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Successful Deployment of a Multi-Crossing Directional Drilling Method at Ormat's New Tungsten Mountain Geothermal Field in Churchill County, Nevada

Ben Delwiche[1], Brad Peters[1], Matt Sophy[1], Chandler Smith[2], and Jeremy O'Brien[3]

1: Ormat Technologies, Inc. 6225 Neil Rd. Reno, NV 89511

2: Scientific Drilling International 31101 Coberly Rd. Shafter, CA 93263

3: Seequent, 20 Moorhouse Ave, Addington, Christchurch 8011, New Zealand

BDelwiche@ormat.com

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ABSTRACT

An innovative drilling method and successful drilling campaign is presented using an example from Ormat's Tungsten Mountain Geothermal field in Edwards Creek Valley Nevada. Initial deep exploration drilling identified a ~290°F high-permeability resource along the eastern flank of the Clan Alpine Mountains near Stone Canyon. The resource is hosted within fractured and mineralized Mesozoic siltstone, slate, and intrusive formations. Permeability is focused within the damage zones of several synthetic steeply SE dipping northeast-striking faults and partially along south-southwest dipping west-northwest-striking faults near their intersections with the northeast-striking faults. However extreme variability of permeability discovered in the fault zones necessitated a drilling strategy that would reduce drilling risk and achieve successful wells.

A 3D geological model was built using integrated subsurface data and utilized to select the initial production well location and to guide directional drilling activities. The well was drilled using a super single drilling rig equipped with a top drive. Based on multiple geological targets generated from the 3D model, complex directional plans were generated. As new data became available they were used to calibrate the 3D model and guide exploration and as directional drilling challenges arose, directional plans were revised and implemented during active drilling to achieve multiple intersections of a single fault zone.

1. INTRODUCTION

Directional drilling has been utilized in the geothermal industry to achieve hard to reach resource targets, to space downhole feed zones, for redrills and forked completions. This paper introduces the rarely deployed multi-crossing directional drilling strategy and case study. The multi-crossing technique has been successfully performed prior on the Big Island of Hawaii at Puna Geothermal Venture (PGV) (Peter Drakos, oral commun., 2018). This technique involves geosteering the bottom hole assembly in order to cross a fault zone of variable permeability at multiple locations in a single drill.

At the newly operative Tungsten Mountain geothermal field in Nevada (26 MWe net since November, 2017) drilling of the initial production well 84A-22ST1 during the summer of 2016 was met with challenges in achieving commercial permeability. During this drilling campaign, live data were synthesized with other datasets and used to formulate and execute a new drilling strategy which led to the success of this well. This strategy involved geosteering the bottom hole assembly in order to multi-cross a fault zone of variable permeability. Up to six confirmed fault crossings in a single well path were achieved. These methods then became integral to planning of additional wells at Tungsten Mountain and contributed to the successful completion of well field development.

The decision to multi-cross the fault zone of interest is elucidated by the exploration history and the associated constraints on the resource which culminated prior to drilling 84A-22ST1. Initial interest for a potential geothermal resource near the eastern flank of the Clan Alpine Mountains near Stone Canyon was based on 1) anomalous temperatures reported from prior nearby mineral exploration holes, 2) local anomalous temperatures reported from a shallow temperature survey, 3) a series of massive calcite veins containing bladed calcite and chalcedonic nodules which were coincident with a west-northwest-striking fault zone and an intersecting northeast-striking fault, and 4) alterations of ash-flow tuff exposed at the surface and in tailing piles from nearby mineral prospect pits (Kratt et al., 2008, 2010; Site Description, 2014; Delwiche and Spielman, 2017).

Initial geothermal exploration began with core hole 75-22. The well was drilled during the summer of 2011 to 1000 ft to investigate the intersection of west-northwest- and northeast-striking faults and encountered anomalous shallow temperatures up to 225°F at 700 ft depth (Figures 1 & 2). The first deep core hole 67-22 was then drilled to 3982 ft during the summer of 2012. Well 67-22 crossed the west-northwest-striking fault, and encountered commercial temperatures near 300°F associated with the northeast-striking fault near 3700 ft depth, but the permeability in this well was low. An acoustic image log from this well also established that the northeast-striking fractures were dilated in the local stress field. These results encouraged drilling of slim hole 84-22, which was completed to 4087 ft during November of 2013 using a truck mounted drill rig. This well construction consists of 7-

inch casing to 1936 ft and 6-1/8-inch hole to total depth completed with a 4-1/2-inch slotted liner. This well was drilled near the range front, encountered slate and siltstone basement rocks at only 1430 ft depth, and a total loss of circulation occurred where the northeast-striking fault was intersected near 3950 ft depth (Figures 1 & 2). The rig test on this well indicated high permeability with a producing fluid temperature of ~285^{o}F.

An image log was collected in 84-22, but could not pass or image the fault zone at 3950 ft depth. However the location of the fault was well constrained by a combination of surface data and directional surveys collected by a tri-axial magnetometer in 84-22 during wellbore imaging. The fault was estimated to strike northeast and dip steeply ~84^{o} southeast (Figure 1). The encouraging temperature and permeability in 84-22 justified twinning the target with a full-size well, 84A-22. Thus, prior to spudding 84A-22, the northeast-striking fault of interest was defined by 1) a small cuesta at the range front consisting of hydrothermally altered ash-flow tuff and 2) the downhole intercept in 84-22. Based on near-isothermal temperatures in 84-22 below 2000 ft depth and slate/siltstone basement rock below 1430 ft depth it was inferred that the reservoir in the eastern part of the field is primarily contained within the relatively homogeneous slate and siltstone basement rock formation within the fracture network of the fault zone (Figure 2). Thus commercial temperature and permeability could be encountered shallower than where it was encountered in 84-22.

During the initial drill of full-size well 84A-22, 13-3/8-inch casing was cemented to 2003 ft into the basement rock formation. The production hole was drilled with 12-1/4-inch tricone bits to intercept the northeast-striking fault. The wellbore intersection with the northeast-striking fault was inferred to occur at 2820 ft based on 1) a 40 barrel mudloss accompanied by 2) cuttings samples that contained traces of euhedral natrolite (hydrous sodium aluminum silicate, $Na_2Al_2Si_3O_{10} \cdot 2H_2O$), euhedral quartz, and cataclasite consisting of angular slate fragments cemented in an amorphous silica matrix, and 3) a formation change from slate to a granodiorite intrusion. The granodiorite was not encountered in 84-22, and it appeared the intrusion was plugging the fault zone.

Since only minor fluid losses occurred at the fault intercept a redrill was planned. Given the results of 84A-22, the low permeability in 67-22, and that the slim hole 84-22 feed zone had collapsed during a prior long-term test, there was general concern about achieving adequate permeability on a redrill. So this author worked with a directional planner from Scientific Drilling International (SDI) to understand the feasibility of multi-crossing the fault. Several fault crossings were planned with dogleg severities not to exceed 4^{o}/100 ft to minimize torque and drag. SDI's well planners used a torque and drag simulation to evaluate drilling issues such as stuck pipe. From a planning perspective, multi-crossing of the fault appeared feasible, but would require collaboration between drillers, geologist, and well planners to effectively mitigate challenges to achieve a successful well.

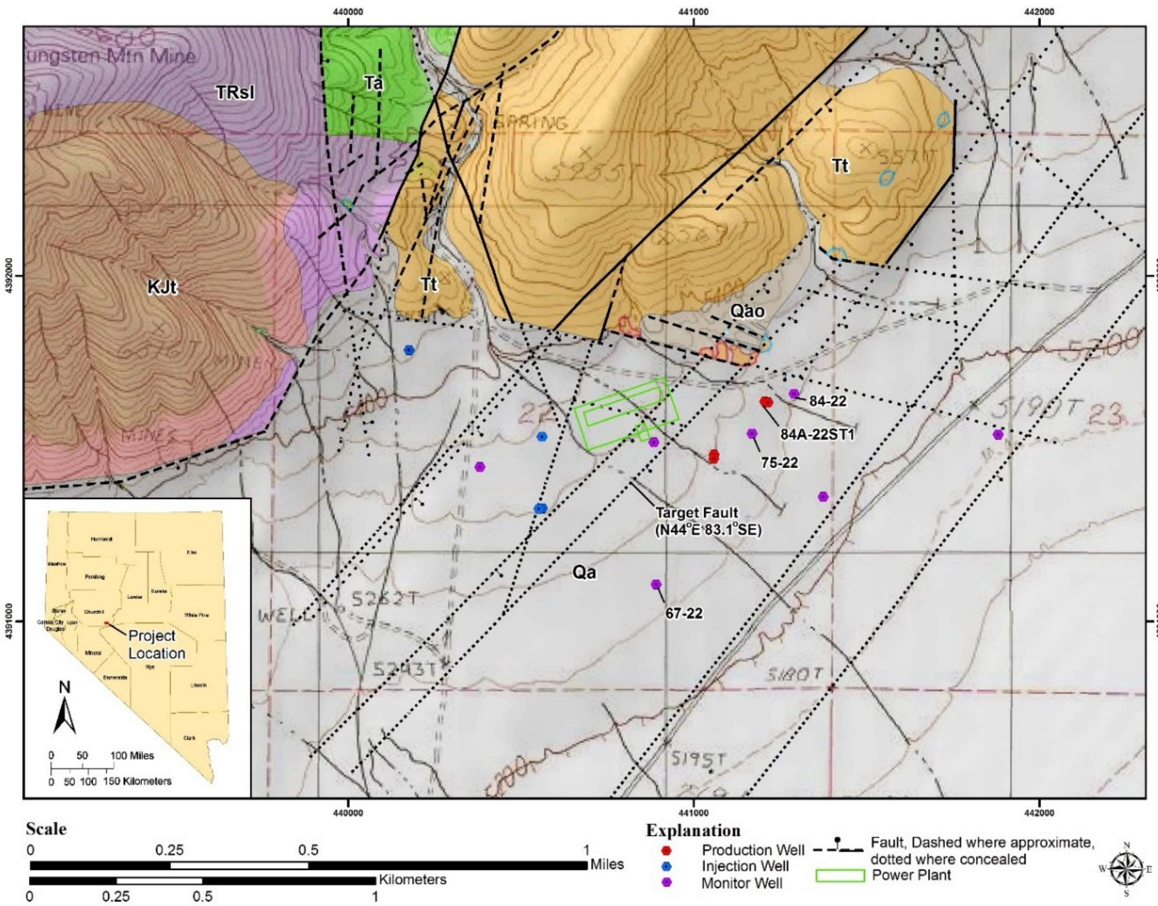


Figure 1: Tungsten Mountain wellfield map with general geology. Units: Qa: Young alluvium; Qao: Old alluvium; Tt: late Oligocene ash-flow tuff sequence; Ta: mid-Oligocene andesite, dacite, and volcaniclastics; KJt: Mesozoic Tonalite; TRsl: Triassic slate and siltstone.

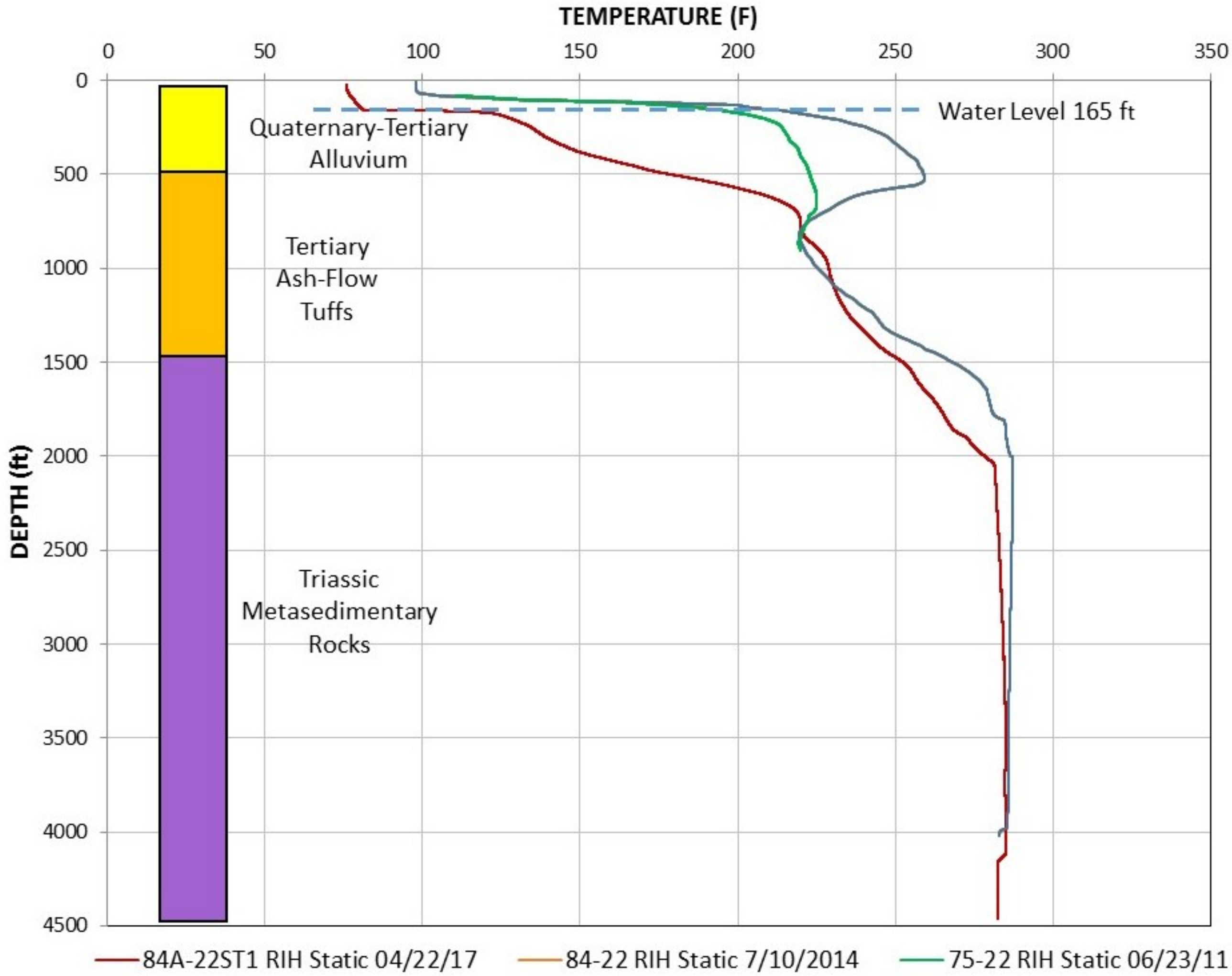


Figure 2: Plot of static down hole temperatures and general lithology's.

2. METHODS

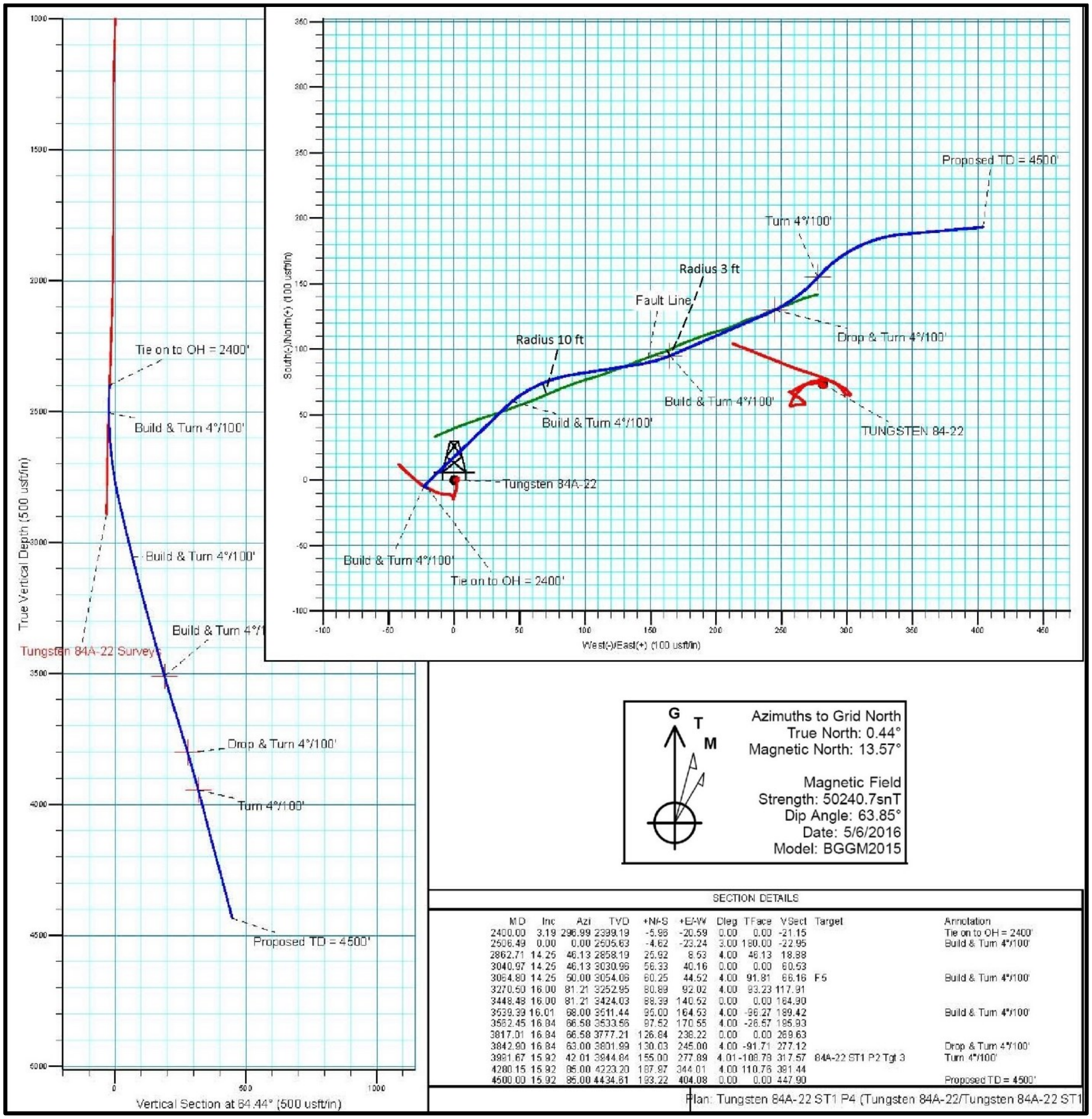
2.1 Modeling

Prior to drafting the directional plan for 84A-22ST1 the redrill targeting workflow utilized all available data to update the 3D geologic model. Data to import into the model may include directional surveys, drilling parameters, mudlog data, and any newly collected downhole geophysical data (electrical or acoustic images, gamma, density porosity, neutron density, etc.). Directional surveys and wellhead coordinates must be checked for accuracy. Upon importing survey data, drill paths are calculated using the method of spherical arc approximation also known as the minimum-curvature algorithm. This method is widely considered to be the most accurate approximation of actual drill paths between survey points and is an industry standard (API, 1985; Use Manual for Leapfrog Geothermal v. 3.5). Error ellipses associated with the well positions are generated by the well planner using software such as Compass 5000 and evaluated (e.g. Figure 7). This uncertainty effects both the position of the well being drilled and the position of the fault targets if the modeled fault is tied to downhole data. The other drilling parameters and logged data are used to define the distributions of rock-types, alterations, temperature, and faults.

At least three widely separate locational constraints on a given fault are needed for adequate modeling precision and directional planning. The fault attitude in the model is of particular concern since its accuracy (location and orientation) has a large impact on the depth at which the wellbore intercepts the fault. With a multi-crossing plan, there is also a risk of entirely missing the fault. In this case study, the fault plane is defined by a cuesta and scarp at the surface near the range front and by the two deep fault intercepts in 84-22 (3950 ft) and 84A-22 (2820 ft), respectively (Figure 2).

2.2 Directional Planning

Drafting a multi-crossing directional plan can be an iterative process between a geologist and directional planner. First, using the 3D geologic model, a line is selected along the targeted fault zone at a location below the current total depth of the well. The orientation of the line should be selected such that the required doglegs and total build angle of the drill path are minimized to achieve the line. If such data are available, the probable location of permeability should also be factored into selecting the fault line. Point targets are then selected at intervals along this fault line and a spreadsheet of target coordinates are generated and provided to the directional planner to evaluate. The directional planner evaluates the current well position and construction and determines with the geologist an appropriate formation and depth for a kick-off point (KOP). Build angle rates are limited to ≤4°/100 ft, and the drill path is modeled to approach the fault plane subparallel. The fault also needs to be crossed such that the arc of the drilled path is oriented normal to the fault plane. This is necessary to minimize the length of the drilled path between fault intercepts. Radial distances between the arcs of the well path to the fault plane must be planned between each anticipated fault intercept (Figure 3). This radius is determined by looking at the error of position associated with both the fault plane and the survey path. The thickness of the fault zone (if known) may also be factored into choosing a radius. The radius of the first two well path arcs may be larger than subsequent arcs because the position error of the fault is reduced once a crossing or two of the fault is achieved. For this initial multi-crossing directional plan, the first well path arc (between the first and second fault intercepts) radius was set to 10 ft in order ensure that the initial fault crossing was achieved (Figure 3). For the second well path arc (between the second and third fault intercepts) a radius of 3 ft was chosen (Figure 3). If the initial or second surveyed fault intercept etc. deviates from what would be expected in the model, then the modeled fault may be edited, target coordinates regenerated, and a revised directional plan drafted and implemented. The directional planner and geologist may need to work through several drafts and then evaluate the plan with a torque and drag simulation before distribution and review by drilling engineers, directional drillers and rig crews.



MD	Inc	Azi	TVD	+N/-S	+E/-W	Dleg	TFace	VSect	Target	Annotation
2400.00	3.19	296.99	2399.19	-5.96	-20.59	0.00	0.00	-21.15		Tie on to OH = 2400'
2506.49	0.00	0.00	2505.63	-4.62	-23.24	3.00	180.00	-22.95		Build & Turn 4°/100'
2862.71	14.25	46.13	2858.19	25.92	8.53	4.00	46.13	18.88		
3040.97	14.25	46.13	3030.96	56.33	40.16	0.00	0.00	60.53		
3064.80	14.25	50.00	3054.06	60.25	44.52	4.00	91.81	66.16	F5	Build & Turn 4°/100'
3270.50	16.00	81.21	3252.95	80.89	92.02	4.00	93.23	117.91		
3448.48	16.00	81.21	3424.03	88.39	140.52	0.00	0.00	164.90		
3539.39	16.01	68.00	3511.44	95.00	164.53	4.00	-96.27	189.42		Build & Turn 4°/100'
3562.45	16.84	66.58	3533.56	97.52	170.55	4.00	-26.57	195.93		
3817.01	16.84	66.58	3777.21	126.84	238.22	0.00	0.00	269.63		
3842.90	16.84	63.00	3801.99	130.03	245.00	4.00	-91.71	277.12		Drop & Turn 4°/100'
3991.67	15.92	42.01	3944.84	155.00	277.89	4.01	-108.78	317.57	84A-22 ST1 P2 Tgt 3	Turn 4°/100'
4280.15	15.92	85.00	4223.20	187.97	344.01	4.00	110.76	391.44		
4500.00	15.92	85.00	4434.61	193.22	404.08	0.00	0.00	447.90		Proposed TD = 4500'

Figure 3: Initial multi-crossing plan (P4) including three fault intercepts.

2.3 Choosing a Directional Assembly

Different possible configurations of the directional bottom hole assembly (BHA) may be utilized to accomplish a multi-crossing plan. A conventional conservative BHA may consist of a bit, mud motor with 1.5° bent sub, stabilizer with float, shock sub, non-magnetic drill collar with directional sensor, non-magnetic pony collar, hang off sub, gap sub, non-magnetic pony collar, six drill collars, jars, two more drill collars, and a cross-over below drill pipe (Figure 4a). The magnetic sensor utilizes magnetometers to measure wellbore position and can be subject to magnetic interference from the drill string, casing in offset wells, or minerals in the formation. This BHA configuration allows for maximum reduction in potential magnetic interference of the drill string and allows for surveys to be collected 73 ft behind the bit. A high degree of confidence may be placed in the accuracy of your surveys, however, comparing surveys to predictions and reacting to deviations from anticipated yields is limited by the distance between the bit and survey tool.

Alternatively the BHA may be optimized such that directional surveys are taken closer to the bit than the conventional configuration. Scientific Drilling International proposed a reconfigured BHA which consisted of a bit, mud motor with 1.5° bent sub and float, stabilizer with Gain Inclination and Gamma, a non-magnetic drill collar with directional sensor, hand off sub, gap sub, non-magnetic pony collar, shock sub, six drill collars, jars, two drill collars, and a cross-over below drill pipe (Figure 4b). This configuration may be subject to magnetic interference of the drill string although there is software such as Mag Comp which can compensate for the interference. Inclination measurements are taken with the Gain tool 33 ft from the bit and directional surveys are taken 51 ft behind the bit. The Gain tool utilizes gravity accelerometers to determine inclination and therefore is not effected by magnetic fields. This configuration allows more proactive evaluation of trends, greater accuracy of predictions, and allows a faster reaction time if encountering unexpected results such as changing inclination or azimuth from what was anticipated.

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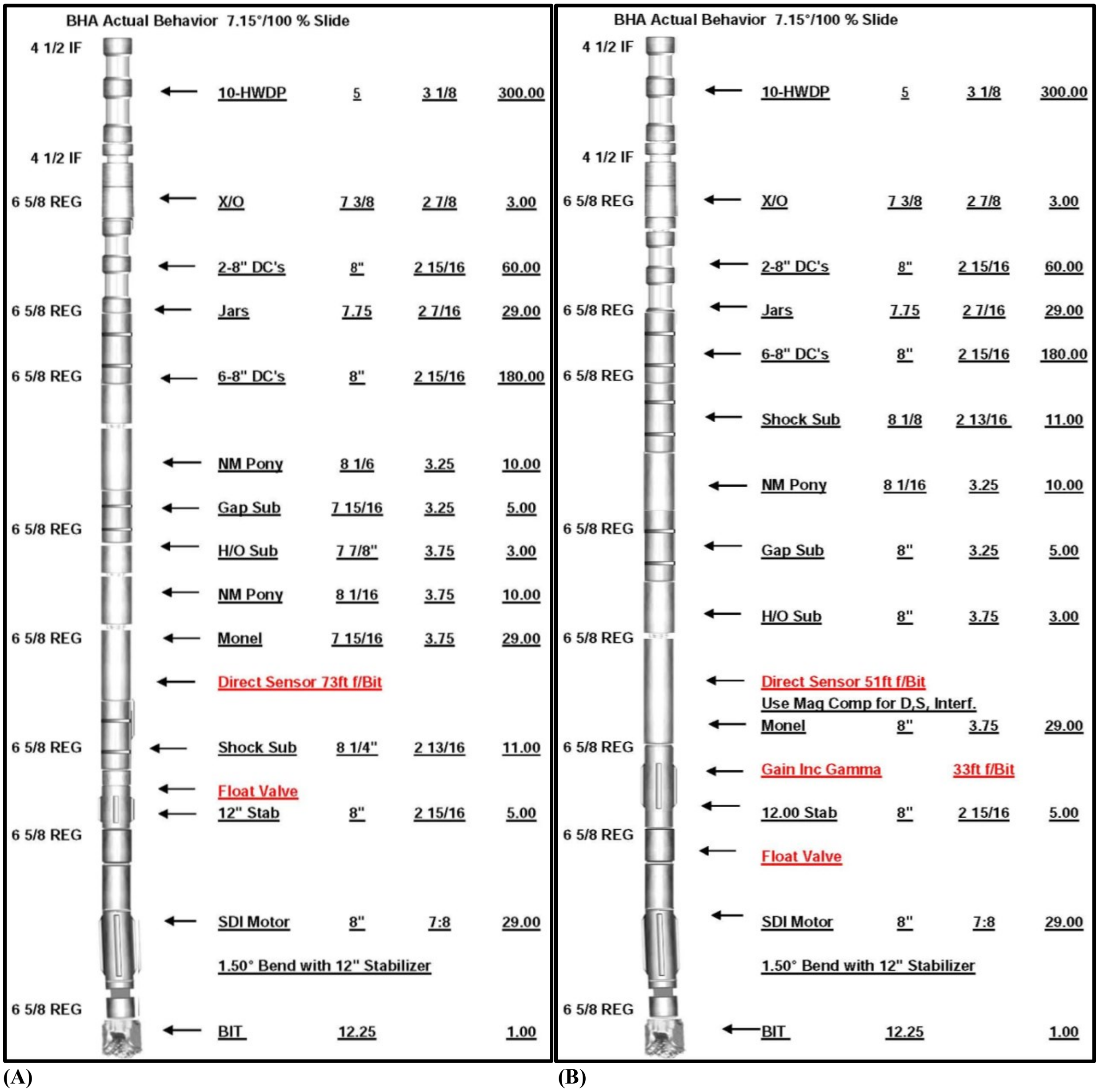


Figure 4: Schematics of directional bottom hole assemblies used. (A) conventional and (B) optimized.

2.4 Directional Drilling

While drilling directionally, surveys should be gathered every stand of drill pipe or about 42 ft and evaluated for accuracy. Slide intervals should be reamed to reduce drag and torque. The directional surveys including projections to bit should be regularly updated to the 3D geologic model and compared to the planned path and targets. The surveyed path needs to follow closely the planned path, generally within a 5 ft radius. Frequent challenges may arise in following the plan and drilling risks including washouts in drill pipe, twist-offs and getting stuck are anticipated to be elevated while multi-crossing a fault. These anticipated challenges and risks associate with sliding through formation of a heterogeneous nature. Such formations are characterized by rock competency contrasts and variation of fabrics across the fault zone due to fracturing, shearing, and mineralization. If the survey path diverges too far from the planned path, a new directional plan may be necessary to regain the fault in a manner which conserves drilling depth while limiting dogleg severity and minimizes drag and torque (Chandler, 2011; Hearn et al., 2012).

All drilling parameters should be monitored closely in order to gauge potential problems and to identify fault intercepts to compare with predictions. At the depth where a fault is inferred to have been intercepted, the last directional survey could be up to 73 ft above the zone of interest depending on the placement of the MWD in the BHA (Figure 4a). Therefore, once a fault intercept occurs, a projection to bit is necessary to estimate the location of the fault for comparison to what was expected in the 3D model. However, given the influence of formation heterogeneity on the well path, the bit projections may be deviated from the actual survey once the MWD reaches the fault intercept depth. Although the bit projections may be deviated, for modeling purposes, the location of the fault intercept inferred from the bit projection generally will not change significantly from the fault intercept as constrained by a directional survey. So, using the bit projection, the location of the fault intercept in the 3D model can initially be compared to the modeled fault for a cursory assessment and possible plan modification. Then once a directional survey at the depth of the fault intercept is acquired, the fault in the 3D model may be updated, new targets generated, and the directional plan and drill path may be refined/adjusted.

2.5 Completion

For typical Ormat wells in Nevada, fluid losses are monitored during drilling and if significant losses occur and are sustained (generally >200 bph), the decision could be made to rig up air compressor and flow test equipment and drill directionally with aerated fluid in order to lift cuttings out of the hole and maintain open fractures. If a sustained total loss of circulation occurs the directional BHA would be replaced with a slick BHA with mud motor. This reduces lost-in-hole costs in the event of stuck pipe while drilling in fractured formations. When drilling parameters indicate that adequate fracture permeability has been crossed, the hole is typically deepened beyond the last zone of interest for adequate rat hole. The hole is reamed to ensure gauge back flowed with air to remove cuttings. A 9-5/8” slotted liner is then installed, and a production flow test performed.

3. RESULTS

The redrill targets for Tungsten Mountain 84A-22ST1 were selected in order to intersect a fault at multiple intervals. Surface data including a fault scarp and downhole parameters including two interpreted fault intercepts from two offset wells 84-22 and 84A-22 provided the constraints for modeling of the fault plane. The fault of interest was modeled as a planar feature striking N44^{o}E and dipping 83.1^{o}SE using Leapfrog Geothermal software. Well position error was generated by the directional planner using Compass 5000 software (Figure 7). Target coordinates were gathered along a line on the fault plane oriented N77^{o}E and plunging 75.6^{o} and in a direction towards the 84-22 feed zone at 3950 ft depth and known permeability. A radius of 10 ft was chosen for the first well path arc (between fault intercepts 1 and 2) and a 3 ft radius was chosen for the second well path arc (between fault intercepts 2 and 3). Dogleg severity was planned as <4^{o}/100 ft and three initial fault intercepts were planned (Figure 3).

A conventional BHA was initially considered as the most cost effective and was deployed for the initial directional work (Figure 4a). After pumping a balanced cement plug near 2400 ft, the well was sidetracked by time drilling to kick out of the original 84A-22 hole. Achieving the first fault intercept required sliding and building a left-hand turn to ~045^{o} azimuth and inclination of ~15^{o} from vertical before turning back right (Figures 5a & 5b). Maximum dogleg severities between 4.3^{o} to 5.68^{o}/100 ft occurred from 2652 to 2865 ft. The fault was encountered at 3060 ft in slate formation and was evidenced by a subtle 20 bph loss. No other drilling parameters indicated a possible fault except that the depth at which losses occurred was accurately predicted to the model.

The hole was deepened maintaining the survey path close to the planned path. This required a right-hand turn up to 083^{o} azimuth and building inclination up to 17^{o} before turning back left and dropping inclination (Figures 5a & 5b). At 3420 to 3430 ft in slate formation a 75 bph loss occurred with a drilling break at 3419 ft. Cuttings samples in this interval contained a notable increase in mineralizations including predominately calcite fracture fill with lesser silica fracture fill and occurrences of euhedral comb quartz growths (Dong et al., 1995), abundant pyrite (FeS_2) and arsenopyrite (FeAsS) as porphyroblasts and vein fill, and rare epidote ($Ca_2(Al,Fe)_2(SiO_4)_3(OH)$). Again, this intercept was very close to the predicted fault location, but this time the indicators of a fault were much more obvious and provided confidence in the fault model. Maximum dogleg severities between 3.5^{o} to 5.0^{o}/100 ft occurred from 3078 to 3291 ft. After this fault intercept, no revision of the 3D model was necessary and since the survey path closely maintained the planned path, a revised plan was also not necessary.

The locations of the initial two fault crossings were accurate to the 3D model predictions and provided confidence in the deeper targets. The well was deepened towards the third fault target, which involved turning left and dropping angle (Figures 5a & 5b). The well was steered away from the plan in an attempt to stay in the fault zone and along the string of target coordinates. At 3595 to 3635 ft the fault was intersected in slate formation, which was marked by a drilling break with a sudden drop in the hookload, a 392 barrel mudloss (maximum rate of 330 bph), and abundant mineral and fracture indicators in the cuttings samples including euhedral natrolite and quartz, dogtooth calcite, amorphous silica fracture fill, and slickensided fracture material. Between 3466 and 3594 ft depth, dogleg severities were <3°/100 ft. Within this fault zone, the lack of formation competency caused the BHA to drop below the fault until the formation was hard enough for the bit to build angle on slides. Mudlosses below the zone tapered to ~80 bph so the well was deepened to achieve greater fracture permeability.

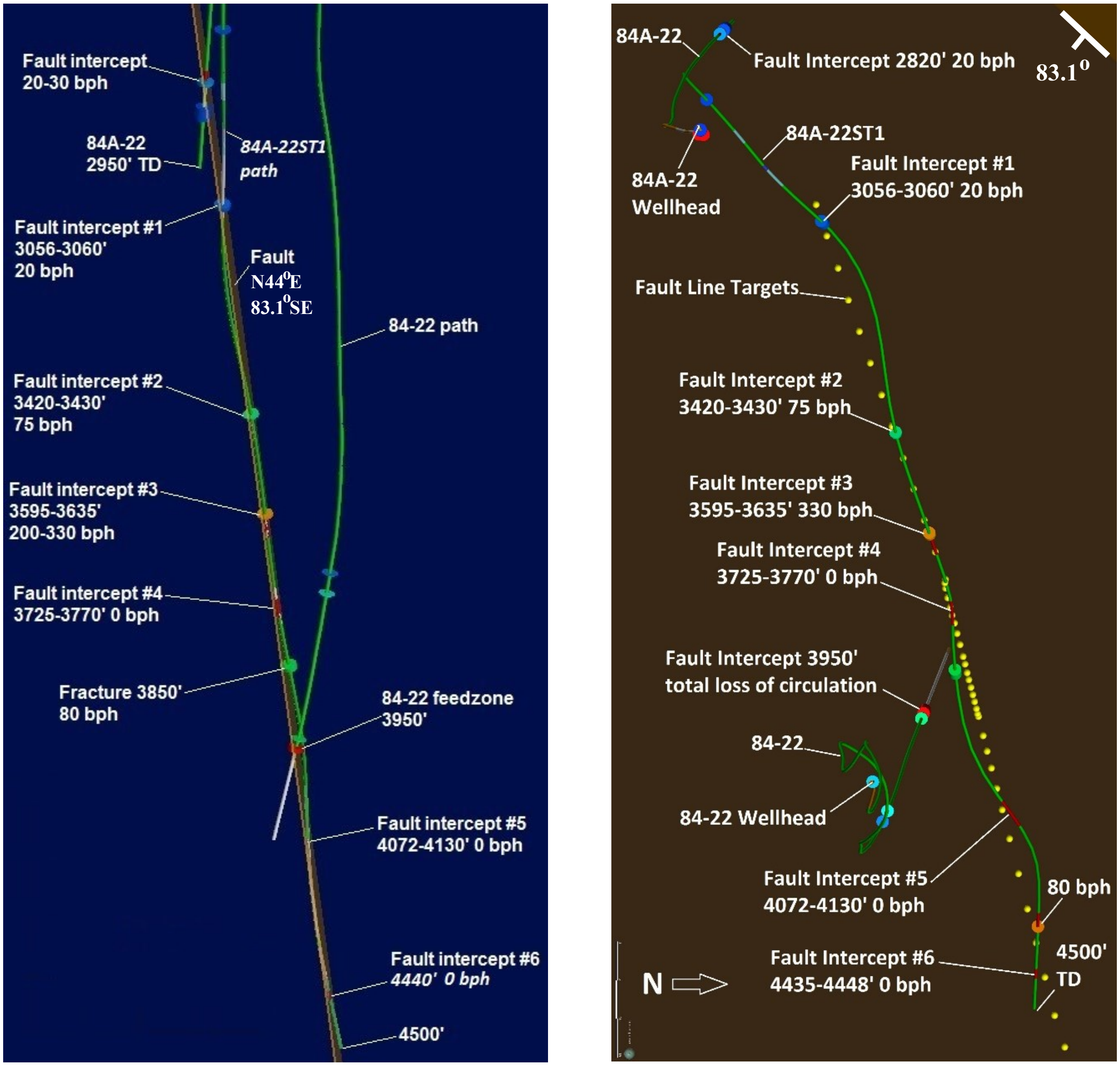
The initial three fault intercepts agreed well with the modeled fault, however additional permeability was required so a revised directional plan was drafted to add additional fault intercepts. The drilling team deployed the optimized BHA in order to improve survey predictions and react more rapidly (Figure 4b). After a bit trip and installing the new BHA, the well was deepened from 3702 ft and the BHA steered towards the right while building inclination. The fault was encountered a fourth time in slate basement rocks from 3725 to 3770 ft (Figures 5a & 5b). The fault intersection was accompanied by cuttings samples that consisted of secondary silica and calcite, cataclasite, and slickensided material. There were no additional mudlosses or drilling breaks associated with this fourth intercept. Upon exiting this fault zone, a dogleg of 7.48°/100 ft was incurred at 3740 ft, which resulted in deflection of the well path away from the fault zone and an increase in the depth until the next anticipated fault crossing (Figures 5a & 5b).

The plan was adjusted to accommodate the survey path and the BHA was steered towards the left and inclination reduced. The MWD surveys indicated that inclination and turn were not changing rapidly enough to regain the fault (Figures 5a & 5b). The fault was intended to be crossed near the 84-22 feed zone between ~3950 to 4000 ft depth, but the lack of angle resulted in pushing the anticipated fault intercept deeper. The difficulty in achieving the build angle was attributed to relatively harder mineralized formation towards the direction of the fault zone. The path diverged from the plan so a new plan was drafted. Longer slides were attempted in order to cut towards the fault and resulted in doglegs 5.6 to 6.1°/100 ft between 3976 to 4062 ft. The fault was crossed again near 4072-4130 ft depth. Again, no additional mudlosses were measured although the usual mineral and fracture indicators were noted. Upon deepening the well, a drilling break/fracture was encountered at 4352 to 4362 ft where an additional ~80 bph of mudlosses occurred. This did not correlate well to the modeled NE striking fault. The FMI log gathered later from 84A-22ST1 indicated fractures near this depth strike northwest and dip moderately northeast.

The well path was again turned towards the right and inclination increased in order to achieve a final sixth fault crossing. Additional mudlosses began again at 4366 ft in slate formation accompanied by increased silica, common arsenopyrite and rare epidote in the samples. This was presumed to be the sixth intercept of the fault. However, apparent from the wellbore imagery, the fault appears to be at 4440 ft depth and is defined by a large open fracture (Figure 6). Losses incurred at 4362 and 4366 ft likely relate to partially open fractures which connect in close proximity to the northeast-striking fault zone.

Although a total loss of mud circulation was not encountered while drilling, numerous fault crossings were inferred based on drilling data and alteration minerals in well cuttings. Since further drilling could lend to additional drilling risks, the well was completed to 4500 ft, reamed, back flowed with air assist to clean out, and completed with a 9-5/8" slotted liner to 4470 ft.

A production test was conducted on June 2, 2016 to determine well productivity before moving the rig off the well. Open ended drill pipe was set at 2003 ft and the well was lifted using an air compressor at 500 CFM. Fluid returns came to surface after thirty minutes of air lift. After one hour and twenty-five minutes of cleanout, produced fluid was diverted through an atmospheric separator with James tube and weir box to determine enthalpy and total flow. Once the test was completed, the air was shut off and after ten minutes, the well was shut in to measure the pressure buildup response for one hour. The maximum flow temperature of 274°F was seen between 3655 to 3875 ft during the test. The average flow rate with air calculated using the weir box was 1522 gpm during the test. A difference of 5.9 psi of pressure drawdown between static and flowing was measured so a productivity index of 260 gpm/psi was calculated indicating a very permeable well. Wellbore spinner logs indicated fluid entering the wellbore from 3900 to 4100 ft and near 3600 ft. Two other production tests performed later also confirmed high permeability and the well was put into production in November, 2017.



(A) **(B)**

Figure 5: (A) Profile view of well paths looking N44ºE. Well path color scheme: green is slate, red is fault zone, and white is no sample returns. (B) Map view of well paths including fault targets (yellow points).

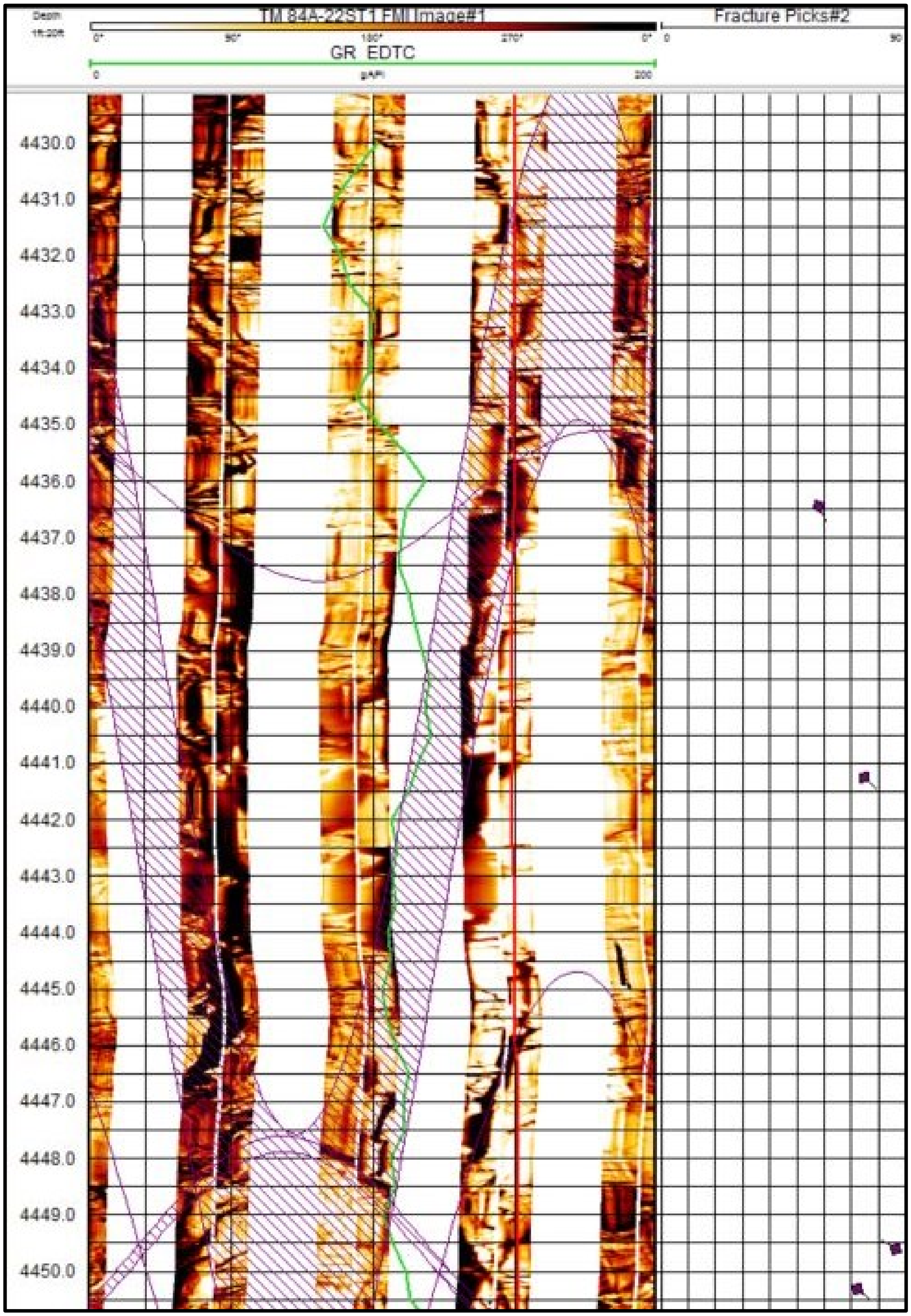


Figure 6: Formation Micro Image of fault zone at 4440 ft depth. An irregular partially open fracture strikes 43˚, dips 75˚SE, and has an aperture of 4 to 5 inches.

4. DISCUSSION

Multi-crossing a fault zone lends to additional drilling challenges and risks, but appropriate preparation and methods can mitigate potential problems. Thorough reaming of slides, doglegs, and tight spots helps reduce torque and drag. Heterogeneities across a fault zone indeed lend to challenges in following a directional drilling plan and can lend to incurring doglegs, deflections, or not building enough angle. In relatively hard formation the bit may be able to build angle during slides, but if drilling subparallel to hard formation in relatively softer formation with the goal of achieving the harder formation, deflection of the bit can result in not achieving the target. Adjusting slide lengths based sole on observed survey behavior or 'drilling the trend' may not be the best approach for following the plan. Rather choosing slide lengths which would hedge estimates as to what would best avoid or mitigate the most detrimental potential outcomes. Acquisition of surveys as close as possible to the bit allows faster response to well bore deviations. In subsequent wells at Tungsten Mountain, the optimized directional BHA was deemed worth the additional costs compared to the conventional directional BHA.

Other technologies which monitor downhole parameters as continuous measurements such as resistivity, gamma, and neutron porosity may also be considered for deployment, but each come with their respective price tag and relative benefit in the particular geologic environment and achieving the goals. The price tag associated with rotary steerable systems is also significantly more than a pulse mud motor system and may lend to expensive repairs if the tools are damaged due to harsh conditions (hard fractured formation and high temperatures) or lost in the hole due to stuck pipe.

Successful multi-crossing of a fault zone requires a high degree of precision. Therefore, a calculated assessment of error associated with both well position and the location of geologic targets needs to be factored into directional planning (Figure 7). There is error associated with surveys, well locations, surface geologic features, and also raster data used to identify geologic features (Stockhausen et al., 2016). An assessment of these position error will guide an appropriate radius and thickness of formation from the fault which the path should traverse to reduce risk of missing the targeted fault zone. Achieving one or two fault crossings will help significantly in the calibration of your model and refining of your directional plan. In experience with drilling multiple fault-controlled geothermal field, steeply dipping fault zones commonly are planer in nature. However, faults can still bend or jog, terminate, pinch and swell, or may be offset by other cutting faults. Thus it is important to assess these variables when considering a multi-crossing directional plan, and to have an integrated understanding of the geology, faults, temperatures and other subsurface parameters to refine well targeting in the 3D model. This then allows for rapid updating of the subsurface model as drilling occurs.

During the redrill of Tungsten Mountain 84A-22, by following a multi-crossing directional plan and related methods, six intercepts of a single fault zone were achieved. Well 84A-22ST1 was the first successful production well at Tungsten Mountain, and the multi-crossing methods established during the drilling campaign contributed to the successful completion of wellfield development (Figure 8). The wellfield consists of 4 production wells and 4 injection wells, which have been in commercial operation since November 2017 (26 MWe net).

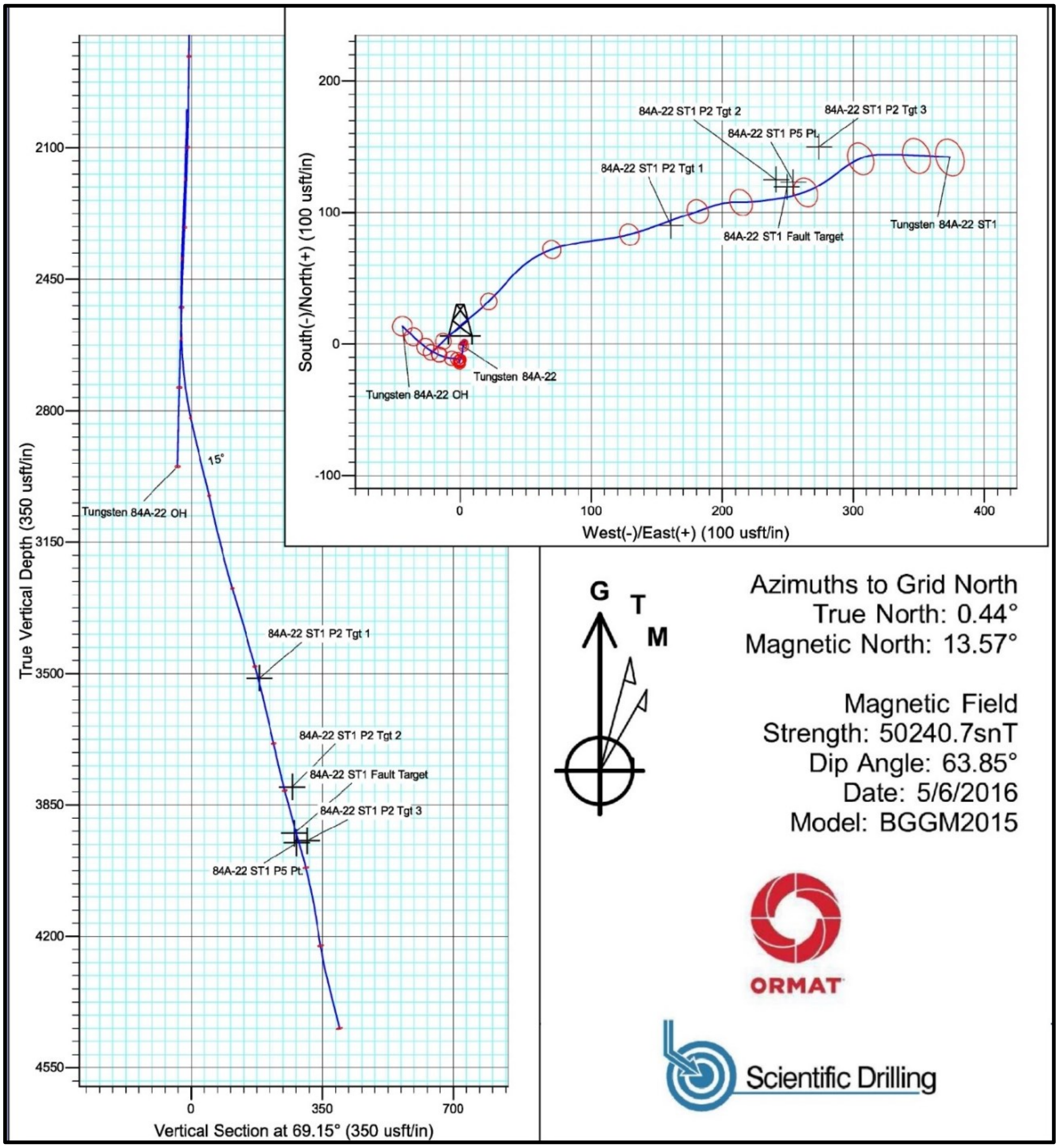


Figure 7: Well 84A-22/84A-22ST1 final surveys including error ellipses (red).

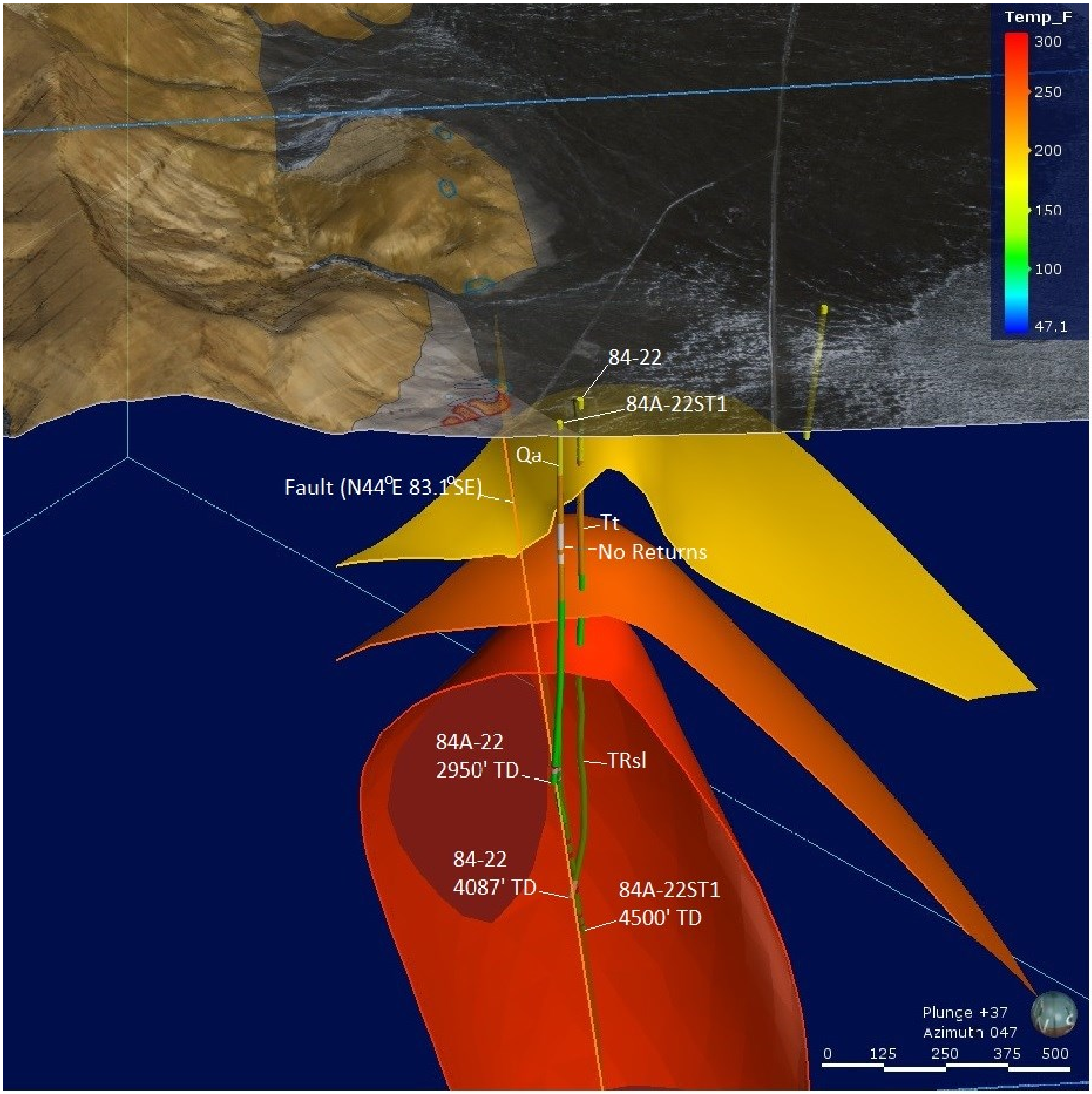


Figure 8: Leapfrog model perspective of wells, general geology, and isotherms. In drill holes: Qa: Quaternary alluvium; Tt: Tertiary ash-flow tuff; TRsl: Triassic slate and siltstone. On map: orange unit is ash-flow tuff, red polygons delineates hematite/silica/clay hydrothermal alterations, blue polygons delineate silica/calcite/chlorite hydrothermal alterations.

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