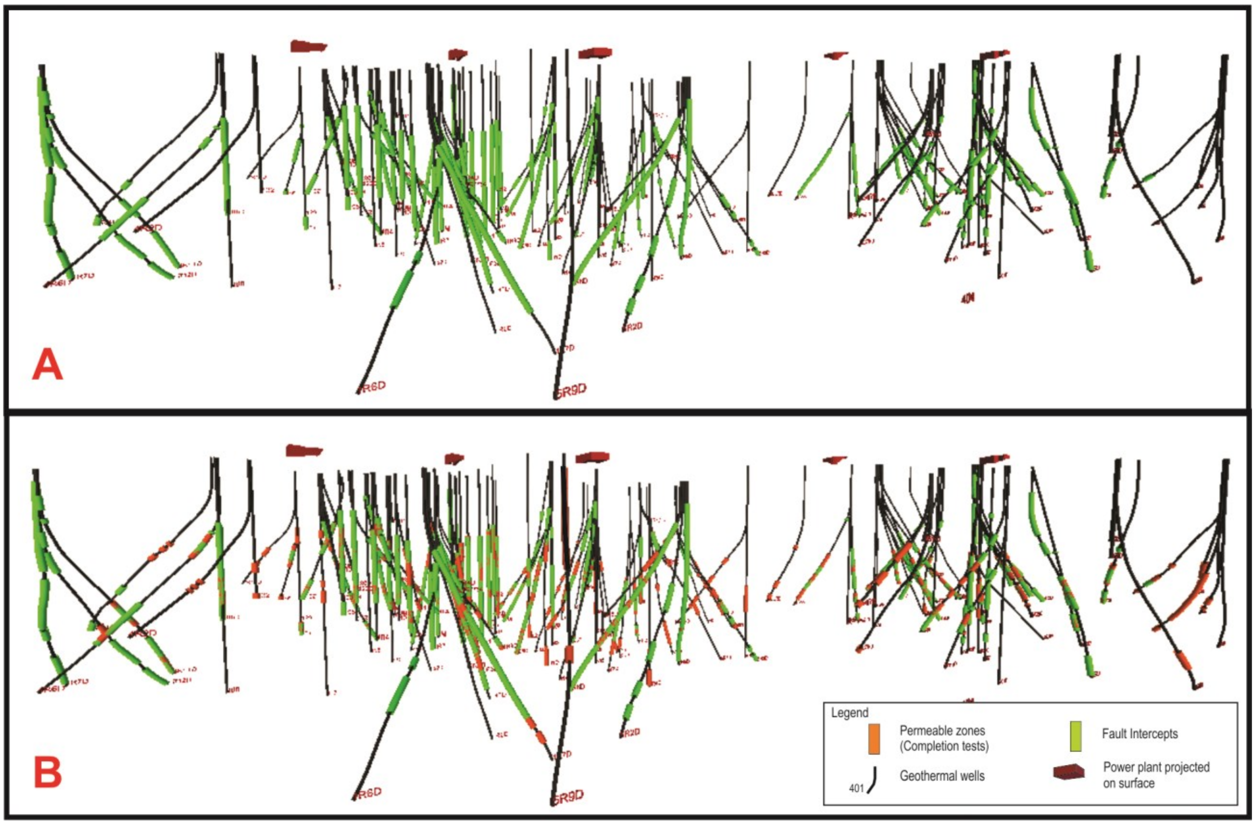

Figure 5: Cross section across Tongonan and Mahanagdong geothermal reservoir fault intercepts (A) and permeable zones based on completion tests (B).

5. PERMEABILITY INFLUENCE OF FORMATION TEMPERATURE

As a typical characteristic in high temperature geothermal environment, subsurface temperature affects the reservoir permeability. This characteristic is very evident in Tongonan and Mahanagdong reservoirs. As shown in Figure 6, almost all the permeability in the production wells are located at temperatures higher than 220°C, which are enclosed by the iso-contour. There is some associated permeability at relatively lower temperature of 180-200°C but the production casings of all wells are set at a minimum temperature of 220°C. It is also apparent that the depth of the high temperature geothermal resource is deeper in Mahanagdong than in Tongonan, and that the boundary in between is a represented by a relatively lower temperature block.

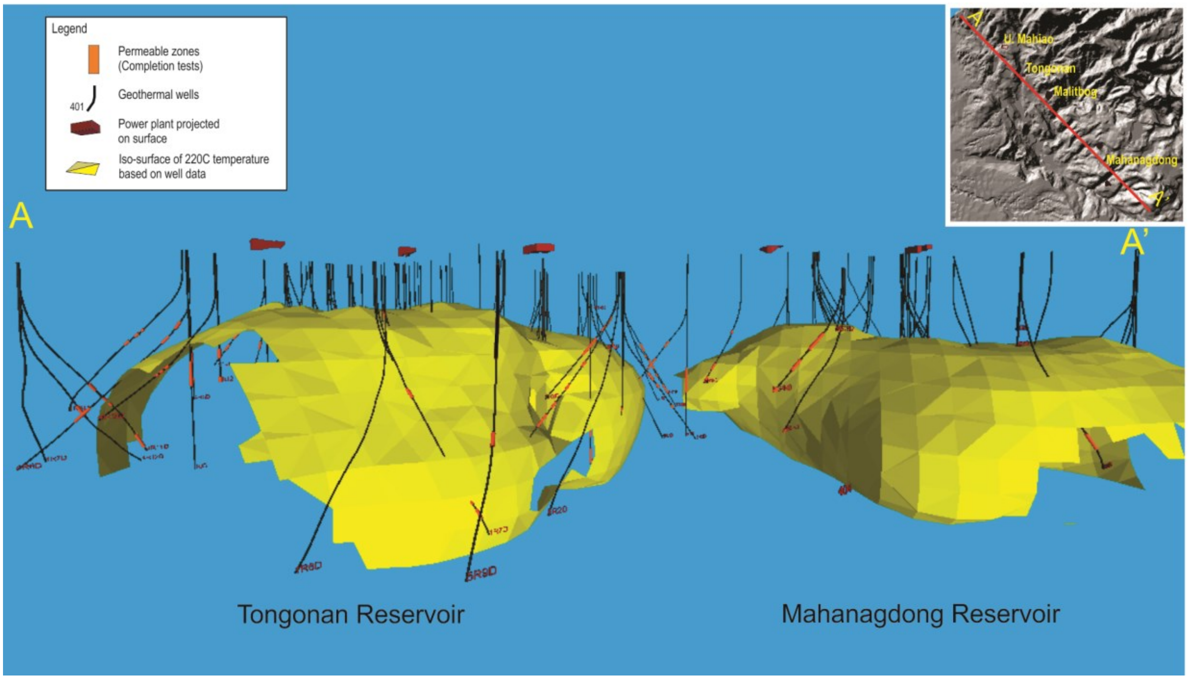

Figure 6: Cross section across Tongonan and Mahanagdong geothermal reservoir showing iso-surface of 220C reservoir temperature based on stable well temperature data.

The location of the 220°C temperature correlates very well with the 15 ohm-meter resistivity surface of the area based on all the available MT data. Although the temperature in Tongonan goes way above the top of the 15 ohm-m iso-contour, there is a close correlation in Mahanagdong (Figure 7). As the 3D image is rotated, it appears that there is still good correlation of the temperature and resistivity in the areas north of Upper Mahiao and east of Mahanagdong. These areas appear to be of good interest for further assessment.

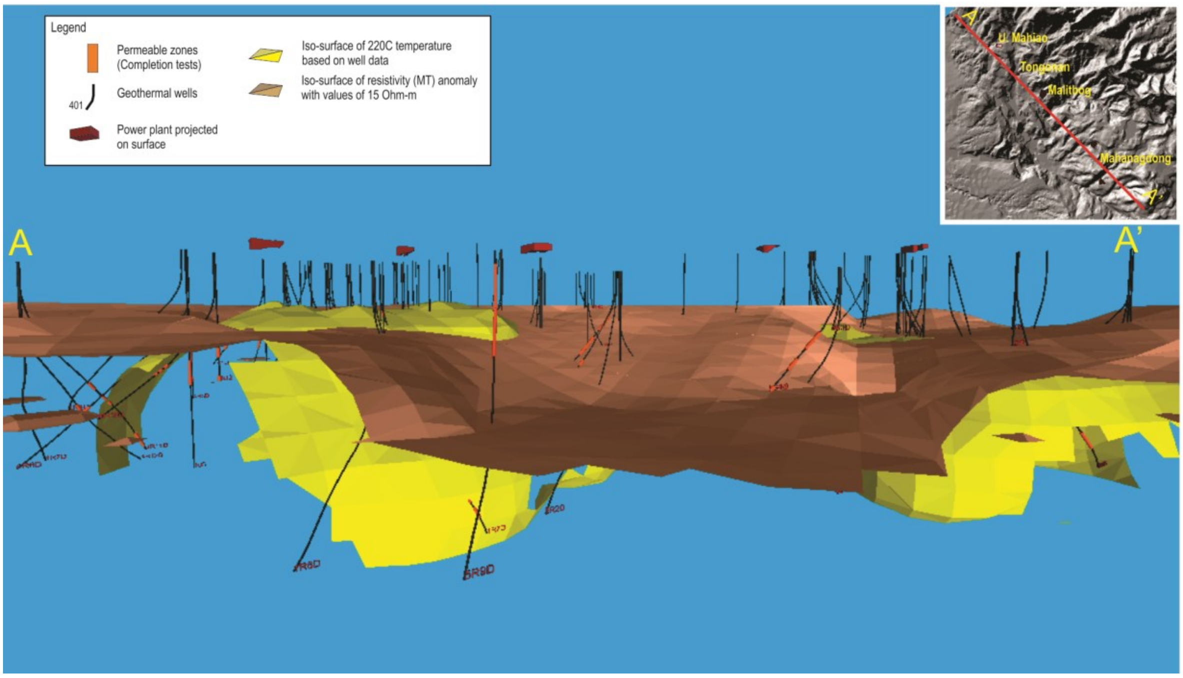

Figure 7: Cross section across Tongonan and Mahanagdong geothermal reservoir showing iso-surface of 15 ohm-m resistivity value based on MT data. Also shown is the iso-surface of 220C reservoir temperature based on stable well temperature data.

5. TEMPORAL CHANGES IN WELLBORE PERMEABILITY

Continuous production in the geothermal reservoir of LGF have resulted to massive drawdown of reservoir pressure and have induced other various processes such as cold water inflow, injection returns and formation of two phase zones. One observable phenomena that recently caught attention is the enhanced permeability of some wells that are known to have little or limited permeability. There are two possibilities to explain this: (1) change in the physical phase of the geothermal fluid from liquid to two-phase system due to drawdown; and (2) continues slow tectonic movement along the Philippine Fault as evidenced by recent large magnitude earthquakes and daily recorded micro-seismicities. The two-phase condition of the reservoir fluids changes the hydrology and hydrostatic condition in the boreholes and favors the transport of fluids through the limited permeable horizons even during well drilling. Since there is now free movement of 2-phase fluids, the overall permeability and subsequent productivity of the wells is apparently enhanced.

6. IMPLICATIONS TO DRILLING STRATEGY

Owing to the massive reservoir pressure drawdown that puts the geothermal resource under further stress than how it already has been due to tectonic movement, the medium to long-term strategy to be able to sustain steam production at LGF is to develop the peripheral areas to disperse the production and injection of fluids and manage its effect to the operations. This strategy necessitates opening-up new pads and drilling into untapped sectors of the geothermal field. Understanding the different factors that control reservoir permeability would provide the basis for proper pad citing and well designs. Areas north of Upper Mahiao still promises to have a good potential for off-field injection based on recent microtectonic analyses. Several faults were assessed to be under extensional stress regime and have been recommended as drilling targets. Furthermore, this area is considered to be still within the influenced of the permeable mobile block as evidenced by the presence of faults that are sub-parallel to the main branch of the Philippine Fault, and conjugate faults oriented northeast-southwest. Moreover, there is a good correlation of subsurface temperature and resistivity anomaly that may possibly extend the resource to the north of Upper Mahiao. Further integrated assessment if necessary to finalize the strategy on this area.

Farther down in Mahanagdong area, several faults were identified to be under extension and may be considered as candidate targets for drilling. However, the Central Fault Line still limits the western boundary of the permeable block as the areas west of CFL are located in the immobile block of the field. On the east side Mahanagdong, faults under extensional stress regime may be targeted for future well drilling. Figure 8 shows the permeability model indicating the mobile and immobile parts of the field.

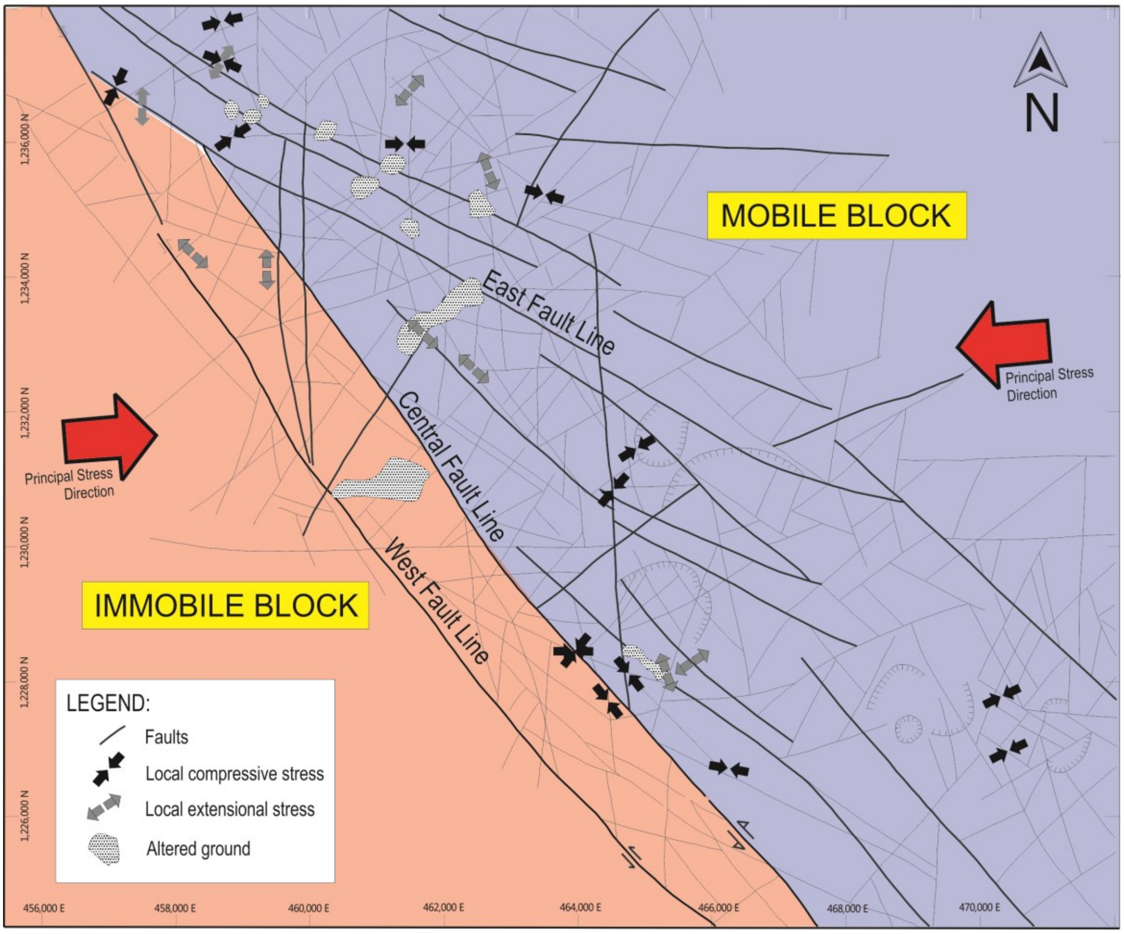

Figure 8: Structural and permeability model of the Leyte Geothermal Field.

7. CONCLUSIONS

Faults are the main factor controlling permeability at the geothermal reservoir of LGF as influenced by the left-lateral movement of the Philippine Fault system. As much as the major fault systems are responsible for the formation of synthetic and antithetic fault systems, they also define the boundaries of the permeable and impermeable blocks in the area. The Central Fault Line marks the permeable boundary on the western side of Tongonan and Mahanagdong geothermal reservoirs. The area east of the Central Fault Line is mostly permeable. The boundary on the east, however, cannot be clearly defined especially in Upper Mahiao since the entire eastern block is considered to be a mobile block and most fault structures have moderate to good permeability. How the geothermal resource extends farther east is subject to further detailed resource assessment.

The type of lithology also was regarded as another factor controlling permeability west of the Central Fault Line. The nature of the formations such as the Basement Complex and Mahanagdong Claystone are already inherently impermeable. BC inherently act as plastic to deformation so even the presence of faults will render it impermeable. However, the poor permeability in MC is also possibly influenced by its lack of fracture since it is located at the immobile block of the field.

Recent changes on the apparently higher permeability of zones drilled by new wells even along faults with previously recorded low permeability are probably attributed to: 1) phase change of the geothermal fluid from liquid to two-phase which resulted to a change in the hydrostatic pressure exerted into the formation; and, 2) continuous tectonic movement along the Philippine Fault system.

The long-term strategy for the sustainability of the geothermal resource at LGF is to expand production and injection wells in the periphery of the field. And this necessitates opening of new areas for drilling. Microtectonics analyses of areas in the north of Upper Mahiao, eastern and south Mahanagdong indicates that these areas are within the permeable mobile block at LGF. Faults under extensional stress regime have been identified as promising targets for well drilling.

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