Low-Latitude Periglacial Activity

IN THE EOLIAN UNITS OF THE SAN LUIS VALLEY, COLORADO

Tyler Meng | GIS & GPS Applications in Earth Science | 7 December 2017

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*The cover photo was taken by Tyler Meng from the southern rim of the Crestone Crater looking west. Two adult humans can be seen standing in the center of the frame as a scale reference.

INTRODUCTION

The San Luis Valley is a high-elevation basin that extends from southern Colorado to northern New Mexico. The valley is bound to the west by the San Juan Mountains, a volcanic complex that was emplaced starting in the late Eocene [1]. It is flanked by the Sangre de Cristo Range to the east, which makes up the footwall of the Sangre de Cristo fault, an extensional structure that marks the eastern boundary of the Rio Grande Rift [2]. The basin is filled largely with the alluvium of the Rio Grande River and its tributaries, but on the eastern edge of the valley the alluvium is overlain by multiple units of eolian sediment that are sourced from the San Juans to the west [3]. This region contains an active dune field within Great Sand Dunes National Park, but some of the surrounding eolian surficial units have stable topography and are proposed to be slightly older than the unconsolidated active dunes; some of the sand dates back to the Pleistocene [3,4].

In the sand to the north of the active dunes, there is a peculiar elliptical depression with a raised rim, which has been dubbed the Crestone Crater as a nod to the nearby town of the same name. It major axis is approximately 100 m, and for year the local consensus was that this feature was the result a small impact correlated to stories of a large fireball seen by farmers in the 20th century, but multiple geologic and geophysical investigations have failed to yield conclusive evidence for the impact hypothesis [5,6]. Recently, new LiDAR data revealed the presence of more similarly shaped surface expressions nearby the Crestone, and they seem to be confined to this stabilized unit of eolian sand [7]. While these could be preserved eolian blowout features, many of which are also found in the Great Sand Dunes regions, this seems unlikely since blowouts do not generally have a raised rim around the entirety of the feature [8].

Instead, a new hypothesis has developed for the origin of the Crestone Crater and its nearby relatives: periglacial processes. The last major glaciation throughout Colorado occurred in the Pleistocene—the same time that the eolian unit began to arrive—and many of the high mountain valleys of the Sangre de Cristo Range contain till that has been mapped to estimate the extent of ice in the past [2]. While glaciers did not extend down to the elevations of the Crestone Crater, their proximity indicates that the climate could have been cold and wet enough to support freeze-thaw cycles in saturated sediments downhill from the glaciers. The hypothesis is that the combination of the stabilized eolian sediment, cold climate, and a high water table led to the formation of periglacial features, particularly open system-hydraulic pingos [9]. This could have implications for the understanding of aquifer infiltration in the San Luis Valley, as aquifer properties have been under close scrutiny [10].

To test this hypothesis with a GIS, the questions to answer are as follows:

- What is the spatial distribution of hypothesized periglacial features in relation to glacial deposits?
- What was the approximate volume of water held in glaciers?
- What was the percentage of water in glaciers compared to that of ancient Lake Alamosa, and could glacial melt have contributed to local water table levels in a favorable way for periglacial activity?

DATA COLLECTION

To investigate these questions, two different resolutions of DEM's from the National Elevation Dataset were utilized alongside maximum glacial extent shapefiles provided by the Colorado Geological Survey [13,14], geospatial data for the Great Sand Dunes region from the National Park Service website [4], Colorado GIS data from the ColoradoView [15] website run by the Natural Resource Ecology Laboratory at Colorado State University, and some original point and polygon files produced for the project. All of the data came with metadata that contained information about the locations, resolutions, and original projections of all of the data, which is summarized in Tables 1 and 2 below:

Table 1: Raster Data

Name	Projection	Resolution	Extent
n38w106 n38w107	None	1/3" ~ 9 meters	1°x1°
ned19_n37x25_w105x50_co_sanluisvalley_2011 ned19_n37x50_w105x50_co_sanluisvalley_2011 ned19_n37x75_w105x50_co_sanluisvalley_2011 ned19_n37x75_w105x75_co_sanluisvalley_2011 ned19_n38x00_w105x75_co_sanluisvalley_2011 ned19_n38x25_w105x75_co_sanluisvalley_2011 ned19_n38x25_w106x00_co_sanluisvalley_2011 ned19_n38x25_w106x00_co_arkansasvalley_2010	None	1/9" ~ 3 meters	15'x15'

*these raster .img files follow a naming convention: they contain their geographic coordinates in the name. Both were referenced to the North American 1983 GCS.

Table 2: Vector Data

Name	Projection	Description
glaciers.shp	NAD83_UTM Zone 13N	Past ice
CO_boundary.shp	NAD83 UTM Zone 13N	Boundary polygon
STREAMS.shp	NAD83 UTM Zone 13N	All Colorado streams
HIGHWAYS.shp	NAD83 UTM Zone 13N	All Colorado highways
GRSAGLG.shp	NAD83 UTM Zone 13 N	Geology of Great Sand Dunes
Colorado_cities.shp	Albers Equal Area Conic	Colorado population centers

PREPROCESSING

Before manipulating or analyzing any of this data, it was necessary to merge all of the rasters into one image dataset for each resolution. Figure 1 shows an example of the dialogue for using the 'Mosaic' tool to merge several of the individual 1/9 arcsecond (high-resolution) rasters with one of the existing raster datasets, known as the target raster.
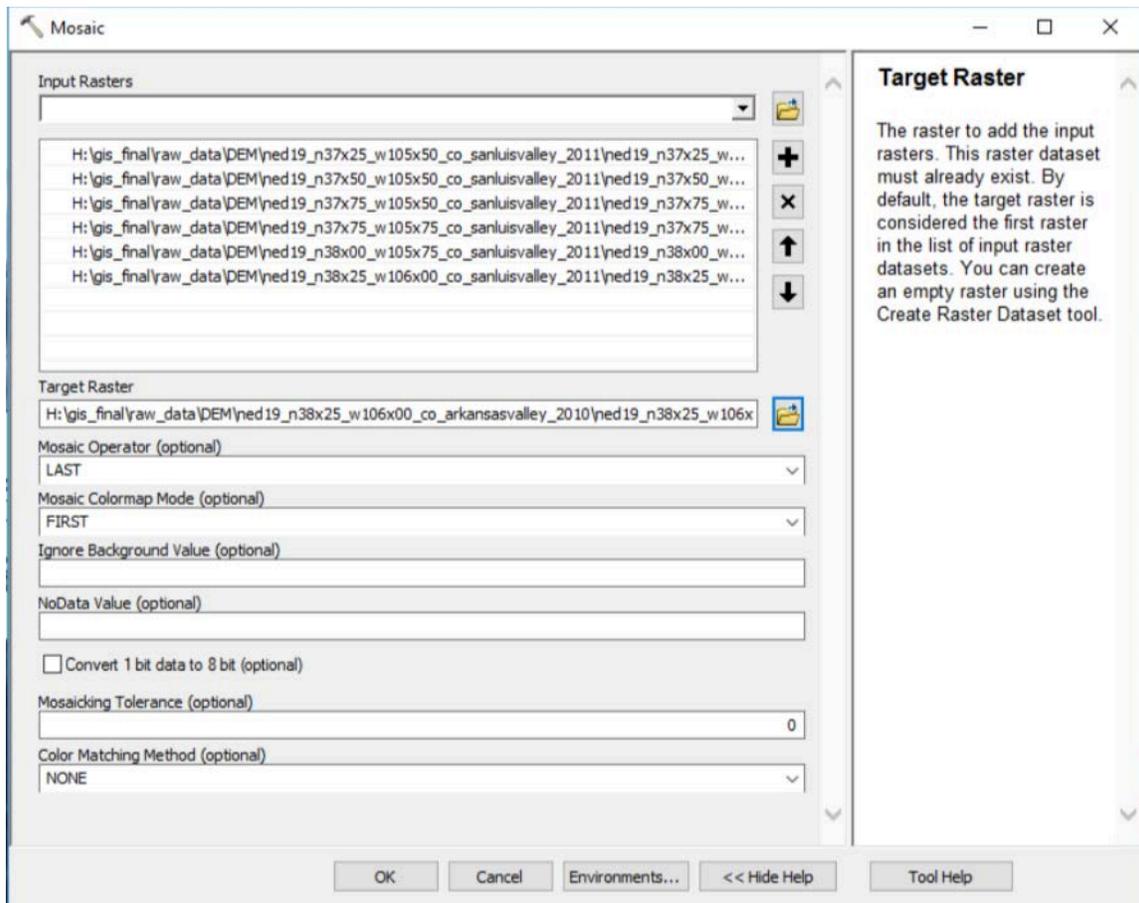
Figure 1: Using the mosaic tool to combine multiple rasters into one continuous dataset.

Now, with two merged raster mosaics of different resolutions, it is necessary to make sure that all of the datasets have the same projection to ensure spatial accuracy. Luckily, much of this data was already projected to NAD83 UTM Zone 13N. However, all of the raster data was unprojected, and the cities shapefile also needed to be re-projected from its original Albers Equal Area projection. To keep files organized, these new projections were output directly into a new personal geodatabase, named SLV_TMM.mdb. Figure 2 shows the step needed to create this personal geodatabase in ArcCatalog, while Figure 3 shows an example of using the "Project Raster" data management tool on the low-resolution DEM mosaic.
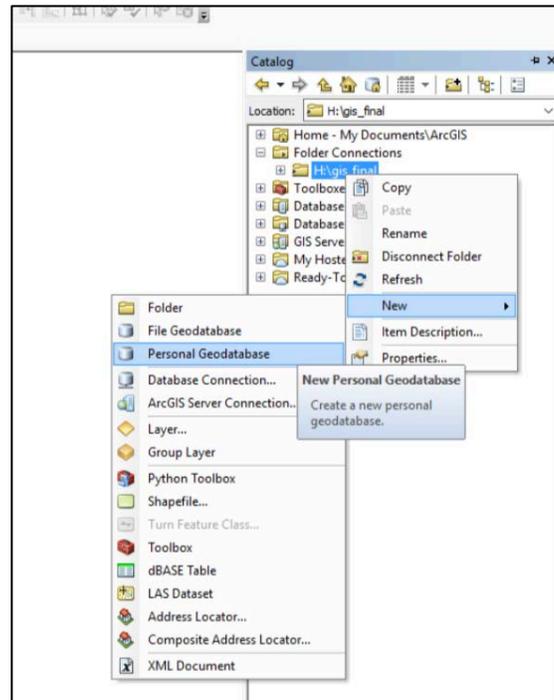
Figure 2: Creating a personal geodatabase for file management.
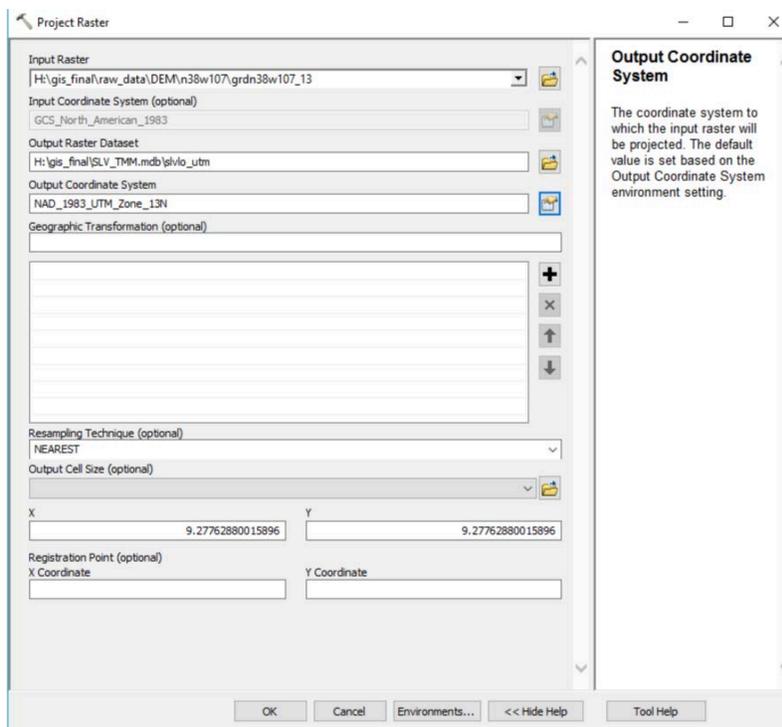
Figure 3: Make sure to have a good amount of time and memory budgeted when using the "Project Raster" tool. .

One thing to keep in mind when preprocessing large raster data sources it that wide spatial extent combined with high resolution can lead to large file sizes. For example, the projected high resolution DEM mosaic has an uncompressed size of approximately 3.5 GB, so it is important to allocate enough storage space when performing high resolution raster analysis.

After projecting the raster data, the Colorado cities shapefile must also be projected into UTM Zone 13N from Albers Equal Area. Like the previous datasets, this was projected as a new feature class in the personal geodatabase created for the analysis. Similar to "Project Raster," the "Project Tool" easily transforms the input shapefile from Albers to UTM as shown in Figure 4. Data files that already had the correct projection were also added to the geodatabase using the "Feature Class to Feature Class" tool (Figure 5), accessed by selecting the option to import a feature class into the geodatabase.
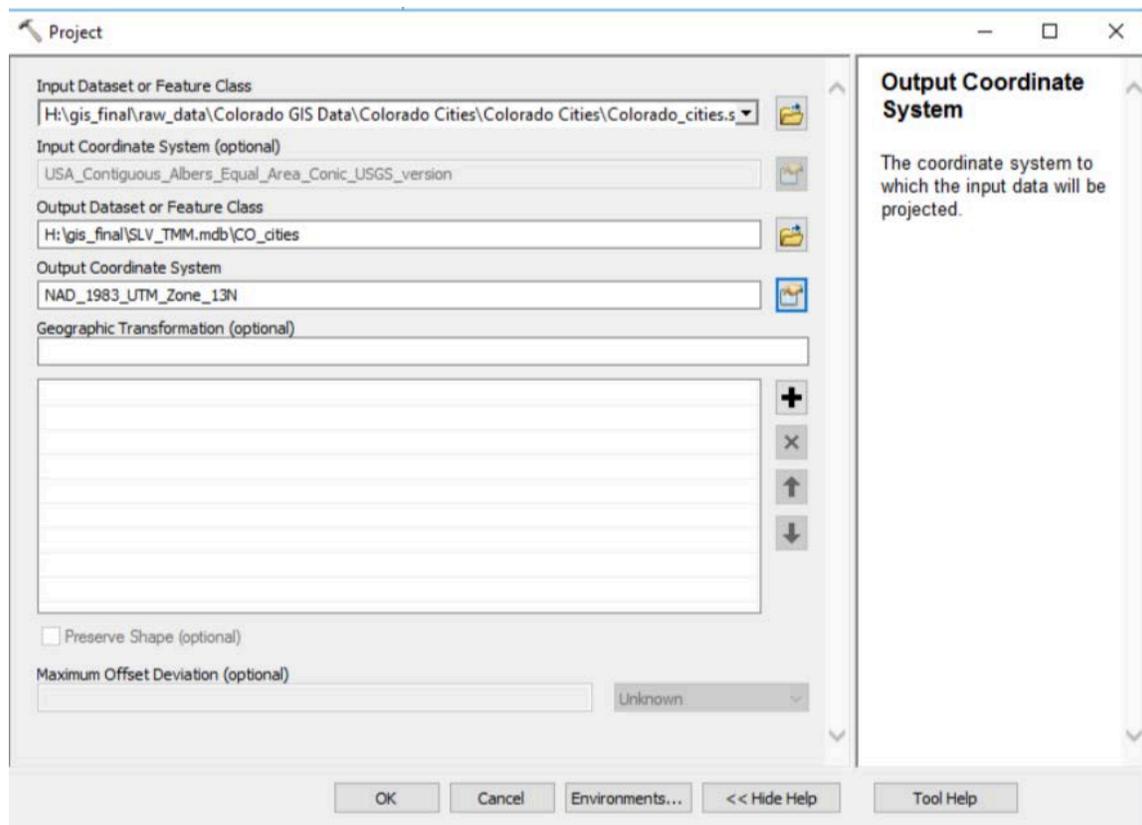
Figure 4: Projecting vector files is similar to projecting raster files, but generally quicker.
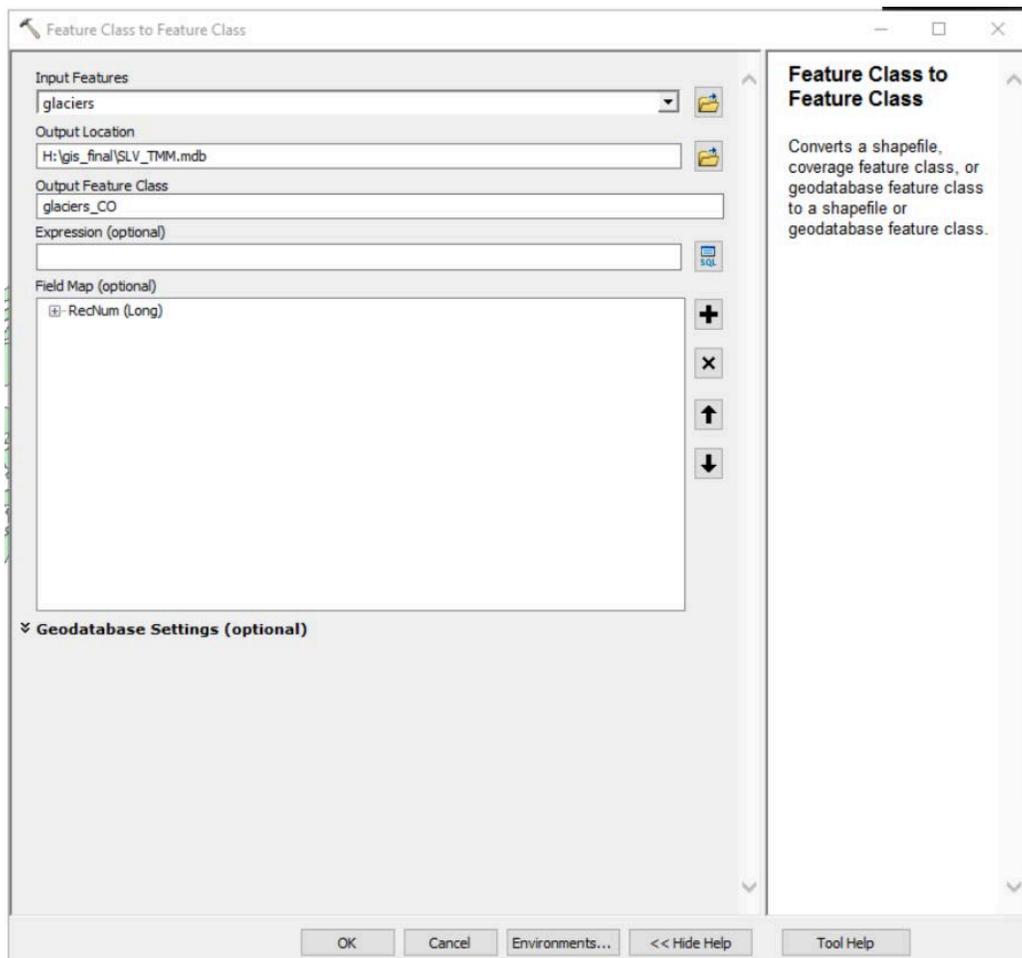
Figure 5: Populating the geodatabase by converting the original downloaded shapefiles into feature classes.

One benefit of converting these shapefiles to feature classes is that geometries such as perimeter and shape area are automatically calculated, making the analysis a little bit easier. However, upon converting the glaciers shapefile into a feature class, it became apparent that something was wrong with the data: some of the areas were negative (Figure 6). This turned out to be a geometry error for some of the shapes, in this case some of the polygons had the incorrect ring order. This meant that some of the inner edges of polygons were being interpreted at external edges, which led to inaccurate area calculations. Some research revealed that the solution requires just one extra step of preprocessing involving the "Repair Geometry" tool, which is trivial to use (Figure 7). Now that all of our data sets have the same projection, are located in a single geodatabase, and have the correct geometry, we can now begin the analysis.

Figure 6: Attribute table for the glaciers feature class showing the issue of negative calculated shape areas.
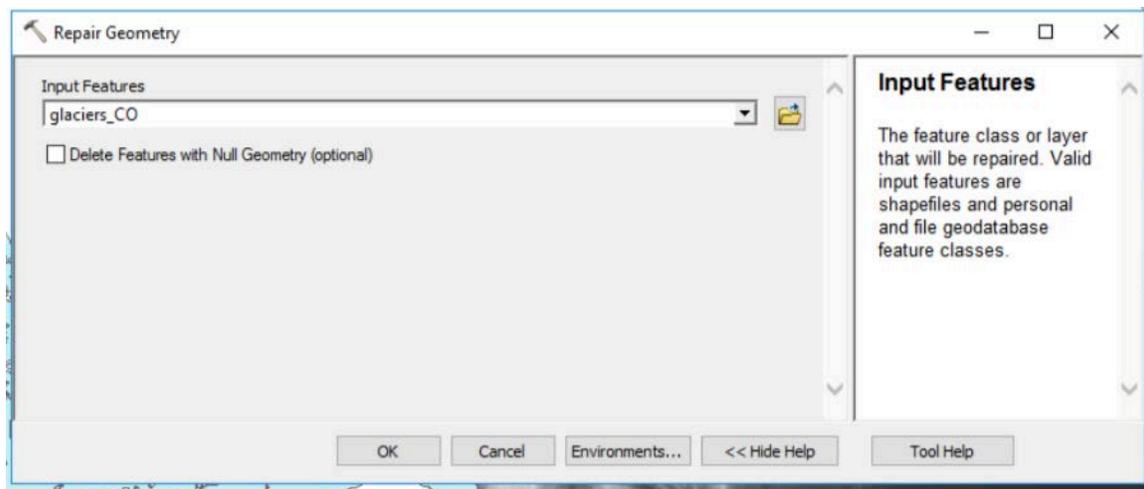
Figure 7: The only argument needed to run the "Repair Geometry" tool is the feature that one wishes to repair.

ANALYSIS

To begin data analysis, the first step was to map out the locations of these hypothesized periglacial features, or pingos. First, a new Point feature class was created. This was also placed in the UTM Zone 13N coordinate system and given an XY Tolerance of 0.001 meters, shown in Figure 8. A length 15 text field named "Comment" was added to allow clarification on any of the picked pingos.
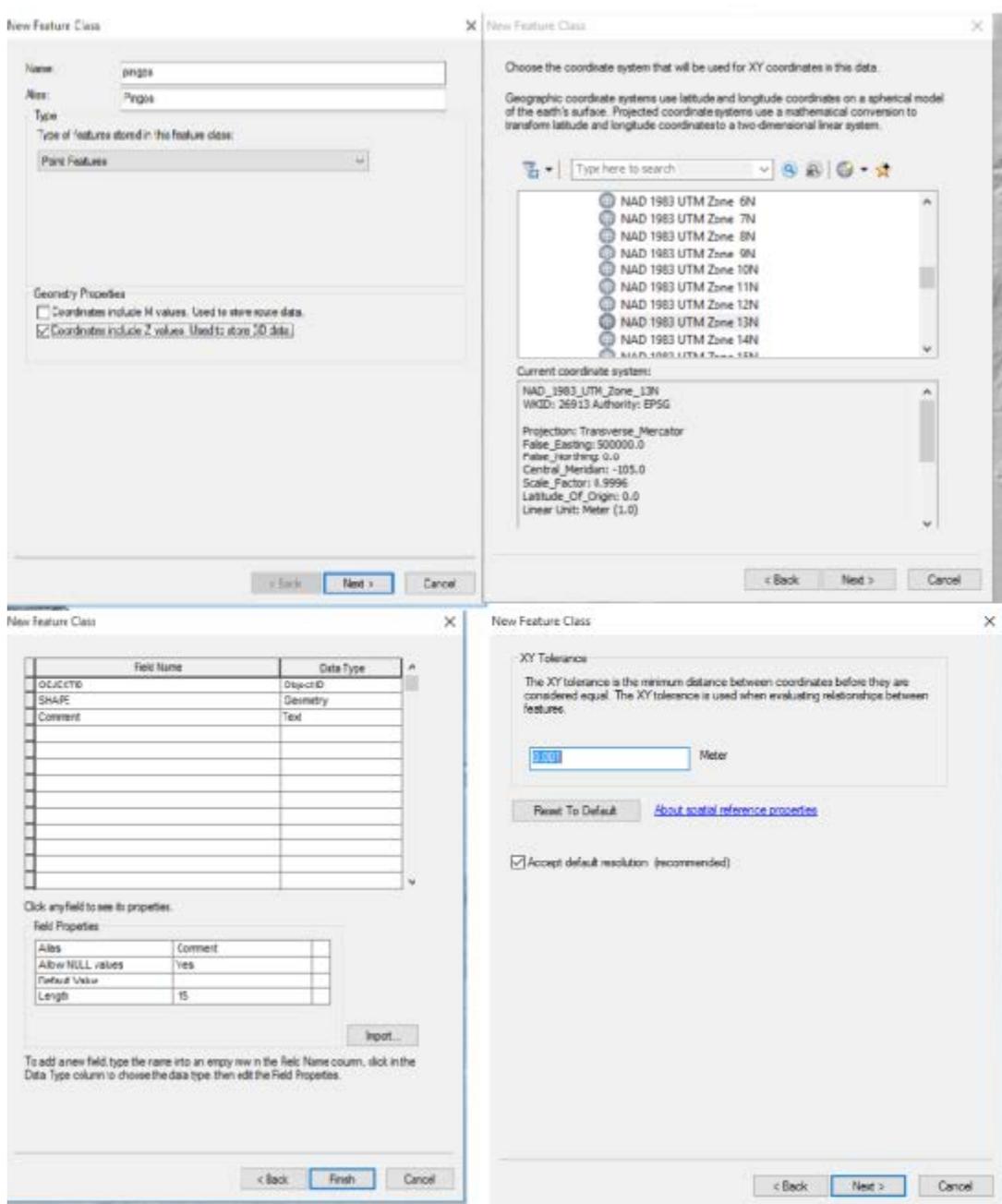
Figure 8: Steps to create a new "Pingos" feature class.

Before mapping the pingos, the LiDAR data must first be converted to a form that is visibly more similar to the terrain, and this is done with the "Hillshade" tool (Figure 9). To start mapping pingo locations by referencing the hillshaded DEM, an editing session was started and applied only to the Pingos feature class (Figure 10). Clicking at the desired locations with the "Point" construction tool maps these points to the new feature class (Figure 11).
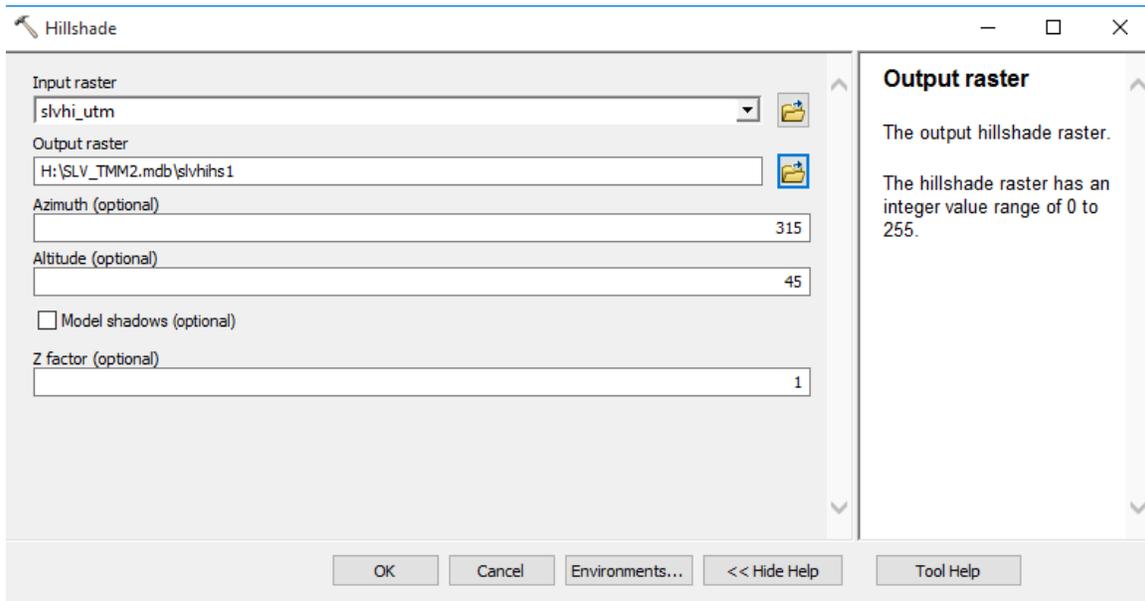
Figure 9: This example shows the creation of a hillshade from the high resolution DEM mosaic, which makes the LiDAR data much more accessible to visual analysis.
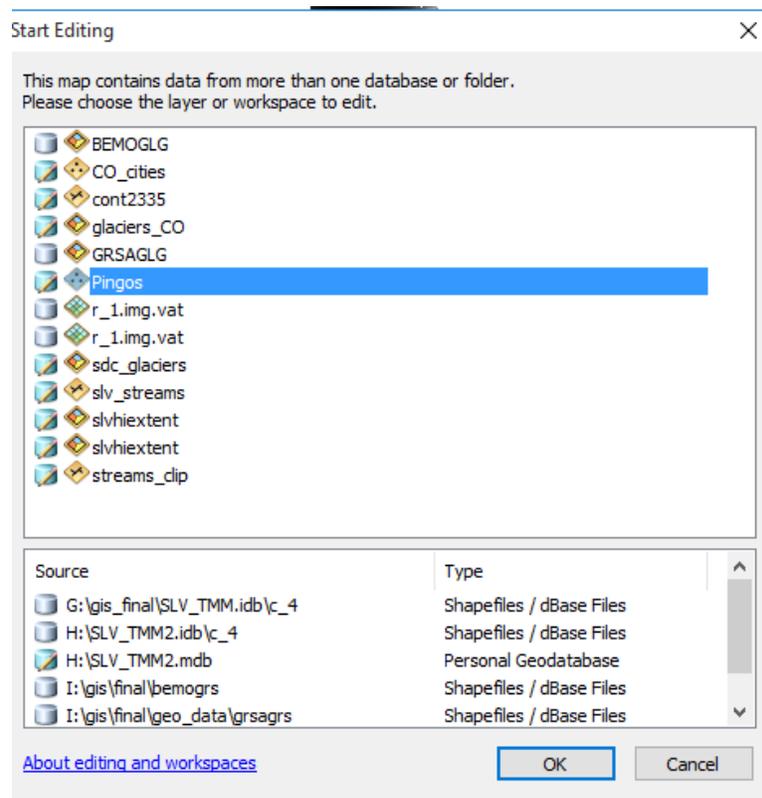
Figure 10: Beginning an editing session to map pingo locations.
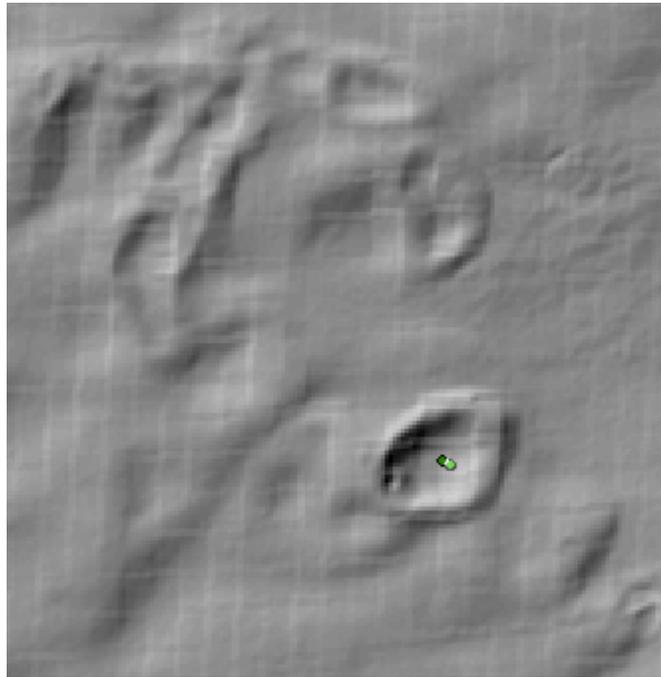
Figure 11: Mapping the location of the Crestone Crater. For consistency, the goal was to map the location of the center of each feature interpreted to be periglacial.

A total of 52 features were mapped to the hillshade before overlaying the surface geology data, and the edits were saved for later comparison with other geologic data. It should be noted that these features were selected based on the criteria that they had raised rims completely and smoothly surrounding a central depression, as opposed to parabolic dunes and blowouts that have a sharper crest signature. They were also classified and symbolized with a "Likelihood" field, which uses ordinal rankings to qualitatively determine the similarity of the mapped feature to the original Crestone Crater. The next part of the analysis involves estimating the maximum volume of glaciers in the Sangre de Cristo Range in comparison with the maximum volume of Lake Alamosa. To calculate the volume of glaciers, it was first necessary to create a layer of only glaciers within the Sangre de Cristo Range from the entire Colorado glacier dataset. This was accomplished by selecting all of the glaciers within a desired polygon and exporting those data to a new feature class. After estimating an ice thickness, a volume can be approximated for the entire glacial complex, further discussed in the following section.

To estimate the volume of Lake Alamosa, a shoreline must first be mapped out. This was accomplished by creating a contour line at 2335 m elevation, which was the maximum extent of Lake Alamosa [11]. The "Contour" tool makes this an easy task (Figure 12). Next, to smooth the edges of the polygon created by this contour, a new polygon was drawn to a shoreline feature class using the same editing technique as mapping out the pingo points, but this time a polygon was traced. The northern end of the shoreline was outside of the extent of the low resolution DEM, but a majority of the lake was digitized as a polygon (Figure 13).
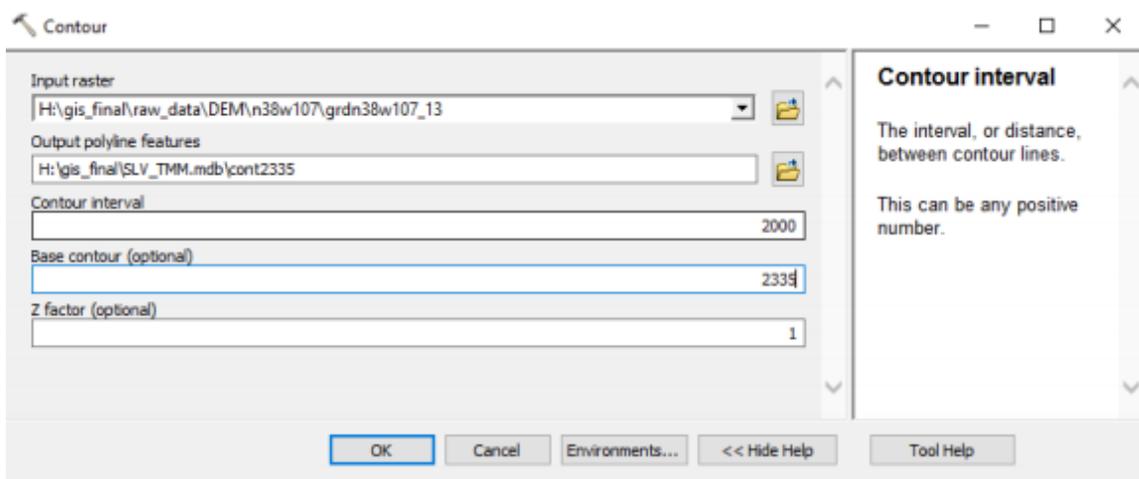
Figure 12: Constructing the 2335 m contour line approximates the maximum height of the shoreline for Lake Alamosa.
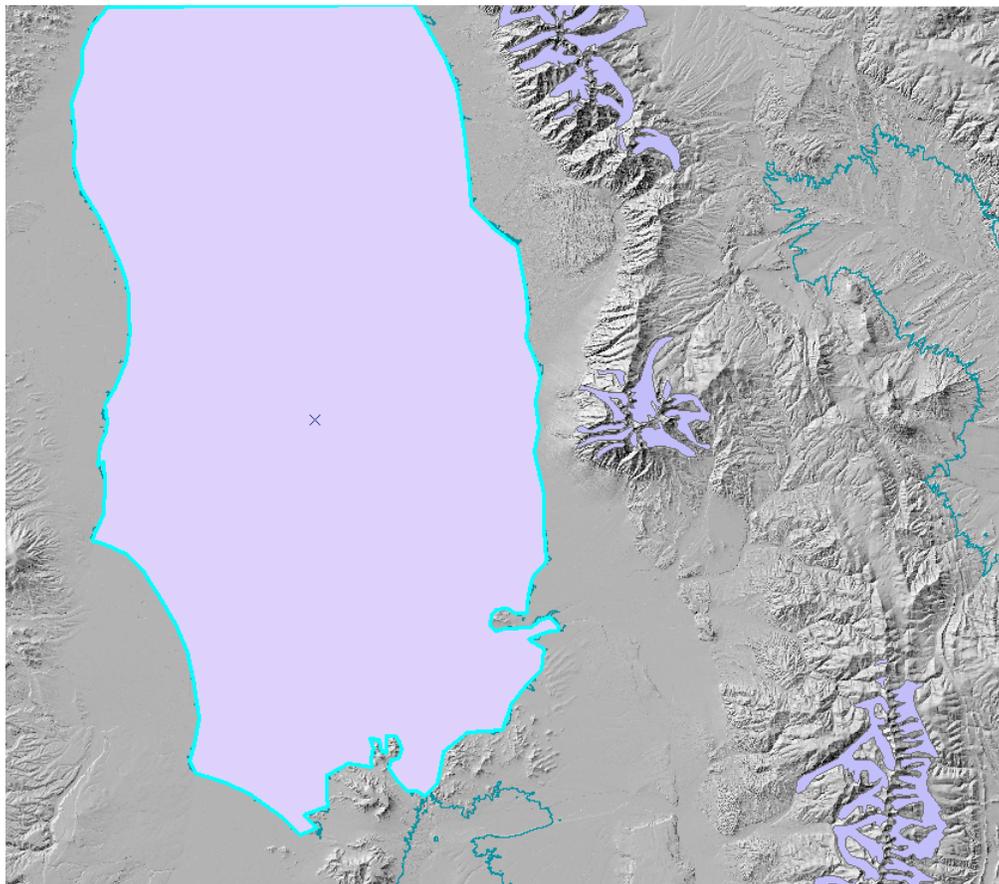
Figure 13: New polygon for Lake Alamosa traced from contour line. Snapping was utilized to ensure this polygon was closed but still closely correlated to the 2335 m contour line.

The next step of analyzing Lake Alamosa is converting the polygon vector file into a raster file using the "Polygon to Raster" tool (Figure 14). It is important to specify that the cell size is that of the low resolution DEM, which is going to be used to calculate the depth of the Lake. When converted, this gives the entire raster image a value of 3, so to calculate the depth of Lake Alamosa, raster calculator must be used with the conditional statement that subtracts the DEM elevation from 2335 (shoreline elevation) wherever there are Lake pixels (Figure 15).
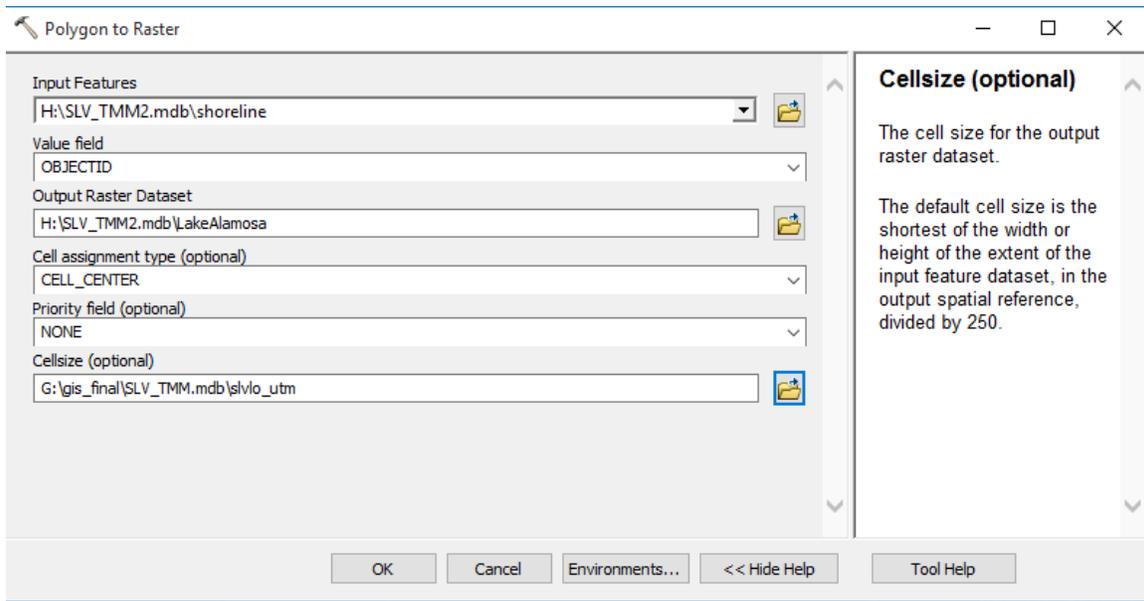
Figure 14: Converting the Lake Alamosa polygon into a raster file.
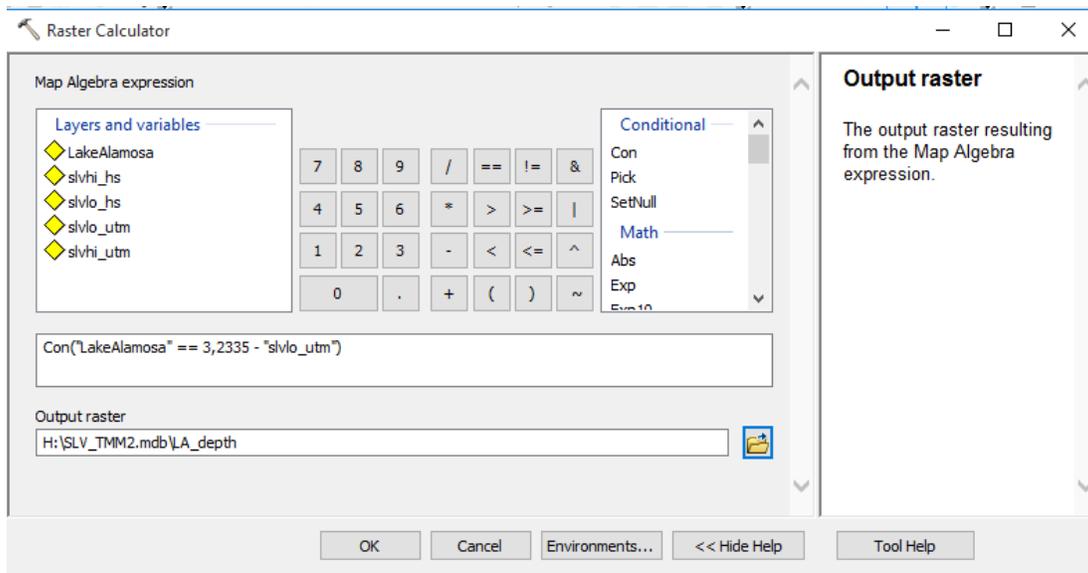
Figure 15: Using raster calculator to estimate maximum depth of Lake Alamosa.

One final processing step to make analysis of these features a little bit easier is to clip the stream data to the extent of the high resolution raster. This is done by selecting all of the streams that intersect with the DEM and then exporting the selection to a feature class (Figure 16). Now that the stream data set is small enough, it can further be clipped just to the extent of the DEM (Figure 17). After the pingos have been identified and mapped and the extent and depth of ancient Lake Alamosa has been calculated along with the area of glaciers within the Sangre de Cristo Range, we can now compare these results with the local geological and hydrological data and interpret the findings.

Figure 16: Exporting the streams that intersect with our area of interest.
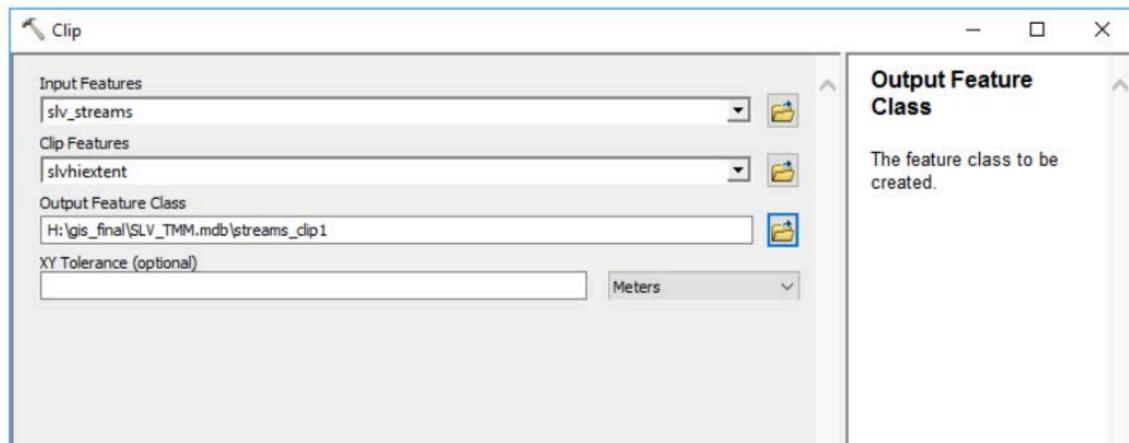
Figure 17: Clipping the streams so there are no streams outside of the extent of the DEM.

RESULTS AND DISCUSSION

After mapping the pingos based on observation of the DEM Hillshade and comparing those mapped locations to the surface geology and maximum extent of Lake Alamosa, it was found that about 83% of these mapped features reside on the Qssh sand sheet unit, while the others are found on the Qes unit or in areas without geology data, but near to Qes Additionally, this map did not seem to have observed "pingo terraces" mapped out. These terraces seem to be raised units that are topographically about 10 m above the surrounding alluvium (Figure 18), and in the future these distinct terraces could be mapped to a polygon file. Another notable finding from this analysis is that nearly all of these features are found between the maximum shoreline for Lake Alamosa and the mountain front. The horizontal distance of pingos from the shoreline ranges from 0 to 8 km, and ranges 2 to 9 km from the glacial extent. Furthermore, the biggest clusters of these features appear to be negatively correlated with the existence of Bull Lake fan alluvium when considering the bounding of surface units by the streams (Map 3). These findings could suggest that these pingos formed during a groundwater regime that was controlled by the water table and shoreline stratigraphy of a full Lake Alamosa. After formation, melt from the glacier eroded the surfaces that contained the periglacial features, and this erosion could have been coincident with the deposition of the Bull Lake Fan Alluvium. Additional eolian modification has certainly been ongoing, which could explain why only a small portion of the features are well-preserved.
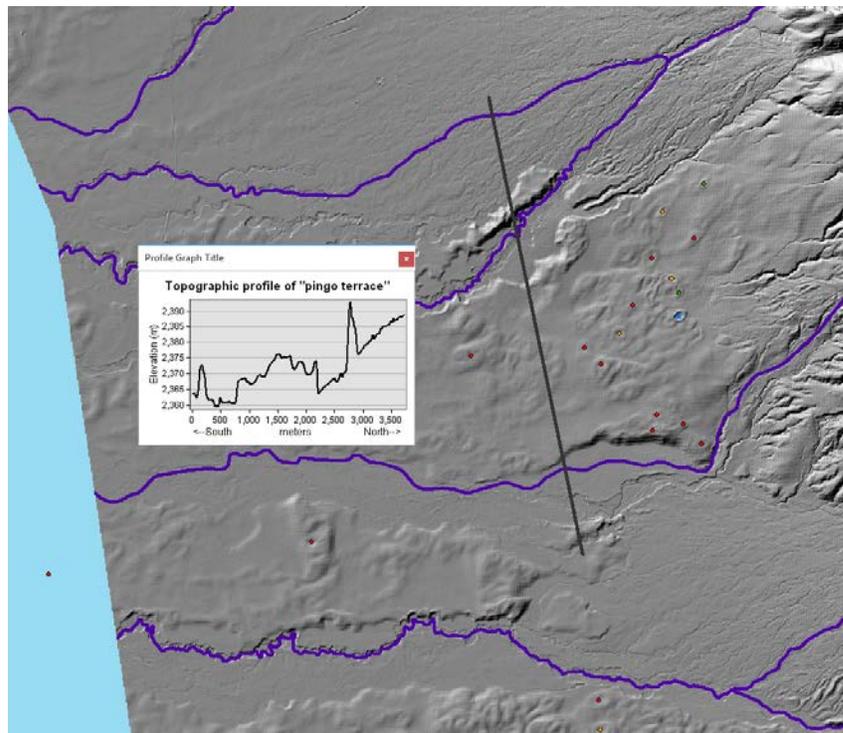
Figure 18: Topographic profile showing the raised surface that these rimmed depressions are found on in relation to streams that could have eroded the surface.

The entirety of the 1/9" hillshade was examined in search of these features, but they were only found in the localized Crestone region, suggesting a very specific set of conditions for these features to form. These specific conditions could include the hydrologic constraints controlled by the proximity to a large body of water, a large volume of runoff, and grain geometry that is favorable to pingo formation. Future work should investigate the sensitivity of pingo formation to these parameters. These models should also include climate factors to understand whether or not pingos could form during a glacial maximum or when less ice is present.

The analysis of the volumes of water stored in the Sangre de Cristo glaciers compared with the storage of Lake Alamosa were somewhat surprising. At its highest extent, Lake Alamosa had a volume of approximately 9e10 cubic meters, while the glaciers held a volume of ice that was equivalent to about 4e10 cubic meters, or approximately half that of Lake Alamosa. These calculations assumed an average Lake Depth of 25 m and an average glacier thickness of 80 m, or about half of the maximum glacier thickness [12]. This could bias the glacier volume towards a higher result if the assumed mean thickness is too high, and additionally if any glaciers included were outside of the drainage into Lake Alamosa, but the goal was to calculate a maximum volume. Since these glaciers only account for about 4% of the glacial extent in Colorado, it can be definitively concluded that an enormous amount of ice was stored throughout Colorado, regardless of the thickness.

In conclusion, the spatial analysis of hypothesized pingo features revealed that they are confined to a relatively small range spatially and geologically. A reconstruction of Lake Alamosa shows that all of these pingos are found within a small band of eolian sand between the ancient shoreline and the Sangre de Cristo mountains. It is hypothesized that the lake, glacial melt, or both influenced the ground water hydrology of this eolian sand unit, leading to favorable conditions for the formation of periglacial features. Since the lake and glaciers stored comparable volumes of water, it is possible that enough groundwater was present to differentially freeze in a high elevation Pleistocene climate, leading to ice lenses that grew into pingos. Since some of these features are so well preserved, it is also possible that these processes could be ongoing. More work is needed to understand the sequence stratigraphy and related groundwater hydrology for lake-full and receding scenarios. Higher temporal resolution would be useful to understand if these processes are continuing to modify the highest "Likelihood" pingos through the present day. Groundwater flow and freeze/thaw modeling based on the local geology would also help answer these ongoing questions, especially if the pingo terrace units are mapped and considered a distinct unit. Finally, more high resolution DEM's should be utilized to continue to search for similar features in similar conditions at different locations. All of these methods could be very helpful in distinguishing the origin of these features by both process and age.

ACKNOWLEDGEMENTS

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Colorado Glacial Extent and San Luis Valley Areas of Interest

1:3,000,000

Explanation

- Colorado Boundary
- Maximum Glacial Extent
- 1/3" DEM Coverage
- 1/9" DEM Coverage

Estes Park

Denver

Grand Junction

Crested Butte

Colorado Springs

Salida

Pueblo

Durango

Alamosa

N

0   50   100 Kilometers

Coordinate System: NAD 1983 UTM Zone 13N
Projection: Transverse Mercator
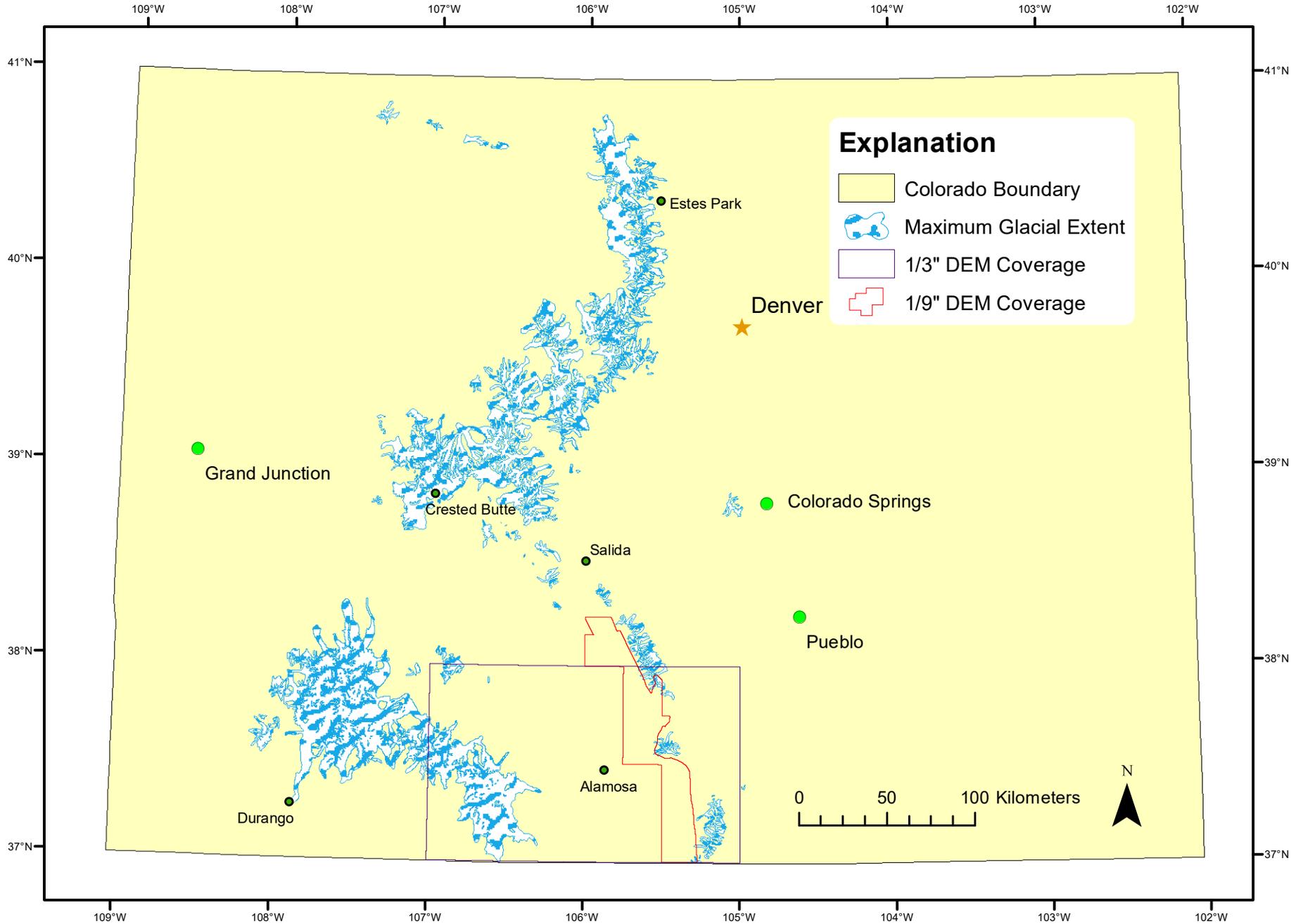
Ancient Lake Alamosa Extent
Compared with Maximum Glacial Extent and Mapped Periglacial Features
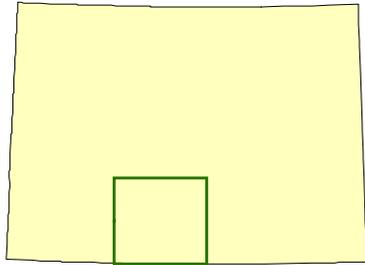
Mapped Pingos

- ● least confident
- ● somewhat confident
- ● very confident
- ★ Crestone Crater
- Lake Alamosa

Lake Depth

59 m

0 m
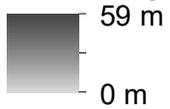
1/9" DEM Coverage

Maximum Glacial Extent

*pingo confidence based on qualitative comparison of features to original Crestone Crater

**Lake Alamosa extent based on maximum shoreline elevation of 2335 m

***Hillshade based on mosaic of 1/3" DEM's merged at 106W meridian

Sangre de Cristo Range

Crestone

Lake Alamosa

Rio Grande River

Monte Vista

San Juan Mountains

Alamosa

Blanca

Rio Grande River

50 Kilometers

1:900,000

Coordinate System: NAD 1983 UTM Zone 13N
Projection: Transverse Mercator
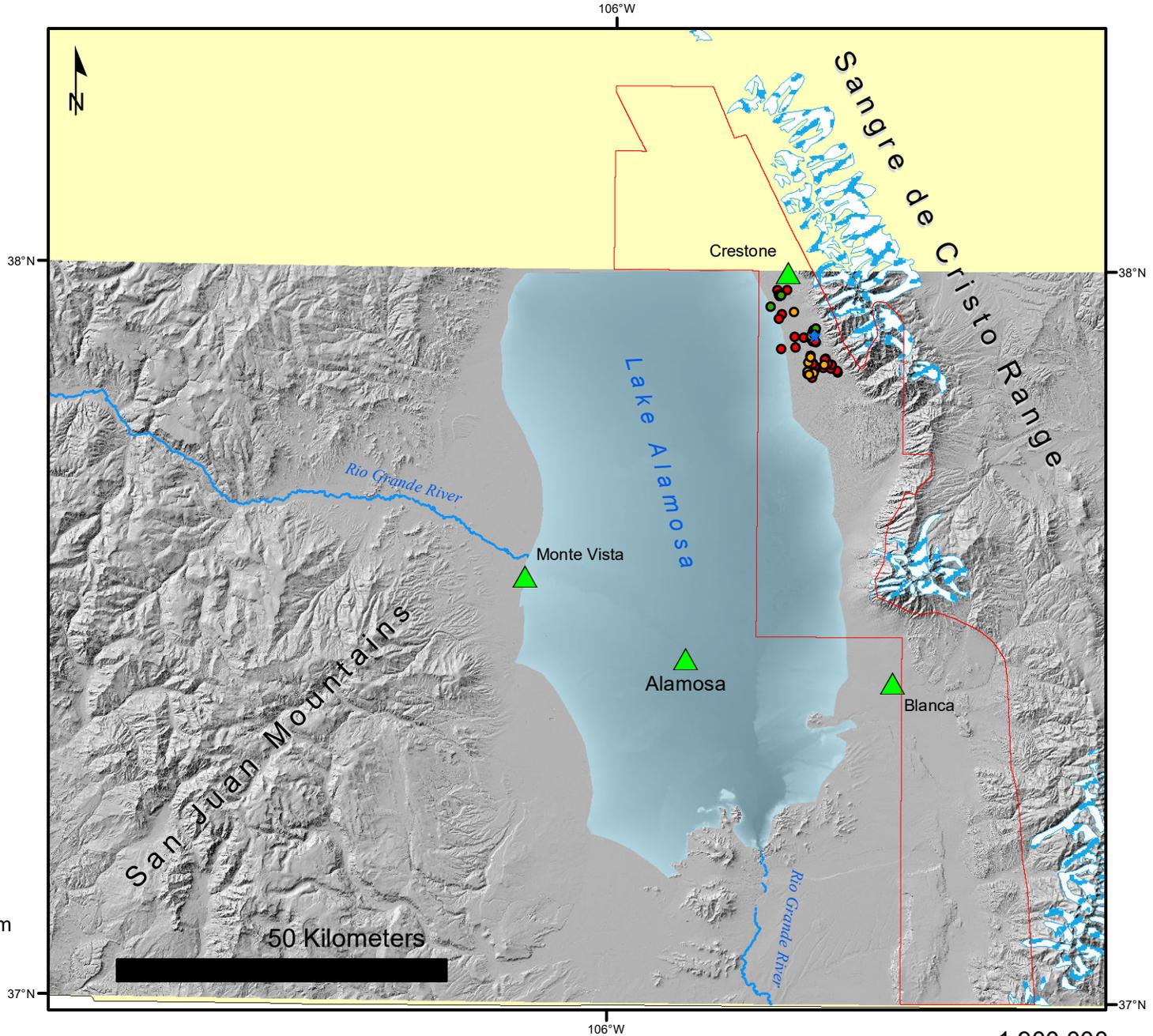
Mapped Pingos and the Geology of the Crestone Region

Geologic Units

- Qal - alluvium
- Qaf - alluvial-fan deposits
- Qes - eolian sand
- Qdf - dunefield
- Qssh - sand sheet
- Qsbk - sabkha
- Ql - landslide deposits
- Qrf - rockfall deposits
- Qrg - rock-glacier deposits
- Qpf - Pinedale fan allluvium
- Qpl - Pinedale lacustrine clay
- Qpt - Pinedale till
- Qbf - Bull Lake fan alluvium
- Qbt - Bull Lake till
- PPNsu - Sangre de Cristo Formation (undivided)
- PPNsc - Sangre de Cristo Formation, Crestone Member
- PPNsl - Sangre de Cristo Formation, Lower Member
- PNm - Minturn Formation
- PNmu - Minturn Formation, upper part
- PNmq - Minturn Formation, quartzose red-beds
- MDOr - Mississippian, Devonian and Ordovician Sed Rocks
- Oh - Harding Sandstone
- Yqm - Quartz Monzonite
- Xm - mafic intrusive rocks
- Xqm - quartz monzonite
- Xlgn - leucocratic gniess
- Xgn - mixed gneiss
- WATER

Mapped Pingos

- ● least confident
- ● somewhat confident
- ● very confident
- ★ Crestone Crater
- Maximum Glacial Extent
- Streams

Lake Alamosa

Great Sand Dunes

Crestone

Qes

Qbf

Qssh

Qdf

Northing (meters)

Easting (meters)

N

0   5   10 Kilometers

Coordinate System: NAD 1983 UTM Zone 13N
Projection: Transverse Mercator
Hillshade is 1/3" or 1/9" resolution based on availabilty

1:150,000