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Multi-lateral Geothermal Wells in Volcanic-hosted Reservoirs – Objectives, Challenges and Results

Jim Stimac[1], Marino Baroek[1], Dexter Pazziuagan[1], Ronald Vicedo[2]

[1]Chevron Salak Geothermal Ltd, Sentral Senayan II, 26th Floor, Jl. Asia-Afrika No. 8, Jakarta, 10270, Indonesia

[2]Chevron Geothermal Philippines Holdings, Inc, 14th Floor, 6750 Building, Ayala Avenue, Makati City, Philippines

jstimac@chevron.com

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ABSTRACT

Three multi-lateral (forked) wells have been drilled by Chevron in three different geothermal fields in Indonesia and the Philippines. Two of the wells (Nag-66 in Tiwi and Awi 20-1 in Salak) were drilled as injectors in areas with relatively low permeability. Multi-lateral completion was selected to enhance the overall injection capacity while minimizing capital investment. A third well was drilled as a deep producer to reduce steam costs. All three wells were successfully forked and remain operational. The two that have been put in service met or exceeded injection or steam rate targets (Nag-66, Bul-109) with some cost benefit. The third well (Awi 20-1) had low initial injectivity in both legs but has improved through hydraulic stimulation.

All three wells were completed with an "openhole fork" design, where the second leg was sidetracked from the parent bore by means of a retrievable whipstock. The forked leg was completed with slotted liner up to near the fork junction, but a short section of openhole at the junction itself remained unsupported by casing or liner. We describe the methods used to assess the stability of the formation and pick the forking point. Openhole caliper logs and "Bingham" strength estimates can be used to evaluate formation stability to reduce costs, but sonic and density logs provide the most definitive information. Integration of data from offset wells, wireline logs, and correlation of these data with drilling parameters informed decisions and minimized the risk of junction collapse.

On the drilling and completion side, the major challenges were related to acquiring the appropriate whipstock system, the whipstock placement including orientation and ensuring subsequent milling operations would place the kick-off point within the pipe body, the cut and pull operation for the liner in the forked leg, the whipstock retrieval operation, re-entry into the parent bore and cleanout of the bridge plug placed in the parent bore.

1. INTRODUCTION

Drilling production and injection wells is one of the major capital investments required for geothermal energy production, and the cost of wells has a significant impact on the economic viability of projects. Therefore optimizing well design to best exploit reservoir conditions, while minimizing the well costs, is a major focus of developers. One means of reducing drilling costs is to drill multi-lateral wells (Steffen, 1993; Golla and Haas, 1998; Moos et al., 2001). This well design minimizes the surface footprint while potentially increasing the production or injection rate compared to single penetrations.

The first geothermal wells to be forked were drilled in the Geysers field as early as 1979. The method was adopted in an attempt to increase the output of low-productivity wells with relatively low incremental investment. Although the first attempted forked completion did not improve the well's productivity (DX-44), refinement of the method eventually led to success. Yarter et al. (1989) documented five early successes in forking production wells at The Geysers geothermal field. Since wells in the steam-dominated Geysers field do not require production liners, forking operations are somewhat simpler than in volcanic-hosted, liquid-dominated fields where slotted liners are typically required to prevent collapse of weak formations.

Yarter et al. (1989) compared the anticipated cost of steam for single penetrations, redrills and forked wells at The Geysers. They concluded that forked wells outperformed redrilled single penetrations and original penetrations. Steffen (1993) summarized the status of multi-lateral drilling at The Geysers, focusing on process improvements that reduced risk. He emphasized that: "As with any methodology, actual field experiences and observations provide the surest way to continually improve performance and minimize risk." Steffen (1993) outlined the approach used for 3-legged wells where the original leg was left as a "casing stub", and the "second" and "third" legs were drilled as the primary reservoir targets. The remaining original leg could then be deepened. This approach was claimed to minimize the cost of potentially losing access to the original hole, and significantly reduced their overall project risk. Table 2 shows the costs of forking wells at The Geysers, and the estimated % savings over drilling single penetration wells.

Table 1. Forking results at The Geysers (data from Steffen, 1993).

Table 2.1-1. Forking results at the Geysers (data from Steffen, 1993).

Completion Type	Avg. Cost/Well	Aggregate costs-individual completions	Net Savings	% Savings
Fork of Existing Well (4)	1.100	1.596	0.496	31%
New 2-Leg Wells (3)	2.491	3.192	0.701	22%
New 3-Leg Wells (2)	3.533	5.340	1.807	34%

Note: all costs in $MM.

Table 2. Cost of Nag-66 forking compared to single penetration wells in the same area.

Table 2.2-1. Cost of Nag-66 forking compared to original SEHBIS wells.

Well	Actual Cost	Days	kph	Completion Date	$/kph	Day-adjusted cost
Nag-66FRK	**0.975**	**36**	**370**	**6/97**	**2635**	**0.858**
Nag-66OH	1.104	44	380	1/87	2905 / 3182	1.209
Nag-67OH	0.998	44	~ 1000	3/87	998 / 1209	
Nag-68OH	1.042	39	~ 300	7/87	3473 / 4030	
Nag-69OH	1.692	76	~ 400	8/88	4230 / 3023	

Note: well costs in $MM. Day-adjusted cost was obtained by taking the average cost of the original holes and dividing by the average number of days required to complete the wells. This was used to calculate an adjusted day cost for the fork since it was drilled a decade later than all the original holes. Injectivities shown in red are estimates by Y. Arcedera. $/kph is given for the actual cost (first number) and the day-adjusted cost (second number).

In this paper we describe the forking of three wells in liquid-dominated, volcanic-hosted reservoirs. These show that these wells were all successful and provided some financial benefit over single penetrations. We highlight the geological and drilling work that can be done to minimize risks.

2. MULTILATERAL WELL AT TIWI AND BULALO

2.1 Injection Well Nag-66 (Tiwi Field, Philippines)

Nag-66 was the first geothermal well to be successfully forked in the Philippines, and perhaps the first attempted in any liquid-dominated geothermal field. The well was drilled as a hot brine injector to the southeast of the production zone, and later forked to improve its capacity. This area has a relatively deep reservoir top and low injectivity. The forking operation was accomplished by setting a bridge plug and retrievable whipstock, milling through the 9-5/8" casing at a depth of 2828' MD, and sidetracking the well to 6526' MD. Following drilling of the sidetrack, a 7" slotted liner was run into the 8-1/2" sidetracked leg, the whipstock was retrieved, and the bridge plug was pushed to the bottom of the original penetration (Golla and Haas, 1998).

The fork junction was left as a "barefoot" or openhole completion. Thus selection of a suitable interval of competent formation was a critical part of the drilling plan. The rock type chosen was a relatively silicified andesite lava flow that occurred in the original hole based on rock cuttings. Experience has shown that massive lava flow interiors are typically among the strongest rocks present in andesitic volcanic sequences provided they do not contain abundant existing fractures. No openhole logs were run to verify the conditions at the junction.

This relatively simple drilling operation was adapted from technology developed in the oil and gas industry, and pioneered in The Geysers Geothermal field (see *Section 2.1*). It was recognized at the time that the same approach could be applied to production wells (Golla and Haas, 1998), but was not attempted until Bul-109 was drilled in 2003.

The forking operation was deemed a success, as the injection capacity of the well was increased from 380 kph to 750 kph, an incremental gain of 370 kph. The forked leg was completed in mid-1997 at a cost 40% lower than the average cost of drilling a new injection well at that time according to Golla and Haas (1998). At a cost of $0.975 million, this yielded $2,635/kph injection capacity. Comparison of drilling costs for Nag-66 relative to other injection wells drilled in the same area is given in Table 2.

To investigate forking wells as a viable alternative to drilling single penetrations, a re-examination of the condition of Nag-66 was completed as early 2002 (Regulacion, 2002). The main purpose of this study was to determine whether the fork junction had remained open and capable of sustaining injection despite the fact it was left unsupported. It was not possible to selectively enter the forked leg, or to conduct a long-term injection test, but it was determined from records of injecting wellhead pressure (IWHP) and orifice plate measurements that the well was still capable of accepting brine at a rate comparable to when the fork was completed in 1997. Two static pressure-temperature gradient surveys (PTGS) were conducted in the well in Feb. 2002 and both reached a depth of 5828' MD. Although it is suspected the tool selectively entered the original hole, these surveys showed that the junction was not bridged or the casing collapsed.

2.2 Production Well Bulalo-109 (Bulalo, Philippines)

The potential for multi-lateral wells to improve the economics of make-up drilling was recognized in an optimization study of the Mak-Ban (Bulalo) field in 2001 (Acuña et al., 2001). With an emphasis on obtaining costly deep production and a move toward a 'centralized' drilling strategy, the resource team planning the Bulalo wells in 2002 further investigated the economics of multi-lateral wells compared to single penetrations (Arcedera, 2002). Based on favorable economic predictions, they recommended drilling three wells with a forkable design as part of the 2002-2004 drilling program, and forking one well during the program.

During the same time period, the geoscience group gathered the necessary rock mechanical data to assess the risk of leaving an open junction with unsupported formation. Cores from a number of offset wells were selected and uniaxial comprehensive strength and sonic velocity measurements were made. These data were used, along with the expected reservoir and well operating conditions to predict borehole stability (GMI, 2002; Sugiaman and Gunderson, 2002). A dipole shear sonic log was run in one well (Bul-106) to provide further information regarding formation strength on the well pad and at the depth where forked wells were being contemplated. Using these data, cost-effective methods were devised to select a target formation.

Three wells (Bul-107 to Bul-109) were drilled with a forkable design in 2003. These wells have cemented 10-3/4" tieback casing to a depth of 3700 to 4500 ft MD that served as a platform for the lateral. These three single penetrations were drilled for about the same average cost (about $3.2 million) as the non-forkable design but provided less total steam since shallow steam zones were cased and cemented off. The wells produced 117 kph versus 200 kph for more shallowly cased wells, not factoring in the affects of shallow reservoir interference and higher decline for the two well types.

Bul-109, the third in the series of wells with forkable design, was chosen as the candidate to implement the first forking operation. This was primarily because of budget limitations and the required time to mobilize the equipment (10-3/4" retrievable whipstock, mills, etc.). The successful implementation of forking depends on several factors coinciding to identify an ideal interval in which to place the unsupported junction. Data on rock types and their mechanical properties, reservoir pressure, temperature and permeability, and casing configuration (locations of couplings) and cement integrity are all useful in planning the forking operation.

For Bul-109, rock strength evaluation was assessed with an openhole caliper log, and by using a method developed by M.G. Bingham (1965a, b). Originally applied to oil and gas drilling, relationships between different parameters such as rate of penetration (ROP), rotary speed (RPM), weight on bit (WOB), and bit diameter in newly drilled wells were used in estimating rock strengths. From the data, a "drilling performance line" was generated, leading to estimates of the stability of rock units (Figure 1). The computed rock strength data were then calibrated by comparing them with actual measurements done on existing cores of similar lithologies from older wells (GMI, 2002; Martin, 2002), and strength profiles estimated from a sonic log in a nearby well. Results showed a good correlation between calculated and actual values. From this, a specific value for the uniaxial compressive strength (UCS) required for forking was arrived at. The legs were targeted and directionally drilled to diverge at depth and thereby minimize reservoir interference (Figure 3).

An openhole caliper log was run in the 12-1/4" section to identify washouts and elongated sections of the wellbore. Pressure while drilling (PWD) log data were analyzed to locate permeable and non-permeable sections. A gamma ray log measured how thick the units were in which none of the deformations and permeable zones occurred.

Once the above mentioned data sets were collected and correlated, the identified candidate sections were plotted against the location of casing couplings (Figure 2).

Drilling the fork junction through a casing connection was seen as putting the integrity of the section at risk, thus the requirement to mill within the 40-foot section of only one casing joint. A good casing cement job behind the casing joint to be milled was also required to ensure the casing stayed in place both during the operation and hopefully during production of the well. A cement bond log was run to determine the condition of cement behind casing in the interval of interest.

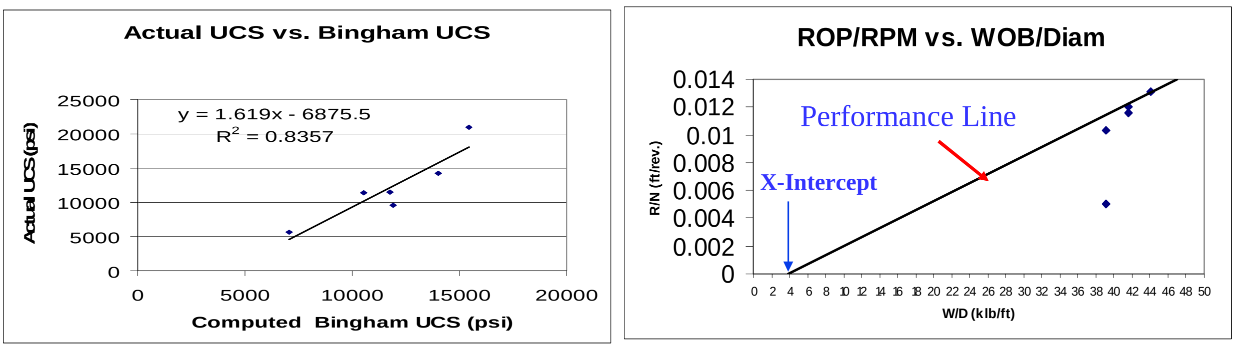

Figure 1: Bingham performance line for Bul-109 well (left) and Actual UCS for estimated Bingham UCS (right).

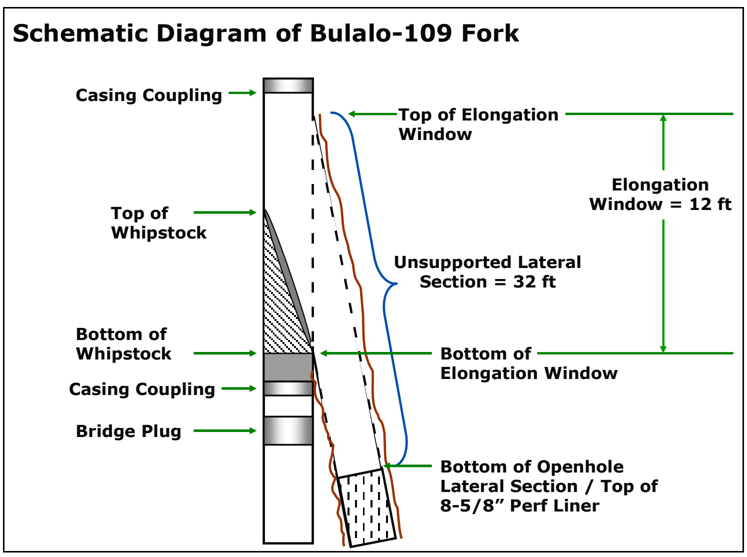

Figure 2: Schematic of Bul-109 forking operation showing the locations of casing couplings, position of whipstock, and the milled section of casing

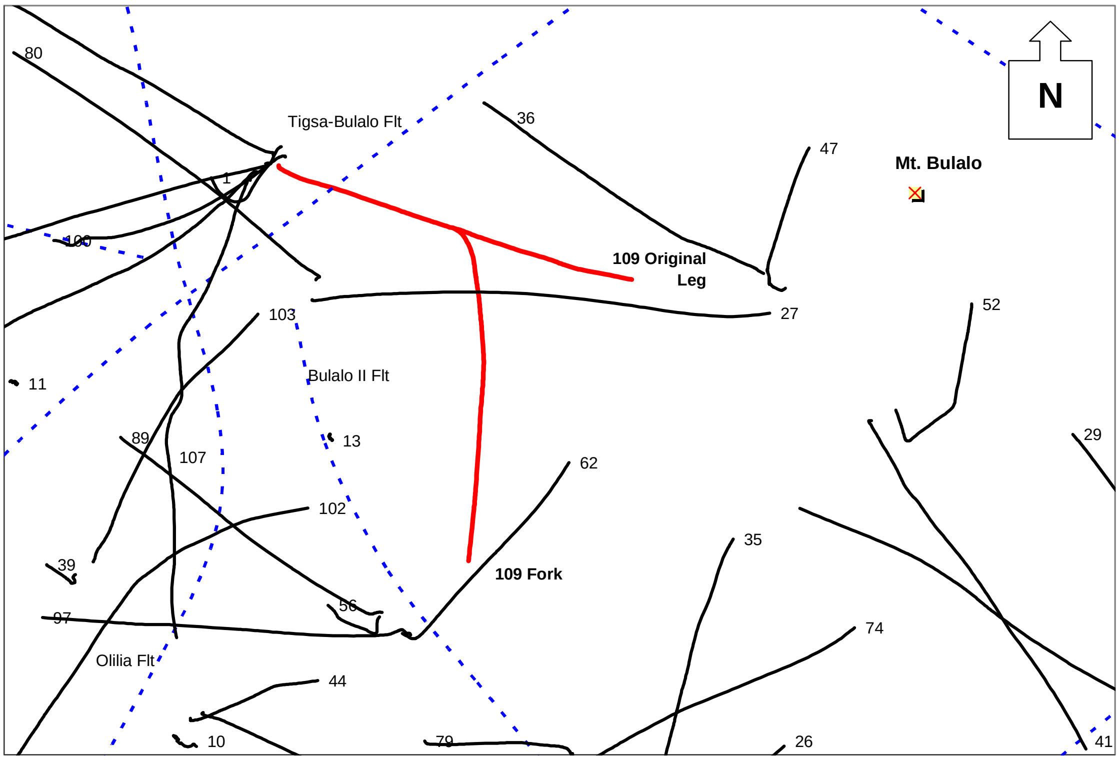

Figure 3: Plan view map of Bul-109 forked well relative to inferred faults and nearby wells. The well is in the central portion of the field, and penetrates beneath Mt. Bulalo

Table 3. Cost and deliverability of multi-lateral well Bulalo 109 relative to single penetrations.

Well Type	Cost ($MM)		Steam Deliverability (kph)		$/kph	
	Estimated	Actual	Estimated	Actual	Estimated	Actual
Standard	**3.0**	**3.56**	**200**	**175**	**15,000**	**20,340**
Multi-lateral	**4.2**	**3.78**	**300**	**320**	**14,000**	**11,810**

Notes: Standard numbers are averages for all single penetration wells (Bul-104 to 106 and 110 to 113). Multi-lateral numbers are averages of forkable wells (Bul-107 to Bul-109).

Year	Type	Well	Actual Cost	Plan kph	Actual kph	$/kph	Comments
D10 Forked							
2004	**D10F**	**109OH+L**	**3.780**	**300**	**320**	**11,812**	**Assuming no repair**
		109WO	**0.622**				**Total repair cost**
		109Total	**4.402**		**320**	**14,536**	**Repaired multi-lateral**

Notes: Costs in $MM. 109WO is cost to mill shallow and deep obstructions.

The method was successfully applied by kicking off a lateral leg in a section meeting all the criteria, and running perforated liners through the leg, completing the well with a 32' interval of open hole immediately below the junction. The project demonstrated cost savings as expected, by capturing production nearly equal to that of two wells, at a much lower cost. To the best of our knowledge, the open-hole interval below the junction has remained open during five years of subsequent production.

As far as the authors are aware, Bul-109 was the first attempt to fork a geothermal production well in a liquid-dominated field. The 10-3/4" tieback well was successfully completed with an open-hole junction and 8-5/8" liner in the 9-7/8" forked leg. Unfortunately, flow testing of the well was delayed due to blockages identified at the lateral junction and in the near-surface casing. The near-surface blockages were determined to be casing collapses resulting from trapped water. These problems were due to a well design that required a long cemented 10-3/4" tieback casing within 13-3/8" cemented liner. It was determined that this design should be avoided due to these cementing difficulties. Subsequent wells, Bul-110 to Bul-113 were drilled as conventional single penetrations because a full understanding of Bul-109 was not yet available.

In January of 2004 the blockages in Bul-109 were cleared and it was found that the 13-3/8” casing, which was the well-control string, was still intact. Bul-109 was flow-tested in mid-2004. Initial TFT data indicated that the well produced about 320 kph steam at 150 psig separation pressure at a flowing wellhead pressure (WHP) of 320 psig (Urmeneta, 2004; Arcedera, 2004). A flowing spinner survey of the original leg indicated that it was contributing 250 kph of 650 BTU/lb fluid (90 kph steam), whereas the lateral leg was contributing 470 kph of 770 BTU/lb fluid (230 kph steam).

The Bul-109 experience proved that drilling and completion of multi-lateral production wells at Bulalo is technically feasible and economically attractive. Bul-109 was completed at a lower cost and provided more steam than expected, yielding a very favorable $/kph steam and NPV compared to single penetration wells drilled in the same program.

2.2.1 Pros and Cons of Multilateral and Single-Penetration Wells at Bulalo

Since multi-lateral wells had been forwarded as a potentially important means of reducing drilling costs at Bulalo, economics were run on single penetration and multi-lateral wells. The expected costs of multi-lateral and single-penetration wells, as well as the potential risks of failure cases were considered.

Some perceived advantages of multi-lateral wells are:

1. Fewer make-up well locations would be required, thus minimizing surface facility footprint and impact on the environment and nearby community. Well-hookup costs and piping costs would also be reduced.

2. The cost of rig moves and skids would be reduced.

3. Since a significant fraction of well cost is related to the upper large-diameter hole sections, forking would reduce overall steam costs.

4. A higher fraction of “deep steam” would be produced than from two single penetration wells, thus the wells would have lower decline through time. This was based on the Mak-Ban (Bulalo) Optimization Study Team result that wells tapping shallow steam would have some interference.

Some perceived disadvantages of multi-lateral wells are:

1. There was higher risk of failure, both due to the mechanical aspects of wellbore completion and due to the potential failure of unsupported openhole junctions under flowing conditions (GMI, 2002).

2. Interference might be higher than in single penetration wells due to the proximity of the legs.

3. Deeper cemented casing shoe depths would add to drilling and cementing costs, and increase the maximum pressures observed at the wellhead and cemented casing shoe. This is a particular concern at Bulalo (Menzies et al., 2007), but may be less of an issue at other fields.

4. Information about the reservoir would be limited due to the inability to selectively re-enter the parent and lateral. In practice it is most likely that any tool lowered in the well will enter the hole with the lowest angle from vertical. This can be mitigated to some extent by obtaining pressure-temperature-spinner logs of each leg at the time the well is drilled.

5. An additional disadvantage related to (3) that was not fully recognized at the time is that setting the cemented casing deeper might limit the maximum depth of both legs due to not meeting a leakoff requirement at the 13-3/8” cemented shoe (see Menzies et al., 2007).

3. MULTILATERAL WELLS AT SALAK, INDONESIA

Multi-lateral wells had been considered at Salak (Awibengkok) for some time, but had not been drilled due to a focus on standardizing drilling processes and procedures. However, a number of deep injection wells were required that presented an opportunity to compare the cost and injectivity of multi-lateral completions to the standard single-penetration well for this application. It was decided to drill one multi-lateral in the 2008 program at a new location (Awi 20-1) on the SW margin of the field based on positive experiences with multi-lateral in the Philippines (Figure 4).

3.1 Well Awi 20-1

Awi 20-1 was planned as a deep injector on the southwestern margin of the proven Salak reservoir, in an attempt to reduce the impacts of injection on the western production area (Ganefianto et al., 2010). The Awi 20-1 well is about 1.6 km to the west of the current location for western brine injection at Awi 9 (Figure 4).

To minimize the risk of shallow injection returns the well was planned to have a deep cemented 10-3/4” casing shoe at approximately 5500’. Since permeability in a nearby Awi 9 well (Awi 9-6OH) was good, Awi 20-1 was planned to be forked to reduce the cost of achieving injectivity targets, similar to described above for Nag-66. It was recognized that one of the most significant risks of drilling openhole multi-laterals is collapse of formations in the openhole interval (Moos et al., 2001; Sugiaman and Gunderson, 2002; Wijnands and Kumar, 2003). Therefore a series of wireline logs were run in the 12-1/4” hole to determine the best location for setting the forked junction. In addition, the Bingham Method (described above for Bul-109) was also calculated for comparison purposes.

3.1.1 Selection of Forking Interval

The forking interval for the lateral leg was selected based on a combination of wireline logs, cuttings and other evaluations. The following are the criteria followed for selecting the fork interval:

- The forking point should be located in an interval with strong formation to reduce the risk of formation collapse in the unsupported openhole junction.
- The forking point should be located in a section where there are no fractures or permeability so as to ensure successful cement placement across the milled section and avoid mud losses while milling casing.

- The whipstock should be set in a section of the pipe such that the top and bottom of the cut window will be within the pipe body. Milling through couplings requires longer time and increases the risk of casing failure and milling assembly failure. Figure 5 shows final setting depth of whipstock in Awi 20-1.

The openhole logs run to determine the forking point in the 12-1/4” hole section were density, dipole shear sonic, gamma-ray, and borehole image log (XRMI). The objective of these logs was to obtain information of the rock strength, and extent of fracturing, which was then used to determine wellbore stability. Such logs add to the cost of drilling, but provide the best evidence of formation properties.

The lowest risk location for the fork junction is determined by identifying a hard and competent rock formation that has a minimum of fractures. By using dipole shear sonic and density logs, rock mechanical properties such as Poisson’s ratio, Young Modulus, Shear Modulus, and Bulk Modulus can be estimated making some assumptions. Figure 6 shows log properties and calculated borehole stability for Awi 20-1.

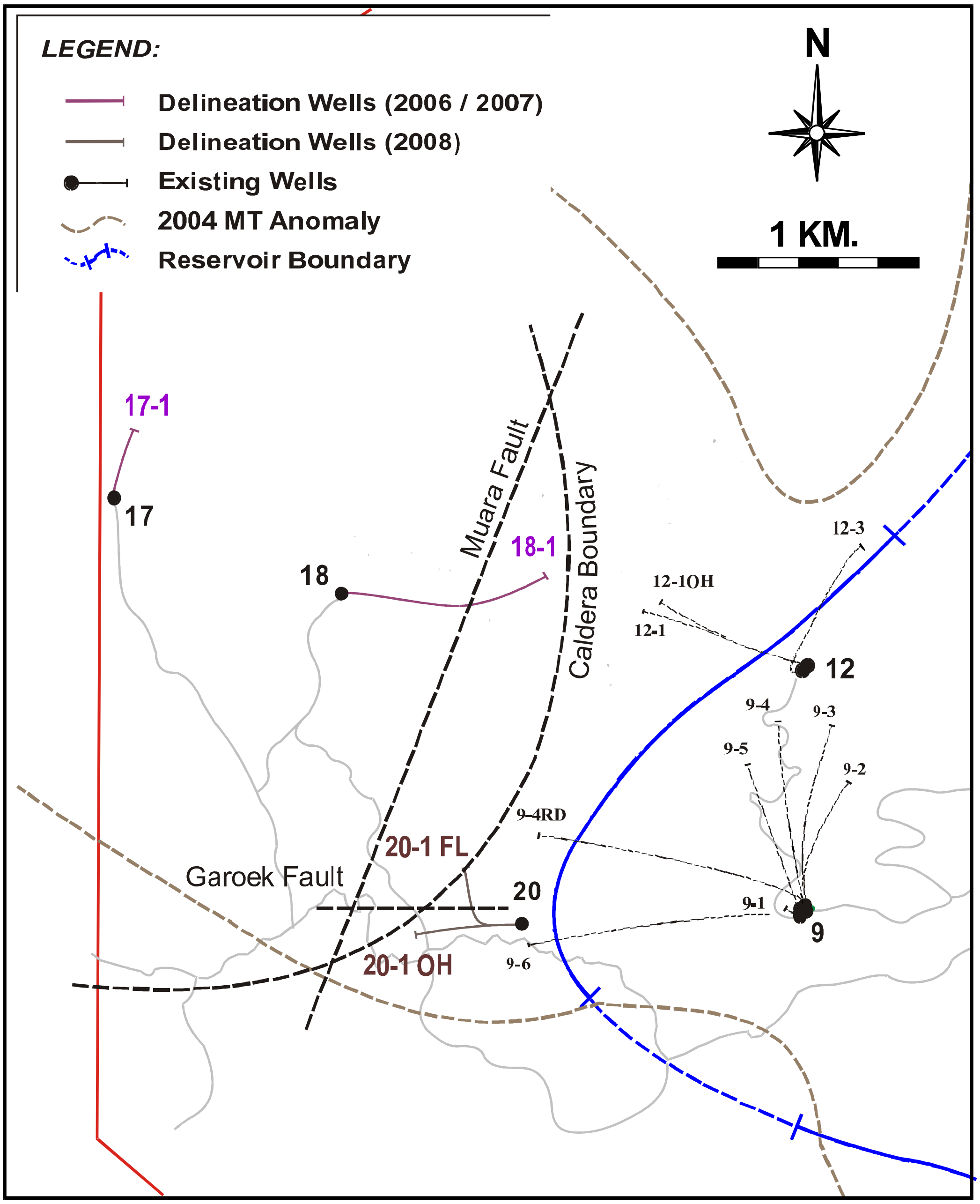

Figure 4: Location of Awi 20-1, on the SW margin of the proven Salak reservoir. Awi 20 is at the margin of Cianten caldera (approximate location of caldera ring fault shown, and about 1.6 km west of the current western brine injection area (Awi 9).

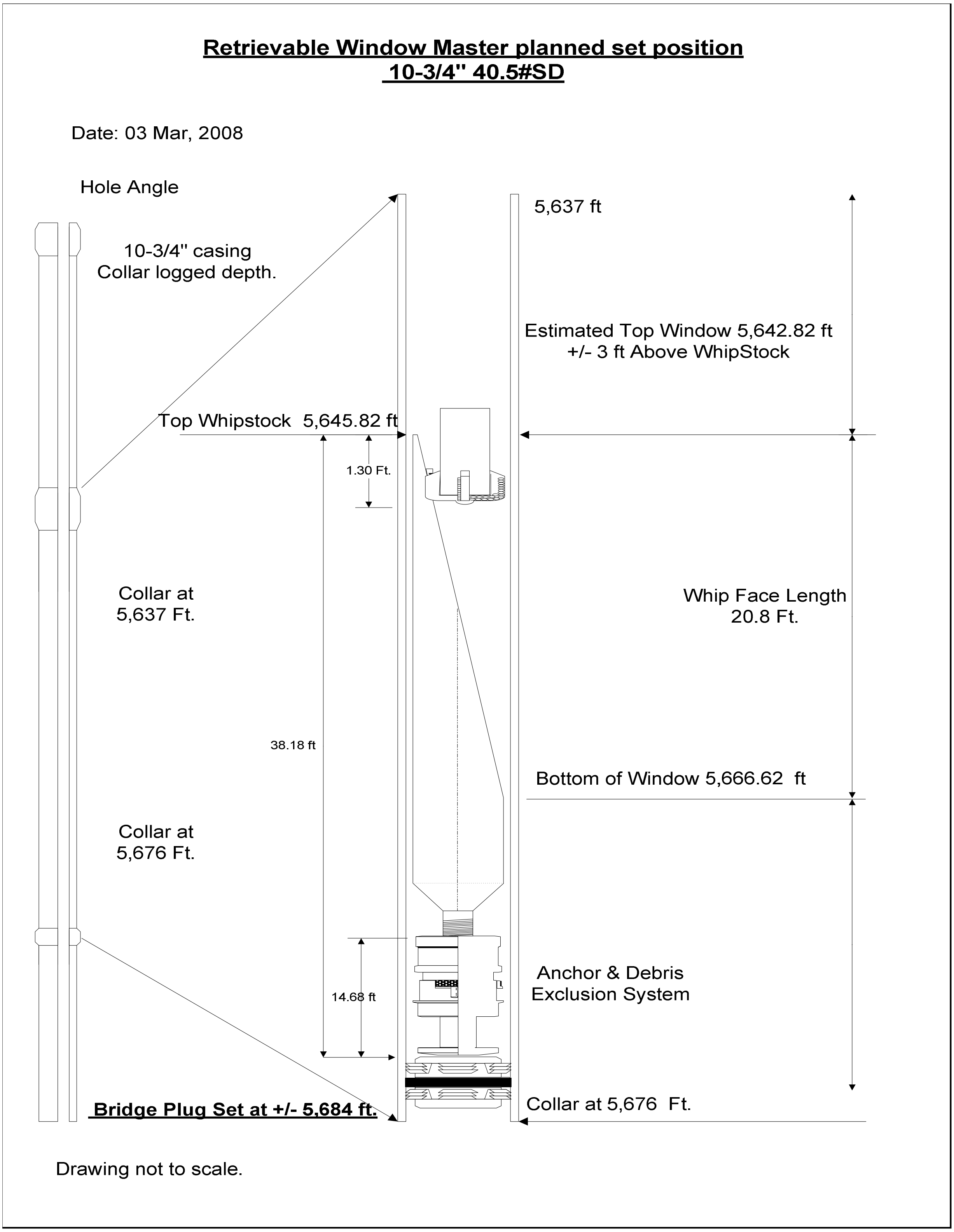

Figure 5: The final setting depth of the whipstock in Awi 20-1. Figure also shows setting depth of bridge plug, exclusion system and dimensions of the whipstock as well as the top and bottom depths of the window.

The log properties and estimated borehole strength indicates the best interval for the openhole fork at Awi 20-1 was between the depths of 5650 and 5680 ft MD (Figure 6). This interval shows a high Young Modulus based on the high sonic velocity and density observed. This suggests a strong competent formation. The caliper log indicates that the borehole is in gauge in this interval, another good sign that the lithology is competent. The gamma-ray log shows little variation, possibly indicating that there are no significant changes in lithology and no formation contacts in the interval. The XRMI log (not shown) also indicated that no major open fractures are present in this interval.

Another attractive feature of this interval is that it is near the cemented shoe of the hole section, where the probability of having a good cement bond to the formation is highest.

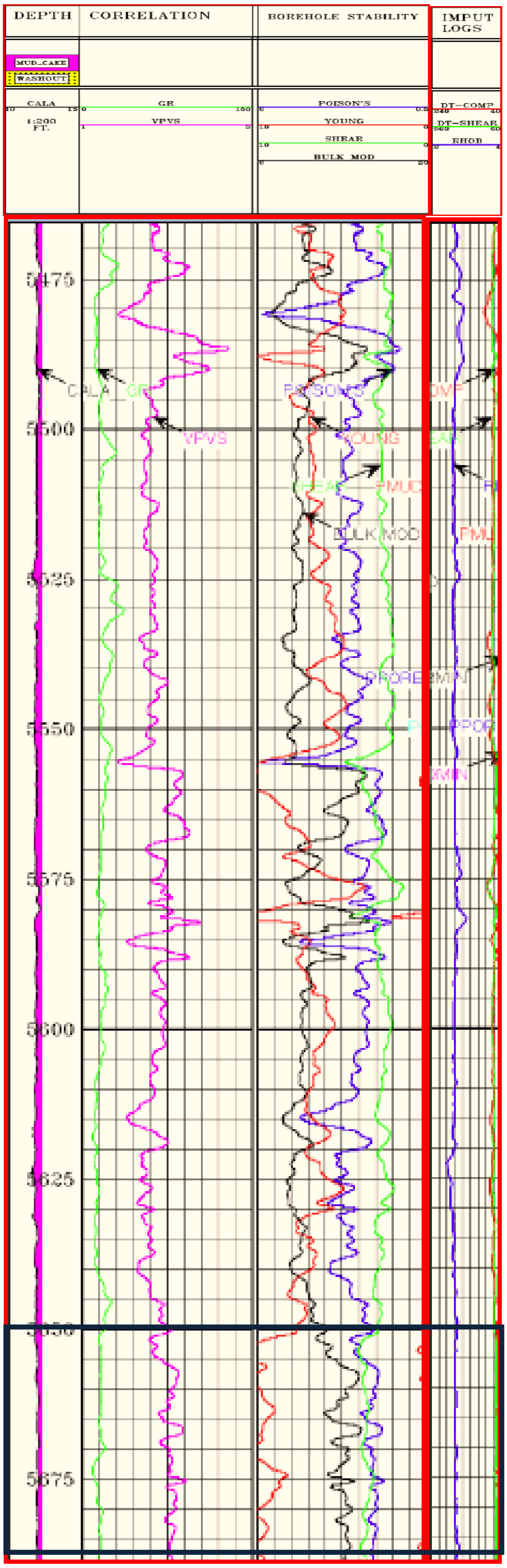

Figure 6: Selecting the window for fork junction using a combination of sonic and density logs. The selected point was between 5650 to 5680', shown in the blue square at bottom. This interval shows a high Young Modulus by virtue of high sonic velocity and rock density, indicating a hard and competent formation.

<u>3.1.2 Well Completion</u>

The forking operation was accomplished by setting a bridge plug and retrievable whipstock. A hole was then milled through the 10-3/4" cemented casing at a depth of 5667' MD (bottom of window), and the well was sidetracked with a 9-7/8" bit to 8034' MD. Following drilling of the sidetrack, a 8-5/8" slotted liner was run into the 9-7/8" sidetracked leg with the top of liner set at 5676' MD, leaving about 9 ft of open hole at the junction to allow pipe expansion upon thermal equilibration. The whipstock was then retrieved, and the bridge plug was drilled out and pushed to the bottom of the original penetration.

3.1.3 Operational Challenges

The original leg of Awi 20-1 was completed with a deep cemented 10-3/4", 40.5 ppf casing, a typical casing design for recent Chevron Geothermal injection wells. The sidetrack operation required setting of a 10-3/4" retrievable whipstock with 9-7/8" milling assemblies. These are not the typical sizes used in oil and gas wells and consequently are not readily available "off the shelf". Several vendors were asked for their proposals but only Baker Oil Tools (BOT) was able to commit to provide all the equipment on the allotted time frame. BOT offered their casing exit system called the WindowMaster One-Trip Window Cutting System. Moreover, only Baker Oil Tools then offered a whipstock system that was capable of "single-trip operation". This was a plus since the "single-trip" operation allows for setting and orienting the whipstock, then milling and kicking off with the forked leg in just one run.

Several parameters had to be followed in order to satisfy the criteria set for choosing the forking point. This required open hole logs to determine the most competent section of the formation. Accurate casing tallies were also essential to know the exact depths of the couplings and the exact dimensions of the whipstock had to be measured properly in order to position the whipstock at the appropriate section of the pipe.

On the retrieval of the whipstock system, the main challenge encountered was in pulling out the anchor and debris exclusion system. The whipstock was retrieved with no problems but the anchor and debris exclusion system was left in the hole. A fishing assembly was run and was able to pull out the anchor and debris exclusion system with 100,000 lbs overpull. A review of what went wrong indicated that the debris exclusion system as not properly sized. The debris exclusion system used was sized for a 9-5/8" casing as there was none available for 10-3/4" casing. This allowed cuttings and debris to accumulate around and packed off the tools.

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