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Integrated 3D Modeling of Structural Controls and Permeability Distribution in the Patua Geothermal Field, Hazen, NV

Neil Peterson[1], Jim Combs[1], Leif Bjelm[2], Sabodh Garg[3], Benjamin Kohl[3], Colin Goranson[4], Robert Merrill[5], Peter van de Kamp[6], Amie Lamb[1]

1-Gradient Resources Inc., 9670 Gateway Drive, Suite 200, Reno, NV 89521 USA
2-Department of Engineering Geology, LTH, Lund University, PO Box 118, SE-22100, Lund, Sweden
3-SAIC, 10260 Campus point Drive, San Diego, CA 92121 USA
4-Geothermal Consultant, 1498 Aqua Vista Road, Richmond, CA 94805 USA
5-Catheart Energy, Inc., 3811 Hogan Court, Sugar Land, TX 77479 USA
6-Consulting Geologist, 40385 Queener Drive, Scio, OR 97374 USA

ABSTRACT

The Patua Hot Springs (Patua) geothermal prospect operated by Gradient Resource Inc. is situated at the southern end of the Hot Springs Mountains near Hazen, Nevada. The project area is located roughly 40 miles east of Reno, NV and 10 miles east of the town of Fernley. Over the course of exploration and resource development at Patua, multidisciplinary data sets have been acquired and subsequently integrated into a 3D model focused on faulting and permeability distribution in the Patua geothermal field. A base concept in the generation of the 3D model is the extensively documented phenomena of Walker Lane strike slip faulting and Basin and Range extensional tectonics, commonly referred to as the Walker Lane Transition. This incorporation of regional stress and strain as it applies to project scale phenomena has resulted in a better understanding of permeability structure.

Data sets used in generation of the 3D model include field mapping of faults and hydrothermal alteration, 2D seismic reflection profiles, borehole seismic surveys, MT, gravity, open hole geophysical logs, borehole imaging logs, lithology logs, brine chemistry, core sample analysis and reservoir pressure data. These sets of geophysical data and published geodetic data were jointly considered with direct measurements of a broad variety for the purpose of constraining the interpretation of structure and to aid in delineating permeable fractured pathways within the Patua reservoir. Interpretation and correlation of roughly 42 miles of 2D seismic reflection data using field mapping, aerial photography, and evident geomorphology indicates the structural controls on geothermal upwelling are sets of NE-striking Riedel Shears propagating from an approximate N70W striking, left stepping segment of the Walker Lane that traverses the project area. This structure is a southern segment of the Pyramid Lake Fault and separates the Hot Springs Mountains from the Virginia Range to the south.

Figure1. Patua geothermal project location map

INTRODUCTION

Geology of the Patua project area consists of cretaceous granitic basement rocks variably overlain by early tertiary rhyolitic flows and tuffs which are overlain by tertiary intermediate to mafic volcanic rocks (basalt, andesite and dacite). These intermed-iate volcanic rocks are in turn overlain by quaternary age lacustrine deposits of Lake Lahontan and quaternary to Holocene alluvial deposits. The tectonic setting is the Walker Lane-Great Basin transition which can be characterized as a complex zone of accommodation where NW striking, left stepping dextral faulting of the Walker Lane system coincides with NE striking Basin and Range oblique slip faults with both dextral and normal components.

METHODOLOGY

The methodology used in generating a 3D model of the Patua geothermal field relies on a series of comparative analyses from a variety of data sets. Such comparative work with regard to the direct measurement techniques enables recognition of similarities that in turn solidify the conceptual model and serve as the framework for the understanding of the spatial distribution of the geothermal reservoir. These data sets and comparisons are ultimately used to calibrate and constrain the interpretive work necessary in use of indirect measurements such as seismic reflection and MT. Without such constraints, the exploratory work, which is commonly the primary justification for drilling of wells, is essentially left in a vacuum and as such, presents a significant risk to the operator in terms of drilling successful wells.

DIRECT MEASUREMENTS & GROUND TRUTH

Field Mapping and Geomorphology

Earliest field mapping of the Patua project area was focused primarily on fault structure. Evident NE striking faults along the eastern and western margins of the Hot Springs Mountains as well as the NW oriented segment of the Pyramid Lake fault at the southern end of the range were recognized and coincidental with published works on structural trends and detailed geologic mapping of the Fernley quadrangle by James Faulds of the University of Nevada, Reno. Based on known ages of lacustrine deposits of Lake Lahontan, it is evident that the present day topography and geomorphic expression of the Hot Springs Mountains is a result of Quaternary age NE striking Basin and Range type faulting (Voegtly, 1981).

An area of particular interest at Patua with regard to structure is located in the southern portion of the lease along the south and southwest side of Black Butte. Here, the regionally dominant, NW striking Walker Lane fault (which constitutes a restraining bend or left step in a right lateral fault) is offset dextrally by Holocene rupturing that continues NE into the Hot Springs Mountains. Simply put, there is a discrete right step (releasing type bend) that is manifest within a restraining bend. Here, dextral shear strain and compression along the NW striking Walker Lane feature are translated into a localized area of tensional stress and strain accommodation along NE striking faults. Work done on structure, kinematics and modeling of faulting in restraining and releasing bends along strike slip fault systems is described thoroughly by Mitra and Paul in AAPG Bulletin, V. 95, NO. 7 (July 2011), PP. 1147-1180 and supporting references given in that publication. Other works specific to the Walker Lane-Great Basin transition structural settings are well documented in numerous publications by Jim Faulds and Mark Coolbaugh as well as numerous other professors and students from the University of Nevada, Reno.

Mapping of the distribution of hydrothermal alteration was also conducted. Distribution of chalcedonic sinters, hot springs deposits, calcium carbonate (tufa) and argillic alteration were mapped using GPS and aerial photography of the project area. In conjunction, the distribution of important project area faults coincided with the distribution of siliceous sinter deposits. In the southern portion of the project,

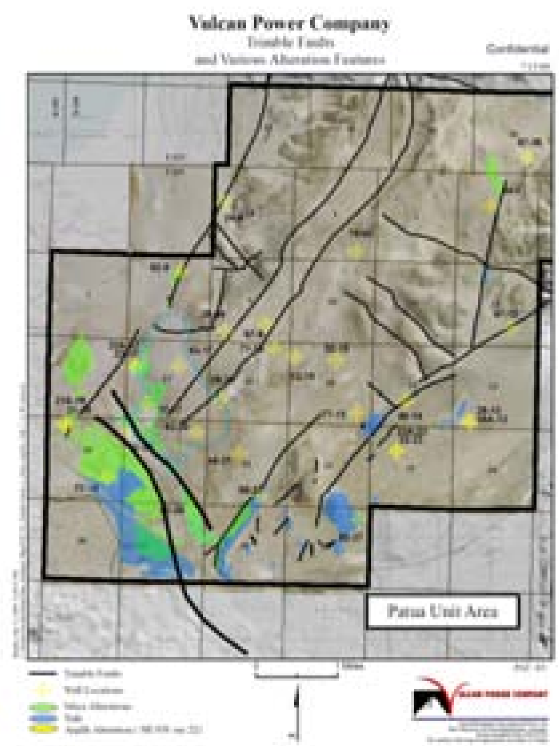


Figure2. 2009 Patua geothermal project map showing faults, siliceous sinters/alteration and calcium carbonate deposits (calcareous cements and tufa deposits).

silica cemented sandstone lenses deposited in Lake Lahontan and chalcedonic sinter deposits (found to be tens of feet thick) are concentrated along the NW striking segment of the Pyramid Lake fault. Furthermore, siliceous alterations are more abundant where the NE striking faults and accommodation zones intersect (or propagate from) the Pyramid Lake Fault.

Drilling Data, Lithology logs, Open Hole Geophysical logs and Borehole Imaging logs

Indications of fracturing from drilling data (i.e. lost circulation zones and intervals with high penetration rates) in combination with the subsequent borehole geophysical and imaging logs are perhaps the most valuable direct measurements. Taken together, these types of direct measurements from within the reservoir provide real constraints on seismic reflection data interpretation and allow mapping of permeable faults that constitute the plumbing network of the geothermal system.

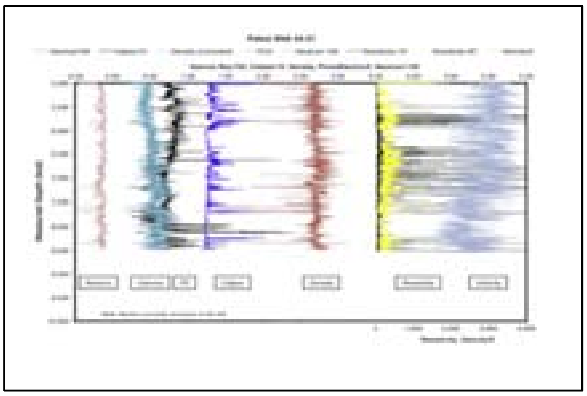


Figure4. Comparison of log responses recorded in the 44-21 well. ZDEN, Resistivity, PE and Acoustic Velocity logs indicate highly fractured and altered rocks. Figure from C. Goranson, 2011.

Lost circulation and increases in rate of penetration (ROP) are, in most cases, the first indication of reservoir permeability. Such evidence used in conjunction with electric logs and borehole imaging logs effectively define the location and orientation of

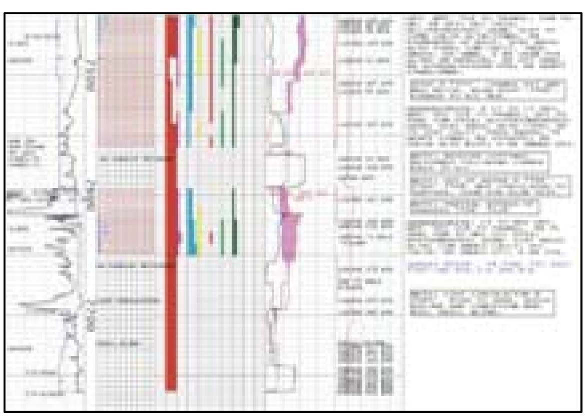


Figure5. Mudlog from the Patua well 44-21 showing characteristic increase in ROP and loss of circulation in the wellbore.

permeable fractures. Additional observations from electric logs with regard to distribution, elevation and thickness of formations, marker beds or other stratigraphic units that can be correlated are of value in modeling project area structure and timing of faulting.

For the Patua reservoir, particular units of interest are the granitic basement and the overlying sequence of silica rich volcanic rocks (rhyolite, rhyodacite and a variety of tuffs). From well data, the top of the plutonic basement rocks varies significantly from well to well.

With regard to the granitic basement, the top of this unit is unique in that it is the only rock unit is the Patua stratigraphic sequence that pre-dates the current Walker Lane-Great Basin transitional tectonic setting. Given this relatively long lived existence, a valuable record of the deformational history can be recognized. In short, various phenomena indicating the presence of a geothermal system coincide with areas where drilling data shows that the basement is down-dropped. Between the 33-23 and 44-21 wells in the north and the 58-29 well south and west of the BBRFZ, normal displacement of basement rocks is on the order of up 3500'.

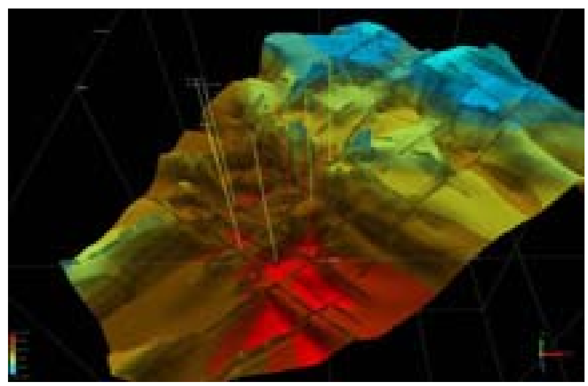
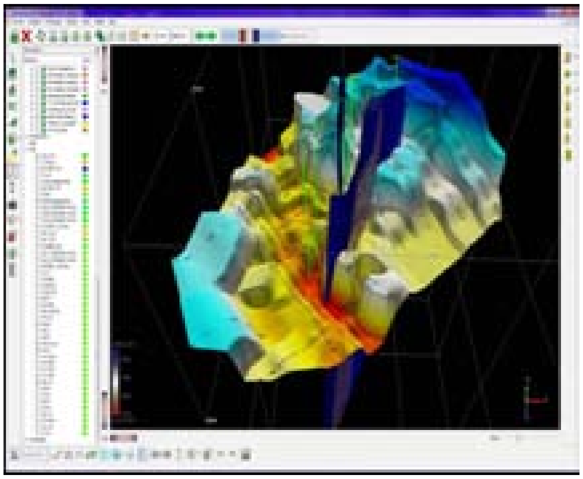
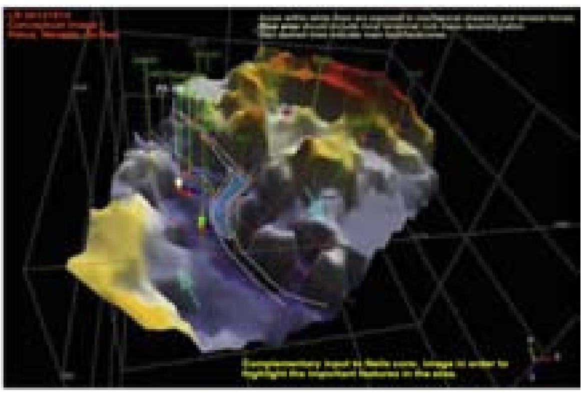


Figure6. 3D rendering of the top of basement granitic rocks in the Patua field. For the area shown in red the top of basement is the near 7000' deep. This is the area W and SW of black butte. Region shown in blue corresponds to uplifted basement rocks in the Hot Springs Mountains. All observed geothermal reservoir manifestations at Patua correspond to areas where the basement is depressed.

Kinematically, and in consideration of the active stress and strain in the field, this depressed area or zone of tensional rock mechanics is a manifestation of shear strain translation on NW striking Walker Lane/Pyramid Lake faults to NE striking riedel type shears. This observation is confirmed by resolution of focal mechanisms in the area recorded by the micro-seismic monitoring equipment currently deployed at Patua.



Figurez. 3D topographic rendering of the granitic basement surface showing wells and NE striking BBRFZ faults.



Figurey. 3D rendering of basement topography illustrating the direction of slip and the net effect of tensional forces generated along theBBRFZ. (Figure by Bjelm, 2012)

The silicic volcanic sequence at Patua further aids in delineating the deformational history of the project area. This section of predominantly rhyolitic rocks rests unconformably on top of the basement and shows broad variation in thickness (absent to >2500' thick) as well as elevation at the top of the formation.

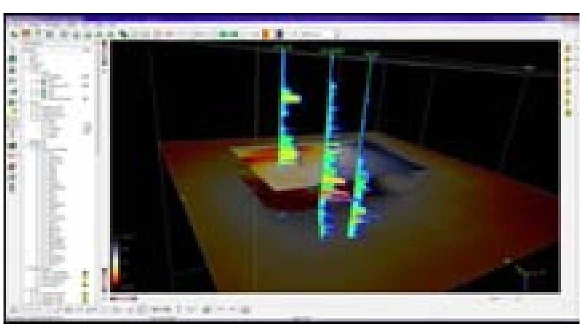


Figure6. 3D model of wells with gamma log traces displayed. The high gamma associated with the silicic volcanic sequence shows the variation in elevation and thickness in the southern portion of the Patua field. Perspective is looking WNW. Z-slices from MT and temperature volumes and are used here for elevation reference.

Using well lithology data and the high natural gamma of these rocks, a 3D rendering of the rhyolitic formation topography was created in combination with seismic reflection data. The resultant rendering bears strong similarities to the basement topography and corroborates the major structural interpretation.

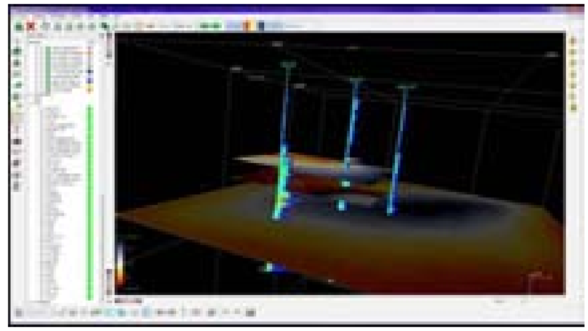


Figure7. Another view of gamma responses in wells drilled at Patua looking NNW. The well farthest to the south has a thick sequence of silicic volcanic rocks (>2000') and the next closest well to the north has only a thin section of the basal portion of the silicic unit. Preserved sections of these rocks indicate faulting has been active from at least the mid-tertiary. Further north, in the uplifted Hot Springs Mountains block the rhyolites are totally absent from the stratigraphic section.

Borehole imaging logs are a key component in mapping permeability in three dimensions, as they provide unique direct evidence as to the orientation of faults as well as stress in the well bore manifest as borehole breakouts. Gradient Resources has incorporated the use of Baker Hughes STAR/CBIL logging tool as part of standard logging procedures. This instrument records both resistivity imaging by use of a 6-arm caliper (STAR) and acoustic imaging (CBIL).

A variety of fracture orientations are often present in a given well, however, when these orientations are considered in a statistical fashion and with flowing survey data, characteristic relationships become evident. For example, in the Patua reservoir, it is apparent that NE-striking faults predominate, but in combination with PTS data, larger magnitude fluid entries commonly have subjugate numbers of NW striking fractures measured in close proximity (on the order of tens of feet in some cases).

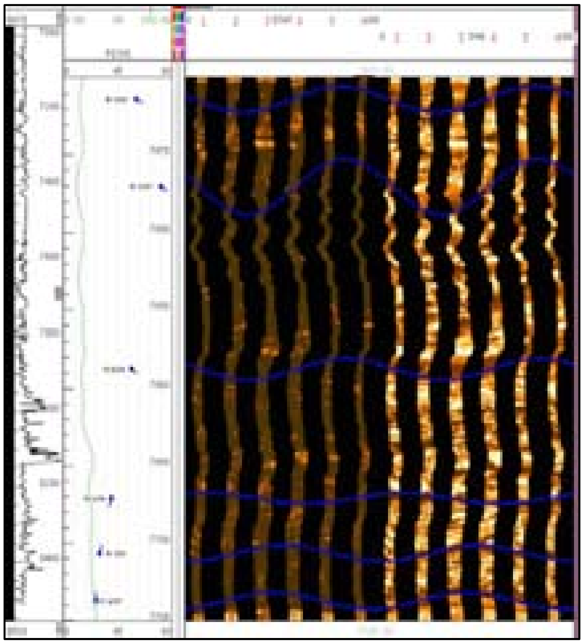


Figure 6. Resistivity imaging log (Baker Hughes STAR tool) showing the variety of fracture orientations in the 44-21 well. This spatial relation is characteristic of the field permeability structure and is illustrative of the Walker Lane-Great Basin transition concept of shear stress translation (Faulds, 2008).

With regard to borehole breakouts, this information gives useful indications as to the direction of least compressive stress and further defines preferential fault orientations, stress and strain, and permeability structure in the reservoir. For Patua, the borehole breakout identified in wellbore imaging logs is oriented E-W and WNW-ESE, which confirms that the presently recognized tectonic regime of Walker Lane-Basin and Range transition type stress and strain is a governing concept of the Patua geothermal reservoir (Faulds, 2005).

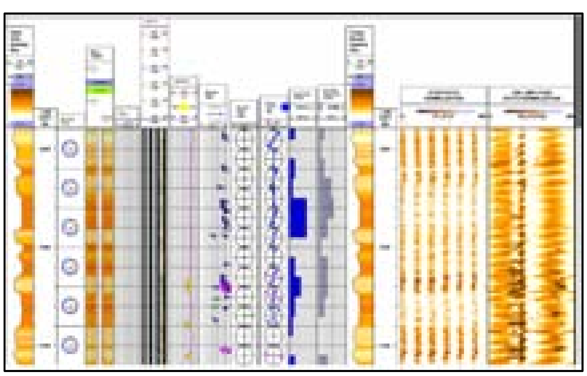


Figure 6. Combined resistivity and acoustic imaging with rose diagrams of fracture orientation, borehole breakout and e-log responses.

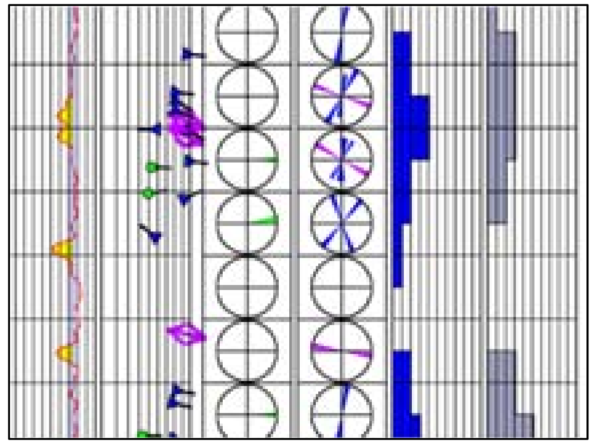


Figure 7. Zoomed in view of borehole breakouts identified in the well. Orientation is WNW-ESE. This orientation is consistent for the various wells where image logs have been recorded.

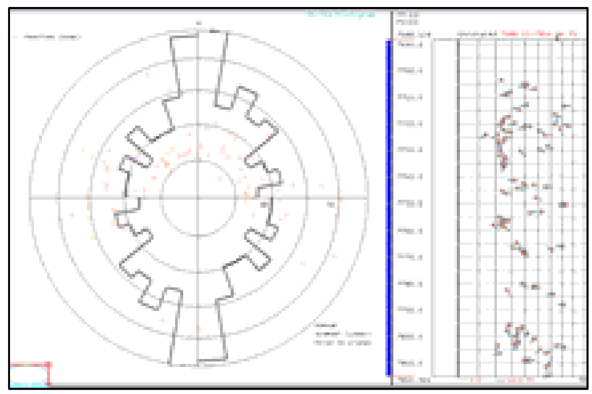


Figure 8. Rose plot of fracture orientations measured using the STAR-CBIL logs from well 77-19. This sort of statistical presentation constrains dominant structural trends in the Patua reservoir.

Flowing pressure-temperature (PT) and pressure-temperature-spinner (PTS) logs recorded during well testing provide further information about the fluid entry location in the well bore and give indications of the degree of permeability associated with discrete fractured intervals. Using this comparative method, a magnitude of permeability can be associated with fractures of a specific orientation or range of orientations.

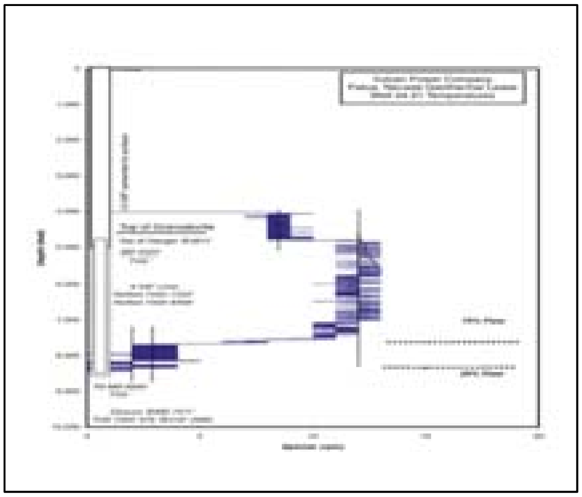


Figure9. Spinner data from the 44-21 well recorded during flow testing. Major fluid entry corresponds to zone of lost circulation encountered in drilling, (Goranson, 2009)

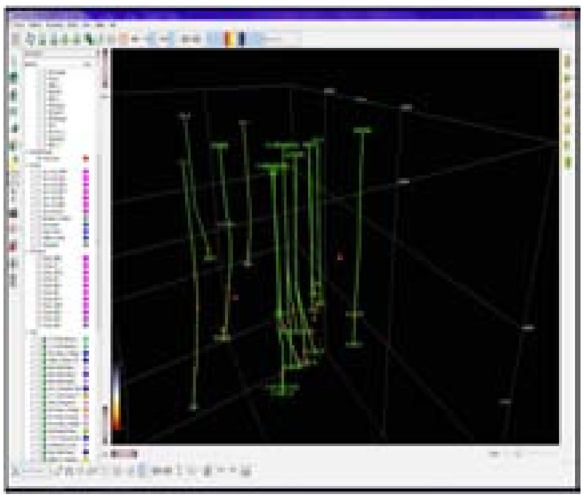


Figure10. 3D modeling of wells drilled in the Patua reservoir showing the locations of fluid entries as identified and constrained with PTS, electric logs and drilling data.

Temperature, Pressure and Chemistry

The spatial distribution of indicators that point to the presence of a geothermal system (by various direct measurements) at Patua are highly correlative. Thermal, chemical, and pressure measurements say the same thing. There is common area of interest in what has been dubbed the "Black Butte Ridge Fault Zone" (BBRFZ) which is located on the west and south side of Black Butte.

Temperature measured in wells at Patua show significant variations throughout the reservoir. Wells in the uplifted Hot Springs Mountains and along the western range front are cooler as a function of elevation (or TVD), varying between 270°F - 305° F. Wells completed in the area W-SW of Black Butte are significantly hotter. The highest temperature measured is in the 16-29_ST2 well at 406°F. The depth of that measurement is greater than 11,000' TVD. Well 58-29, despite casing issues and influx from a cooler zone is 364°F. The recently drilled 21-28 well encountered lost circulation at <7000' measured depth and is the second hottest well as a function of depth in the Patua field. It is situated within the BBRFZ.

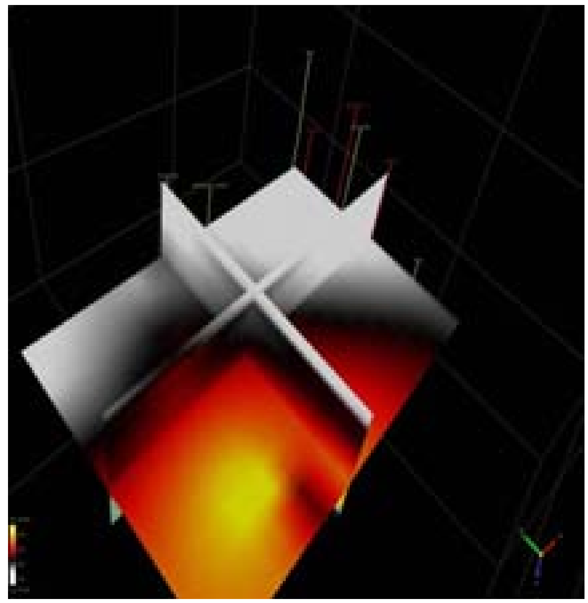


Figure11. Inline, crossline and z-slices of the temperature volume currently in the Patua 3D model. The area of high temperature corresponds to the W and SW of Black Butte.

Chemistry of produced fluids sampled over the course of testing wells at Patua have provided useful and important insights regarding the spatial distribution of the geothermal reservoir and zones of mixing where meteoric waters are present. Additionally, various geothermometer calculations from brine chemistry have elucidated areas most likely to host upwelling geothermal reservoir fluid.

Such indications that are consistently evident are compelling. As to the zone of mixing that has been observed by Colin Goranson in the course of his brine analyses, this important insight further constrains the 3 and 4 dimensional depiction and understanding of reservoir fluid behavior.

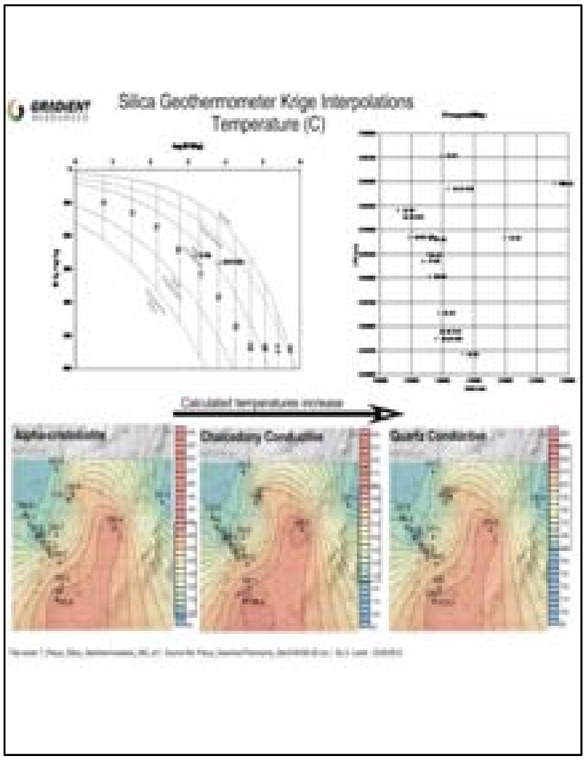


Figure12. Silica geothermometry from known fluid entries in Patua wells. The location and measured concentration of chemical species from known feed zones in the Patua reservoir are mapped and concentrations are contoured using the Kriging method. The area of highest temperature indicated by this method sits to the west and southwest of Black Butte. Nearly identical results are evident from Sodium-Potassium getothermometers in Figure13. (Figure by A. Lamb, 2012)

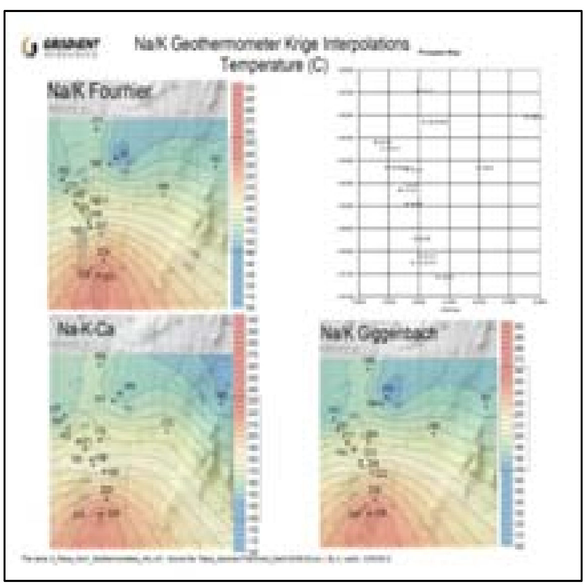


Figure13. Contour map of Na/K geothermometry at Patua. Area of highest temperatures is again along the west and south side of Black Butte in the NE striking Black Butte Fault Zone. (Figure by A. Lamb, 2012)

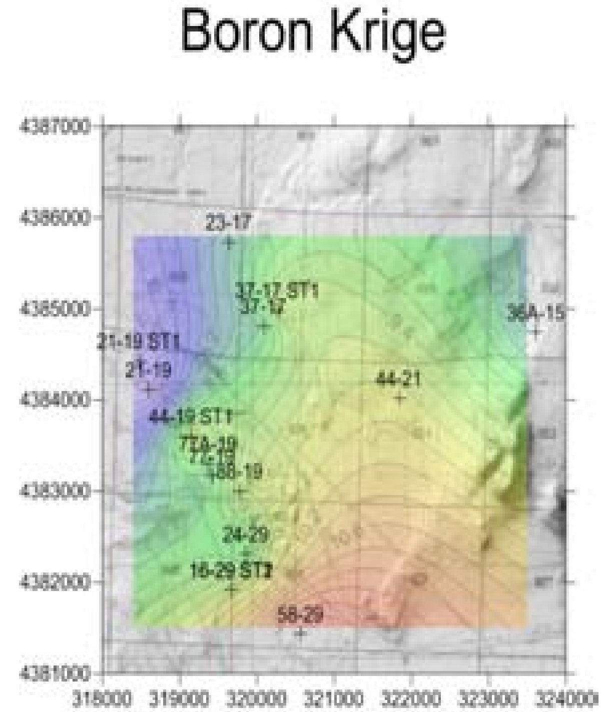


Figure14. Krige contour map of Boron concentration in the Patua reservoir. Nearly identical results with regard to the locality of high temperature fluids are observed when compared to other chemical analyses of geothermal chemical marker species (Figure by A. Lamb, 2012)

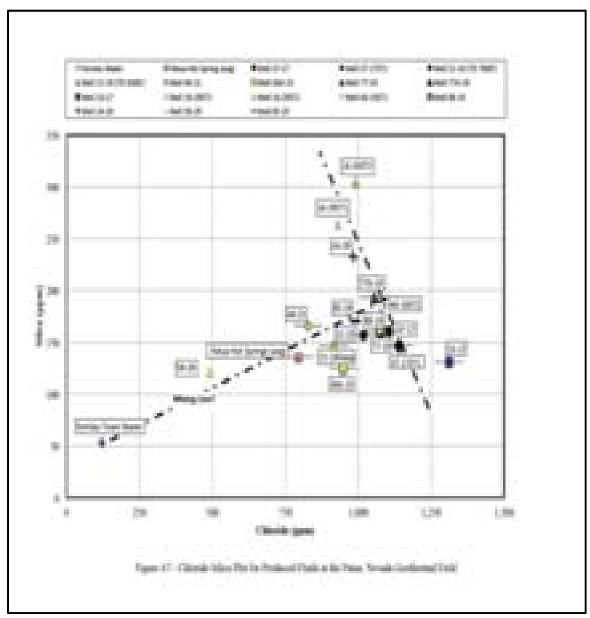
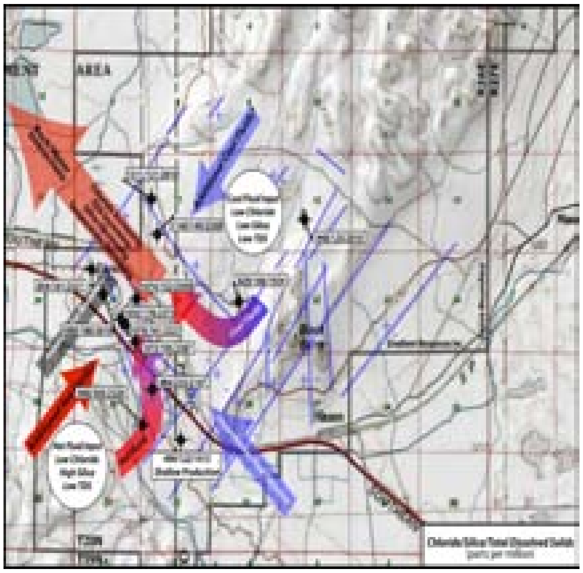


Figure15. Boron Chloride Plot from brine chemistry analyses conducted at Patua.



Figre16. Plot of groundwater movement from C. Goranson. Flow directions derived from chemical analyses and pressure data measured in deep monitoring wells. Depiction shows upwelling around the BBRFZ and outflowing to the northwest.

INDIRECT MEASUREMENT TOOLS

In the development of a geothermal reservoir, there are two general types of data with important distinctions. These data types are direct and indirect measurements. Drilling, logging and testing activities provide real measurements of subsurface phenomena, and as such are fundamentally different from methods such as seismic reflection, micro seismic, MT, gravity and aeromagnetic data. The latter are what I would subsequently characterize as exploratory and interpretive data sets. These initial glimpses at the subsurface before initiation of a drilling development are the primary tools used in determining the course of action for drilling.

This distinct set of surface-based, indirect geophysical methods continues to hold the place as a primary exploration tool throughout drilling development. As such, these tools need to be refined and calibrated as wells are drilled and more direct measurements become available. This is the fundamental motivator for 3D modeling of real subsurface measurements in combination with indirect geophysical measurements at Patua. Calibration and ground truth constraint on interpretive data sets.

2D Seismic Reflection

Seismic reflection data for the Patua project has served as a primary tool for drilling and resource development. A benefit of seismic reflection data is that it has the unique capability of identifying faults and their apparent orientation with some precision, and so they are quite useful in selection of drilling locations and determining a well plan.

Earliest interpretation of faulting from seismic reflection data was primarily constrained by mapped fault structures and evident geomorphology of the Hot Springs Mountains and Hot Springs Flat. Subsequent exploratory drilling based on seismic reflection work in combination with these constraints had a high success rate. Seven of the first eight wells drilled encountered productive permeable fractures with sufficient temperature and flow volume to be considered economic producers for a binary power plant installation.

With direct subsurface measurements available, additional observations of permeability, rock properties and reservoir parameters from wells could be utilized for the purpose of mapping permeability structure. This process, as described in the preceding text, where in-situ measurements from the subsurface are used to calibrate the inherently interpretive use of indirect exploratory data sets is an integral part of data display and use in modeling.

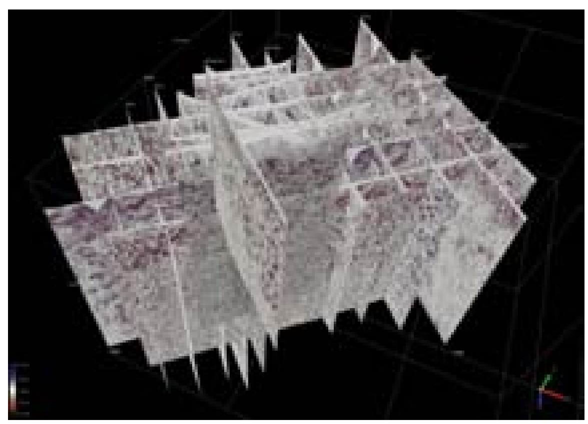
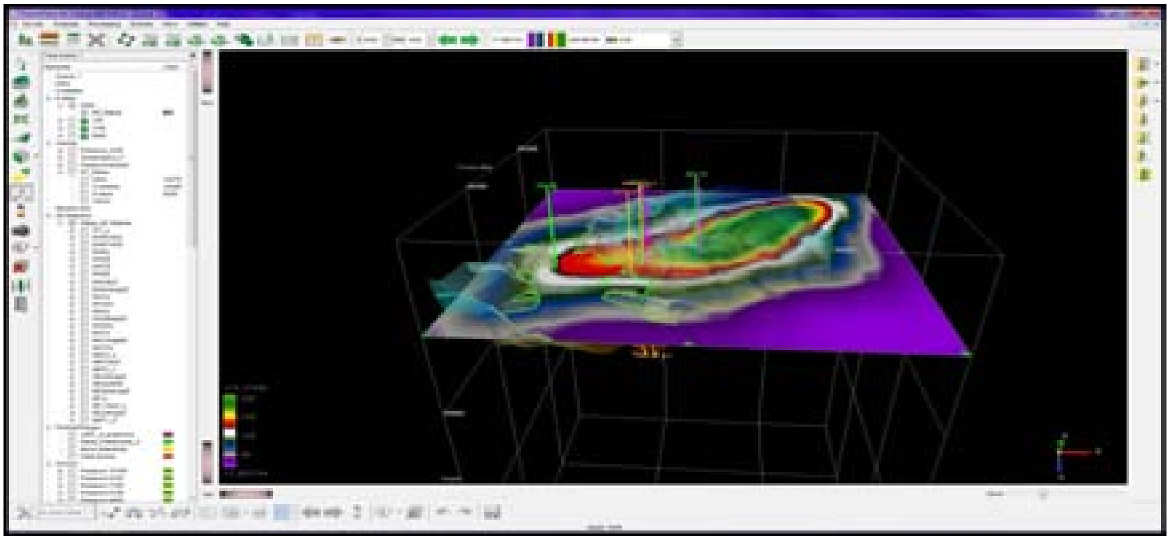


Figure11. Snapshot of 2D seismic reflection lines in the Patua project area. The grid consists of more than 42 miles of 2D seismic reflection profiles.

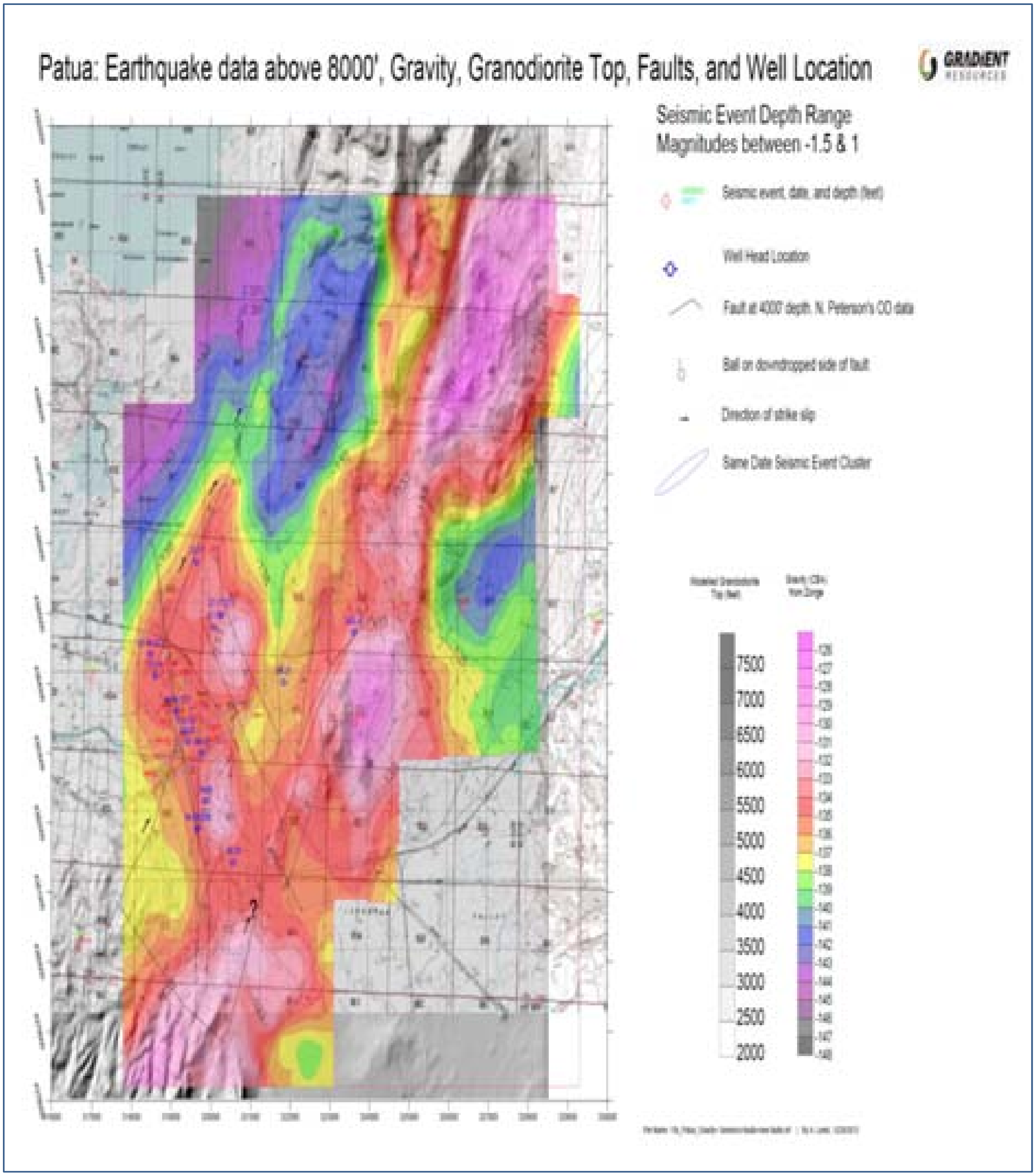
MT AND GRAVITY DATA

MT data for the Patua field was recorded in 2008-2009and subsequent rendering of a full 3D data set for use in the integrated 3D model was done by Robert Merrill. The resultant picture of 3D modeling in the dynamic modeling environment revealed what other data sets had indicated in terms of structural controls, major fault trends and the basement elevation.

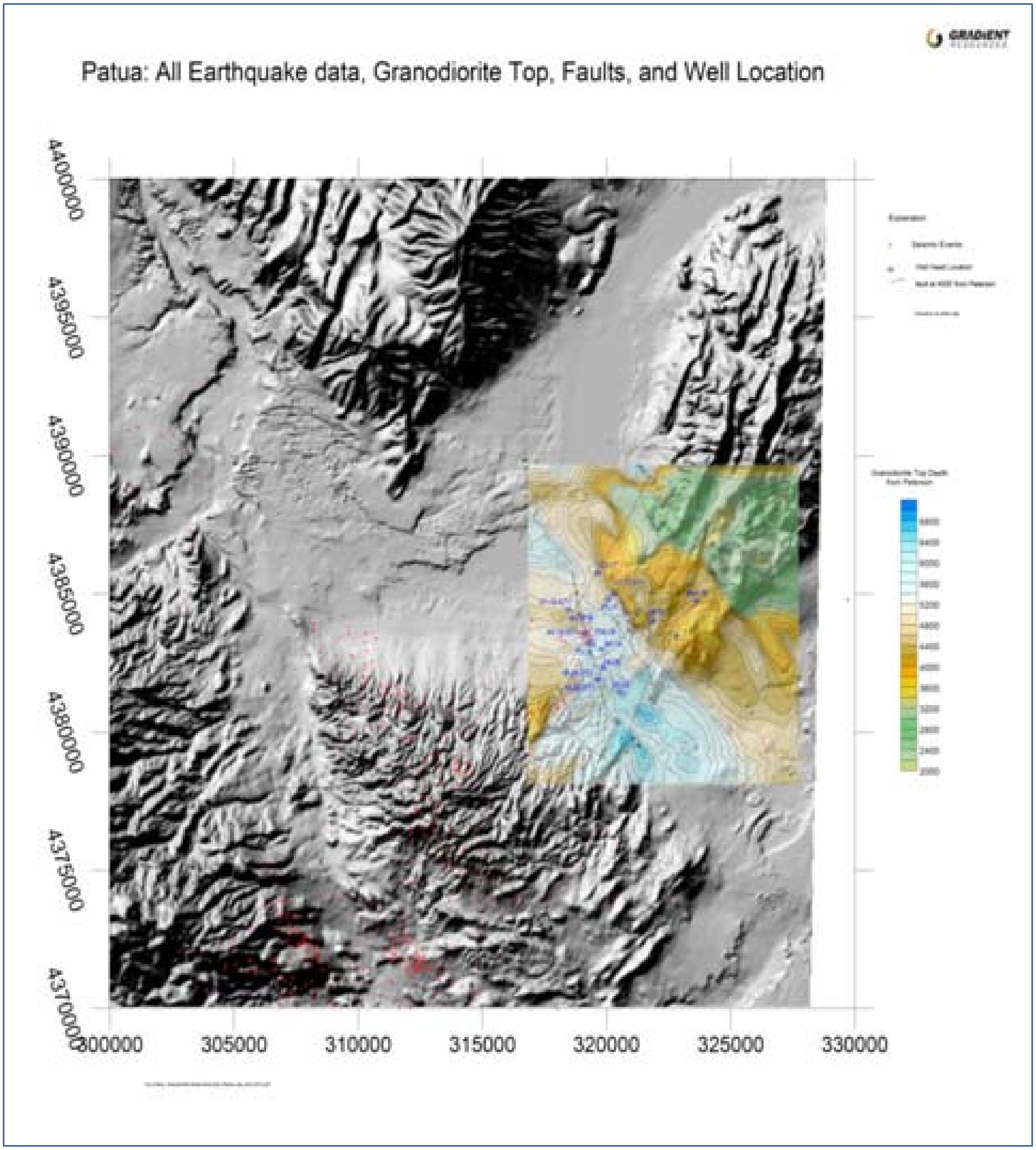


Figured. Comparative presentation in the 3D model of granitic basement topography with MT data. The resistive body in the middle running NE through the project area corresponds to uplifted basement rocks. High horizontal derivative around the margins of the high resistivity (also oriented NE) agrees with the various other data sets indicating NE striking faults as dominant features in the Hot Springs Mountains.

Figureq. Shaded relief map of the Patua project area showing overlay of fault structures and micro-seismic events on the MT data set. (Figure by A. Lamb, 2013)



Figurec. Gravity data for the Patua project area displayed with faults from seismic reflection data and well locations. Fault structure interpretation from 2D seismic reflection profiles (constrained by in-situ borehole measurements) as with the MT data mirrors the gravity distribution. (Figure by A. Lamb, 2013)



Figurep. Shaded relief map showing the Virginia Range (bottom center), the Patua geothermal project area, Hot Springs Mountains (top right) and the southern Truckee Range (top center) with granitic basement contours, well locations and micro-seismic events recorded by the monitoring system installed at Patua in 2012. The dense cluster of seismic events SW of Patua were resolved as right lateral strike slip focal mechanisms associated with the NW striking Pyramid Lake fault. Focal mechanisms for events within the Patua project area were oblique slip with both dextral and normal components of motion along N-NE striking faults. (Kohl, 2012) The micro-seismic monitoring installation at Patua consists of eight triaxial seismometers installed in slim holes. Depths of installation for seismometers is 300' to 1000' depth.

SUMMARY AND CONCLUSION

At the Patua geothermal resource area, volumes of data from a broad variety of disciplines have been acquired in the exploratory and development phases of the project. These sets of data are divided into two distinct categories that ascribe a purpose in the handling of information as it applies to understanding the geothermal reservoir. The first data type is categorized as direct or in-situ measurements. This includes mapped geology, drilling data, lithology logs, open hole geophysical logs, borehole imaging logs, PT, PTS, flow test data, and reservoir pressure interference to name several.

The second category of data recognized is the set of indirect measurements. Such exploratory and more interpretive data sets include seismic reflection, MT, TDEM and gravity. These data should only be used in a constrained way that incorporates both regional understanding of stress, strain and tectonic setting and project scale direct measurements. Finer calibration of interpretation should then rely on the borehole information and direct reservoir measurements. Comparison of indirect measurements such as MT and gravity is also very valuable.

At Patua, the handling of data in this constrained and comparative work flow has resulted in an immersive 3D modeling environment with the ability to view virtually any data set simultaneously with other data while maintaining a high degree of spatial precision. The result of generating such an immersive means of interacting with and manipulating data is a predictive tool that acts in a planning capacity for location selection and well planning as well as a framework for further analysis of incoming data. Utilized successfully, such data analyses and observations should mitigate drilling risk and facilitate the overall execution of the project.

Historically, the use of this model for the purpose of well targeting has been accurate with regard to location of fractures in the subsurface. In recent weeks, as drilling efforts continue, the application of the Patua 3D modeling efforts described here for well planning have further demonstrated a high degree of accuracy with regard to selection of casing points and formation tops, being within 40' of model prediction of the top of granitic basement rocks. Temperature prediction from modeling has also been reasonably accurate. A recent PT survey in the same well was within 10°F of the modeled data.

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