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Are Faults Effective Targets In The Deep Reservoir? A Case Study from the Bulalo Reservoir, Philippines

Ivy F. Guevarra-Segura[1], Vincejet G. Ejera[1] and Mitchel A. Stark[1, 2]

[1]Philippine Geothermal Production Company, Inc., 14F 6750 Building, Ayala Avenue, Makati City, Philippines

[2]Chevron Geothermal Services Company, 5F 6750 Building, Ayala Avenue, Makati City, Philippines

IvyGuevarra@pgpc.com.ph; EJVN@pgpc.com.ph; mitchs@pgpc.com.ph

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ABSTRACT

A statistical method was developed to test if the current model for targeting deep permeability (1,350mbsl to 3,000 mbsl) in the Bulalo reservoir, based on mapped faults projected downwards at dips of 90° $\pm$3°, predicts permeable zones (PZ) with a success rate better than random. The performance measure P_{PZ} is the "hit rate" percentage (i.e., number of PZs inside the fault zones divided by total number of PZs) divided by the percent targeted wellbore length (or percentage of wellbore below the top of reservoir that passed through the target zones). If the resulting P_{PZ} ratio exceeds 1, the performance can be considered better than random. For example, if 40% of the wellbore length was inside the target zones, and 3 of the 5 PZs (60%) were encountered within those target zones, the P_{PZ} would be 1.5, which could be considered 50% better than random. The relevant data set included a total of 44,246 m of drilled wellbore, and 122 PZs (as defined from Permeable-Temperature-Spinner data), from 59 wells.

Overall results show that the production wells in Bulalo have encountered PZs in the targeted fault zones at a rate 13% better than random drilling would have. The method also enabled computation of the performance of each of the fault zones based on all the wells that intersected them. The most successful of the 11 well-established fault zones yielded a P_{PZ} of 1.61, indicating that this zone is 61% richer in PZs than random. One other fault zone target demonstrated high rates of success, while others yielded P_{PZ}'s no better than random or even worse than random. Overlapping fault zones were evaluated as separate targets, and, surprisingly, did not perform any better overall than the individual fault zones, but high P_{PZ}'s were calculated for two of these multiple zones. A more conventional measure of success, i.e., number of PZs encountered per meter drilled, was also calculated for all the target zones. Results show that PZs were encountered once every 235 m in the best-performing fault zones, compared with an average interval of 470 m for all the wells drilled in the deep reservoir.

To determine if the high-performing fault targets also delivered high productivity, the average Productivity Index (PI) was calculated for all the PZs within each target fault zone. A cross plot showed a strong positive trend (55%) indicating that the fault zone targets richest in PZs also have the highest average PIs, which would tend to compound the advantage of targeting these zones. Also addressed was the "sweet-spot" issue, i.e. the high-performing fault zone targets that coincide with a known area of high production; hence it is possible that it is the sweet spot that is driving the performance of those fault targets. But the high-performing fault zone targets show almost equally high P_{PZ}'s outside the sweet spot, such that those fault zone targets can be considered innately productive. Possibly the sweet spot is actually due to a convergence of high-performing target zones.

The same statistical methodology can be used to test almost any geometrically-defined targeting model, and work is ongoing to test alternative targeting models such as fault corridors, non-vertical faults, stratigraphic, and preferentially oriented fractures. The main limitation is data quantity and quality. Given Bulalo's extensive history of drilling and production logging, it is hoped that future drilling can be guided by the quantitative results of this study.

1. INTRODUCTION

Time, cost and drilling risks are incurred in steering wells to specific geologic targets in order to encounter more and higher-permeability fractures. If the performance of target feed zones is no better than random, such zones should not be targeted. More importantly, valid and successful targeting models will generate economic value by saving on development and make-up wells needed in the long-term and performance only slightly better than random may yield significant economic results/benefits over the lifetime of a field. Considerable effort has therefore been expended in geothermal fields worldwide to optimize well targeting based on geoscientific and drilling data.

Production from geothermal reservoirs is predominantly from fractures. In some fields, production is unquestionably associated with one or more fault zones. Numerous examples of fault-controlled geothermal systems from the Basin and Range province of the western US were documented by Faulds, *et al*. (2006). However, many larger fields worldwide fall into the category of distributed-permeability reservoirs where characterizing and targeting permeable fractures is much less straightforward. Efforts to do so generally fall into a few categories:

- qualitative visual analysis of maps and cross-sections to correlate known productive zones with interpreted geologic features (e.g., Sanyal, *et al*., 1982; Hebein, 1986; Hulen, *et al*., 2003; Davatzes and Hickman, 2005; Vicedo, *et al*., 2008);
- cross-plots of productivity vs. well course orientation, depth, lithology and other parameters to identify the best drilling directions or targets (e.g., Beall and Box, 1992; Thompson and Gunderson, 1992; Pioquinto, 2006); and
- analysis of fracture orientation from borehole image logs to identify optimal fracture trends (e.g., Davatzes and Hickman, 2006; Suemnicht, *et al*., 1989).

In addition, Rejeki, *et al*., (2008) combined some of the above-mentioned approaches in a scoring system for evaluating proposed make-up drilling targets.

This paper presents a quantitative method where the targeting model is defined geometrically and evaluated statistically and compared with random drilling. For each fault target, the method generates a number that represents the frequency of permeable zones (PZs) registered in the zone relative to overall drilling results. The advantage of this method is that it provides quantitative information about the performance of the targeting model, thereby providing a more rigorous basis for selecting targets, improving the targeting model, and placing an economic value on the targeting process. The authors are not aware of any other similar methods previously used in either the geothermal or oil and gas industries. The Bulalo field, with its long history of drilling and dense distribution of wells and PZs, is an ideal test case for the method presented in this paper. However the method could be applied to any spatially defined targeting model in any reservoir with sufficient subsurface data.

1.1 The Bulalo Geothermal Field

The Bulalo (also known as Makiling-Banahaw or Mak-Ban) Geothermal Field is located about 60 km south of Manila. It is operated by Philippine Geothermal Production Company, Inc. (PGPC) and has been producing steam for power generation since 1979. With a production area of only 7 km^2 supporting an installed generation capacity of 458 MWe, Bulalo boasts one of the highest power densities of any geothermal field worldwide. A total of 113 wells have been drilled at Bulalo during its development and various make-up campaigns. Throughout the history of the field, drilling data, PZ characteristics and other geologic information were used to better understand the controls and distribution of PZs in the reservoir so that they can be effectively targeted and drilled. After each drilling campaign, the performance of the new wells is reviewed and targeting models are updated toward the goal of maximizing steam deliverability in the next drilling campaign.

Vicedo, *et al*. (2008) presented the most recent conceptual model of the Bulalo geothermal system, updating previous work by Golla (2001). The group identified a sub-horizontal permeable horizon that seems to host most of the shallow permeable zones, a sub-horizontal permeability barrier known as the Andesite Lava Marker (ALM) at about 1,350 mbsl that separates the “shallow” and “deep” reservoirs, and the dominance of fault-controlled permeable zones in the deep reservoir. This conceptual model remains the basis for targeting future make-up wells at Bulalo. Because of depletion and influx of cooler fluids in the shallow reservoir, future wells will be cased down to the ALM and drilled to targets in the deep reservoir; therefore, it is timely to re-evaluate the future deep fault targets.

2. METHODOLOGY

The statistical method used in this analysis was based on comparing the occurrence of PZs in drilled intervals passing through the fault target zones versus intervals outside the target zones. PZs for each well were defined from interpretation of past production logs, Pressure-Temperature (PT) and Pressure-Temperature-Spinner (PTS) surveys and drilling data. In some wells, the PZs are defined with a single depth while, in others, they are defined as depth intervals.

The fault targets were taken directly from the conceptual model of Vicedo (2005), with the assumption that each fault extends from its mapped surface trace vertically downwards at a dip of 90° ± 3°. The 3° uncertainty, based on actual surface dip measurements of a few mapped faults, yields target zones whose width increases with depth, reflecting increasing uncertainty and/or fault zone width with depth. Because this study is concerned with targets below the ALM (or the deep reservoir only), the target zones evaluated therefore have cross-sectional geometries of bottomless triangles, centered on each (assumed) fault, truncated at the top by the ALM (Figure 1).

With the PZs and target zones thus defined spatially and entered into an AutoCAD database, the process of counting PZs inside and outside the target zones was carried out by generating cross-sections along each well course. In cases where the PZs were defined as finite depth intervals (not as single depth points) and were only partially inside a target zone, that PZ was prorated as a fractional hit. The resultant counts were entered into a spreadsheet to enable the calculations detailed below.

For each well penetrating the deep reservoir and hitting a fault such (Figure 1), its targeting performance is defined by the hit rate (R_h) divided by the targeted wellbore length percentage (L_t). The R_h is the number of PZ inside the target zone (P_{tz}) divided by the total number of PZ below the ALM (P_{tot}). The L_t is defined as the well track length inside the target zone (L_{tz}) divided by the total well track length below the ALM (L_{tot}) (Equation 1). This measure of performance, called P_{PZ}, essentially compares the frequency of PZs within the target zone to the frequency of PZs overall along the well track. If there is no difference, this means the target zone is not any richer in PZs than any other random portion of the well track and the calculated P_{PZ} will be 1.0. If the entire well track lies within the target zone, the calculated P_{PZ} will also be 1.0. In general, the more PZs encountered within the target zone and the smaller the target zone as a proportion of the entire well length, the better the calculated P_{PZ} of the well target.

Figure 1 shows an actual example for a well which passed through the Makiling Fault Zone. This well encountered five (5) PZs below the ALM (PZT) where two (2) PZs were inside the fault target (P_{tz}) hence the hit rate (R_h) is 2/5 or 0.40. The total well track length below the ALM (L_{tot}) is 1,729 m but only 368 m of it passed through the target zone, so the L_t is 368/1729 or 0.21. Following Equation 1, the well performance measure, P_{PZ}, is 0.40/0.21 or 1.9. This means that PZs were 90% more prevalent along the well track interval inside the Makiling Fault target zone than along any other random interval along the well track.

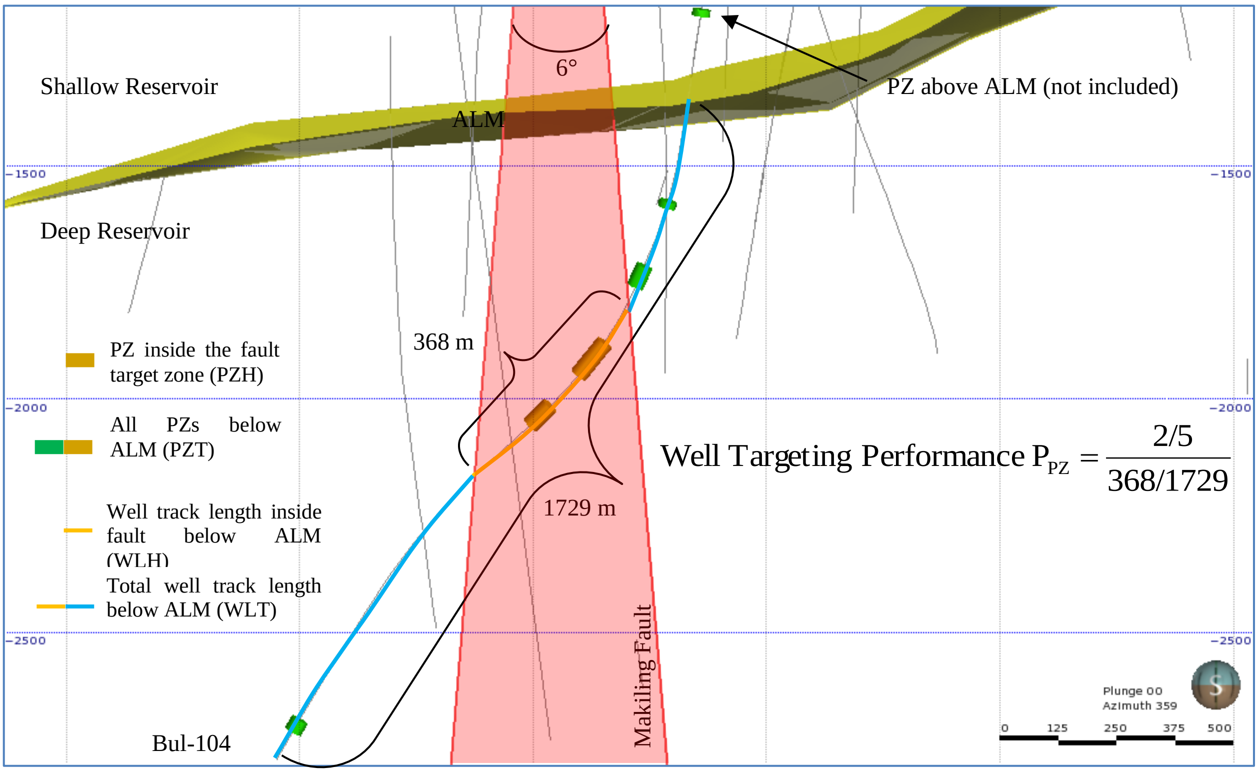

Figure 1. Bul-104 Passing Through the Makiling Fault Target Zone in the Deep Reservoir (below ALM), Showing the Calculation of P_{tz} , P_{tot} , L_{tz}, L_{tot} and the Well Targeting Performance Measure.

Similarly, the performance of a single fault target zone can be computed by summing all the P_{tz}, P_{tot}, L_{tz} and L_{tot} of all the wells that crossed the target zone and plugging them into Equation 2. If the resultant P_{PZ} for the fault target zone is greater than 1, then finding permeability by targeting the fault was better than random drilling.

$$P_{PZ} = \frac{R_h}{L_t} = \frac{P_{tz}/P_{tot}}{L_{tz}/L_{tot}} \qquad \textbf{Equation 1}$$

Where

P_{PZ} is the calculated performance measure
P_{tz} is number of PZs encountered inside the fault target zone
P_{tot} is the total number of PZs below the ALM
L_{tz} is the well track length passing inside the fault target zone
L_{tot} is the total well track length below the ALM

$$P_{PZ} \text{ for a fault target zone} (F_x) = \frac{\sum P_{tz} \text{ in } F_x \ / \sum P_{tot} \text{ in } F_x}{\sum L_{tz} \text{ in } F_x / \sum L_{tot} \text{ in } F_x} \qquad \textbf{Equation 2}$$

Some target zones have been sparsely drilled thus leading to a large uncertainty in performance measure. For the purposes of this study, fault target zones with <2 PZs encountered or <300 m drilled were eliminated from consideration.

2.1 Multiple and Overlapping Fault Target Zones

Many of the wells at Bulalo encountered more than a single fault target zone or zones of overlapping fault targets. If a well passes through two or more fault target zones, a P_{tz} is separately assigned to each of the corresponding target zones. However, if a well passes through a zone of overlapping fault target zones it is impossible to assign the PZs in the intersection volume to either target zone. Therefore, in this study, each zone of fault target intersections is treated as a single and separate fault intersection target. By making this assumption, this allowed determination if these intersection zones performed better than individual fault zone targets.

2.2 Overall Fieldwide Performance of Fault Target Zones

It is almost logical to apply Equation 2 to all the target zones and simply sum and average to compute for the overall fieldwide targeting performance. However, it was not that simple because of double-counting associated with the wells intersecting multiple and overlapping faults as discussed above. To correct this, Equation 3 was used where the number of PZ and the length below the ALM for each well are only counted once.

$$\text{Overall Fieldwide Targeting Performance } P_{PZ} = \frac{\dfrac{\sum P_{tz}}{\sum P_{tot} \text{ below ALM}}}{\dfrac{\sum L_{tz}}{\sum L_{tot} \text{ below the ALM}}}$$ **Equation 3**

3. RESULTS AND DISCUSSION

3.1 PZ Performance Measure

The overall performance measure P_{PZ} of all the fault target zones in the Bulalo deep reservoir is 1.13 (Table 1). This means that well track intervals within those target zones have encountered PZs at a rate 13% higher than random.

Table 1: Data and Calculated PZ Performances Measures for the Target Zones Analyzed

Faults	Length inside Fault(m)	Length below ALM(m)	PZ inside Fault	Total PZ below ALM	PZ Performance	PI Average	Permeability and Productivity Index	No. Wells intersecting Fault	Length/PZ (m)
Bulalo 2 (B2)	3323	7148	12	16	1.61	0.17	0.28	6	277
TB-B2	378	2410	2	8	1.59	0.06	0.10	2	189
Olilia-North (ON)	1346	4955	7.46	18	1.52	0.12	0.18	7	181
T1N-MA-MK	492	1399	2	4	1.42	0.04	0.06	1	245
Tigsa 1-North (T1N)	760	2321	3.5	9	1.19	0.05	0.06	2	217
Tigsa-Bulalo (TB)	2865	6292	9	19	1.04	0.10	0.10	6	318
Tigsa 2 (T2)	750	1004	3	4	1	0.05	0.05	1	250
San Vicente (SV)	3314	5678	8	14	0.98	0.08	0.08	5	414
T1N-MA	814	3128	2.1	10	0.81	0.03	0.02	2	387
Makiling (MK)	524	2577	1	7	0.7	0.05	0.04	3	524
Makiling Arcuate (MA)	252	3128	0.12	10	0.14	0.05	0.01	2	2173
SV-OL	273	1699	0	4	0	n/a	n/a	1	n/a
TB-SV	57	7106	0	4	0	n/a	n/a	1	n/a
Total Performance	**15149**	**23947**	**50.18**	**70**	**1.13**				
(red)	Faults								
(green)	Intersections								

Note: Totals for both Length and Total PZ below ALM are less than the sum of individual lengths and the sum of all PZ listed because of multiple counting where individual wells intersected multiple fault zones.

Table 1 also shows the P_{PZ} results for the individual fault target zones and the overlapping fault target zones in the deep Bulalo reservoir. In only about half of the 13 target zones were PZs encountered at rates better than random. Four fault targets registered P_{PZ} greater than 1.4, namely, Bulalo 2 (B2), Tigsa-Bulalo overlapping with Bulalo 2 (TB-B2), Olilia North (ON) and the three-fault overlap of Tigsa 1 North, Makiling Arcuate and Makiling (T1N-MA-MK) (Figure 2). These results suggest that the PZ performance measures of overlapping fault targets are not any better than those of individual fault zone targets.

Another measure of well targeting performance is PZs per drilled length (Thompson and Gunderson, 1992). This was easily calculated for our fault zone targets (Table 1). For the top-performing four target zones, a PZ was encountered every 235 m on average. A separate calculation using all the wells (not just the 59 wells that intersected fault targets which were considered in Table 1) showed that, on average, wells within the deep reservoir average a PZ per 470 m drilled. So, in the deep reservoir, drilling into the high-performing target zones encountered PZs at a frequency twice the overall average.

Table 1 shows that about 23% of the drilled well tracks below the ALM were located within the four high-performing fault zones. For every 10,000 m drilled below the ALM, about 2,300 m was inside the high-performing fault targets where a total of 9.8 PZs (one per 235 m) was encountered. The 7,700 m drilled outside the high-performing zones encountered 16.3 PZs (one per 470 m) thus a total of 26.1 PZs for the entire 10,000 m drilled was intersected. If future wells could be steered toward the high-performing fault targets, doubling the percentage of well track within these target zones to 46%, the same calculation shows a potential total of 31.1 PZs can be encountered for every 10,000 m drilled or a 19% improvement from past performance.

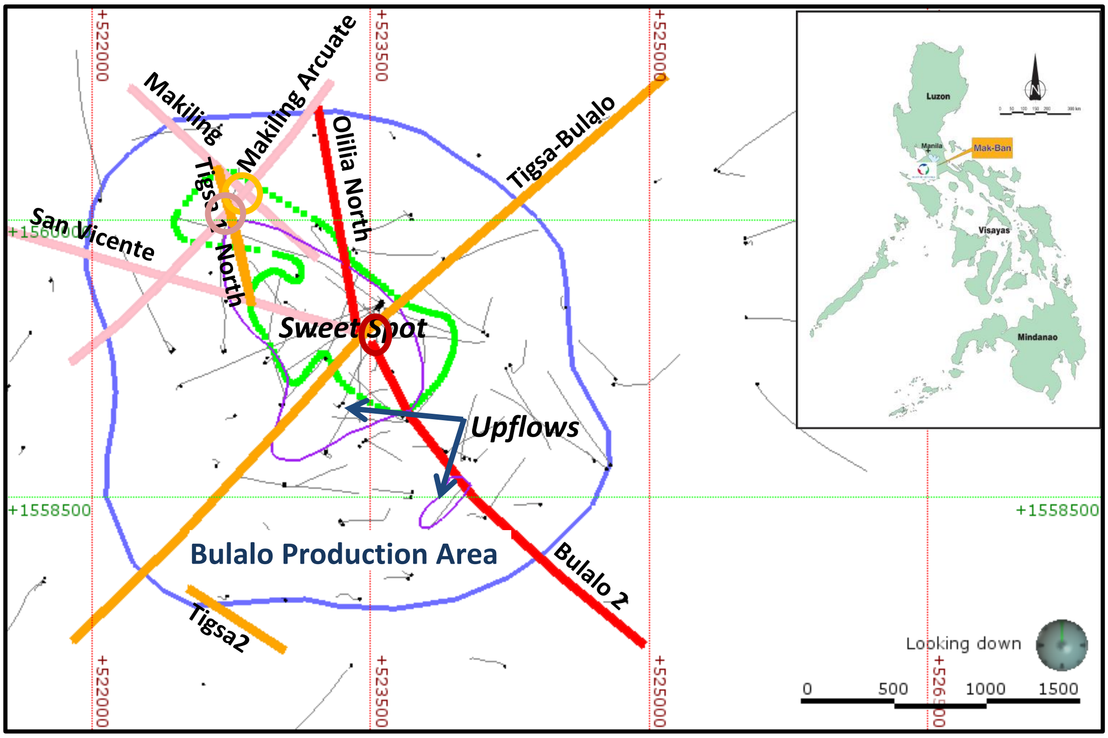

Figure 2. Fault Classification in the Bulalo Field Based on Targeting Performance in the Deep Reservoir: Red (>1.4 P_{PZ}), Orange (1.4-1.0 P_{PZ}) and Pink (<1.0 P_{PZ}). The location of the Bulalo reservoir in the Philippines is also shown (inset).

3.2 Target Zone Productivity

It is not enough to identify a fault target zone that has a high chance of encountering PZs. It is also important to know the productivity of these PZs in these fault targets. To characterize the productivity of each fault target zone, the Productivity Indices (PIs; derived from interpretation of production logs) of the PZs within each fault target were averaged and plotted against the P_{PZ} performance measure for each of the target zone (Figure 3). The positive trend indicates that the high-performing fault zone targets, in terms of PZ frequency, also host PZs with high PI, which would tend to compound the advantage of drilling into these high-performing fault zone targets. Figure 3 also includes a plot for the fault zone intersections although only three of these were analyzed. It appears that the average PIs for the fault intersection targets fall along a substantially lower trend than those for the single fault target zones.

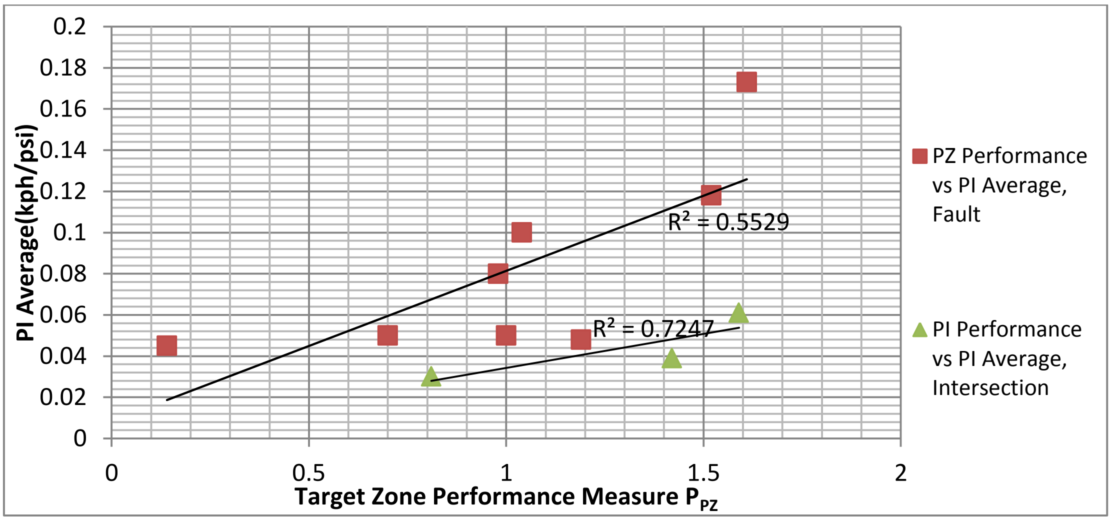

Figure 3. Average PI vs. PZ Performance for Faults and Intersections.

3.3 Sectoral vs. Fault Permeability and Deliverability

Previous workers have long recognized a pronounced "sweet spot" in Bulalo where highly productive wells have been drilled (Sugiaman and Vicedo, 2002; Stimac, *et al*., 2006; Vicedo, *et al*., 2008**)**. As several faults pass through the sweet spot, the authors attempted to determine whether the faults are high-performing because they pass through the sweet spot or is the sweet spot productive because of the high-performing fault zone targets passing through it. This was addressed by segregating and separately analyzing the PZs inside and outside the sweet spot and calculating their P_{PZ} separately for portions of the high-performing faults that extends outside the sweet spot.

The resultant P_{PZ} of both the Bulalo 2 and Olilia faults outside the sweet spot are shown in Table 2, and are similar to the overall values for these fault zone targets, suggesting that these faults are innately permeable. The two high-performing fault intersection targets were both located entirely inside the sweet spot, offering no opportunity to assess their performance outside the sweet spot.

Average PI values of all the target zones, calculated inside and outside the sweet spot, are presented in Table 3. For target zones that pass both inside and outside the sweet spot, average PIs inside the sweet spot are consistently higher than those outside of the sweet spot, confirming previous unpublished findings. Bulalo-2, the fault target zone with the highest overall P_{PZ}, also posted the highest average PI (0.16 kph/psi) outside the sweet spot. The Olilia North fault, which had the second-highest overall P_{PZ}, had a significantly lower average PI (0.04 kph/psi), but that was based on only two PZ's encountered outside the sweet spot. The authors are still investigating the significance of these average PI values.

Overall, these results suggest that the sweet spot is due to the presence of four high-P_{PZ} target zones, plus higher average PI for the PZs located in the sweet spot.

Table 2. PZ Performance of Bulalo 2 and Olilia faults Outside the Sweet Spot

Fault	PZ inside Fault	Total PZ below ALM	Length in Fault	Length Below ALM	Fault zone PZ Performance
Bulalo 2	4	6	1097	2674	1.62
Olilia North	1.6	9	315	2333	1.29

Table 3. PI's for Target Zones Inside and Outside of the Sweet Spot

Fault	Average PI, kph/psi		PZ Count	
	Inside SS	Outside SS	Inside SS	Outside SS
Bulalo 2	0.26	0.16	7	5
Tigsa-Bulalo	0.14	0.03	6	3
Olilia North	0.14	0.04	6	2
San Vicente	0.08	N/A	3	1
Makiling	0.05	N/A	5	1
Tigsa 1-N	0.07	0.04	1	3
Bulalo 1	N/A	0.03	N/A	1
Tigsa 2	N/A	0.11	N/A	3
Makiling Arcuate	0.04	N/A	1	N/A
T1N-MA	0.03	N/A	3	N/A
T1N-MA-MK	0.04	N/A	2	N/A
TB-B2	0.06	N/A	2	N/A

The above results also suggest that relatively higher permeability and productivity could be encountered from certain fault targets in the deep reservoir, partially validating earlier studies of the deep Bulalo reservoir (Vicedo, *et al*., 2008). Figures 4a and 4b show that permeability extends deep in the reservoir below the ALM but with decreasing average PI.

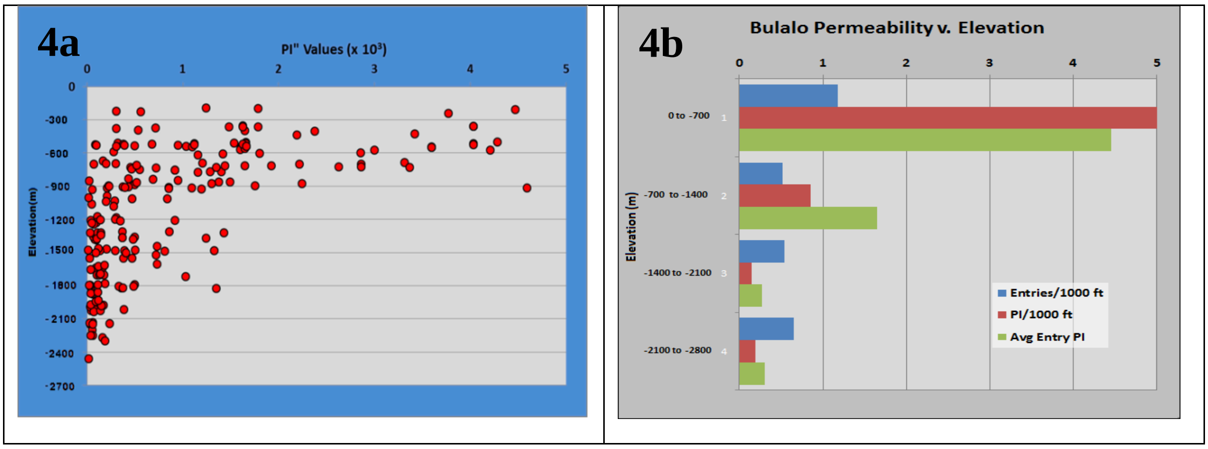

Figure 4. Charts Showing PI Trend with Depth at Bulalo. Similar with most geothermal reservoirs, PI decreases monotonically with depth although the frequency of PZs is fairly constant below the ALM.

3.4 Results vs. Regional Structure and Stress

As seen in Figure 2, the high-performing Bulalo-2 and Olilia North faults are Northwest and North-South striking structures, respectively. Structural geologists have analyzed the regional Macolod Corridor pull-apart structure (Forster, *et al*., 1990; Campagna, 1996; Aquino, 2004; Stimac, *et al*., 2006), and have determined that the direction of maximum horizontal stress is Northeast-Southwest, suggesting that Northeast-striking faults should be extensional and therefore more permeable. Our results did not validate that expectation. One possible explanation is that in this structural setting, the Northeast-striking faults would typically be normal faults, so an alternative targeting model with non-vertical faults might prove more successful.

4. CONCLUSIONS

This study tested the effectiveness of the current model of permeability targeting in the deep Bulalo reservoir, which is based on vertical fault zones, with an angular width or uncertainty of ±3° extending downward from the mapped surface trace. Targeting these fault zones in the deep Bulalo reservoir, in general, has been successful in encountering PZ's at a rate performing 13% better than random. The zones which are most successful in finding PZs are the Bulalo 2 (B2) fault which performed 61% better than random, and Olilia North faults as well as two other fault intersections, all of which performed >40% better than random. The other nine target zones analyzed did not perform much better than random. Analysis of the PZs outside the highly productive central "sweet spot" reveals that the highest-performing fault targets are innately permeable and contribute to the existence of the sweet spot. A positive trend between P_{PZ} of the fault targets and their average PI shows the advantage of drilling high-performing target zones has been compounded by their high average productivity.

By quantitatively evaluating the permeability and productivity of the faults, this study was able to identify faults that have higher chances of encountering more productive PZs and quantified the performance of the fault targeting strategy, thus putting future drilling campaigns on a more measureable perspective. This study shows that if future make-up wells can be steered towards high-performing targets to double the well track length within those target zones, a 19% improvement in the number of PZs encountered may be realized. A similar improvement is expected in steam deliverability considering the high average PIs within the high-performing fault targets. Also, results indicate that many of the previously identified fault targets are no better than random in terms of encountering PZs, which is equally valuable information for when considering future make-up well targets.

Finally, the methodology introduced in this paper can be used to quantitatively evaluate any spatially defined drilling target, given sufficient PZ data. With the rich Bulalo data set, the next step is to evaluate many different alternative targeting models and, possibly, find even better-performing targets for future make-up wells.

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