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Applied Tectonic Geomorphology to Geothermal Exploration in the Tularosa Basin, New Mexico

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ABSTRACT

The Tularosa Basin in south-central New Mexico, the focus of an on-going geothermal play fairway analysis project, has been undergoing extensional deformation for the past ~30 million years, creating a geologic environment that may contain blind geothermal systems. The structural geology of this region is similar to the rest of the Basin and Range, so in determining structural favorability for hosting hidden geothermal systems it is useful to compare this area with known geothermal resource areas. Specifically, this paper details tectonic geomorphology of alluvial fans within the study area and then compared it to that of Dixie Valley, Nevada; arguably the most prolific geothermal system in the Basin and Range. The Rio Grande Rift runs north to south through the study area and is presently extending at a rate of ~0.5mm/yr, thus creating accommodation space for alluvium to fan out into down-dropping basins. To facilitate this study, 10 m DEM data was integrated into a Geographic Information Systems (GIS) program and used to analyze alluvial fan geo-morphometry and quaternary faulting within the proximity of plays identified in Phase I of the geothermal play fairway modelling research project funded by the U.S. DOE Geothermal Technologies Office under contract #DE-EE0006730 (Figure 1). The morphology of alluvial fans is directly associated with base level drops triggered by basin-bounding normal fault offset. By classifying fault segments as having relatively younger and more frequent seismic activity, conclusions about subsurface permeability can be made, which provides critical information about the potential for a productive geothermal system and improve the play fairway model.

1. INTRODUCTION

Alluvial fans are semi-conical depositional landforms along mountain piedmonts (Sanchez & Nunez, 2015). Their size and shape have variability, depending on local geology, regional tectonic activity and climate. In actively extending tectonic regimes, such as the Agri intermountain basin in southern Italy or the Great Basin of western America, periods of increased tectonic movement, on scales >10,000 years, cause steeply dipping normal faults along mountain ranges to increase in seismicity. This means more accommodation space for alluvial fans, and more frequent and intense earthquakes inducing fractures and creating permeability in the subsurface (Giano, 2011; Harvey, 2005; Topal, 2016). By analyzing the geometry of alluvial fans as they are presently, we can reconstruct the seismic & tectonic history to infer subsurface permeability, a critical element to productive geothermal systems.

When a surface locality experiences a shift in climate, from arid to temperate for example, erosion increases proportionally; thus increasing the deposition of alluvium into sedimentary basins and forming larger alluvial fans. This has a significant spatial and temporal effect on the evolution of alluvial fans. However, if the local climate has been relatively consistent in a certain region, then tectonic activity may be the primary control on deposition/erosion of alluvial fans. While changes in climate, on time scales of 100 to 10,000 years, can significantly affect alluvial fan deposition and erosion, regional tectonics can be the primary control in unique geological regions such as intercontinental rift zones (Harvey, 2005). All modern, active alluvial fans are the consequence of climatic and tectonic factors that change over time. Alluvial fan geomorphology can lend significantly to the understanding of long term fault behavior and seismic activity (Topal, 2016; Anderson, 2000).

In this contribution, we analyzed alluvial fans proximal to plays identified in Phase 1 of this study (Figure 2), along an intercontinental rift zone, The Rio Grande Rift, in Southern New Mexico, USA. In Phase 1, a play fairway analysis was conducted using three risk segments composed of entirely pre-existing datasets; namely: heat, groundwater, and permeability (Nash, 2016). That analysis produced multiple high to low priority plays around the rim of the Tularosa Basin, shown in Figure 2. This study was done to refine the permeability risk segment and to help categorize the geologic structural setting within 1 mile of those pre-determined plays. Qualitative and quantitative geomorphic indices were calculated for 50 alluvial fans, drainage basins, and faceted spurs to help better understand slip rates along quaternary faults and, therefore, subsurface fracture networks providing pathways for geothermal fluids. Furthermore, our results were compared with similar geomorphic indices of alluvial fans in close proximity to productive geothermal systems in Dixie Valley, Nevada. This helps validate the interpretations made about the relative significance of alluvial fan geometry correlating with fracture permeability in the deep subsurface. This work also aids in geothermal conceptual model development by adding constraints to upflow/outflow areas in a deep geothermal system. The ultimate goal is to evaluate the potential risk and uncertainty of a site for productive geothermal power generation.

Additionally, the data collected will be compared against favorable areas elsewhere in the world, thereby enabling a broader perspective on the observed phenomena within the study area.

It is known that a correlation exists between alluvial fan depositional geometry and slip rate of range-front normal faults. Previous studies, e.g. Topal, 2016, support this theory, and furthermore show that variations in faceted spur geomorphology are common along typical Basin and Range style geologic settings. The Tularosa Basin study area indeed expresses the typical extensional tectonics expected within an actively rifting zone -- the Rio Grande Rift.

In this contribution, we analyze the pattern and consistency of quaternary faulting along the southernmost end of the Rio Grande Rift in Southern New Mexico, using a combination of alluvial fan profiles and geomorphic features. We then discuss our findings as they relate to permeability in the subsurface with implications on the potential risk & uncertainty for hosting hidden geothermal systems. Furthermore, our observations were qualitatively compared with the geomorphic features of Quaternary fault patterns and mountain front geomorphology of Dixie Valley, Nevada.

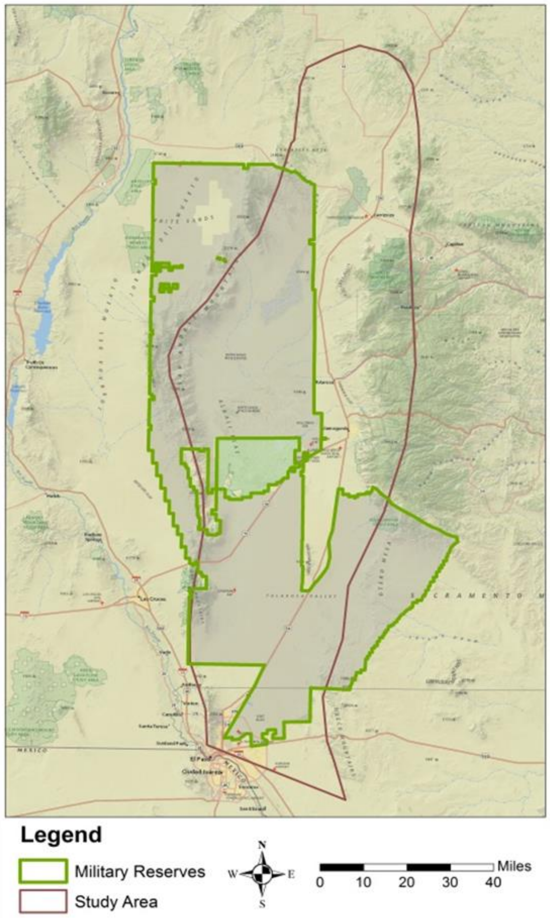


Figure 1. Study area: note the vast expanse of military land.

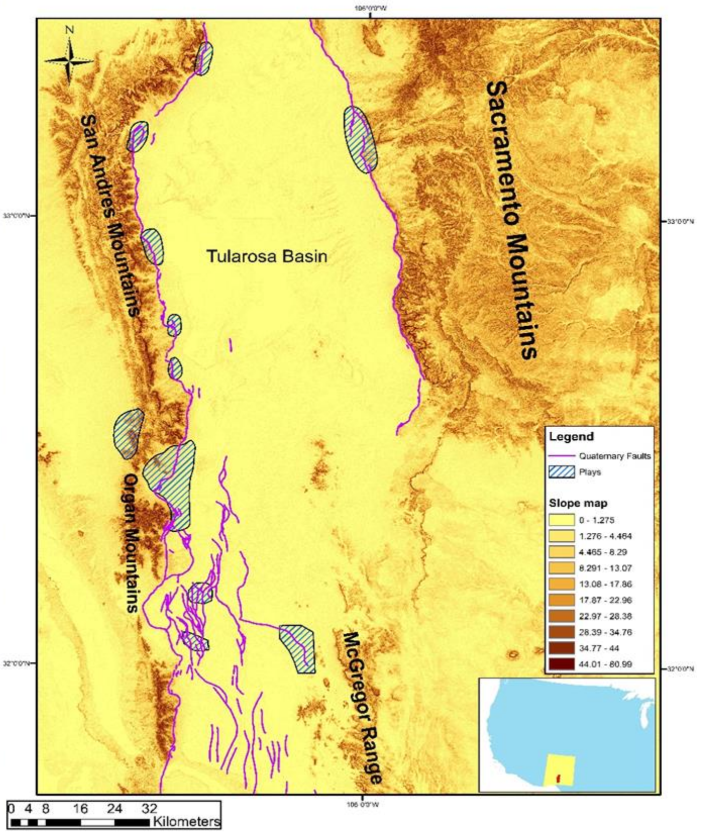


Figure 2. Slope map of the Tularosa Basin, NM, USA. Previously identified plays are shown in blue cross-hatch areas, and quaternary normal faults are shown in purple. As is expected in extensional, Basin and Range-style geologic regimes, the normal faults bound the N-S trending mountain ranges, with a relatively flat, down-dropping basin between.

2. GEOLOGIC SETTING

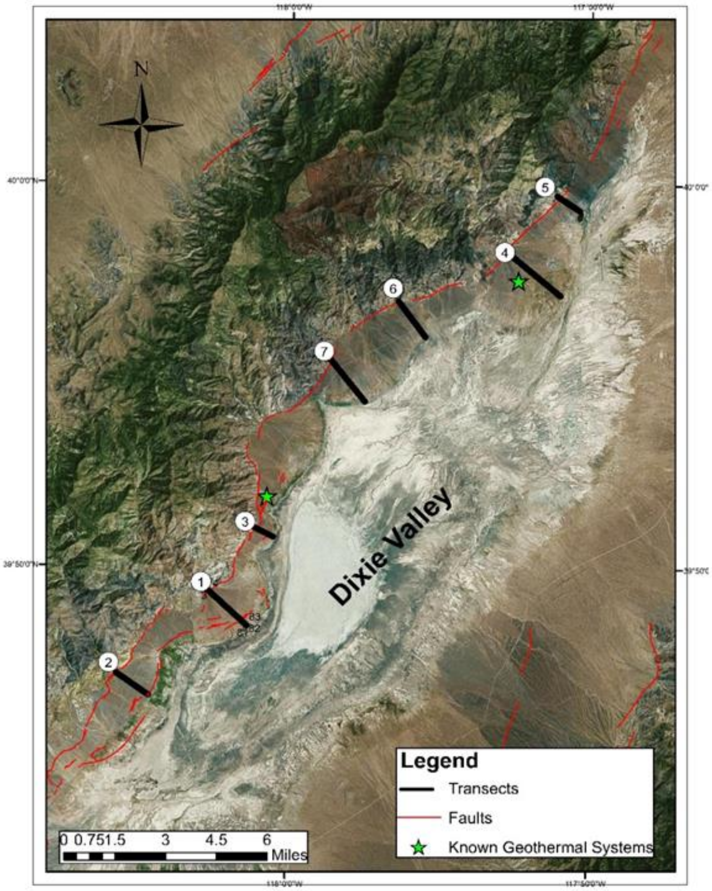
The Tularosa Basin study area has a complex tectonic history, beginning in the Paleozoic when the Pedernal uplift induced siliciclastic sedimentation on the once low-lying shelf of the North American Craton. Sediment deposition was followed by periods of crustal shortening, including Late Paleozoic deformation related to Ancestral Rocky Mountain uplift, and the Late Cretaceous Laramide Orogeny. The current landscape has been shaped by extensional tectonics; resulting in the development of the Rio Grande Rift. Extension began in the Late Paleogene, and presently moves apart at ~0.5 mm/yr in a roughly E-W direction (Sosa et al., 2014). However, seismic activity is infrequent relative to that in the Great Basin, indicating that extension may be slowing in this area. Rates of extension correlate with rates of down-dropping and can be expected to vary along faults. Currently, the greater rift zone extends ~1,000 km, north to south, from central Colorado through the study area in southern New Mexico.

The Tularosa Basin has geologic 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.

3. DIXIE VALLEY

Dixie Valley is located in west-central Nevada, U.S.A (Figs. 3 & 4) within the Central Nevada seismic belt and the Battle Mountain heat flow high. The valley is bounded by the Stillwater Range on the west and the Clan Alpine and Augusta Mountains on the east. This area is home of what is arguably the premier high enthalpy geothermal system in the Great Basin. Within its borders lie several surface geothermal manifestations including Hyder, Sou, and Dixie hot springs and Senator Fumaroles. Deep resource temperatures of 256-275^{o} C have been recorded a few kilometers south of the production field (Benoit, 1994; Blackwell et al., 2000), where Terra-Gen Operating Co., LLC operates geothermal power plants producing a total of 72 MW (terra-gen.com). The geothermal system has generally been described as fault-controlled deep-circulation, although work done by Wannamaker et al (2006) suggests a possible magmatic heat source.

Dixie Valley is unique in that it has the lowest elevation in Nevada outside of the Mohave Desert (<3380 ft. at Humboldt Salt Marsh) because of rapid extension and basin down-dropping. This is also expressed in geomorphic features, such as the prominent Stillwater fault scarp that resulted from the 6.8 magnitude 1954 Dixie Valley earthquake, prominent and little dissected faceted spurs, wine glass shaped canyons, fault offset related knickpoints in channels, and concave and head-ward steepened alluvial fan surfaces. The presence of the remarkable geothermal system and geomorphic features related to the active Stillwater fault system makes this area ideal for geomorphic correlation with other regions undergoing exploration projects.



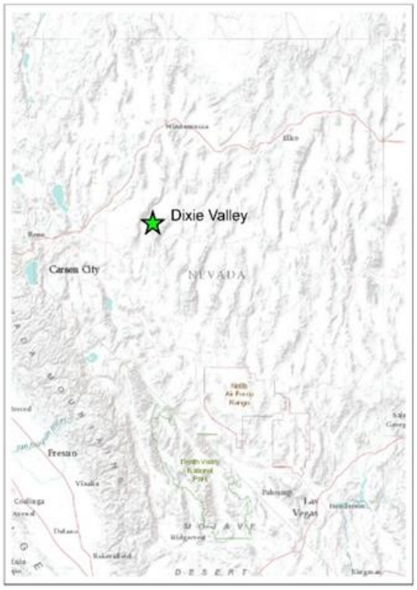


Figure 3 (left). Aerial Satellite imagery of Dixie Valley, with alluvial fan transect locations indicated. Note their proximity to the known geothermal systems.

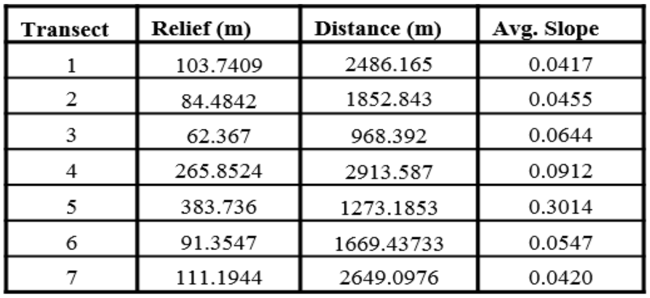
Figure 4 (above) Geographic location of Dixie Valley, Nevada, U.S.A.

4. DATA & METHODS

The primary data acquired to conduct this study were Digital Elevation Models (DEMs) and aerial photography. The DEMs of Tularosa Basin have 10 m resolution, while the Dixie Valley DEMs have 30 m resolution. DEMs for Tularosa Basin were downloaded from the New Mexico Resource Geographic Information System (NM RGIS) and the DEMs for Dixie Valley were downloaded from the W.M. Keck Earth Sciences & Mining Research Library at the University of Nevada Reno. Ideally, the DEMs for both Tularosa Basin and Dixie Valley would be the same resolution to make for easy comparison. However, we were limited in our access to data and could not find 10 meter DEMs for Dixie Valley to work with. Although there is a difference in resolution, it is not large enough to strongly affect our measurements. Initially, using the DEMs, slope maps were created using ArcGIS to identify possible areas of interest for later alluvial fan mapping. Then precise transect lines were drawn through the central axis of alluvial fans with the 3D analyst ArcGIS extension. The attribute data from the mapped transect lines were then converted into a Microsoft Excel spreadsheet for statistical analysis, from which relief, distance and slope could be could be calculated (Tables 1 & 2). A histogram of those data was then constructed (Figure 5) to show the distribution of alluvial fan slopes.

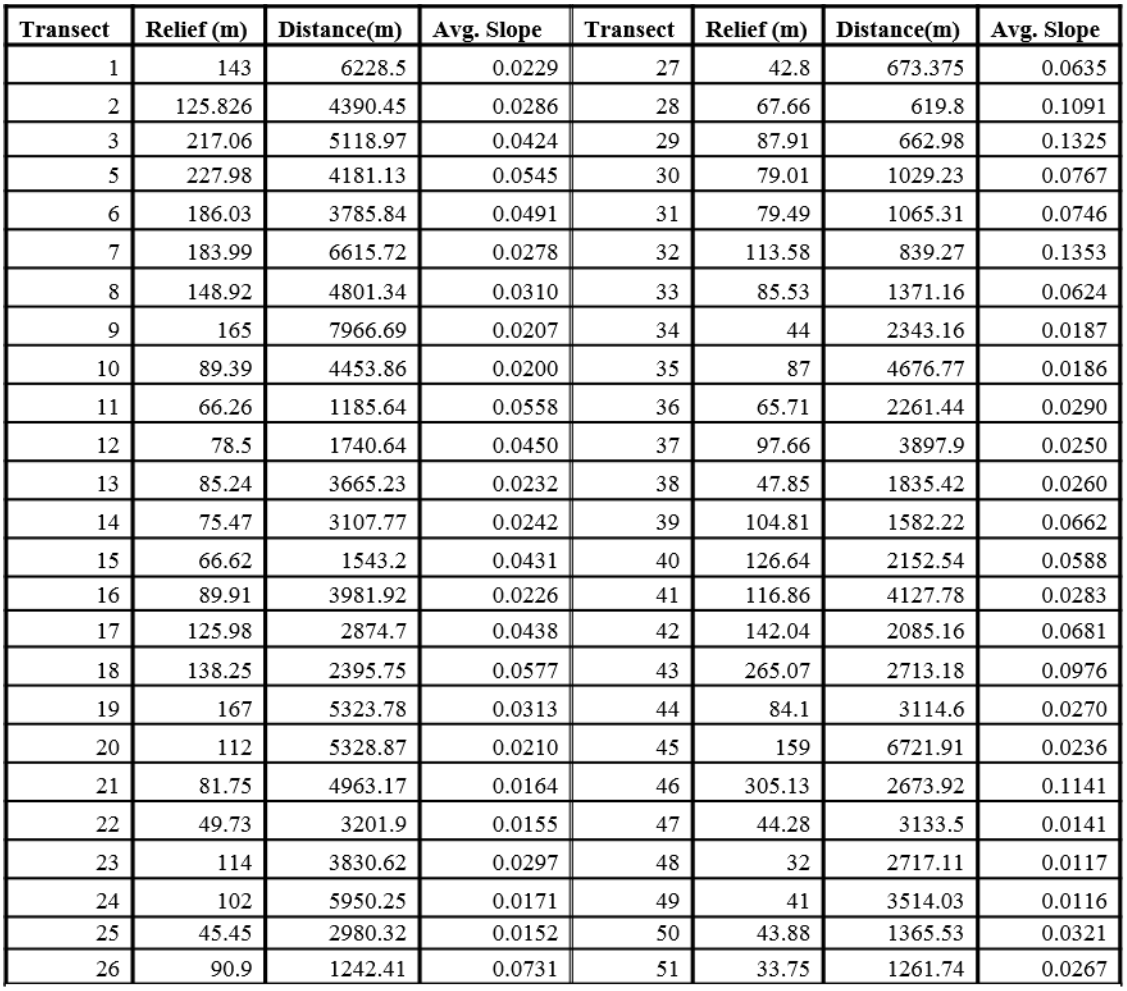
Hundreds of alluvial fans are actively being deposited in the Tularosa Basin. As sediment is deposited, it molds to the landscape and can morph into a variety of shapes that may not resemble a typical alluvial fan. In addition, a number of alluvial fans have been impacted by anthropogenic obstructions such as roads, trails, towns, and other infrastructure. So, we carefully selected 50 of the least obstructed alluvial fans, based on their ordinary, semi-conical geometry. This ensures that their topographic profile is more reflective of the tectonic influence and allows proper correlation with fans in Dixie Valley. Climatic factors cannot be discounted completely, but can reasonably be assumed as playing a minor role in defining the geometry of the alluvial fans as compared with tectonic factors. Therefore, we isolate the tectonic factors, and thus are able to qualitatively estimate down-dropping rates

Aerial photography, downloaded from the NM RGIS, was also used in this study. These photographs are colored digital orthophotography taken within the last 8 years for agricultural applications. This data provides insight into the spatial extent of alluvial fan deposits. The files cover specific quads with an area of roughly 50mi^2. Mapping was focused on a buffered zones surrounding plays in the Tularosa Basin and known geothermal systems in Dixie Valley. DEM data and orthophotography were uploaded into ArcScene, within ArcGIS, where the imagery could be draped on the DEM to allow for 3D visualization and further analysis of geomorphology. Figures 6, 7 and 8 below show 3D images of the mountain front and alluvial fans spreading into the basin. From these images, observations of faceted spur geometry, alluvial fan expanse, and qualitative slope can be made.



Transect	Relief (m)	Distance (m)	Avg. Slope
1	103.7409	2486.165	0.0417
2	84.4842	1852.843	0.0455
3	62.367	968.392	0.0644
4	265.8524	2913.587	0.0912
5	383.736	1273.1853	0.3014
6	91.3547	1669.43733	0.0547
7	111.1944	2649.0976	0.0420

Table 2. Geomorphometric data corresponding with alluvial fan transects in Dixie Valley, Nevada.



Transect	Relief (m)	Distance(m)	Avg. Slope	Transect	Relief (m)	Distance(m)	Avg. Slope
1	143	6228.5	0.0229	27	42.8	673.375	0.0635
2	125.826	4390.45	0.0286	28	67.66	619.8	0.1091
3	217.06	5118.97	0.0424	29	87.91	662.98	0.1325
5	227.98	4181.13	0.0545	30	79.01	1029.23	0.0767
6	186.03	3785.84	0.0491	31	79.49	1065.31	0.0746
7	183.99	6615.72	0.0278	32	113.58	839.27	0.1353
8	148.92	4801.34	0.0310	33	85.53	1371.16	0.0624
9	165	7966.69	0.0207	34	44	2343.16	0.0187
10	89.39	4453.86	0.0200	35	87	4676.77	0.0186
11	66.26	1185.64	0.0558	36	65.71	2261.44	0.0290
12	78.5	1740.64	0.0450	37	97.66	3897.9	0.0250
13	85.24	3665.23	0.0232	38	47.85	1835.42	0.0260
14	75.47	3107.77	0.0242	39	104.81	1582.22	0.0662
15	66.62	1543.2	0.0431	40	126.64	2152.54	0.0588
16	89.91	3981.92	0.0226	41	116.86	4127.78	0.0283
17	125.98	2874.7	0.0438	42	142.04	2085.16	0.0681
18	138.25	2395.75	0.0577	43	265.07	2713.18	0.0976
19	167	5323.78	0.0313	44	84.1	3114.6	0.0270
20	112	5328.87	0.0210	45	159	6721.91	0.0236
21	81.75	4963.17	0.0164	46	305.13	2673.92	0.1141
22	49.73	3201.9	0.0155	47	44.28	3133.5	0.0141
23	114	3830.62	0.0297	48	32	2717.11	0.0117
24	102	5950.25	0.0171	49	41	3514.03	0.0116
25	45.45	2980.32	0.0152	50	43.88	1365.53	0.0321
26	90.9	1242.41	0.0731	51	33.75	1261.74	0.0267

Table 1. Table of geomorphometric data corresponding with alluvial fan transects in the Tularosa Basin, New Mexico.

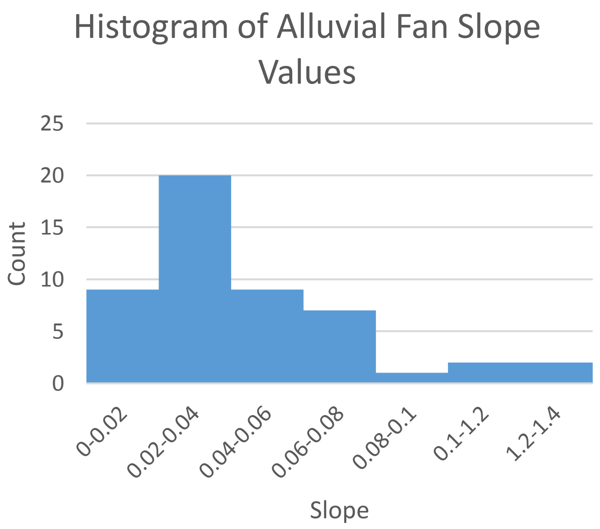


Figure 5. Histogram for geomorphometric values of topographic slope along the central axis of alluvial fans.

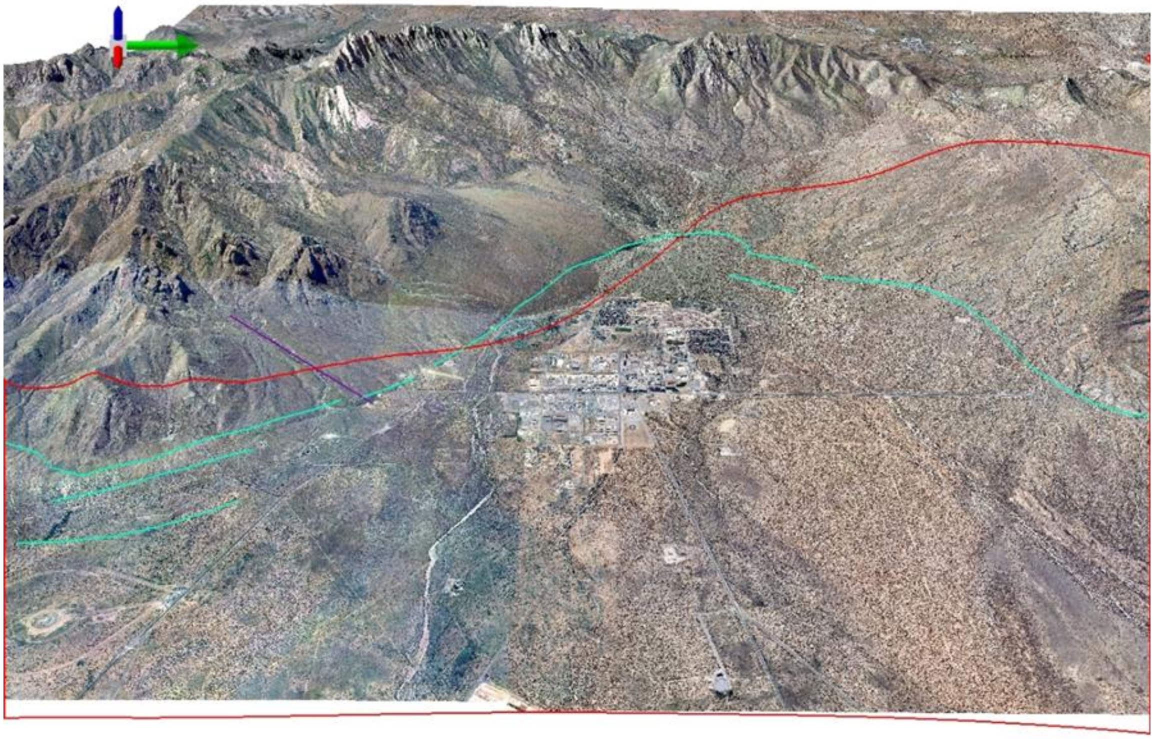
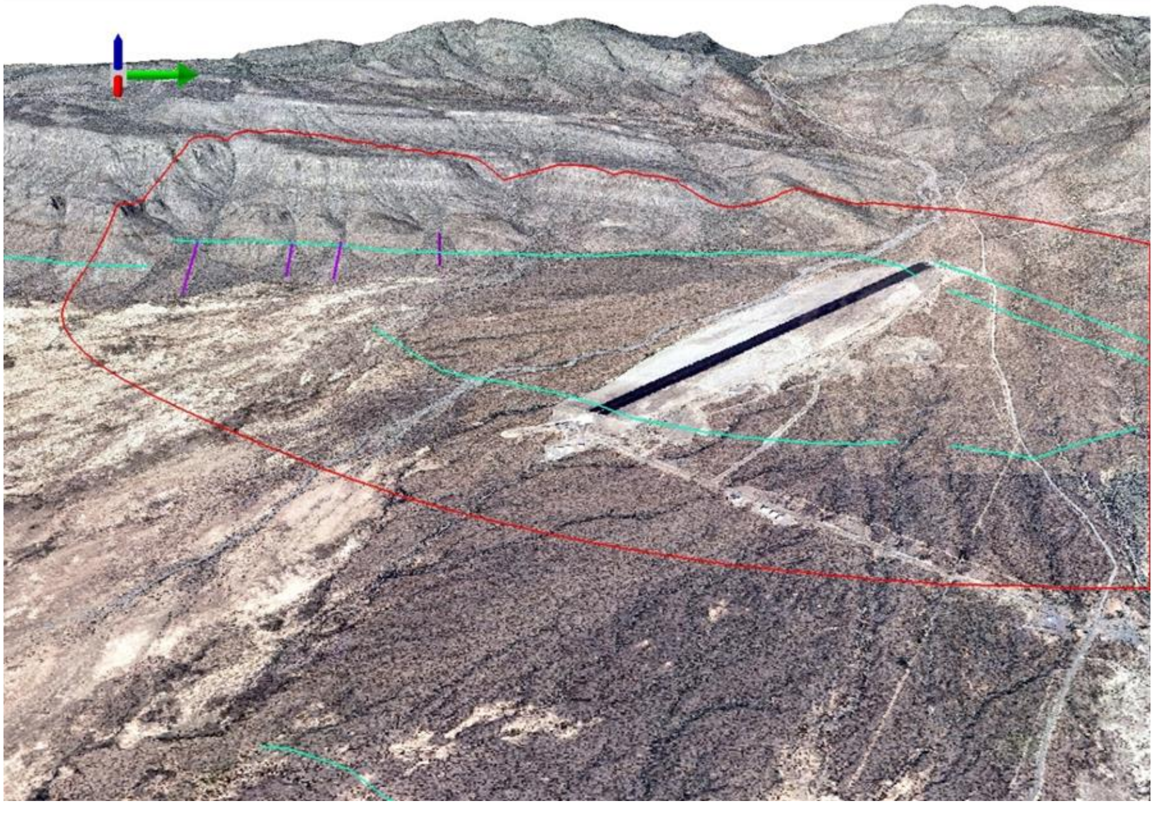


Figure 6 (above) and 7 (below): ArcScene, 3D visualizations of alluvial fans. The red outline are play boundaries, and the turquoise lines are Quaternary faults. There is no vertical exaggeration and North is indicated by the green arrow. Above is transect 43 near the town of White Sands. Below is transect 27 – 30 near the Runway at White Sands Airforce base.



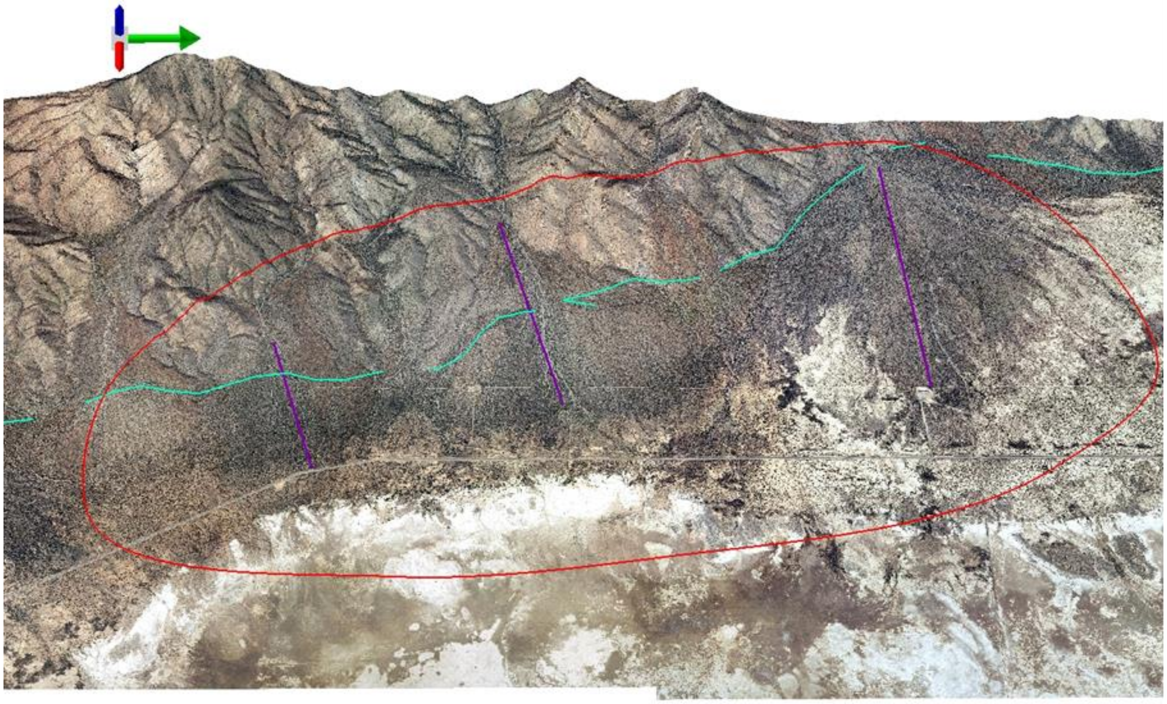


Figure 8: 3D visualization of alluvial fan transects 16, 17 and 18 (left to right purple lines). The red circle indicates a previously identified play, and the turquoise lines are quaternary faults. There is no vertical exaggeration on this image, and North is indicated by the green arrow.

5. RESULTS

The Tularosa Basin has hundreds of actively growing alluvial fan deposits. 50 of the most ordinary alluvial fans were chosen such that they had relatively little depositional obstructions to convolute their shape. An average slope was calculated from the data, yielding 0.043 m/m. From there, outliers can be detected, which may indicate localities where more rapid down-dropping is occurring. Alluvial fans that had a slope greater than 1 standard deviation from the average include transect # 26, 28, 29, 30, 31, 43 and 46 (from Table 1). Figure 5 shows the average slope values in a histogram plot, which clearly shows that more of the alluvial fans analyzed in this study are between 0.02 and 0.04 m/m. Figures 9, 10, 11, and 12 a, b show satellite imagery of different regions within the Tularosa Basin study area and the spatial distribution of alluvial fans with respective transects therein. Those transects are characterized in colors that correspond with average topographic slope, the primary geomorphometric used in this study.

In Dixie Valley, 7 alluvial fans were quantitatively analyzed for topographic relief, surface distance and average slope, the results of which are shown in Table 2. Figure 2 shows the spatial distribution of those transects and proximity to known geothermal systems. Transect 5 has the highest slope of any in this study with a slope of 0.3, and just South of that, transect 4 has a relatively high slope at 0.09. The remaining transects have slopes between .04 and .065. Transect 3 has the third highest slope among those studied here.

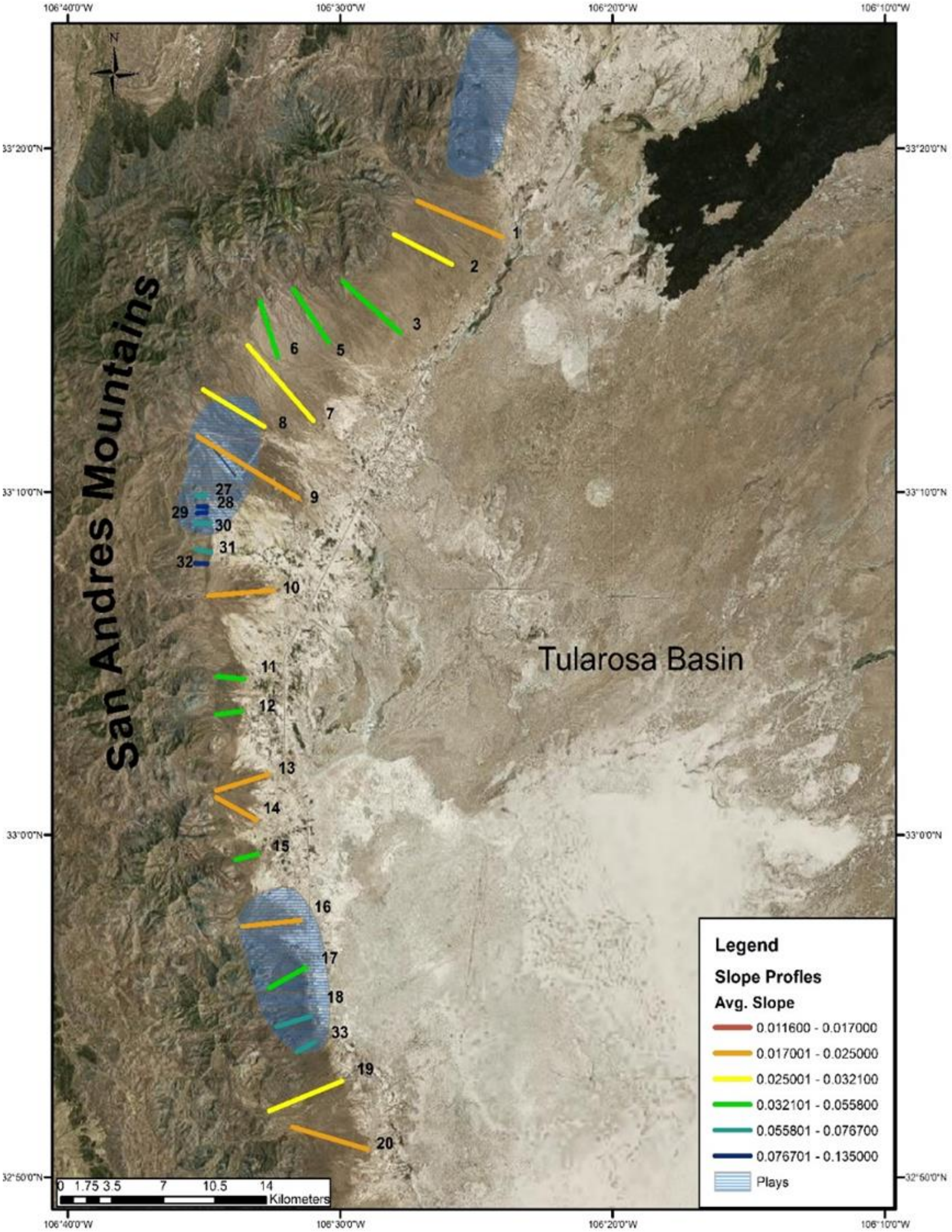


Figure 9: Classified transects of alluvial fans on the eastern side of the San Andres Mountains. Northern most section of the San Andres Mountains shown.

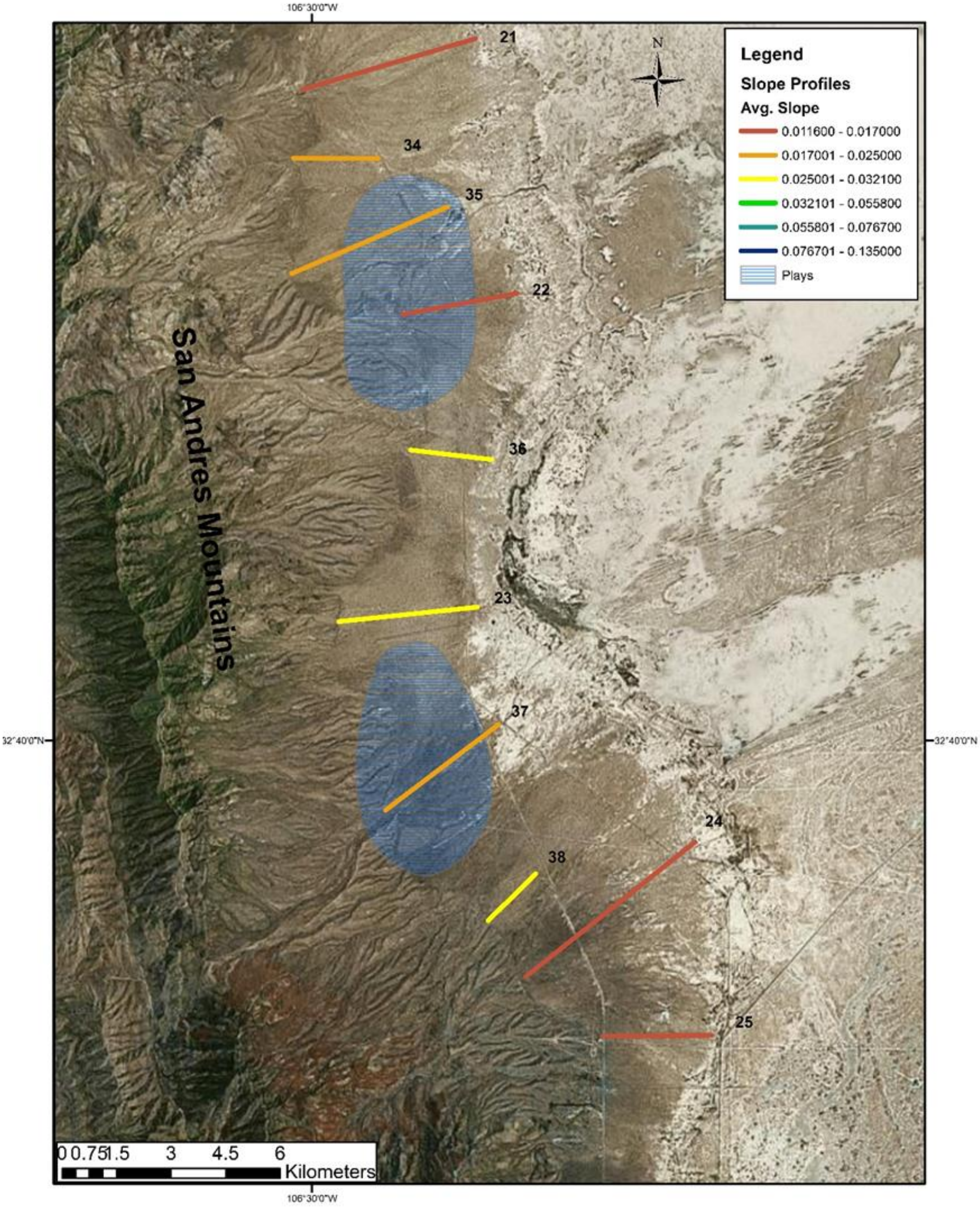


Figure 10: Classified transects of alluvial fans of for the eastern edge of the middle section of the San Andres Mountains near Whitesands National Monument.

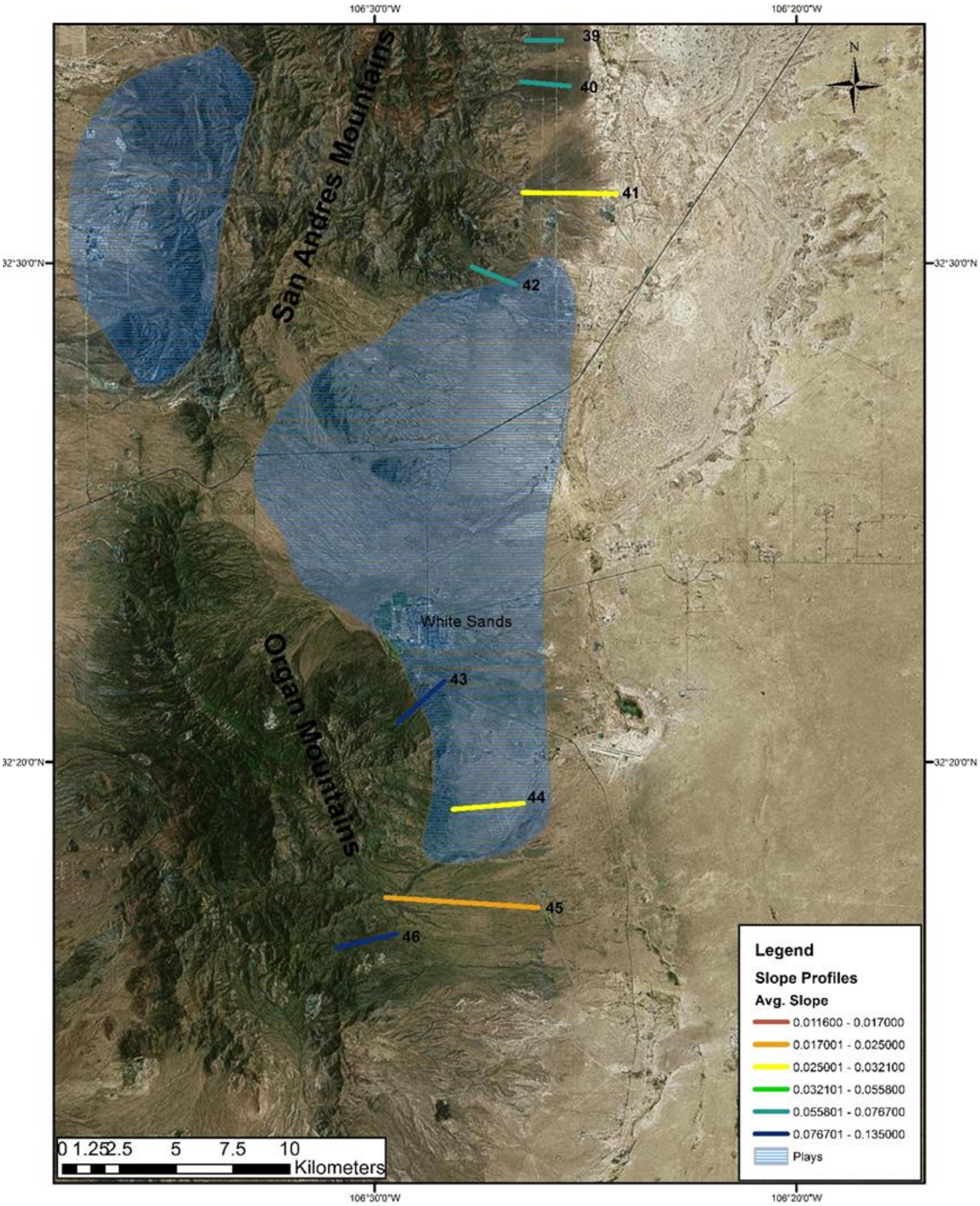


Figure 11: Classified transects of alluvial fans for the eastern edge of the lower portion of the San Andres Mountains, the town of White Sands area, and the Organ Mountains.

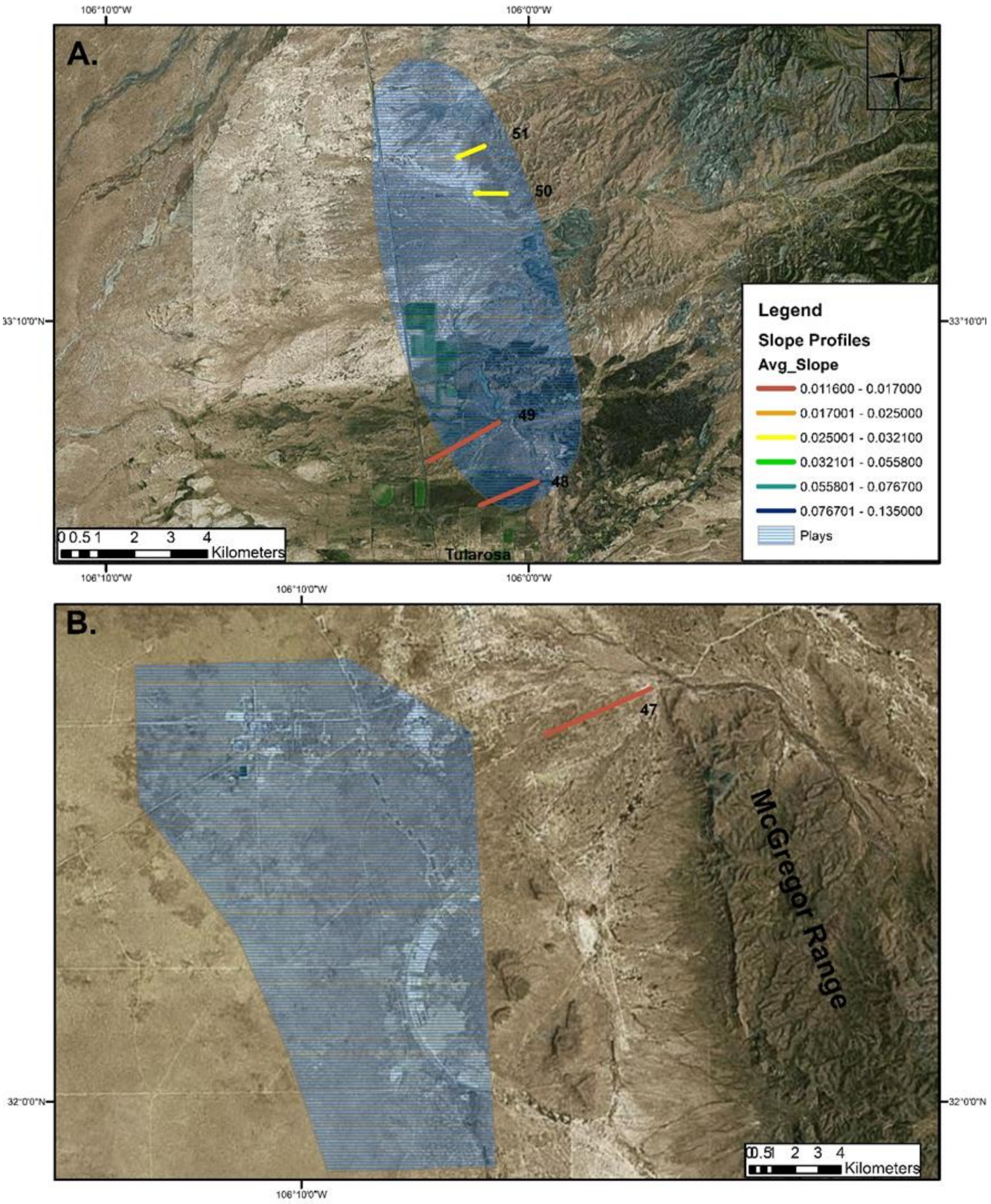


Figure 12: A: Classified transects of alluvial fans on the western edge of the Sacramento Mountains, just north of the town of Tularosa. B: Classified transects of alluvial fans on the western edge of the McGregor Range on the southern end of Tularosa Basin. The Legend applies for both A & B.

6. CONCLUSION

If a transect of the central axis of an alluvial fan has a relatively high slope, then the basin must be down-dropping at a faster rate along that segment that on segments proximal to low-sloping fans. When a segment along a fault has a complex nature, that is, it steps-over, turns, terminates, etc. it is known that the bedrock around that fault gets fractured, creating permeability in the deep subsurface. The results in this study show that there is considerable variability in the slope of alluvial fans throughout the Tularosa Basin and Dixie Valley. From these variations in geomorphometric values, we can identify and constrain with reasonable uncertainty, segments along range-front quaternary faults that have relatively faster slip rates and therefore more permeability than others.

The analogous Dixie Valley alluvial fan geomorphology is valid because it is similar tectonic regime and the alluvial fans' surface geometry are similar. Historic record of the slip rates along faults is highly uncertain on long time scales (~10,000 years) because of the limitations to how deep trenching can expose a fault zone. Historical tectonic evolution of the areas is a better way to understand the fault behavior over time, and is best interpreted from geomorphology. Alluvial fan geometry are just one of many possible geomorphometrics, another common metric is faceted spur geometry, which can be summarized as simple shapes like triangle or trapezoid. In future work, a quantitative analysis of faceted spur geometry would provide additional insight into fault behavior, and increase the probability of accurate interpretations. On longer time periods, Anderson (2000) shows that geomorphometrics like faceted spur and alluvial fan geometry are better for making long term interpretations about fault behavior. This is crucial for understanding subsurface permeability and discovering hidden geothermal systems.

In conclusion, the geomorphometrics of alluvial fans in Dixie Valley and the Tularosa Basin both showed a lot of variability. Generally speaking, one would expect fans with steep slopes where relatively rapid basin down-dropping exists. The Dixie Valley fans with steeper slopes are close, within a mile of the known geothermal systems in the area, where there's enough subsurface permeability to allow for groundwater circulation. This correlation translates to the Tularosa Basin, where we observed steeper sloping fans near previously identified plays. This may help to weigh the prioritization of plays in future phases of research. It is only through drilling geothermal wells to verify if the blind geothermal system exists, that the results of this study can be validated. Steeper sloping fans can be seen in Figures 9, 10, 11 and 12 a, b, and can be used to indicate levels of risk for permeability at depth; which is just one of three components for a productive geothermal system. These qualitative risk values do not directly reflect the existence of a hidden geothermal system, rather they lend to the overall understanding of structure and geomechanics in the subsurface. This is arguably the most important constraint on where and why geothermal systems exist, thus lending to our exploration efforts in the Tularosa Basin.

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