Adaptation of a Petroleum Exploration Tool to Geothermal Exploration: Preliminary Play Fairway Model of Tularosa Basin, New Mexico, and Texas

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ABSTRACT

Investment in geothermal development has not been optimal due to inherent risk, but now risk can be lowered through the proper application of play fairway analysis (PFA) targeting the best geothermal reserves within a region. Both knowledge-based and data-driven models have been tested in this regard, however, neither method has gained significant industry attention. In this study we apply a deterministic method that has been widely used by the petroleum industry to reduce exploration risk through regional analysis for play identification. We have adapted this logic for geothermal application and completed a preliminary PFA for the Tularosa Basin in New Mexico and Texas. Data is critical for PFA, and although there is never enough, especially in underexplored regions such as this, we believe that it is possible to collect adequate data in most areas with geothermal potential for successful PFA application.

Introduction

Play fairway analysis has previously crossed-over into the geothermal arena, although under different appellations, such as geothermal exploration modelling. However, it has not yet been widely accepted or used. There are two basic model types that have both been applied successfully including: (1) expert knowledge-based, where geothermal data are considered through their genetic relationship to known systems and (2) data-driven, often stochastic, statistical models where data from training sites provide evidence to support probability or potential calculations.

Nash and Wright (1996) reported results of an early U. S. Department of Energy, Sandia National Laboratory supported effort, covering part of Nevada, where limited data was used to create a knowledge-based model focused upon genetic relationships of the input data to known geothermal occurrences in the Great Basin. Coolbaugh (2003, 2005, 2007) used a greatly expanded GIS database covering the entire Great Basin, including numerous statistical training sites for weights of evidence and density function calculations coupled with weighted fuzzy modelling resulting in the first spatially comprehensive model for this region. Sabin et al. (2004) discussed the merits of geothermal occurrence models based on co-occurrence of geothermal associated phenomena and using these to identify other localities with similar co-occurrences and the importance of doing so. Hossein et al. (2007, 2010) applied a knowledge-based method, using Boolean logic on vector evidence layers, to create a geothermal model for Iran, where layers of evidence were combined using Intersect and Union techniques in ArcGIS. Younes et al. (2007a, 2007b) discussed the use of feature distances from producing geothermal wells as evidence and integrated these into a knowledge-based weighted-sum model, which yielded 97% accuracy based upon the prediction of known occurrences in Akita and Iwate prefectures, Japan. Fry analysis, spatial association analysis, and evidential belief functions were applied to geothermal modeling in West Java, Indonesia by Carranza et al. (2008). In this study 127 training sites were used. A more recent study, carried out by Moghaddam et al. (2013) for sites in Akita and Iwate, tested several data-driven modelling methods including

Fry analysis, weights of evidence, distance distribution and evidential belief function and found that weights of evidence produced superior results.

All models rely on the spatial correlation of data known to be directly associated with geothermal systems. The chief strengths of data-driven models is that they are not biased by the modeler and that probabilities are often statistically derived. However, the results are sometimes not fully understood nor trusted by explorationists, decision makers and investors. Additionally, statistical models require significant amounts of training data from known geothermal systems or hot springs, which can be limited in frontier exploration areas. The chief strength of knowledge-based modelling is that training sites/data are not required because the technique relies on the expert knowledge of experienced explorationists. In frontier areas lacking training sites, this type of model would be the practical choice. Additionally, this type of model is more easily understood by decision makers and investors and the contribution of each factor is easily extracted. Finally, no studies have been reported contrasting the results of knowledge-based and data-driven models, so there is no evidence supporting which method is best suited for geothermal exploration.

Knowledge-based logic used by the petroleum industry to reduce risk, known as play fairway analysis (PFA), uses three composite risk segments (CRS) representing the integration data representing (1) reservoir risk and effectiveness, (2) seal presence and effectiveness, and (3) petroleum charge to identify plays within a regional framework (Fraser, 2010) to develop a play map. In PFA, the three CRS are integrated, which can effectively be done using vector GIS tools, and classified as following:

1. Low Risk: all three input CRS have spatially correlative low risk values;
2. Moderate Risk: all three input CRS have spatially correlative moderate risk values or a mix of low and moderate risk values; and,
3. High Risk: any input CRS is classified has high risk for a given area.

Our preliminary geothermal PFA model for the Tularosa Basin is based upon the petroleum industry model. We have adapted it for geothermal use by substituting (1) heat of the Earth, (2) fracture permeability, and (3) fluid for heat transfer in place of petroleum industry CRS.

Study Area and Background

Study Area Selection

The Tularosa Basin is a graben located in the southern Rio Grande Rift (Fig. 1). The study area covers approximately 6500 km^2, much of which is underexplored. Several factors went into the selection of the Tularosa Basin for the PFA. The project team of Ruby Mountain Inc. and the Energy & Geoscience Institute chose the basin because it is a challenging, yet ideal test bed to evaluate effectiveness of the team's data collection techniques as well as the effectiveness of our innovative PFA where the identified geothermal resources have significant potential to be further developed.

Tularosa Basin is home to several military installations including White Sands Missile Range and Fort Bliss, which are the first and second largest U.S. Army bases in the United States, together covering more than 10,000 km^2 of southeastern New Mexico. The much smaller Holloman Air Force Base also lies within the study area.

It is anticipated that the PFA models developed by this project will significantly improve the effectiveness of play ID and entry and prioritize exploration on a basin-wide scale, thereby reducing both risk and cost of geothermal exploration. As with most Department of Defense (DoD) facilities, Fort Bliss, White Sands and Holloman AFB are under directives to utilize renewables, but DoD has very limited resources for geothermal exploration and resource confirmation. It does

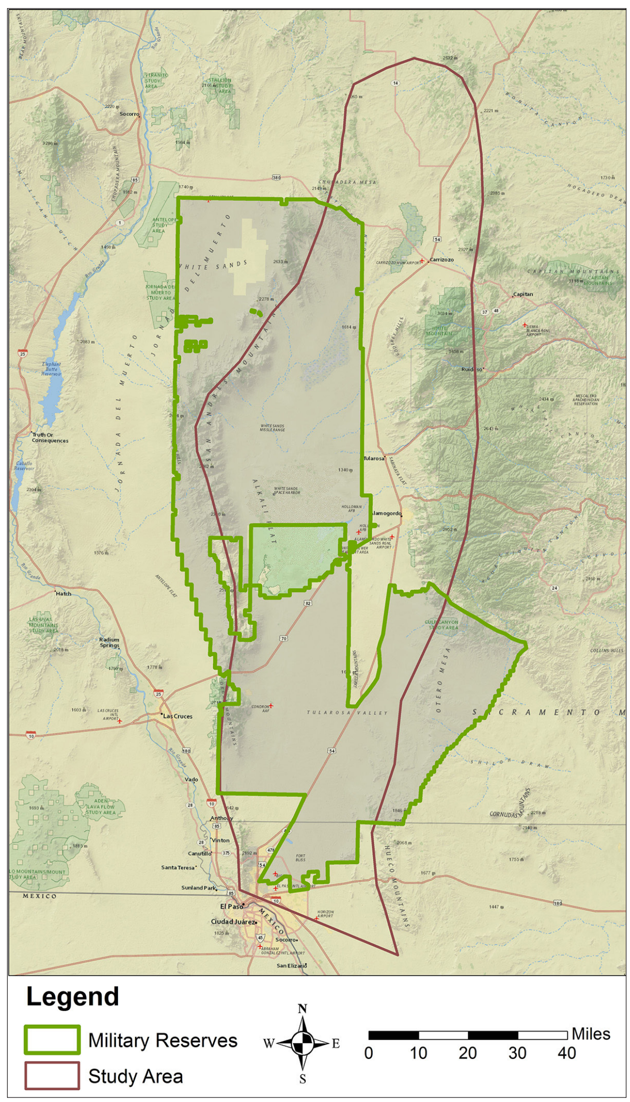

Figure 1. Study area: note the vast expanses of military land within this area.

however, have a desire and a real need for power from reliable, 24/7 renewable energy sources. If geothermal plays can be cost effectively identified and prioritized for DoD, industry can then develop geothermal power for military purchase utilizing existing 10- or 20-year financing mechanisms.

Study Area Characteristics

This area has a complex tectonic history beginning with Paleozoic siliciclastic sedimentation on a once low-lying shelf of the North American Craton. This was followed by periods of crustal shortening, including Late Paleozoic deformation related to Ancestral Rocky Mountains uplift and the Late Cretaceous Laramide Orogeny. The current landscape has been shaped by extensional tectonics, with the resultant development of the Rio Grande Rift. Extension began in the Late Paleogene and is accompanied by high heat flow. However, seismic activity is infrequent, relative to that in the Great Basin to the northwest, indicating that extension may be slowing in this area. Historical earthquakes in the area are, in general, clustered in the northern part of the basin, suggesting that the basin opened on the southern end and active rifting is now focused in the northern reaches.

Four slim holes drilled in a 1997 SANDIA sponsored program near Davis Dome, in the southeastern part of the basin (Fig. 2), recorded high temperatures between 170ºF and ~190ºF (Finger and Jacobson, 1997) suggesting the presence of a promising geothermal system. More recently a study of McGregor Range, Fort Bliss, sponsored by the U.S. Department of Energy Geothermal Technologies Office and implemented by Ruby Mountain Inc., resulted in the drilling of a new test well, RMI 56-5, again near Davis Dome, that reached a depth of 3,030 feet and encountered a high temperature near 200ºF. Initial tests suggest a production rate of 300 gpm (Barker et al, 2015) and water chemistry suggests a reservoir temperature of 235ºF (Barker et al., 2014). Therefore, a deeper well may yield higher temperatures.

The presence of a known geothermal system, Quaternary faults, and relatively high heat flow, suggest that additional geothermal systems may be present in the study area. This, along with military needs for green energy, gave rise to the need of basin-wide PFA to determine if additional promising plays exist.

Data, Data, and More Data

Data, ideally evenly dispersed across the region of interest, is the most critical element of PFA. Although this ideal is rarely going to be met, most areas of geothermal interest in the United States will have adequate data to facilitate initial PFA, but this will likely require an intensive acquisition effort. For this project, an exhaustive literature review provided significant analog data which were digitized and added to the project GIS database. Digital databases, such as the Southern Methodist University (SMU) Geothermal Lab node on the National Geothermal Data System (NGDS), various U. S. Geological Survey web sites, the New Mexico Bureau of Geology & Mineral Resources web site, and the New Mexico Geothermal Resources web site, provided data with coordinates that were easily added to the GIS or shapefiles for direct GIS use. Additionally, primary, secondary and tertiary data resources were identified and subsequent contact lists developed early in the study to assist in the collection of previously unpublished data.

Some of the key sources of unpublished data included: El Paso Water Utilities, Fort Bliss, Fort Bliss Water Utilities, The City of Alamogordo Water Utilities, White Sands Missile Range, and Holloman Air Force Base. Data from the military was obtained through data sharing agreements. Personalized outreach to key military and non-military stakeholders in the region resulted in greater data collection than initially expected and revealed a substantial interest in geothermal resource development.

Data representing the heat of the Earth included (1) water chemistry for geothermometer calculations, (2) temperature gradients, and (3) heat flow (Fig. 3). The initial data collection resulted in ~1600 water chemistry data points; however, poor charge balance resulted in the loss of nearly three-quarters of the data and left 410 remaining data points. Eighty-nine temperature gradient points were used and heat flow came directly from the 2011 SMU Geothermal Laboratory Heat Flow Map of the Coterminous United

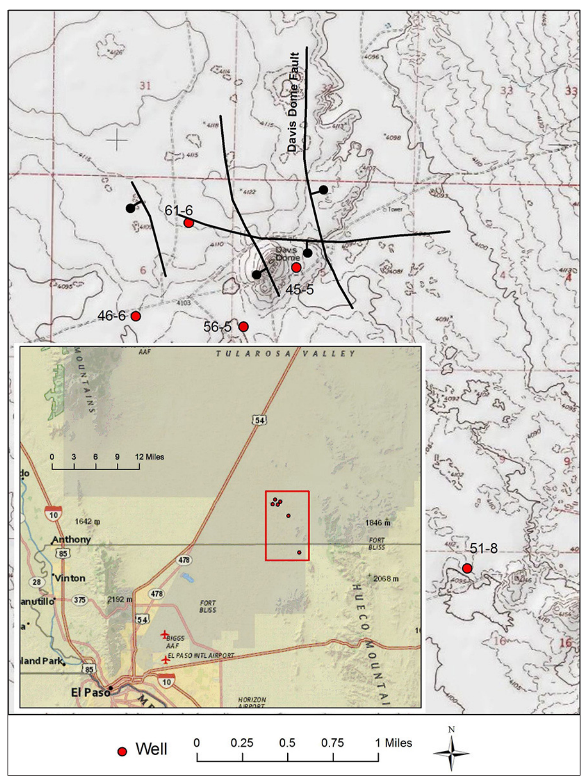

Figure 2. SANDIA slimholes 51-8, 46-6, 61-6, and 45-5 and RMI 56-5.

States (Blackwell et al., 2011). The point data were not ideally spaced, but this is generally to be expected, especially in underexplored basins.

To facilitate the location of zones with fault related fracturing, the U.S.G.S. Earthquake Hazards Program Quaternary Fault dataset was added to the GIS and used as a general reference to spatially constrain further structural analyses. This was followed by an analysis of these and nearby faults to determine if geometries, known to be associated with geothermal systems in the Great Basin (e.g. Faulds et al., 2013), are present. Bouguer gravity and total magnetic intensity data (Pan American Center for Earth and Environmental Studies, University of Texas at El Paso) were used to augment this analysis. From this, twenty-three areas were chosen containing fault step-overs, splays, terminations, intersections, and an accommodation zone. Further scrutiny of these zones will be completed before the final PFA is applied.

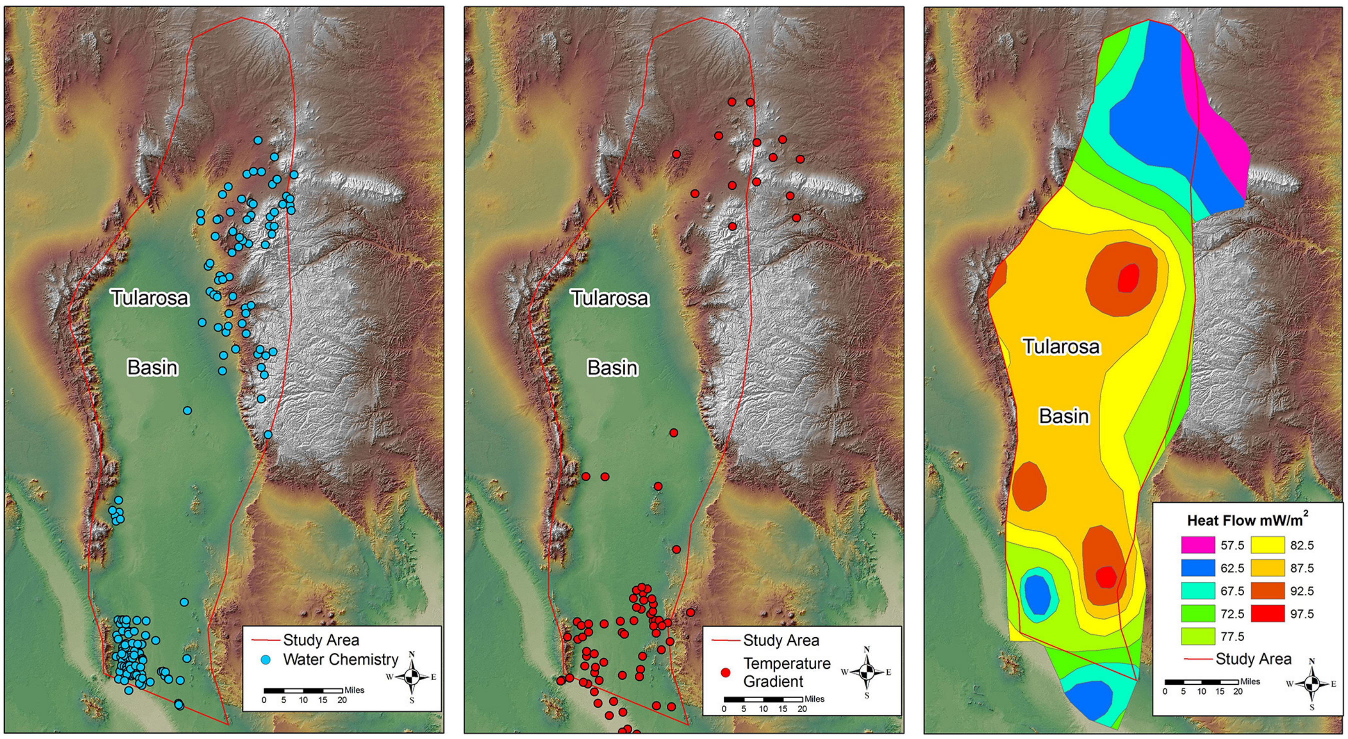

Figure 3. Tularosa Basin water chemistry (left) and temperature gradient (center) data location points and heat flow contours (right).

For initial application of PFA, the presence of fluid for heat transfer was determined from (1) wells that penetrated ground water and (2) the Pleistocene Lake Otero shoreline. Flyn and Buchanan (1993) determined that Pleistocene lakes were a source of major aquifer recharge in the Great Basin and the majority of geothermal resources in the area produce from deep paleolake charged aquifers. Considering this, it stands to reason that Lake Otero provided a good deal of aquafer recharge in the west-central part of the study area. Precipitation on the Sacramento Mountains, bounding the east side of the basin, is a historical and current source of recharge.

CRS Data Processing

Heat of the Earth CRS

Interpolation of point source data to statistical surfaces was accomplished using the inverse distance weighted (IDW) method in ArcGIS. However, as seen in Figure 3, there is often a clustering of data points, so these clusters were constrained spatially to disallow extrapolation to unrealistic values. The constraint was applied to geothermometers and temperature gradient data. Heat flow data were vectorized from the original raster map.

The interpolated data were then classified into (1) Low Risk, (2) Moderate Risk, and (3) High Risk and vectorized. The Low Risk classification was based on values associated with known geothermal systems in the Great Basin. The Moderate Risk classification was based upon the range between the lower end of the Low Risk class and values that should represent entry into deep direct use applications. The High Risk classification included all other values. The three final vector datasets were then fused using the Union Overlay technique in ArcGIS to create the heat of the Earth CRS. This retained the data from all three input datasets in an associated table. It must be noted that to facilitate use of a table produced by the Overlay procedure, fields should be carefully named to reflect their origin.

Fracture Permeability CRS

Areas believed to have a high probability of containing fault-related fractures were buffered with a radius value of 1.5 km. These are areas believed to be Low Risk. Additionally, a 1 km buffer was applied to Quaternary faults and these areas classified as Moderate Risk. All other areas are High Risk. A Union Overlay was then applied to the data to create the fracture permeability CRS.

Heat Transfer Fluid CRS

Deep fluid is believed to be widespread in the Tularosa Basin, which is on the windward side of the high and wide (~42 miles) Sacramento Mountains which bound the basin for 85 miles. This mountain range rises to a height of 9,695 ft and receives significant precipitation and snowpack in the winter. The Cloudcroft area, a small town nestled high in the range, has annual precipitation of ~30 inches (Western Regional Climate Center - http://www.wrcc.dri.edu/). These mountains are the principal recharge driver in the northeastern part of the basin.

Tularosa Basin is bounded on west by the San Andreas Mountains, which at their highest point reach an elevation of 8,965 ft, have length of ~75 miles breadth of ~12 miles. It is likely that the San Andreas Mountains supply relatively little recharge. However, Pleistocene Lake Otero, which flanked this range, probably had a significant hydrologic impact on west-central part of the basin.

To develop this CRS, wells known to have encountered groundwater were buffered with a 2 km radius and the Pleistocene Lake Otero shoreline was buffered outwardly for 2 km. These areas were classified as Low-Risk and all other areas were classified as High-Risk. Prior to final PFA, hydrologic modelling will be completed to give added confidence. Final CRS layers can be seen in Figure 4.

Preliminary Model Discussion

The preliminary PFA model was completed by using the Union Overlay method in ArcGIS. This creates an output which initially may appear more like spaghetti than a model (Fig. 5). This can be eliminated by adding a new field in the table to record final classification values. The ArcGIS Dissolve process can then be used to fuse all polygons with correlative classes. The output can then be symbolized (Fig. 5). Five plays were identified by this model – two in the Davis Dome area of Fort Bliss' McGregor Range and three in the White Sands Missile Range area. The model chose small "bulls eye" areas

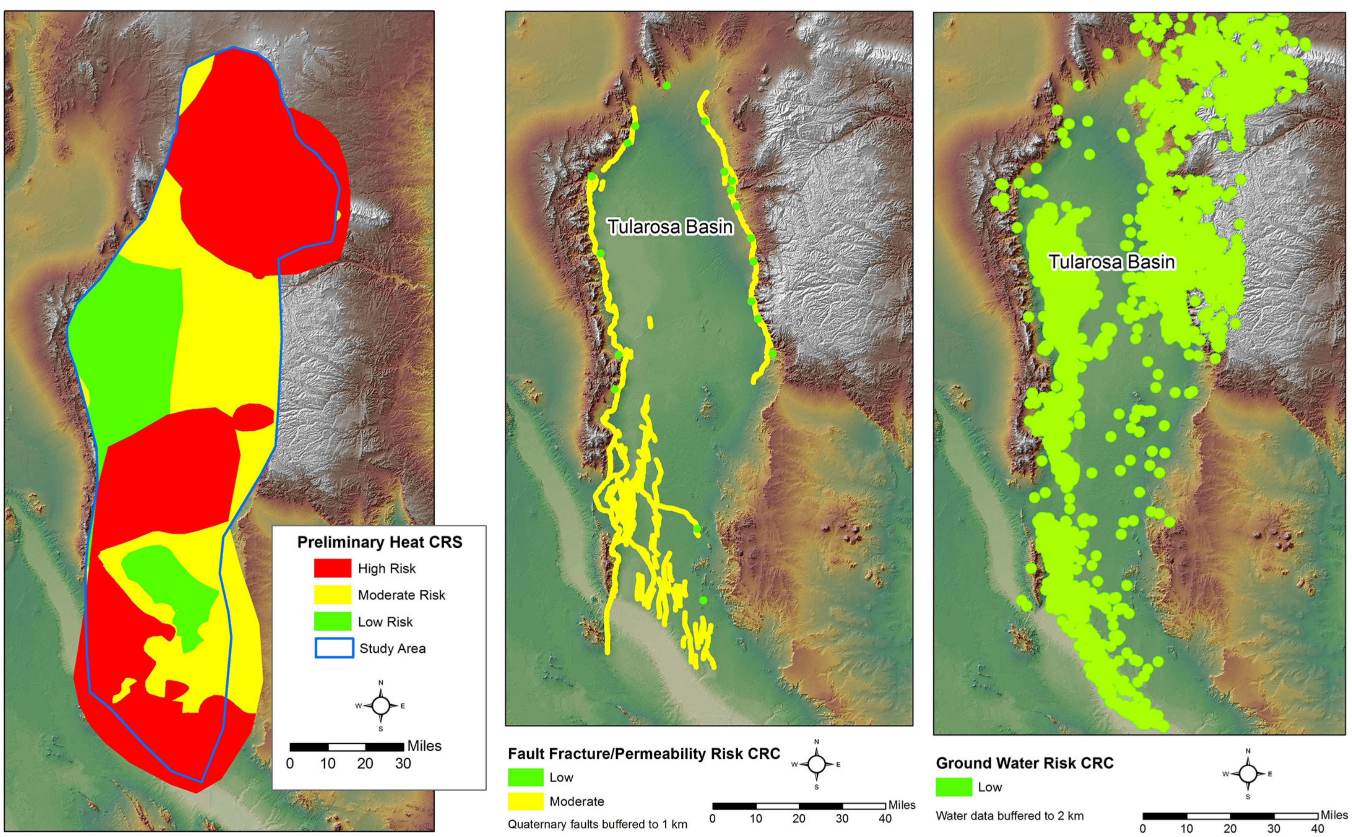

Figure 4. CRS layers representing the heat of the Earth (left), fracture permeability (center), and fluid for heat transfer (right).

as it was constrained in this regard by the fracture permeability CRS. The known geothermal resource near Davis Dome was correctly identified as low risk.

A certainty layer was also created based upon the spatial correlation of data, but only applies to the heat of the earth CRS. Where all three input datasets were spatially correlative and had the same classification, high certainty was assumed. In the case where only two data sets were present for a given area, moderate certainty was assumed. Where there was coverage by only one dataset, high uncertainty was assumed.

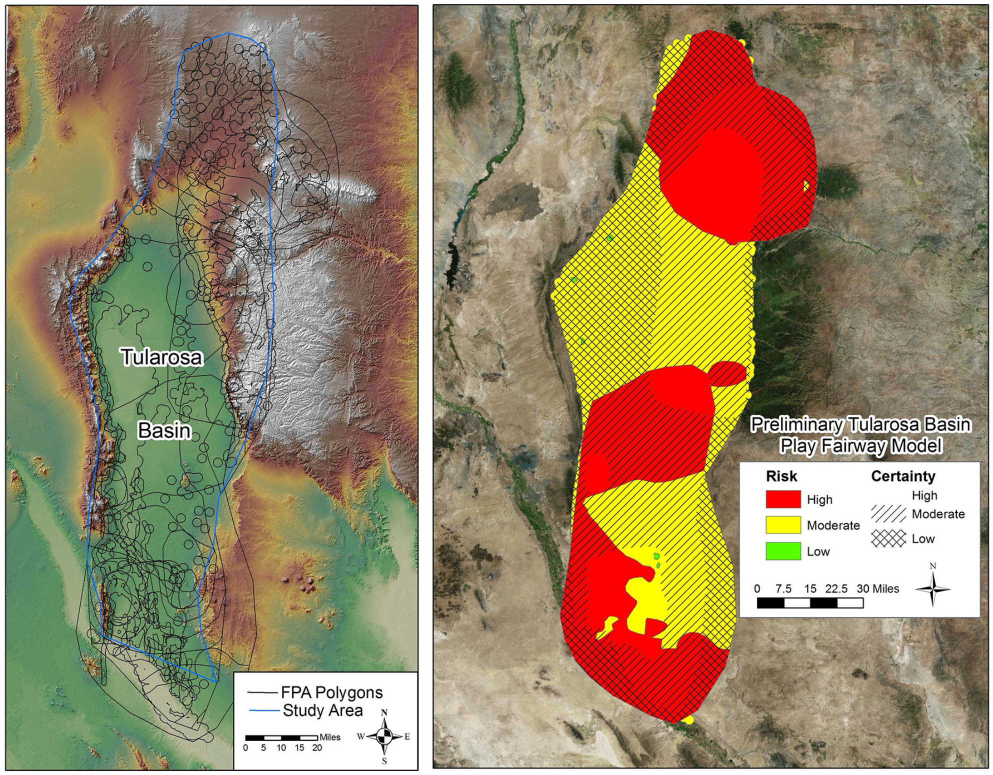

Figure 5. CRS layers fusion results from the ArcGIS Union Overlay (left) and the final preliminary PFA model after the application of ArcGIS Dissolve.

Conclusions

A basin-wide preliminary PFA was completed for Tularosa Basin. Petroleum industry PFA logic was adapted for geothermal use and applied. An intensive data search produced a less than ideal spatial data spread. However, the model picked a known geothermal resource and four additional plays. More data is expected and will be added to the GIS prior to final PFA development in summer of 2015. We believe that the petroleum industry logic is a solid approach which produces an end product that is easily explained and understood. The method is elegant in its simplicity and will no doubt be a useful tool for future application in underexplored areas.

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