

A Comparison of Two Geothermal Play Fairway Modelling Methods as Applied to the Tularosa Basin, New Mexico and Texas

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ABSTRACT

Play fairway analysis (PFA) is a term derived from the petroleum industry, where datasets related to charge, reservoir, and seal are integrated into composite risk segment (CRS) layers, which are in turn integrated into a final deterministic PFA model which represents areas within a basin most likely to contain reservoirs, thus reducing exploration and development risk. The Tularosa Basin Geothermal PFA project replaces charge, reservoir, and seal with heat, fault related permeability, and ground water for geothermal exploration CRS development. Quantitative geothermal exploration models have also been developed in the past, but their use has been limited. One such model is created through the application of the weights of evidence (WoE) method, which considers the correlation of evidence layer values with those of training sites located at known geothermal systems and hot springs. This project tested the WoE method alongside the deterministic petroleum industry PFA method to compare the effectiveness of both techniques within the study area.

Supporting data for both PFA analyses consisted of heat flow, temperature gradients, and quartz geothermometers (heat CRS), Quaternary faults and zones of critical stress (fault related permeability CRS), and wells that penetrate ground water and springs (ground water CRS). For the petroleum industry logic PFA, these data were integrated into a final GIS vector based model which identified eight plays. WoE used raster input data and produced a probabilistic raster output, which identified ten plays. Of the 12 total identified plays, six were identified by both methods, two were unique to the deterministic method, and four were unique to the WoE method. Complimentary deterministic and probabilistic certainty maps were produced to help prioritize plays. The highest priority play was McGregor Range at Fort Bliss in Otero County, New Mexico, which was identified by both methods. This play contains the only known geothermal system in the basin. A medium-high priority play was gleaned from the WoE identified plays and a medium priority play from those produced by the deterministic method.

Both methods allowed the delineation of geothermal plays. However, most were low certainty, which was primarily due to data paucity. WoE identified the greatest number of plays; however, it is unknown if its apparent greater sensitivity is real. Play veracity will require additional work. Of the medium to high priority plays, economic analysis indicates that development could take place with reasonably low risk.

1. INTRODUCTION

The Tularosa Basin Play Fairway Analysis (PFA) project tested two distinct geothermal exploration methodologies covering the entire basin within South Central New Mexico and Far West Texas. The first method was a deterministic approach developed by the petroleum industry (Fraser, 2001) while the second was the stochastic weights of evidence (WoE) method that has been used for mineral exploration (and Bonham-Carter et al., 1988 and Bonham-Carter, 1996) and which has seen some use in geothermal exploration (Coolbaugh, 2003, Coolbaugh et al., 2005, and Coolbaugh and Raines, 2007). Moghaddam et al. (2013) found WoE to be a superior data driven method for geothermal exploration when applied in Akita and Iwate prefectures, Japan.

To support PFA, an exhaustive data collection was undertaken to secure data representing heat of the Earth, geologic structure, and ground water. All data collected was reformatted as necessary and added to a geographic information system (GIS) to support modelling. Data for PFA would ideally be evenly spaced and contiguous throughout a study area. However, being an underexplored region, containing vast military testing ranges, large portions of the Tularosa Basin lacked data. For this study, a significant and technically sufficient dataset was created covering significant parts of the study area to support PFA development.

2. STUDY AREA

Tularosa Basin is located in the southern Rio Grande Rift. This extension basin reaches from El Paso, Texas, near its southern boundary, northwardly for about 270 km. It is a sparsely populated region within the Chihuahuan Desert that is home to several military installations, including Fort Bliss, White Sands Missile Range, and Holloman Air Force Base, which cover approximately one half of the land area (Figure 1) which would benefit greatly from geothermal energy development to help meet their Net Zero Energy goals. In 2013, the presence of developable geothermal energy in this area was confirmed through a DOE funded drilling project at McGregor Range at Fort Bliss, Otero County, New Mexico. This, in part, provided impetus for a new DOE funded geothermal play fairway analysis project covering the entire basin.

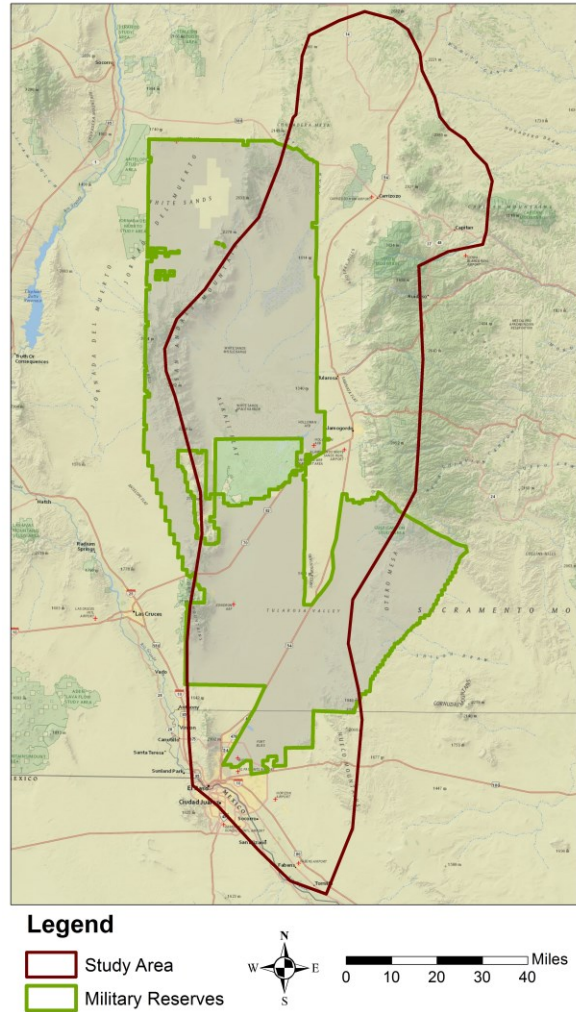


Figure 1. Study area including military reservation boundaries.

2.1 Study Area Geology

The Tularosa Basin is a graben, located in South-Central New Mexico, is associated with the Rio Grande rift. The tectonic history of this region begins in the Paleozoic, when the Pedernal uplift created a large sedimentary basin on the shelf of the North American Craton. Further tectonic deformation is associated with the Laramide orogeny of Late Cretaceous through Late Eocene time, which shortened the crust in the NE-SW direction, causing uplift and tilting of basement bedrock and a prominent NW trending structural grain. Laramide deformation was followed by Oligocene magmatism exhibited in widespread ash-flow tuff sheets, Sierra Blanca volcanism, and intrusions throughout the region (Lanks, 1995). This igneous activity is associated with the formation of the Rio Grande rift in the late Oligocene (~30 Ma). E-W extension of the Basin and Range has had a significant influence on the Rio Grande rift, which is extending at a rate of ~0.5 mm/yr. The rift runs N-S for about 1000 km from Colorado straight through the Tularosa basin area.

The Tularosa Basin has geologic structure characteristics similar to many other basins in the Basin and Range of the Southwestern U. S. such as crustal thinning, high angle normal faults along range fronts, and down-dropped blocks of crust relative to the N-S trending mountain ranges. Normal range-front faults often show Quaternary offset and are accompanied by wide zones of minor faults, exemplifying the broad zone of extensional deformation around the Rio Grande rift. Critically stressed areas along deep faults, such as those found bounding Tularosa Basin, penetrating relatively thin portions of the continental crust (~30 km) are ideal conduits for productive geothermal systems. With groundwater abundant in the basin due to Pleistocene Lake Otero and runoff from the high-wide Sacramento Range, Tularosa Basin is an excellent location for the development of geothermal power.

3. PLAY FAIRWAY ANALYSIS

To support the PFA, previously published data for the Tularosa Basin PFA was collected from internet accessible databases and literature. Additionally, a substantial collection of unpublished data from local water utilities and other organizations was tapped. This effort resulted in 99 temperature gradient points, 414 water chemistry analyses with good charge balances, Quaternary faults, Pleistocene Lake Otero shoreline, and 6,192 water wells which penetrated ground water which were all added to the GIS. These data were carefully georeferenced to a common coordinate system, projection, and datum to facilitate model integration. The GIS fed two different types of PFA model development, one deterministic and the other stochastic.

3.1 Petroleum Industry Logic PFA (Deterministic)

For petroleum industry PFA, composite risk segment (CRS) maps are created representing charge, reservoir, and seal. Polygons within the CRS are classified as low, medium, and high risk depending upon data input values and the judgement of the PFA modelers. The CRS are then overlain and newly generated polygons are reclassified based upon CRS input values (Table 1).

Table 1. Petroleum PFA classification rule examples.

Charge CRS Class	Reservoir CRS Class	Seal CRS Class	Final PFA Class
Low Risk	Low Risk	Low Risk	Low Risk
Low Risk	Low Risk	Medium Risk	Medium Risk
Low Risk	High Risk	Low Risk	High Risk
Medium Risk	Medium Risk	Medium Risk	Medium Risk
Medium Risk	Medium Risk	High Risk	High Risk
High Risk	High Risk	Low Risk	High Risk

For geothermal PFA purposes, charge, reservoir, and seal were replaced in this project with heat, fracture permeability, and ground water. Heat of the Earth was represented by heat flow, temperature gradients, and geothermometers (redundancy is due to spatial distribution variability); fracture permeability was represented by areas of critical stress mapped along Quaternary faults (Faulds et al., 2013, Faulds et al., 2010, Faulds et al., 2006); and ground water was represented by water wells that had penetrated ground water at depth.

Since this PFA method requires the overlay of polygons, point data representing temperature gradients and geothermometers were used to create raster statistical surfaces using the inverse distance weighted method in ArcGIS. The resultant raster data were then classified and converted into polygon feature classes. Classifications were based upon analyst’s opinions (Table 2). Heat flow polygons were taken directly from Blackwell, et al., 2011. These three polygon geometry datasets were then overlain using the Union method in ArcGIS to produce the heat CRS (Figure 2).

Table 2. Heat data classification values.

Temperature Gradients	Quartz* Geothermometer	Heat Flow (mW/m ²)
0 °C/km – 60 °C/km = High Risk	0 °C – 60 °C = High Risk	55 – 70 = High Risk
60 °C/km – 80 °C/km = Medium Risk	60 °C – 80 °C = Medium Risk	70 – 85 = Medium Risk
>80 °C/km = Low Risk	>80 °C = Low Risk	>85 = Low Risk

*The quartz geothermometer was chosen because it best estimated a known geothermal resource temperature at McGregor Range.

Areas of critical stress along Quaternary faults were given a 2.5 km buffer resulting in 5 km diameter circles, unless data indicated that a larger area may be present, and classified as low risk. Quaternary faults were buffered at 1 km and classified as medium risk (Figure 3). Water wells were given a buffer of 2 km resulting in circles with 4 km diameters (Figure 4). This dataset had a binary classification of either high or low risk. The three CRS were then overlain using the Union method in ArcGIS to create the final deterministic PFA (Figure 5). Plays were combined where they were neighboring one another. Eight plays were identified using this method.

Finally, a certainty map was created based upon the spatial distribution of data. Where data were adequately distributed, high certainty was assumed. Moderate certainty was assumed where data were present, but not optimally distributed. Where data were missing or very sparse, low certainty was assumed (Figure 6). Three of the eight plays have high certainty.

3.1 Weight of Evidence (Stochastic)

Spatial Data Modeler was used for WoE (Sawatzky et al., 2009). The WoE method requires the use of training sites to establish evidential theme weights. There is only a single training site (known geothermal resource) located in Tularosa Basin, and it was believed that this site’s best use for proof of concept. Therefore, all of the data used for the prior deterministic PFA was expanded into other parts of New Mexico as well as Nevada and Utah, with the exception of water wells, and statistical surfaces prepared. These were then classified based upon data ranges. Fifty training sites were chosen over this area based upon known geothermal resources and hot

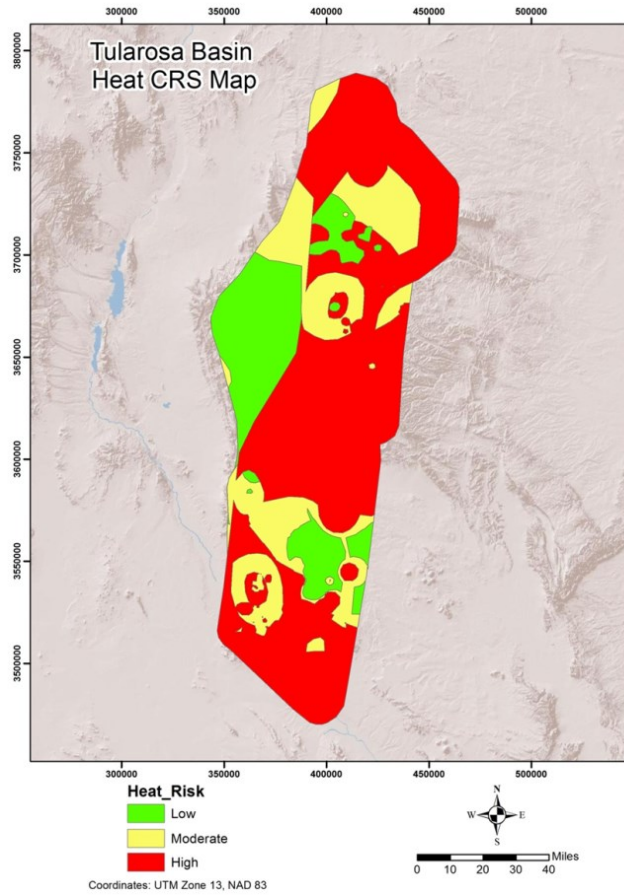


Figure 2. Heat CRS.

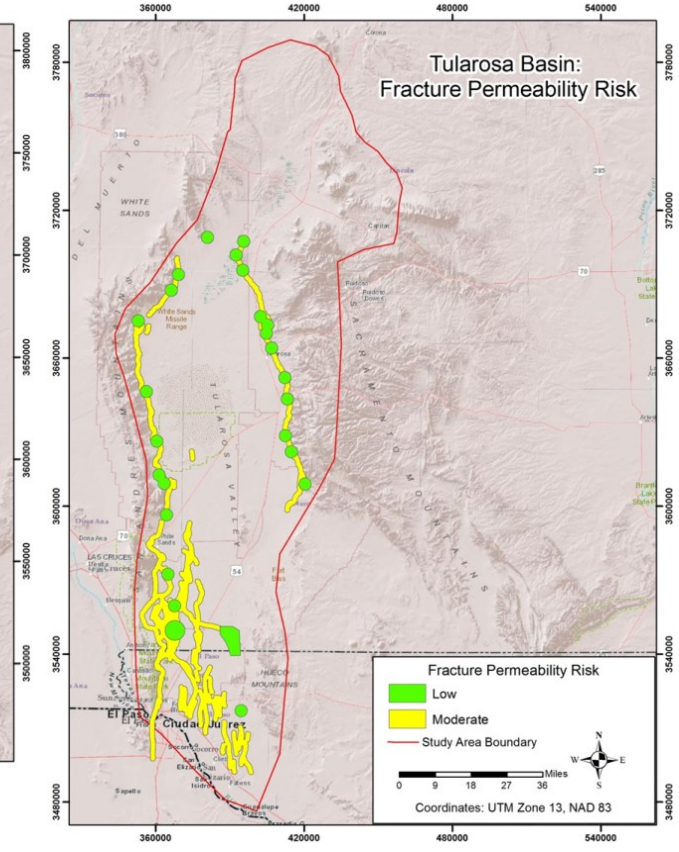


Figure 3. Zones of critical stress and buffered Quaternary faults.

springs (Figure 7). An effort was made during this exercise to choose locations with structural similarities to the zones of critical stress in Tularosa Basin. The Faults Structural Inventory of Great Basin Geothermal Systems and Definition of Favorable Structural Settings (<http://en.openei.org/datasets/dataset/structural-inventory-of-great-basin-geothermal-systems-and-definition-of-favorable-structural-setti2>), was used to assist in this and as an evidential layer for WoE.

In weights of evidence analysis, positive weights indicate a significant contribution by the data whereas a negative value indicates no contribution. Therefore, an examination of class weights can help give a better idea of the data relationships to geothermal systems. When considering heat flow data, positive weightings were produced for the following ranges:

- 164 – 189 mW/m², Weight = 1.8805,
- 241 - 166 mW/m², Weight = 2.6463,
- 319 – 343 mW/m², Weight = 2.7381.

The temperature gradient layer of evidence had positive weightings for the following ranges:

- 80 – 100 °C/km, Weight = 0.8071,
- 160 – 180 °C/km, Weight = 1.9264,
- 180 – 200 °C/km, Weight = 2.6685,
- >=200 °C/km, Weight = 2.3096.

Quartz geothermometers had a positive weighting (1.0452) for values >=100 °C. The critical stress layer of evidence was a binary raster and WoE produced a weight of -.32137 where it was classified as 0 (no critical stress) and 5.2212 where it was classified as 1 (critical stress present) – the strongest weighting of any of the evidential layers. Quaternary faults also had a binary classification with Class 0 having a weight of -0.7771 and Class 1 (fault present) having a weight of 1.9035. This PFA method produced a post probability model, which can be seen in Figure 8, which predicted 10 plays.

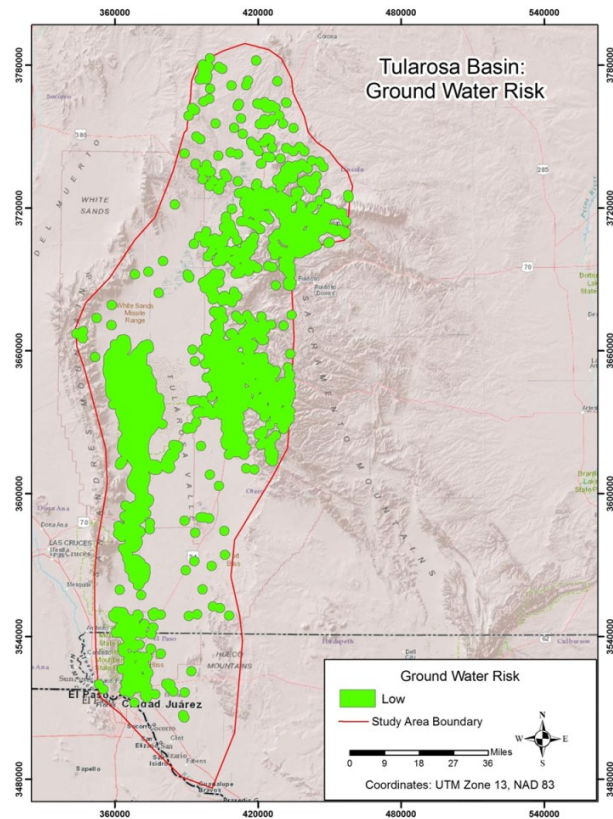


Figure 4. Ground water CRS. Green areas indicate a high potential for ground water.

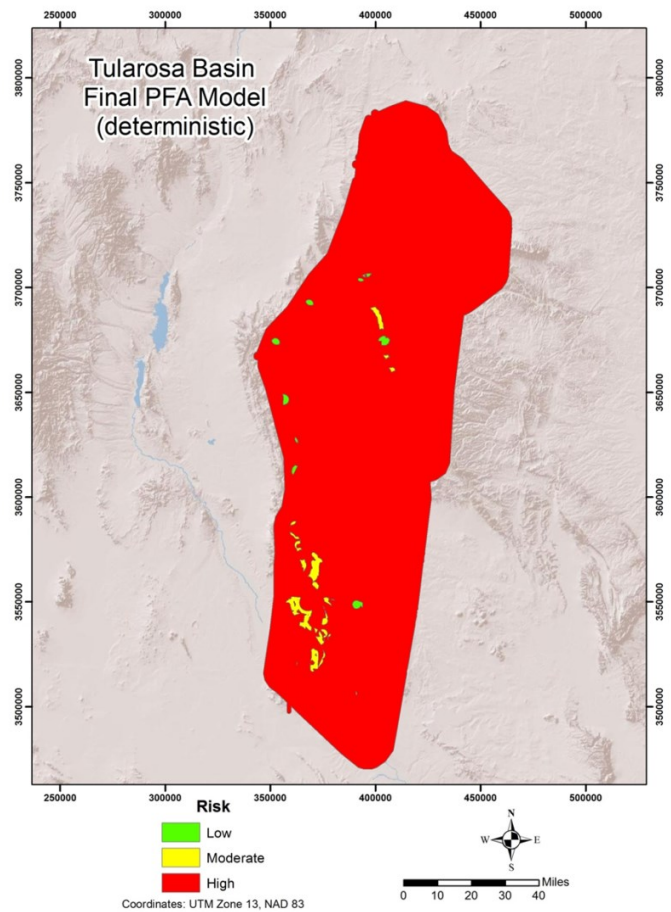


Figure 5. Deterministic PFA model. Green areas indicate plays.

Certainty was again addressed for this model. However, this time probability kriging was used on the heat input datasets using the following cutoffs:

- Geothermometers = 80 °C,
- Heat flow = 85 mW/m²,
- Temperature Gradients = 80 °C/km.

The resultant raster surfaces were converted to polygons and overlain using the ArcGIS Union method to produce the certainty layer. Quaternary faults were not used because they either exist or they do not. Areas of critical stress were not used because of potential interpretation bias of the analyst and because of their binary nature. The certainty results in this case were more conservative than in the deterministic results discussed previously, with only a single high certainty play – McGregor Range at Fort Bliss – which is the known resource in the area (Figure 9). Four plays were identified as having moderate certainty.

4.0 ECONOMICS

Preliminary economics were done on high priority plays 1, 2 and 9 (Figure 10). Play areas were estimated using structural characteristics for this exercise.

4.1 Gross Revenue

A target plant capacity of 10 MW per 10 sq. km. was used as the basis for gross revenue calculations. Plant and well field parasitic load was assumed at 25%, based on industrial experience (Verkis Consulting Engineers). Flash plants normally show records of 4% to 7% parasitic loads while binary plants’ parasitic loads may range from 15% to 40%, or higher depending on the high use of pumps to flow the wells.

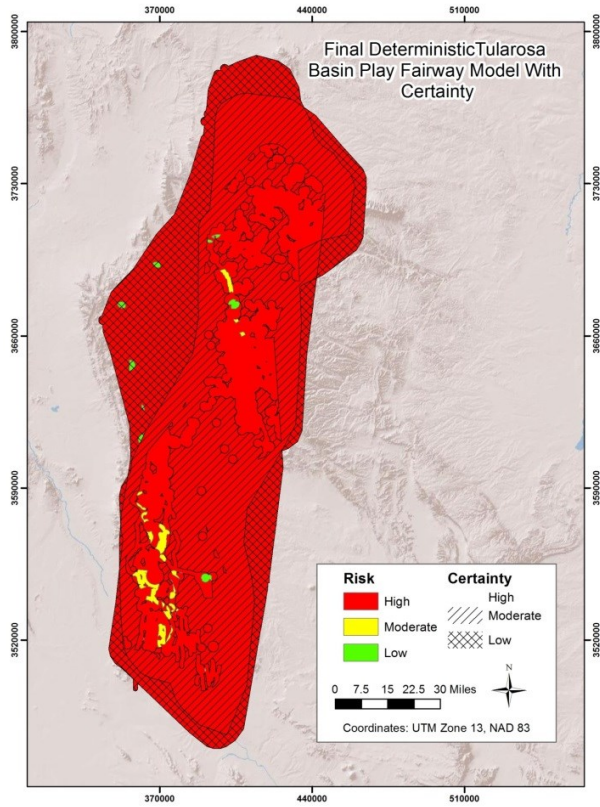


Figure 6. Deterministic PFA certainty.

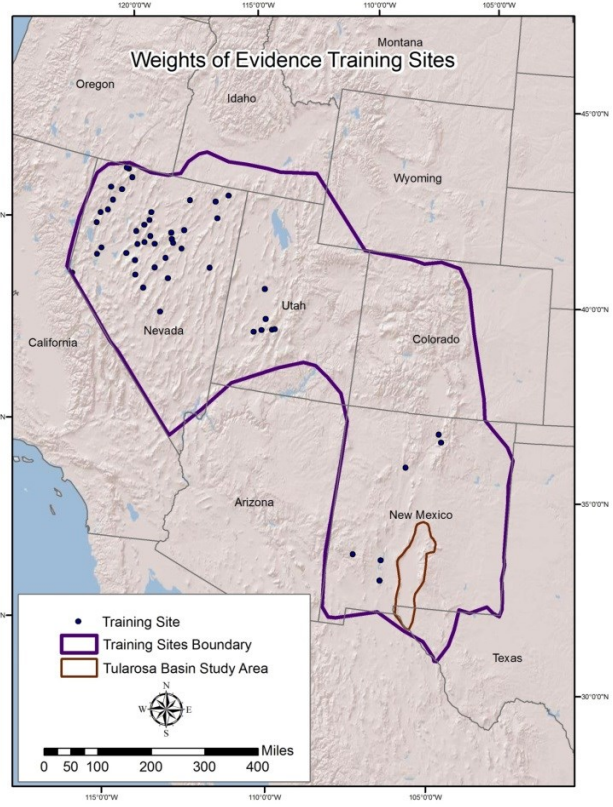


Figure 7. Weights of evidence training sites.

Net present value of future annual revenue estimate is calculated as the product of the Estimated Net Generation and the electricity price over a lifetime of 30-years. A discount rate of 2%, the average US inflation rate from 2010 to 2014, was used in the calculation.

4.2 Cost of Exploration

Well exploration cost was estimated using the formula defined in The 2011 Geothermal Well Cost Update (Mansure and Blankenship), which calculated to around US \$3 million per well. The total cost of exploration for all three plays ranged from \$1,360 to \$1,516 per kW installed capacity.

4.3 Development and Plant Cost

An additional five (5) production wells and two (2) injection wells for a 10-MW plant capacity per 10 km² was used in constructing a deterministic cost profile for each play. These are representative values from existing Basin & Range plants but we would expect more sophisticated probabilistic modeling to be used when the surface exploration and temperature gradient data are in hand.

Operating cost assumptions and plant cost estimates were provided by industry experts and validated by information taken from an Icelandic review of low temperature geothermal power plants (Verkis Consulting Engineers).

4.4 Economic Results

The Levelized Cost of Power (LCP) (\$/kWh) was calculated as the initial capital investment, including exploration costs plus the cumulative present value of future costs discounted by the assumed inflation rate, divided by the cumulative power generation over the project life. LCP for all three plays was about \$0.08/kWh.

The analysis described herein dispenses with some sophistication in modeling parameters for which reasonable values can be assigned. This is appropriate for an initial screening exercise in which the object is to learn whether there is sufficient economic attractiveness to pursue further work in a basin. The results clearly demonstrate that the unusual market conditions (i.e., \$/kWh price) in the Tularosa Basin make all three plays viable candidates for exploration and development. The results are similar for all three plays identified by the PFA process. Table 3 shows each has an expected net present value greater than \$120 million.

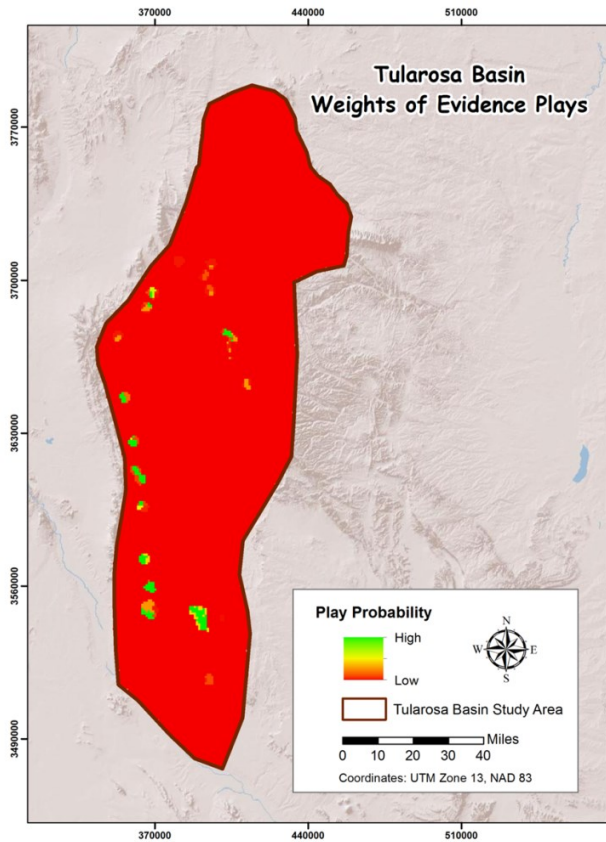


Figure 8. Weights of evidence PFA. Green areas represent plays.

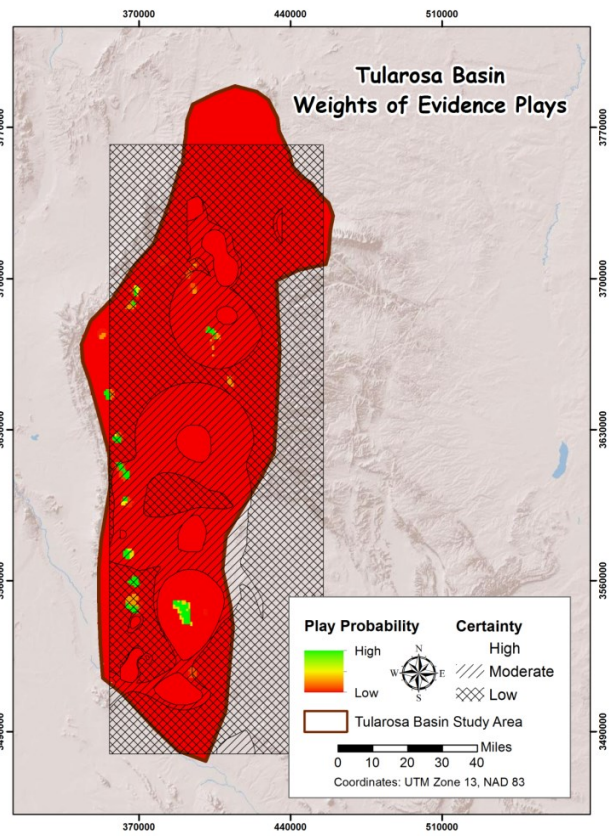


Figure 9. WoE PFA with certainty overlay.

5.0 CONCLUSIONS

Both the deterministic petroleum industry logic PFA, converted for geothermal use, and the WoE PFA methods identified potential plays and they both identified the McGregor Range known geothermal system. Six plays were identified by both methods with two additional plays being identified exclusively by the deterministic method and four additional plays being identified exclusively by the WoE PFA (Figure 11). Redundant results may give more confidence; however, only additional work will shed light on the veracity of the results of either method. A work plan has been completed for Phase 2 in which (1) geologic reconnaissance will be done on each play, (2) detailed geologic mapping and outcrop fracture analysis will be done for high priority plays, (3) water well sampling and temperature logging will be done on each play, (4) a shallow temperature survey will be done in an area suspected of having surface temperature anomalies, (5) gravity survey infill will be done for high priority plays, and (6) a magnetotelluric survey will be done on the highest priority play. It is expected that this additional work will help determine the viability of the plays and lead to the re-prioritization of plays for additional temperature gradient work, which is sparse or missing over most of the plays.

Economic analysis indicates that the three high priority plays can sustain profitable development. However, this was based upon a number of assumptions that will be further substantiated by additional work to be completed in Phase 2 of the Tularosa Basin Geothermal PFA effort. The encouraging results of Phase 1 point toward the future development of one or more geothermal plants in the Tularosa Basin, at reasonable risk, which will help with military Net Zero energy goals.

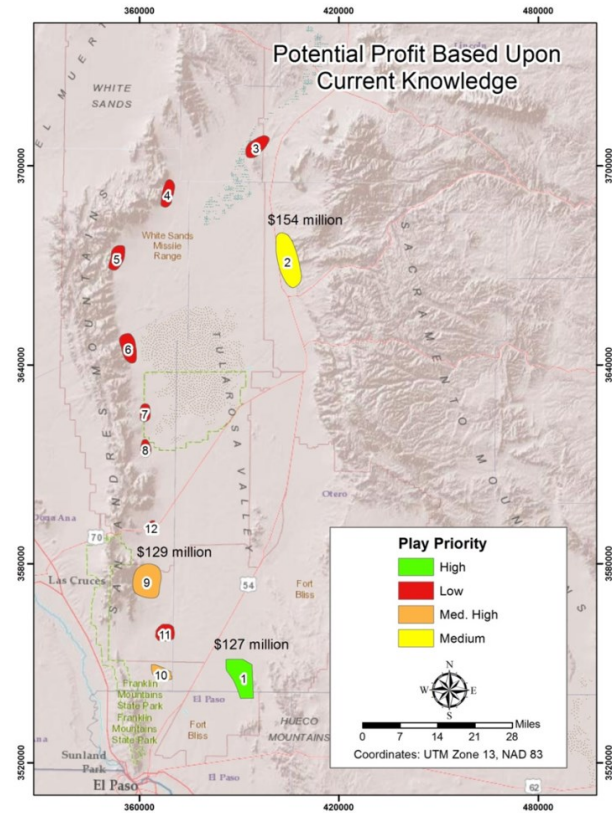


Figure 10. High priority plays 1, 2, and 9 for which economic analysis was performed.

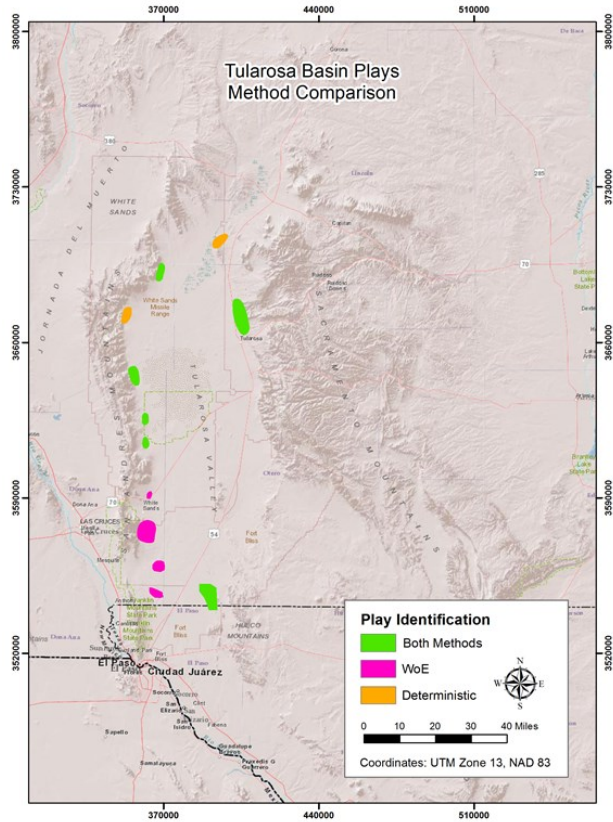
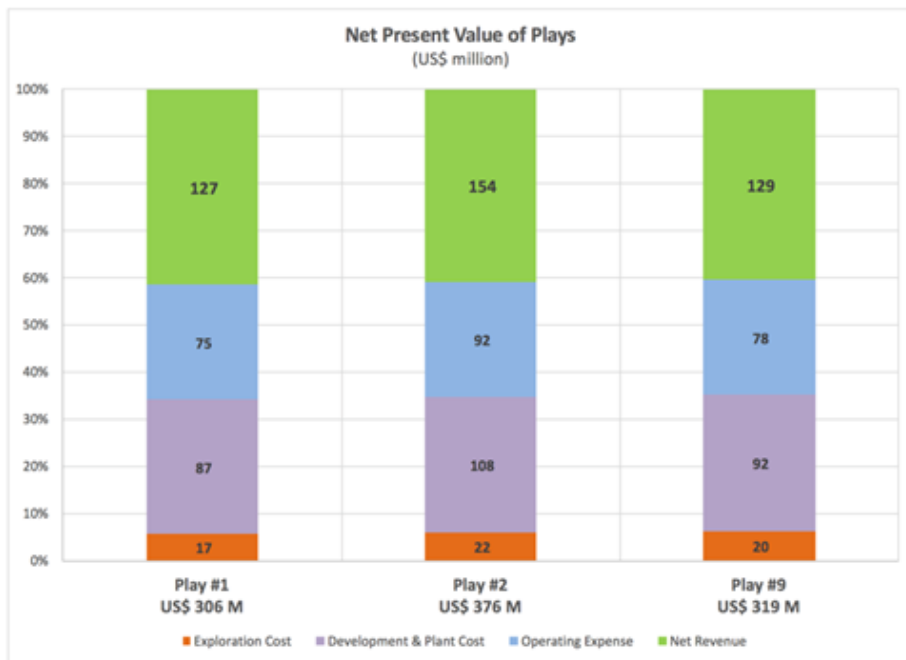


Figure 11. Plays as identified by deterministic and weights of evidence PFA methods.

Table 3. Net value of high priority plays.



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