GEOLOGICAL APPROACH TO SUCCESSFUL GEOTHERMAL WELL DRILLING

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Abstract

Geothennal wells of PNOC-EDC target subsurface faults as the main source of permeability in the open hole. This is a consequence of having very limited to nil primary permeabilities in the thick volcano-sedimentary deposits and intrusive bodies underlying most geothermal systems being developed by the company. This lack of specific permeable horizons in the subsurface from which fluids can be extracted necessitate that geologists make use of all data available to them in identifying possible fault intercepts in wells to be targeted by drilling.

For a well targeting a fault with a still unestablished subsurface dip range, close monitoring of the cuttings and drilling parameters can greatly help pinpoint likely fault intersections as drilling proceeds. In the case of several wells having drilled through a common fault on the other hand, enough geological data supported in part by drilling and well test information can be correlated to come up with a specific dip range representative of the fault's main dip value. The dip range arrived at can then be used to make a reliable projection on when a new well will intersect a fault based on its programmed profile.

Two wells drilled in LGPP were chosen to exemplify how these procedures help geologists in identifying subsurface permeable faults whose intersections dictate the degree of success of drilling. Wells MG-9D and 4R4D's re-entry were chosen due to the methods by which their intercepts with a specific fault were identified, one during actual drilling phase where problems related to a geological structure were successfully addressed, and the other prior to drilling in an attempt to locate additional targets to improve the very limited capacity recorded after completion of the well. In both cases, the procedures used in identifiing their respective target faults proved their effectiveness which led to the successful attainment of the objectives for drilling.

1.0 INTRODUCTION

Faults are the most prominent geologic structures in all Philippine geothermal areas. Aside from being a major controlling factor in the geomorphology of a locality, these faults play an important role in the transport of fluids at the surface and deep within the geothermal system. For the most part, circulation of geothermal waters within known hydrothermal systems is situated along active faults where fracture permeability exists (Wohletz and Grant, 1992). These faults and fracture zones are frequently kept open by seismic activity providing regular pathways of circulation for geothermal systems, making them attractive targets for exploration (Garg and Kassoy, 1981).

Circulation in a geothermal system occurs in such a way that meteoric waters penetrate downwards through faults in areas of the field where there are no uprising hot fluids. On the other hand, magmatic water vapor in areas under very high pressure and temperature may rise from somewhere near magmatic intrusions and enter the fissures and voids of the aquifer (Armstead, 1983). The former occurs at the peripheries of the system where faults act as conduits by which groundwater seeps down, replenishing the geothermal reservoir whch otherwise would be quickly diminished of fluids through years of continuous exploitation. The latter takes place within the confines of the system where faults act as channelways for hydrothermal fluids to move up from deeper sections to higher elevations.

In all PNOC-EDC projects including the Leyte Geothermal Power Project (LGPP) (Fig. 1), faults remain primary targets of drilling for production and reinjection wells. However, an incongruence of fault dips manifested at the surface and as encountered downhole is continuosly being observed in wells being drilled Most faults encountered in LGPP wells exhibit near vertical dips in the subsurface ranging between 85° to 90" on the average. In some instances however, evidence of certain faults point to lower dip values. To optimize well-fault intersections, identification of the main dip values representative of the subsurface fault zones is needed

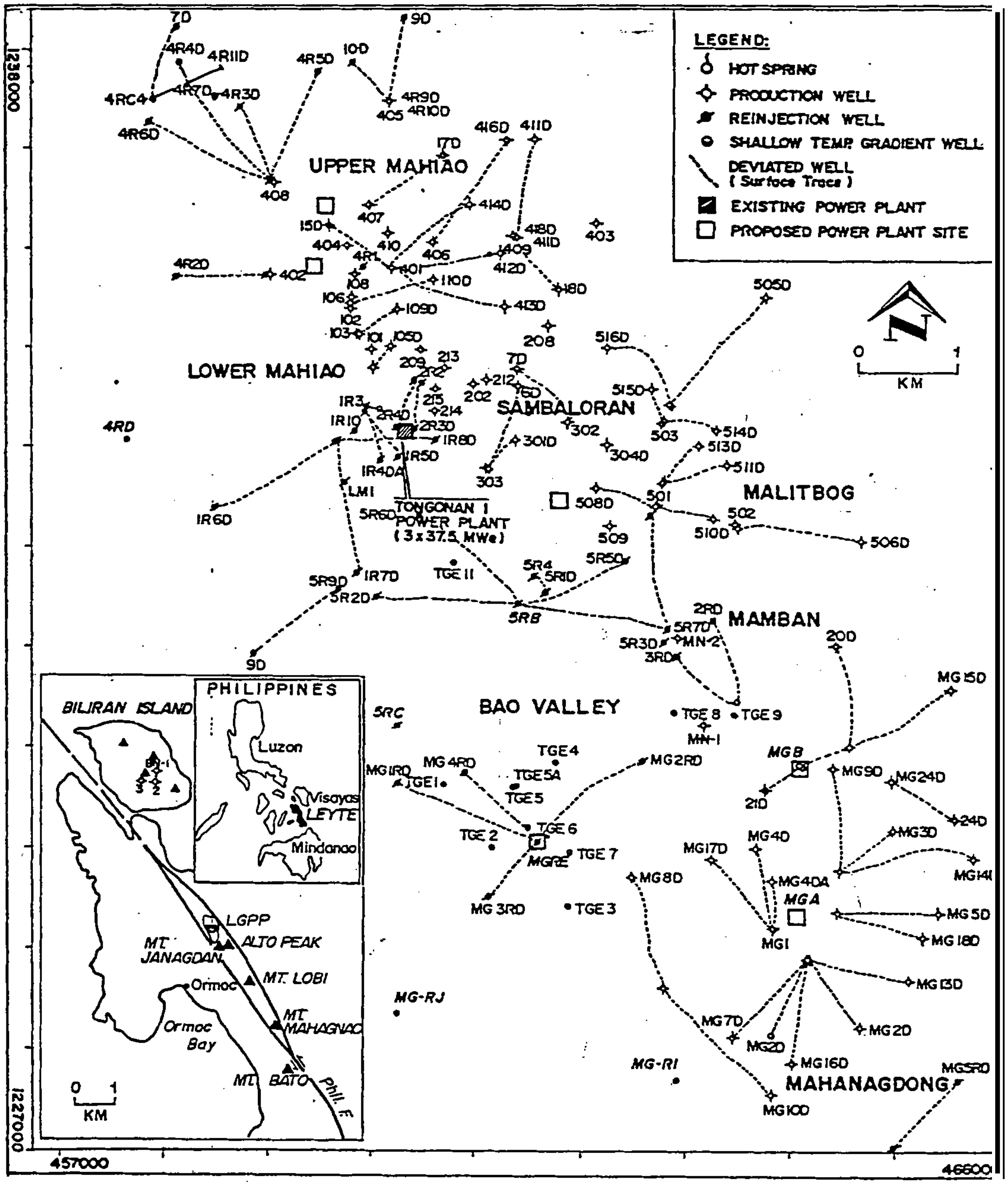

Figure 1. Location Map of LGPP

In this paper. two LGPP wells were chosen as case studies to show how geological data supported by other pertinent well information are used in the identification of subsurface fault zones and their corresponding dip values leading to a more successful drilling operation. MG-9D, drilled in the Mahanagdong sector to the south, was analyzed against the North Mamban Fault by direct evaluation of evidence in the cuttings and correlating these with changes in the various drilling parameters as drilling progressed The other well, a re-entry of well 4R4D in the northern sector of Upper Mahiao, was studied by correlation of geological evidence supported by drilling and well test data from wells that have previously intersected Litid North.

2.0 METHODS OF EVALUATION

Although megascopic and petrographic analyses of cores and drill cuttings are probably the most straight forward methods of identifying evidence of permeable fault intersections, these can no longer be employed once total loss of circulation (TLC) and subsequent blind drilling commence. As such, geological evaluation or in the case of blind drilling, the absence of it, can be supplemented by drilling information as drilling progresses and by well measurements after the well has been completed

2.1 MEGASCOPIC AND PETROGRAPHIC EVIDENCE

Megascopic and petrographic analyses of drill cuttings both utilize the same set of evidence to ascertain whether a fault has been intersected or not. The only difference is that petrography allows confident analysis of very minute details of alteration minerals. But for purposes of immediate identification of possible fault intersections on-site, megascopic analysis would suffice most of the time.

Movement along fault surfaces cause intense deformation of the rocks producing strong foliation of fibrous (chlorite and clays) and opaque minerals (magnetite, pyrite, etc.) (Zaide and Bueza, 1985.). These products of fault movement are often identified as sheared rocks, whose relative abundance signify penetration of a fault. The presence of drusy/crystalline minerals on the other hand, are used as indicators of the degree of permeability of said structure. Fluids passing through open spaces of a fault and its associated fractures, deposit vein materials from solution. The degree of crystallinity or drusiness of veins formed is directly proportional to the original size of the voids and open fractures. Since larger vein cavities allow the unhampered growth of crystals, the more crystalline veins are, the greater the inherent permeability associated with the fault.

The intensity of alteration of country rocks can also be used as a qualitative indicator of fault intersections in certain instances since it is through the faults that alteration fluids are channeled

2.2 DRILLING EVIDENCE

From a drilling perspective, downhole losses of drilling fluids, unaccountable pressure drops, well kicks and problematic sections of tight holes, stuck pipes and formation collapse of an otherwise stable formation, can all be regarded as evidence of a well's probable penetration of faults. This is especially true during blind dnlling when no cuttings can be analyzed to show which sections of the hole are permeable based on geological features.

The loss of circulation of drilling fluids expectedly accompany a well's penetration of permeable fault zones with the fluids entering fractures, cavities and open veins. The dimensions of the open spaces would dictate the rate of loss. Losses accompanied by pressure drops which could not be traced to problem with surface equipment or wash outs in drill pipes are usually good indications of highly permeable faults.

Well kicks are encountered when structures channeling and acting as entrapments of gases are entered by the bore. Though such occurrences are unwelcome, they nevertheless suggest the intersection of faults.

Problematic stuck pipes, tight sections and formation collapse by themselves are not direct proofs of fault intercepts. It is only when they plot on the same sections of the hole as other evidence that they are confirmed as caused by entry of the well into a highly fractured fault zone.

2.3 WELL TEST DATA

Well completion tests and heat-up surveys aim to identify potential feed zones, determine the well's overall permeability (estimate of injection capacity) and quantify reservoir parameters such as temperature and pressure. The location of feed zones is identified by water loss surveys at which fluids are lost or gained by the well and from temperature and flow profiles obtained during injection at a steady rate. The permeable zones identified from these tests are directly correlated to structures whose inferred intercepts based on geology are closest to them.

Correlations of the above mentioned evidence can be done with confidence after three or more wells have been drilled to a fault wherein a well-fault intersection is assumed and represented by a single point. Geological and drilling evidence as well as completion test results of individual wells are plotted together. Each evidence recorded should not be regarded as diagnostic of faulting. However, their coexistence or consistent clustering suggests possible fault intersection (Licup, 1985). The depths where most of the evidence are concentrated are therefore taken as intersection points which are then used to calculate for the main fault dip in the well. The common dip in all the wells that have intersected the fault is interpreted to be the main dip of the fault. Using this method, the likely depths of intersection with structures of future and currently being drilled wells can be computed with a higher degree of certainty.

3.0 CASE HISTORIES

MG-9D VS. NORTH MAMBAN FAULT

MG-9D was the ninth production-delineation well drilled in the Mahanagdong sector of the Leyte Geothermal Power Project (Fig.1). The well was primarily designed to intersect structures within the northern boundary of the sector's geophysical (resistivity) anomaly. This was to *test* the viability of this portion of the resource after adjacent well MG-3D produced hot, neutral pH fluids with temperatures reaching 300°C at -1000 mRSL.

One of the targeted *structures* of MG-9D was the North Mamban Fault (Fig.2) with a strike running almost parallel to the programmed welltrack and a dip towards the west. The dip at an outcrop was measured to be 85°. Very narrow target limits were specified at the programmed PCS setting depth of 1500 mMD to avoid early intersection of North Mamban's fault zone prior to reaching said depth. But an apparent premature intersection with this fault (Fig.3) at an equivalent dip of 83" was noted after continuous total and partial losses of circulation beginning at 1217 mMD were encountered Numerous drusy veins and sheared rocks were noted in the cuttings. Efforts were exhausted to try to regain circulation and *seal* off the loss zones but very little progress was recorded after eleven cement plugs were conducted down to 1362 mMD.

Compounded problems were predicted to *occur* if the welltrack was allowed to continue bitwalking along North Mamban Fault. Primarily, a good cement job was unlikely due to the presence of a long permeable section of the well against the fault. The 1500 mMD PCS setting depth would ultimately fall within the fault's intercepts. Due to the inherent difficulty of bottoming out this loss zone prior to setting the PCS, it was decided to sidetrack the original leg to the left away from the computed 83".

Close monitoring of the cuttings did not identify the same evidence such as numerous drusy veins and sheared rocks indicative of permeabilities as the well was veered to the left. Increasing intensity of alteration of the rocks into illite-smectite, chlorite, quartz and calcite and veins of anhydrite, *quartz* and epidote were noted in the cuttings prior to penetration of North Mamban but these indications pointed out that the 1500 mMD PCS setting depth could very well be already within the fault. Thus, the PCS was set earlier at 1433 mMD. *As* expected, North Mamban Fault was again intersected at an equivalent dip of 83" at 1459 mMD. Due to the same oblique intersection of the well with North Mamban Fault, a large portion of the open hole was within said structure.

The geological evaluation of the cuttings from *this* well helped in the early arrival at a decision which averted further complications related to the target structure before they occurred in the sidetrack hole.

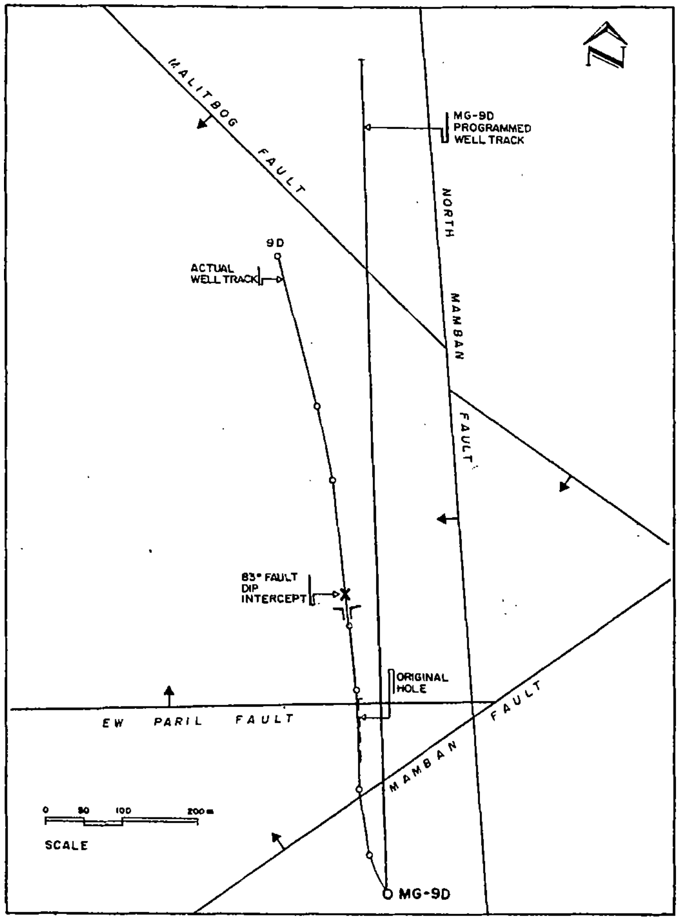

Figure 2. Plan View of Well MG-9D

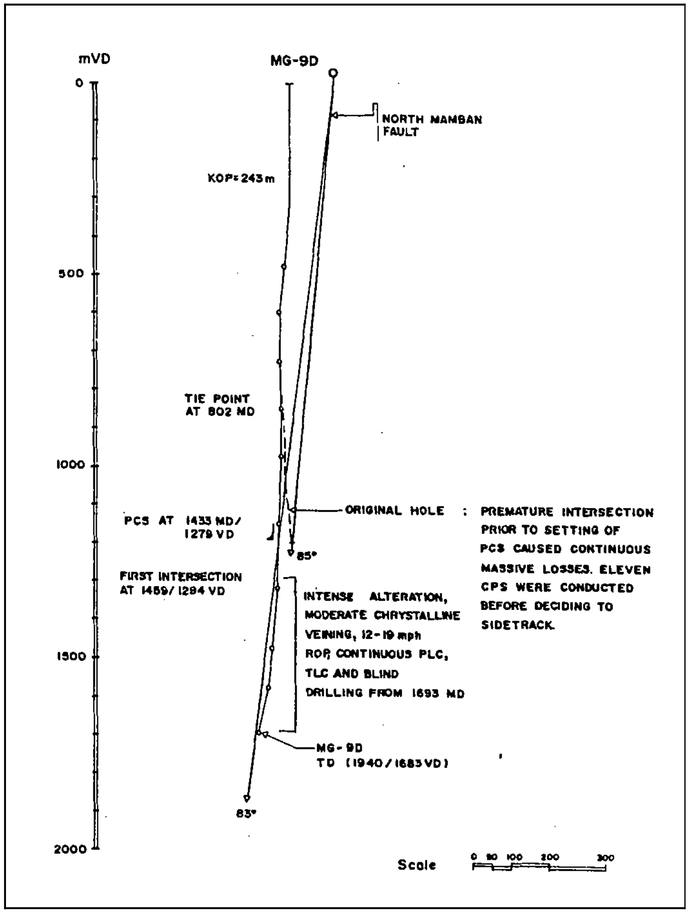

Figure 3. Profile of Well MG-9D vs. North Mamban Fault (Section Perpendicular to Fault Strike)

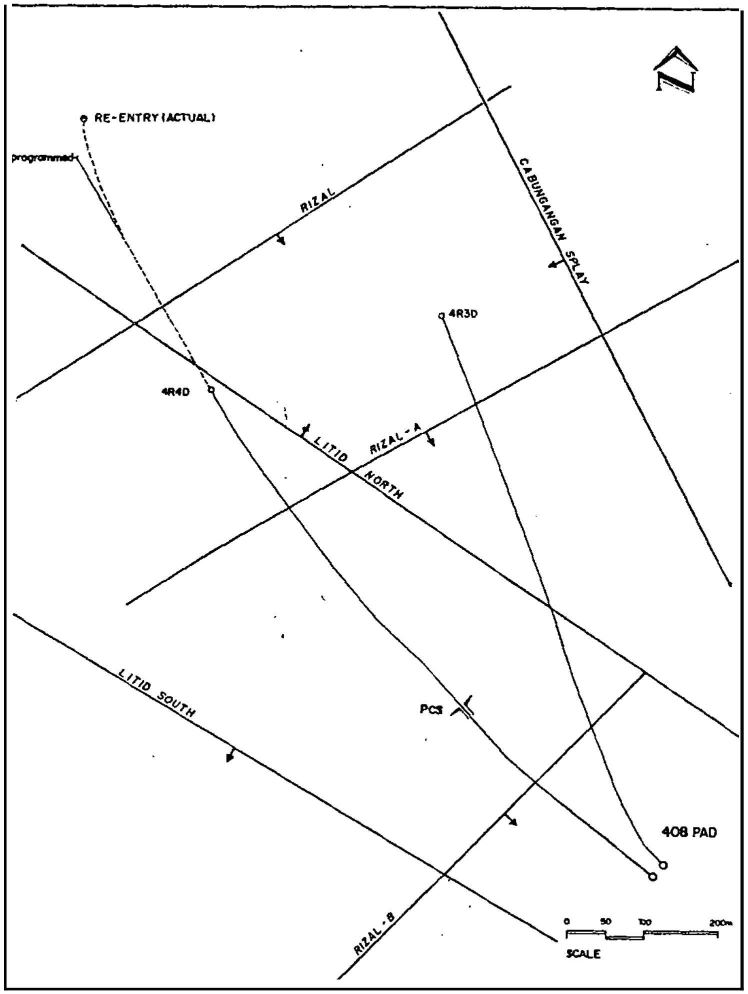

Figure 4. Plan View of Well 4R4D Re-entry

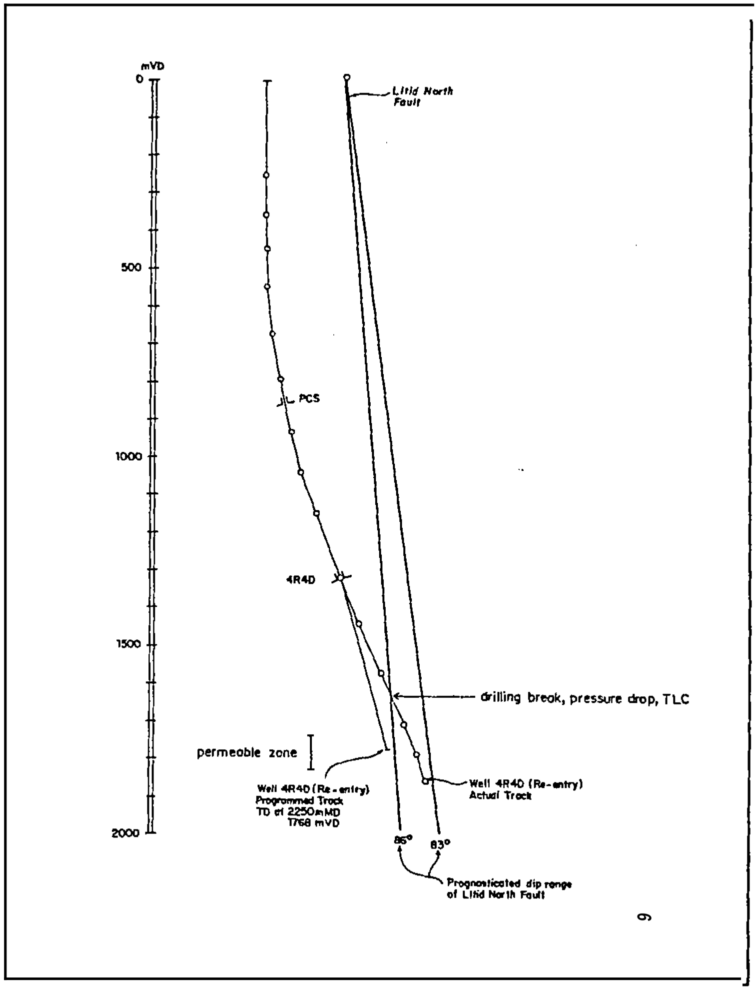

Figure 5. Profile of Well 4R4D vs. Litid North Fault
(Section Perpendicular to Fault Strike)

4R4D VS. LITID NORTH FAULT

4R4D is an additional reinjection well drilled at 408 pad to augment the reinjection capacity required for the Upper Mahiao and South Sambaloran Power Development (Fig. 1). The well was originally designed to exploit the permeability related to Rizal-A, Rizal and Litid North Faults. The program assumed an 84°-86° SW dip for Litid North based on outcrop measurements and on the uncertain SW dip computed in adjacent well.4R3D. A small rig (PNOC-EDD Rig #9) with a capacity to drill 1700 mMD was used expecting to bottom out Litid North before 1700 mMD.

The well was initially drilled down to 1710 mMD/1386 mVD until mechanical problems were encountered where the BHA could hardly be pulled. Litid North was supposed to have been bottomed out at said depth. Several wells have since been drilled through Litid North and recent evaluation of several *structures* in the vicinity of 4RC4 pad (Medrano, et.al., 1995) by fault dip correlation showed that said fault was dipping towards the northeast with a dip range of 83'-85' (Table 1).

On September 20, 1995, 4R4D was reentered by PNOC-EDD Rig #5 to obtain and maximize permeability related to the Rizal and Litid North faults. The programmed extension TD was designed at 2150 mMD to bottom-out the Rizal Fault. However, because of the results of the assessment on 4RC4 pad, a re-extension was recommended in order to intersect and maximize permeability related to the very permeable Litid North Fault at its evaluated 83-85' northeast dip (Fig. 5).

Upon reaching 2217 mMD/1754 mVD, a 3-8 mph drilling break, pressure drop and total loss of circulation which eventually led to blind drilling were encountered. Deviation surveys indicated an abrupt right turn and drop in *drift* angle which was due to bit walk along the fault. Completion test results showed a permeable zone at 2200-2300 mMD which was attributed to the Litid North Fault. Its injectivity index increased to 46.5 li/s-MPa with vacuum WHP from a pre-deepening index of 13.5 li/s-MPa with a WHP of 4.8-6.0 MPag.

Based on these data, Litid North Fault was computed to have a dip range of 84-86' towards the northeast in well 4R4D.

The re-extension would not have been strongly recommended had it not been for the results of 4RC4 pad assessment which showed that the Litid North Fault was indeed dipping towards the northeast.

Below is a tabulation of the evidence of Litid Norh Fault recorded in wells drilled in the Upper Mahiao sector of the Leyte Geothermal Power Project.

Table 1. Evidence of Litid North at the Indicated Dips in Upper Mahiao Wells

WELL	mMD	mVD	DIP	EVIDENCE
412D	2100	1764	84° NE	Blind drilling from 1586 mMD, minor permeable zone based on completion test.
414D	1474	1393	84° NE	Presence of drusy minerals at 1475 mMD, drilling break at 1474 mMD, PLC, and within the minor permeable zone at 1400-1650 mMD based on completion tests.
416D	722	710	83° NE	Presence of rare wairakite veins and shearing, PLC of 0.6 BPM at 722 mMD, increase in ROP fiom 5 to 8 mph at 741 mMD. Cased-off.
418D	1674	1612	83° NE	Blind .drilling from 1607 mMD, drilling break from 1674-1684 mMD, within the delineated permeable zone from 1600-1700 mMD based on completion tests.
4R3D	2113	1828	84° NE	Blind drilling from 1726 m, DB at 2113 m, major permeable zone based on completion test.
4R5D	1223	1121	84° NE	TLC at 1223 mMD, reduced to 2.0-0.5 BPM. PLC down to 1226 mMD. Cased-off.
4R7D	2028	1856	85° NE	Presence of shearing, mylonites, PLC of 1-3 BPM, DB from 5 to 8 mph at 2027 mMD.
	2047	1871	85° NE	Influx of epidote at 2040 mMD, major permeable zone at 2047 mMD based on completion test.

4.0 CONCLUSIONS

Plotting different megascopic and petrographic evidence supported by drilling and completion test results of intersections of likely fault zones in existing wells can provide a quantitative estimate on the probable main dip of structures intersected in each well. Subsequent well to well correlation of the same intersected faults further limit the dips into specific ranges. When used in the calculation for projecting well-fault intersections, dip values from such method of correlation prove to be very useful in well dnlling monitoring.

For structures yet to be intersected or those with unverified subsurface dip ranges, close monitoring of samples by megascopic and petrographic analyses supplemented by other data as drilling progresses is the best method by far which can give insight on the presence of likely fault zones in the subsurface.

The wells recently drilled in the Leyte Geothermal Power Project further emphasize the importance of identifying well-fault intersections. From the preparation of the well design, to actual drilling and post drilling assessment, the evaluation of well-fault intersections and identification of fault dips play important roles in a successful geothermal dnlling program especially in decision making.

Dip correlation for well-fault intersection projections and the different methods employed in evaluating faults by PNOC-EDC geologists in identifying possible fault intercepts and establishing their dip ranges have so far been effective tools in geothermal well drilling programming and planning. As drilling of more wells is pursued in LGPP and other projects where faults shall remain as primary targets, it is expected that these methods will further be fine-tuned to serve as efficient and reliable tools for predicting and evaluating permeable zone intersections.

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