

**Estimating the Volume and of the Huckleberry Ridge Tuff, Yellowstone and the Impact of its Eruption
on Topography**

By Robert Zinke

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Geo 327g/386g

Introduction

The Huckleberry Ridge Tuff is the product of one of the largest known volcanic eruptions in history. This extensive ash-flow sheet was deposited 2.0-2.2 Ma and formed what is now known as the Island Park Caldera. Three distinct and irregular ash-flow deposits, each distinguished by different sizes and distributions, are identified as members A, B, and C (Christiansen, 2001). Estimating eruptive volumes of caldera-forming eruptions is an important part in understanding the potentially devastating effects of these events.

Purpose:

This project estimates the volume of ash-flow material erupted during the formation of the Island Park Caldera using published isopach maps of the Huckleberry Ridge Tuff and ArcGIS software.

Building upon that, this project seeks to develop a fundamental understanding of the maximum displacement of ground surface beneath a caldera due to an eruption as big as the one that produced the Huckleberry Ridge Tuff.

Both of these estimates can be expressed units of length in varying dimensions (i.e. meters, square meters, or cubic meters).

Data Collection

Despite its intermittent exposure and vast extent, the Huckleberry Ridge Tuff has been studied and mapped by a number of geologists. To estimate the volume of the tuff deposits, I determined it would be best to use isopach maps – maps showing depth of the ash-flow deposit at any location expressed as contours. In order to georeference the isopach maps; I used a map of the United States as well as a map of the present boundary of Yellowstone National Park.

- Isopach maps downloaded as PDF files from Christiansen, R. L. *The Quaternary and Pliocene Yellowstone Volcanic Field of Wyoming, Idaho, and Montana*. Western Region, Menlo Park, CA: U.S. Geological Survey, 2001. Print.
- Map of states including Wyoming, Idaho, Montana taken from class folder at R:\geo-class\GEO-327g_386g\Lab_Data_Spring2012\Lab2\Mapproj\states
- Park boundary map taken from class folder at R:\geo-class\GEO327g_386g\Yellowstone_erosion_demo\Park Boundary
- Density of molten rhyolite from Magnúus T. Gudmundsson, Thórdís Hógnadóttir. *Volcanic systems and calderas in the Vatnajökull region, central Iceland: Constraints on crustal structure from gravity data*. Institute of Earth Sciences, University of Iceland, Askja, Sturlugata 7, 101 Reykjavík, Iceland. Received 28 April 2006; received in revised form 26 July 2006; accepted 5 September 2006
- Yellowstone caldera boundary from R:\geo-class\GEO327g_386g\Yellowstone_erosion_demo\Caldera_bndry
- Raster of Yellowstone National Park elevation from R:\geo-class\GEO327g_386g\Yellowstone_erosion_demo\elev_yel

Data/ArcGIS Processing

In a blank ArcMap document, I loaded a map of the United States' state boundaries ("states") from the class folder at R:\geo-class\GEO-327g_386g\Lab_Data_Spring2012\ Lab2\Mapproj\states.

Because this project primarily involves calculating areas and thicknesses, and the most logical units to describe these dimensions in is meters or kilometers, I re-projected the states into UTM Zone 12 coordinates. To do this I used the ArcToolbox>Data Management>Projections and Transformations>Feature>Project tool. I input the original "states" file which is in geographic coordinates (GCS_North_American_1983) and selected the output coordinate system as Projected>UTM> NAD83>NAD83 UTM Zone 12N.prj.

I superimposed on the states map a shapefile of the "Park Boundary" from R:\geo-class\GEO327g_386g\Yellowstone_erosion_demo\Park Boundary which was in the appropriate coordinate system (NAD_1983_UTM_Zone_12N) as the "states" map. Figure 1 below show the result.

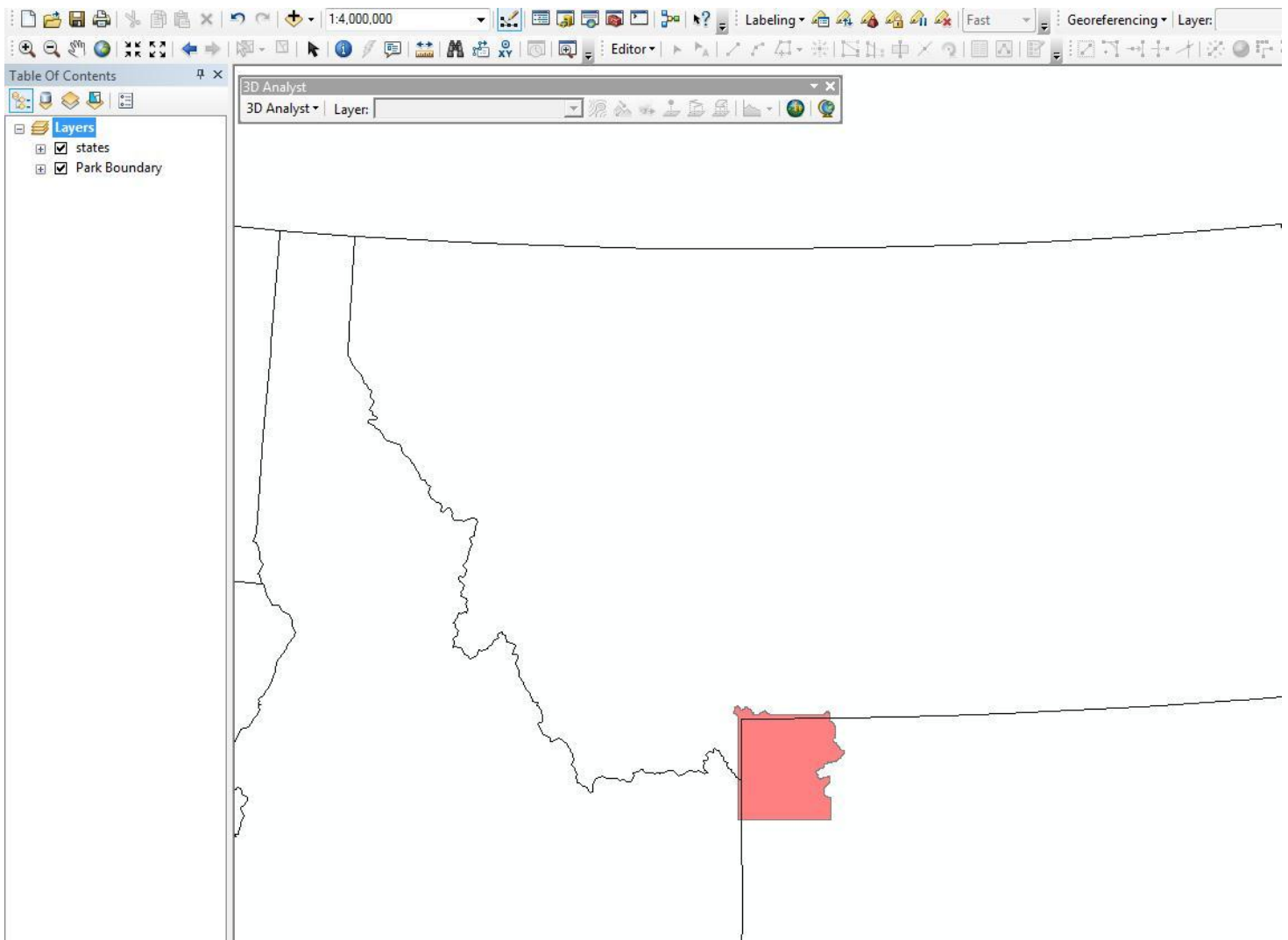


Figure 1 – state and park maps in UTM coordinates

For the project's main objective of calculating a volume of total erupted material, I chose to digitize isopach maps – maps which express the thickness of a specified material in the form of contours. The Huckleberry Ridge Tuff is divided into members A, B, and C. I obtained isopach maps of each of these members from a PDF of Christiansen, 2001 (see reference). These images I saved as JPEGs and loaded into ArcMap. Figure 2 below is an imported image of a non-georeferenced isopach map from Christiansen, 2001.

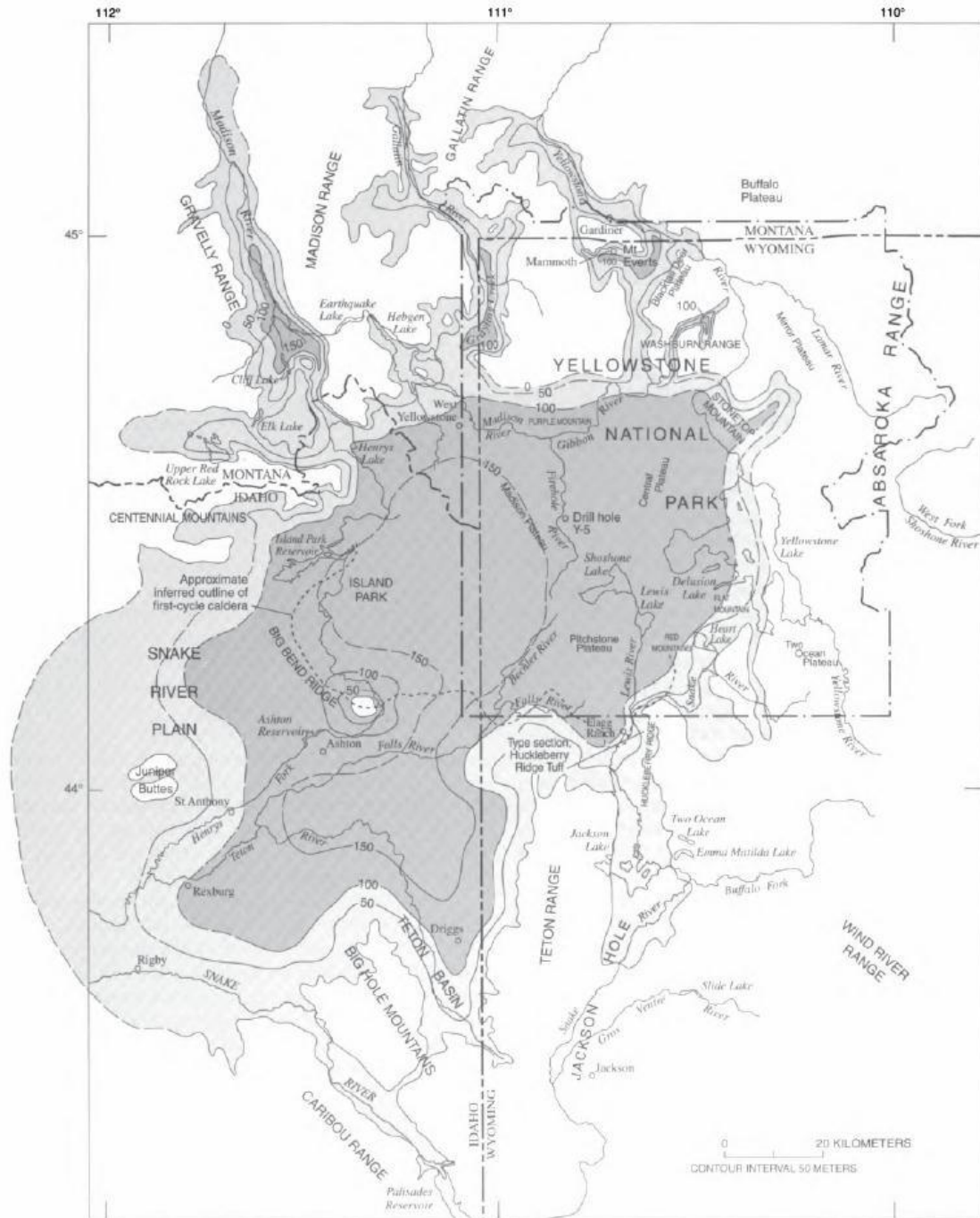


Figure 33.—Areal distribution and thickness of member B, Huckleberry Ridge Tuff, in relation to topographic features in the Yellowstone Plateau volcanic field that affected its distribution. Member B spread widely on surfaces blanketed by older ash flows. The calculated initial area is 15,400 km² and initial volume is 1,340 km³. Shading is darker for thicker sections. Isopachs in meters, dashed where inferred.

Figure 2 – Undigitized PDF of an isopach map in ArcGIS

I georeferenced all three of these maps by matching up very distinct and widely spaced points that are common between the document in ArcMap (containing state and park boundaries at known locations) and the isopach maps from Christiansen (2001). This was done using the Georeferencing tool shown in the upper portion of the screen, with the desired layer selected. Examples of this process are seen below. The top image (figure 3) shows the selection of points, such as along the park/state boundary intersections. The bottom image (figure 4) shows a georeferenced map.

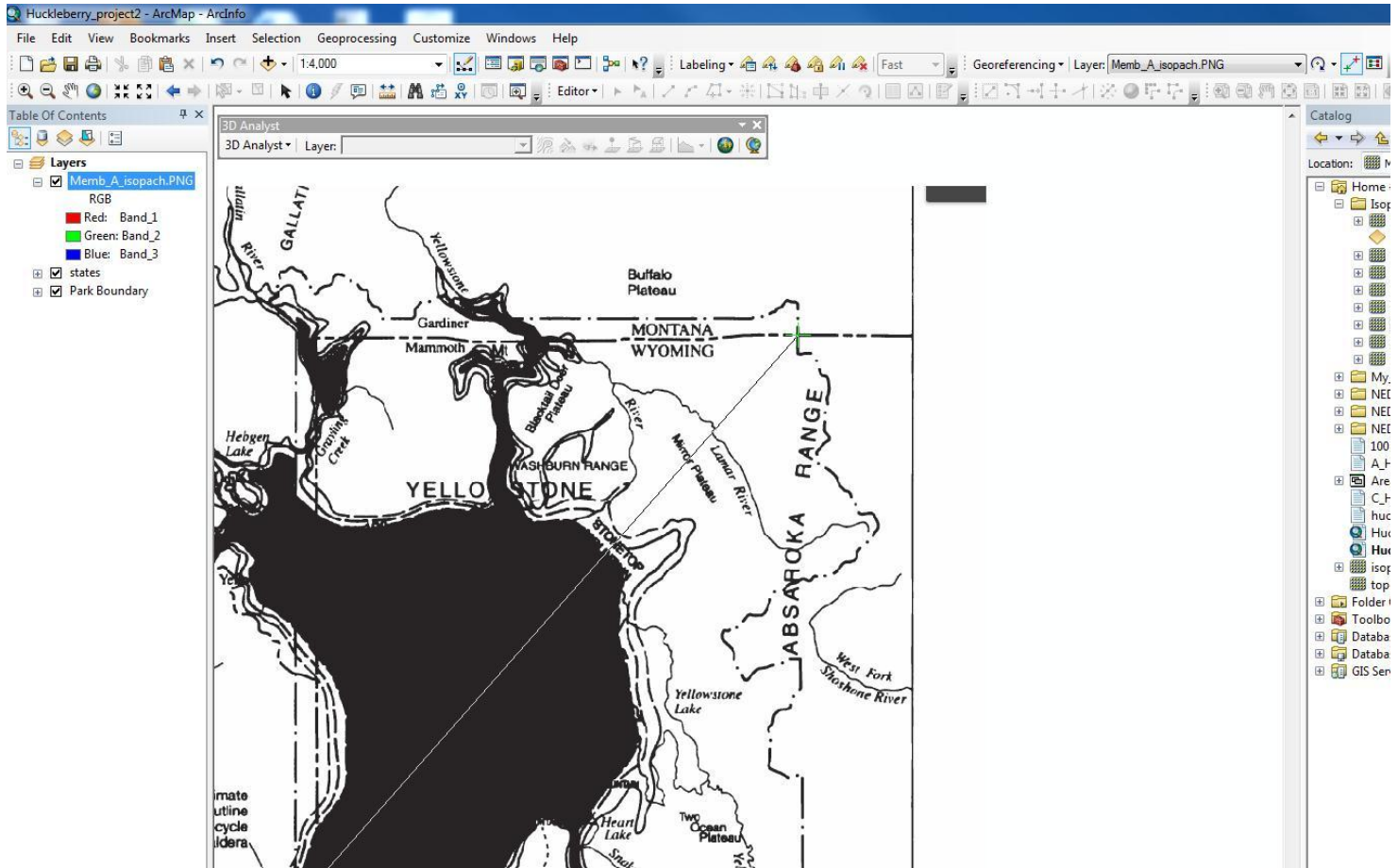


Figure 3 – common point selection during georeferencing

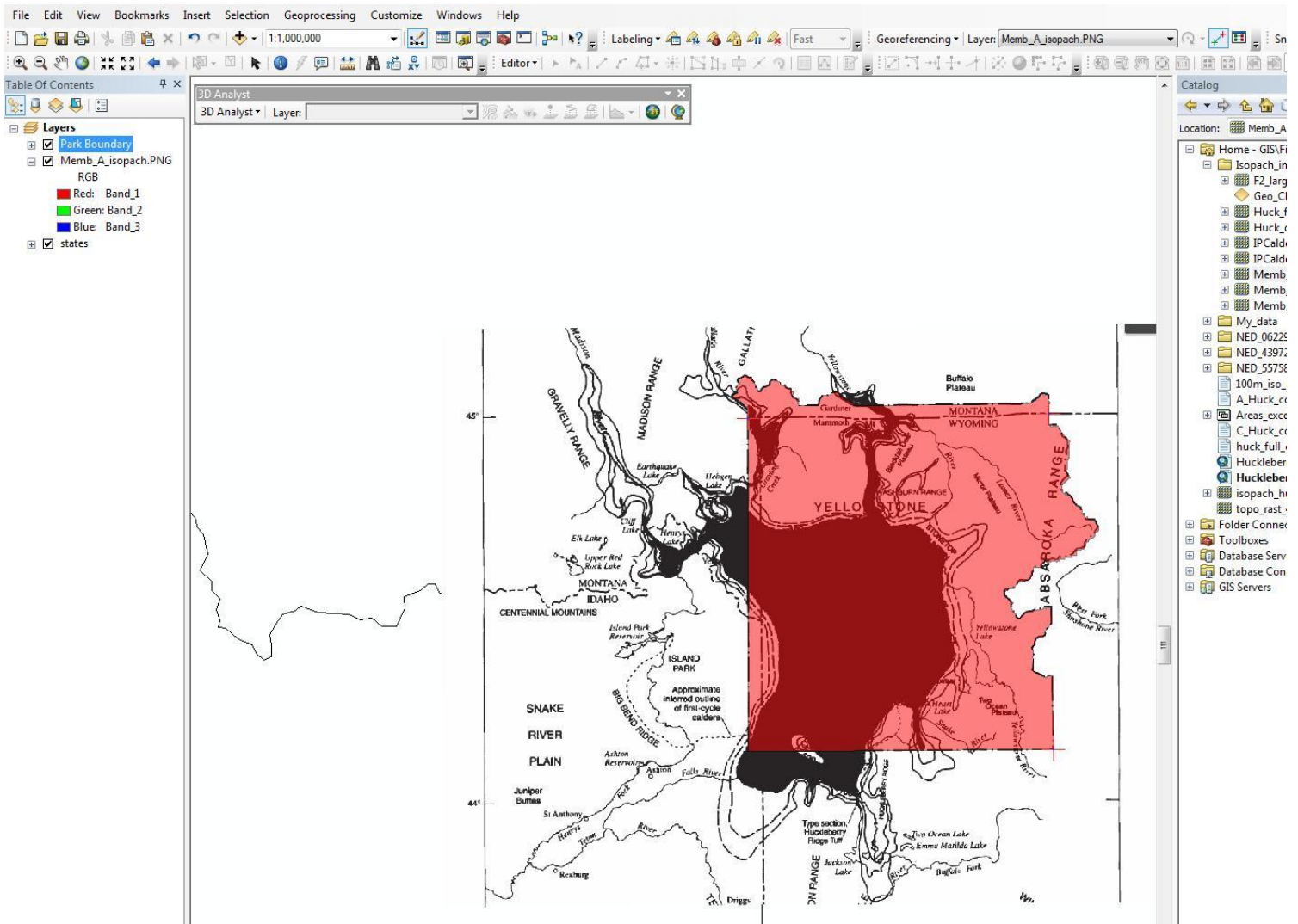


Figure 4 – georeferenced isopach map

Once an image is georeferenced, it shows what the information on that map would look like in the reference frame of the map to which it was georeferenced to within a degree of error. However, the features shown on the isopach maps in this project made no sense to the software. They were just images that could not be analyzed.

In order to transfer the information in these maps into a format usable by ArcMap, I digitized the contours (isopach lines) showing the thickness of the ash-flow deposit beneath. To digitize the isopachs I created separate polygon files to represent each thickness contour. I created polygons by creating a new folder in my “Final Project” folder in ArcCatalog. This I labeled “My_data.” For organizational purposes, I added a new personal geodatabase in “My_data” called “Yellow_isopachs.” By right-clicking

on the geodatabase icon, I selected New and Feature Class. Through this function I created new polygons to represent isopachs. These were named according to the member of which they were a part and the thickness that they represented (i.e. "a_iso_onefifty" is the 150 m isopach of member A). See figure 5 below.

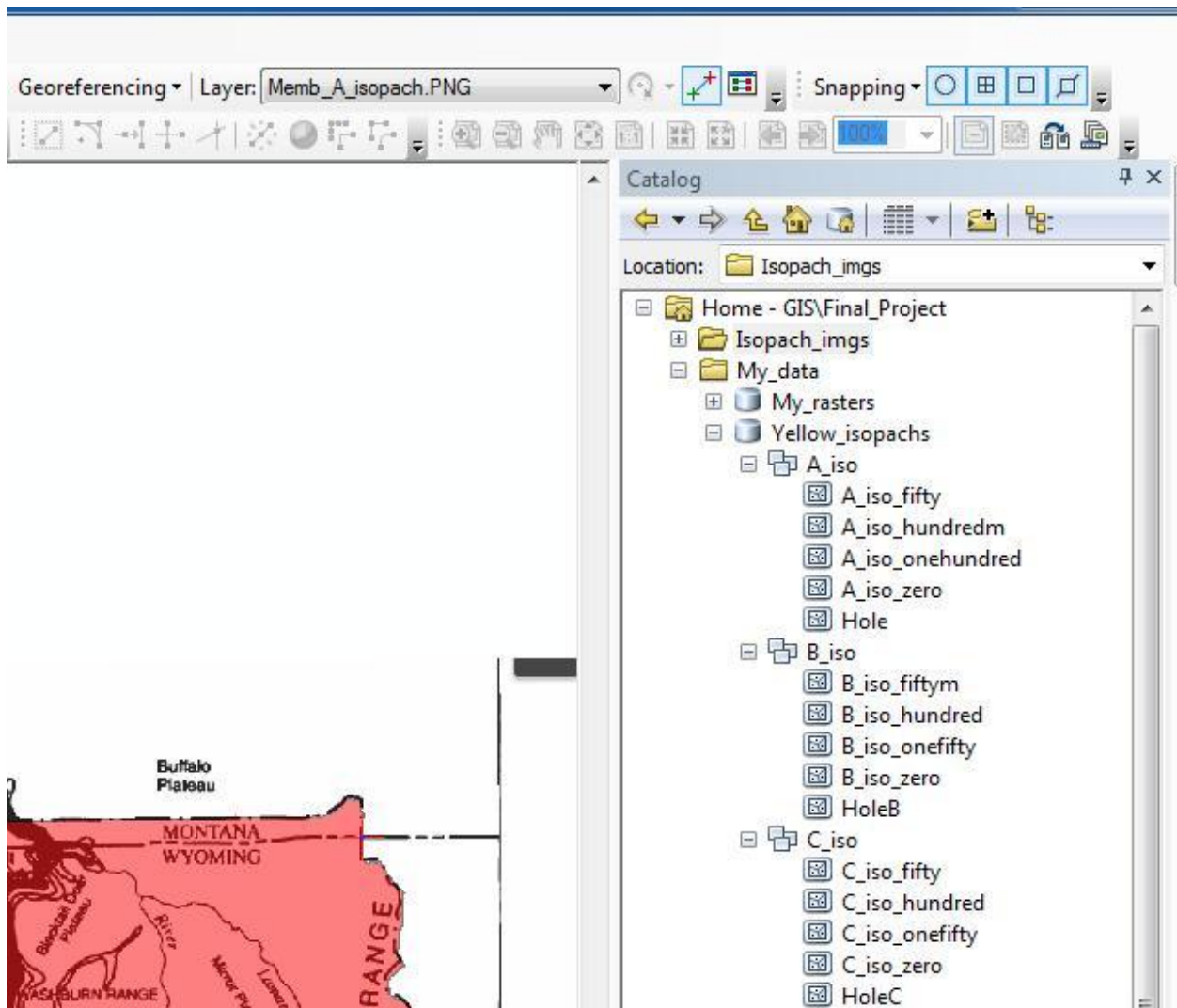


Figure 5 – files of isopach polygons

To create polygons in ArcMap that represented the outlines of each isopach, I activated the Editor in ArcMap. I created a template for each new polygon and carefully traced each isopach line by selecting dozens of points along the line. This process created a polygon that covered the area enclosed by each isopach. I thus had polygons for 0, 50, 100, and 150 meter isopachs for members A, B, and C based on the isopach maps from Christiansen (2001). Figure 6 below shows the polygon created for the 0 m isopach of member A based off of the georeferenced map.

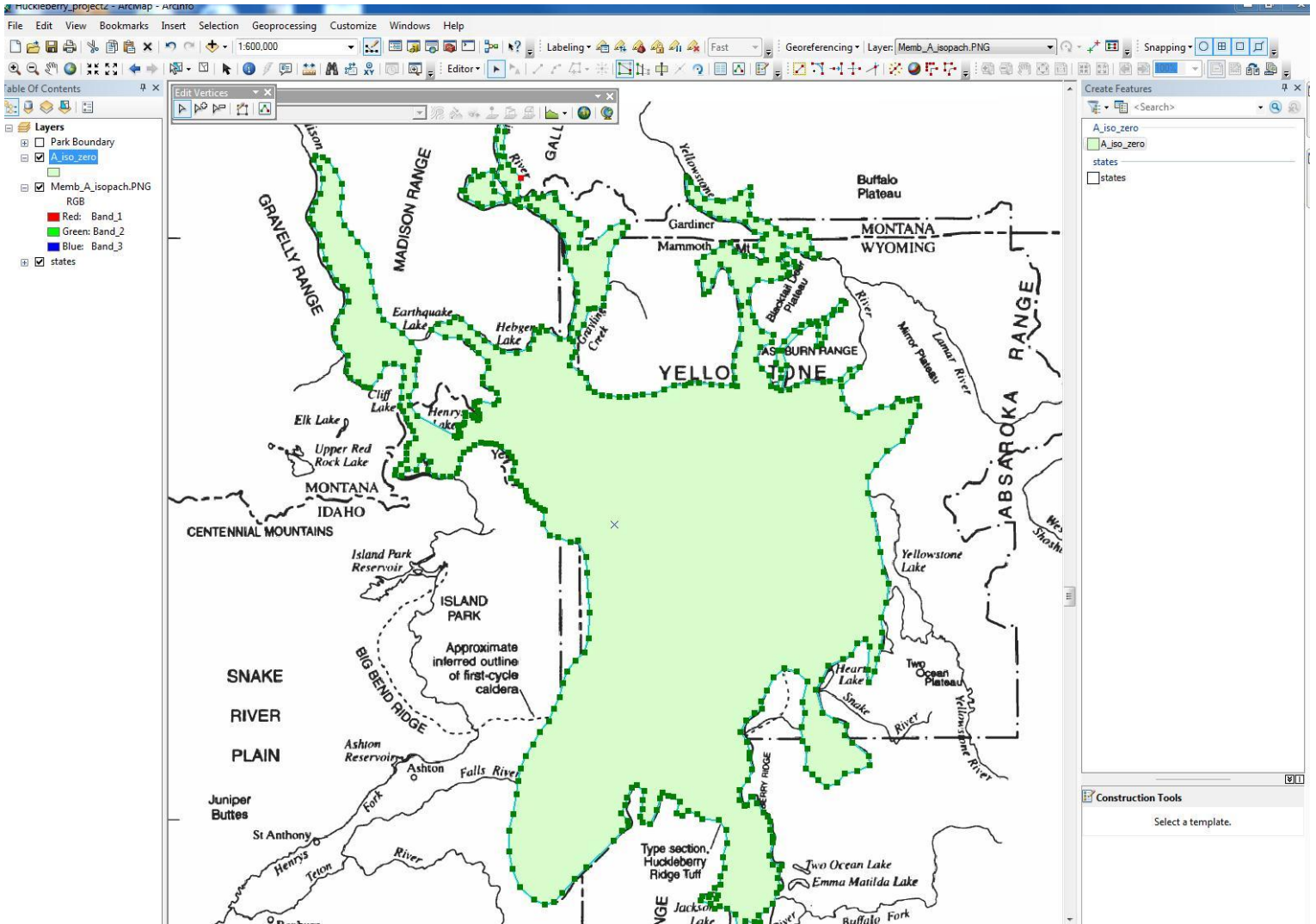


Figure 6 – digitized isopach polygon

While in the Editor, I assigned each polygon “Contour” values that corresponded to the thickness it represented. This was done by opening the attribute table for each polygon, adding a new field labeled Contour, and typing in the thickness value (0, 50, 100, 150) as a float number.

After digitizing each isopach as a polygon, the ArcMap software could now work with the digitized features shown on each isopach map. The issue with the polygons I created was that the area of each polygon included the area covered by the polygons within it. For instance, the 0 meter polygon included the area of the 50 meter polygon that it enclosed. To solve this issue, I “clipped” each polygon to contain only the area that it exclusively covered. The top image below (figure 7) shows all of the isopach lines for all three members. The lower image (figure 8) shows the isopach lines in member C only being clipped.

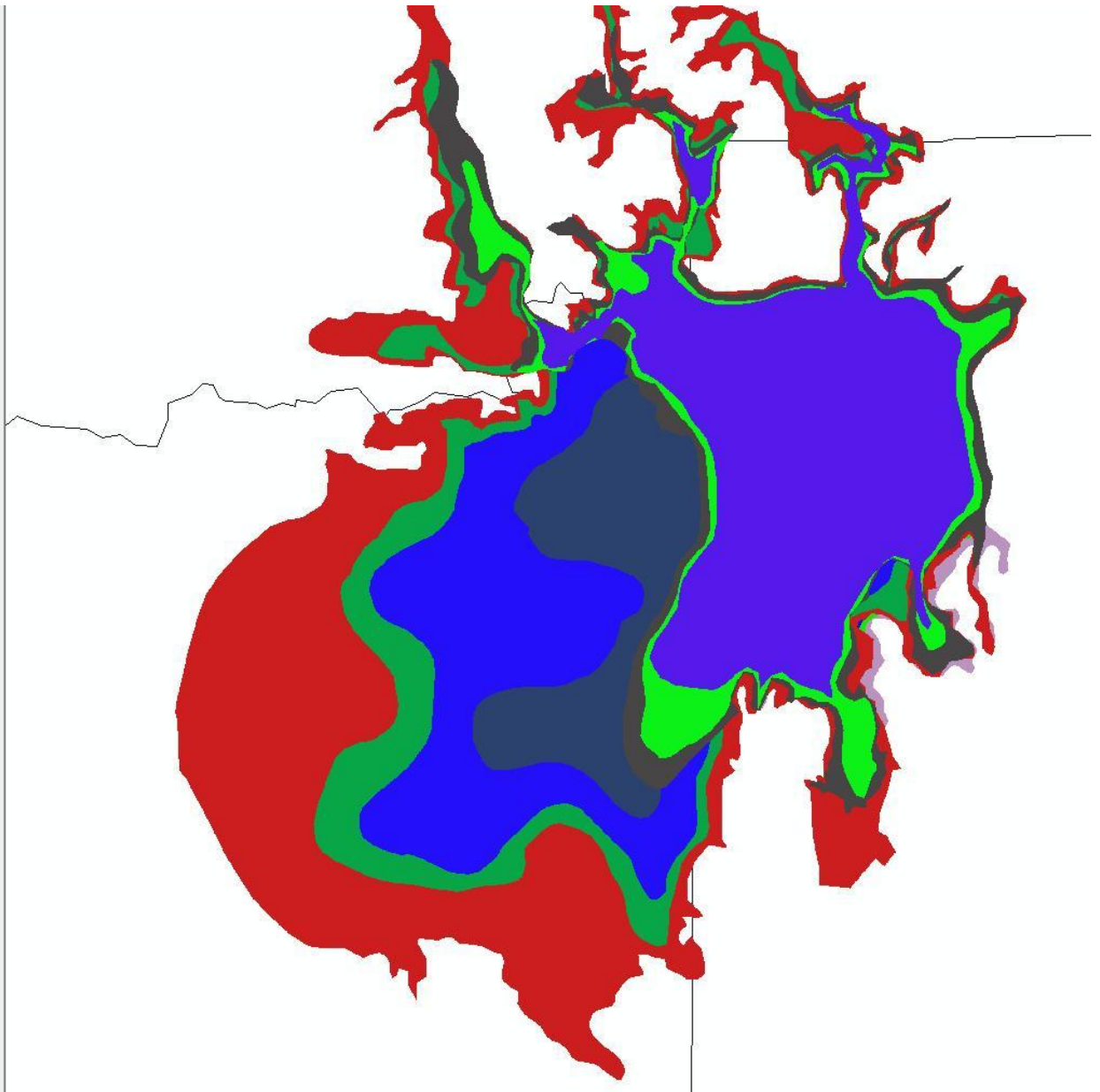
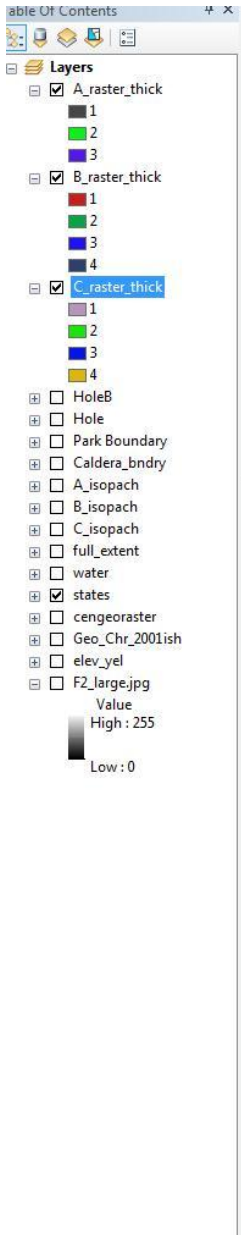


Figure 7 – all isopach polygons digitized

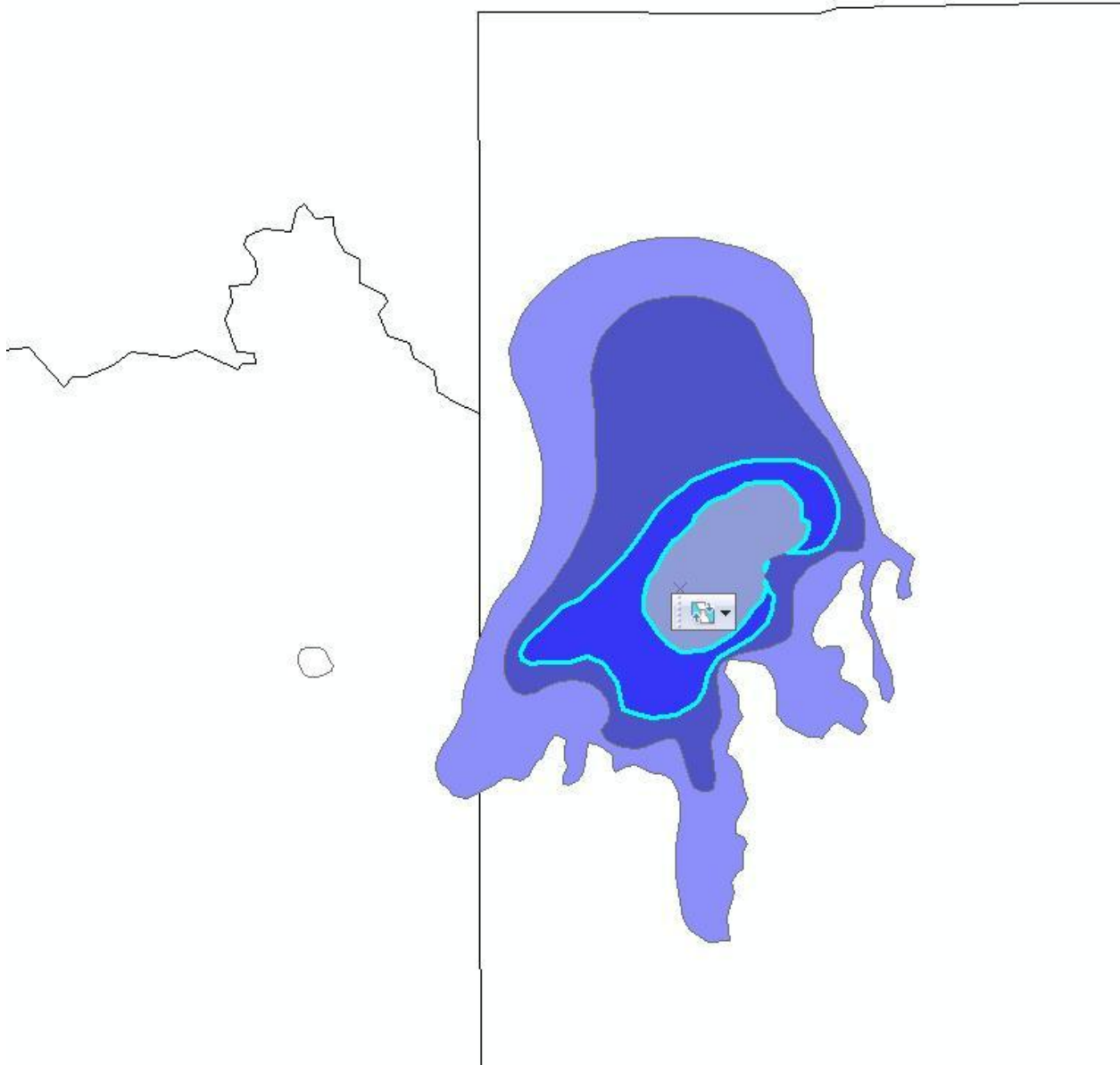


Figure 8 – “donuts” created during clipping of isopach polygons (member C shown above)

The total areas of the isopach polygons for each member (A, B, C) was calculated in ArcMap by opening the attribute table for each member and creating an attribute field called Area. The area in square kilometers of each polygon was calculated using the Calculate Geometry option. Each member’s area was compared to the footprint of each member published in Christiansen, 2001. My calculated areas in ArcMap matched reasonably with those published (see Results). Figure 9 shows the areas as calculated in the attribute table for each polygon. The area for member B is shown.

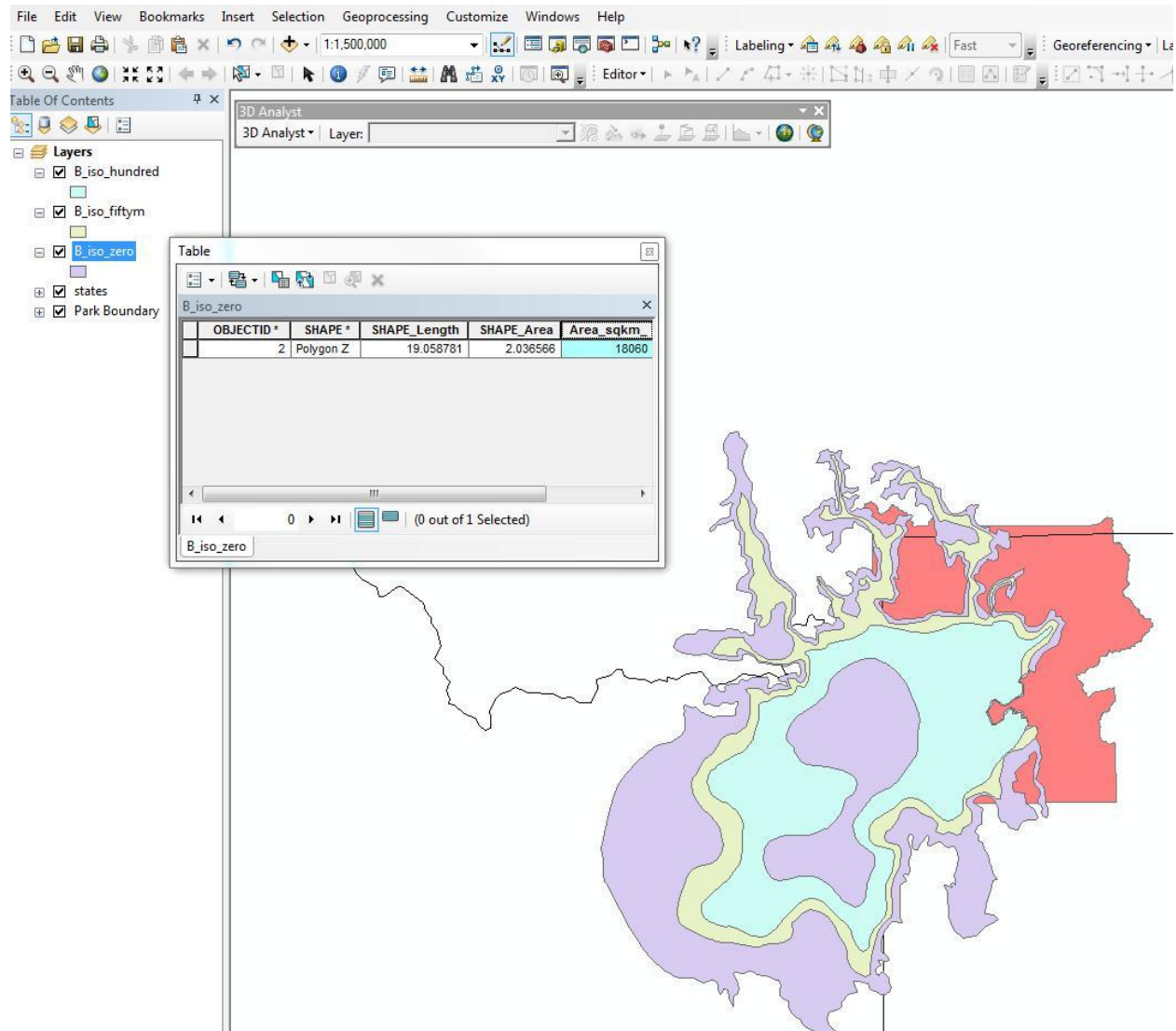


Figure 9 – areas calculated for polygons in Attribute Table

Before attempting to calculate the total volume, I first grouped each member's isopach polygons into a single file. This was achieved by using the Merge tool in ArcToolbox>Data Management. The inputs were simply the different contours for each member and the process was repeated for all three members. The features were merged so that they could later be input and operated on as a single unit corresponding to each member, A, B, and C. Figure 10 shows the lines merged as a single unit. Each line maintained its attribute corresponding to thickness.

- A_feat_line
- topo_rast_c6
- topo_rast_a6
- topo_rast_b5
- Park Boundary
- states
- water
- C_iso_oneyifty_1
- B_iso_oneyifty_1
- A_iso_hundredm_1
- full_extent

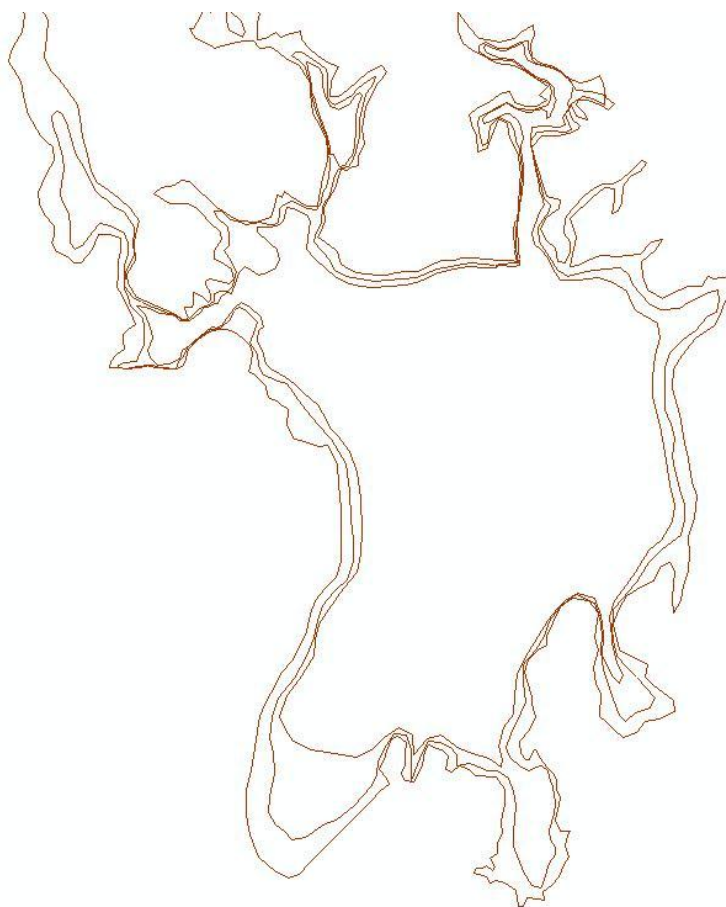


Figure 10 – lines merged

Now, with polygons representing the isopachs, I wanted to interpolate the thicknesses of the ash-flow deposits at many points in each deposit, the summation of all of these thickness measurements would yield a close approximation of volume of each member. I decided that a raster with thickness values corresponding to each cell would provide thousands of localized thickness measurements.

Dr. Helper and I determined that the best way to create a raster from the isopach lines is to treat the isopachs as contours and then convert the contours to rasters for each member.

In order to convert the isopach polygons to lines resembling topography lines, I used the Polygon to Line tool in ArcToolbox>Data Management. To access this tool, activated the 3D Analyst extension, then ArcToolbox>3D Analyst>Raster Interpolation>Topo to Raster.

To create a raster of the ash-flow thicknesses found in the first member (A), I set the input feature to my A isopach set of topo lines. I named the output file topo_rast_a to indicate that it's a raster created

from topo lines for member A. The Output cell size I set to 500 m because this is a round number and is sensible for the large scale of the project. The z values represent the thickness of the ash-flow deposit, so I set the Smallest z value to 0 (meters thickness, where there is no deposit) and the Largest z value to 190 (so that the thickness could be interpolated above the highest contour). Drainage enforcement was set to NO_ENFORCE because we are not dealing with hydrology, and the Primary type of input data was set to CONTOUR, since this is what we are trying to show in raster format. The tool used for member A is shown in figure 11 below.

This step was repeated for members B and C.

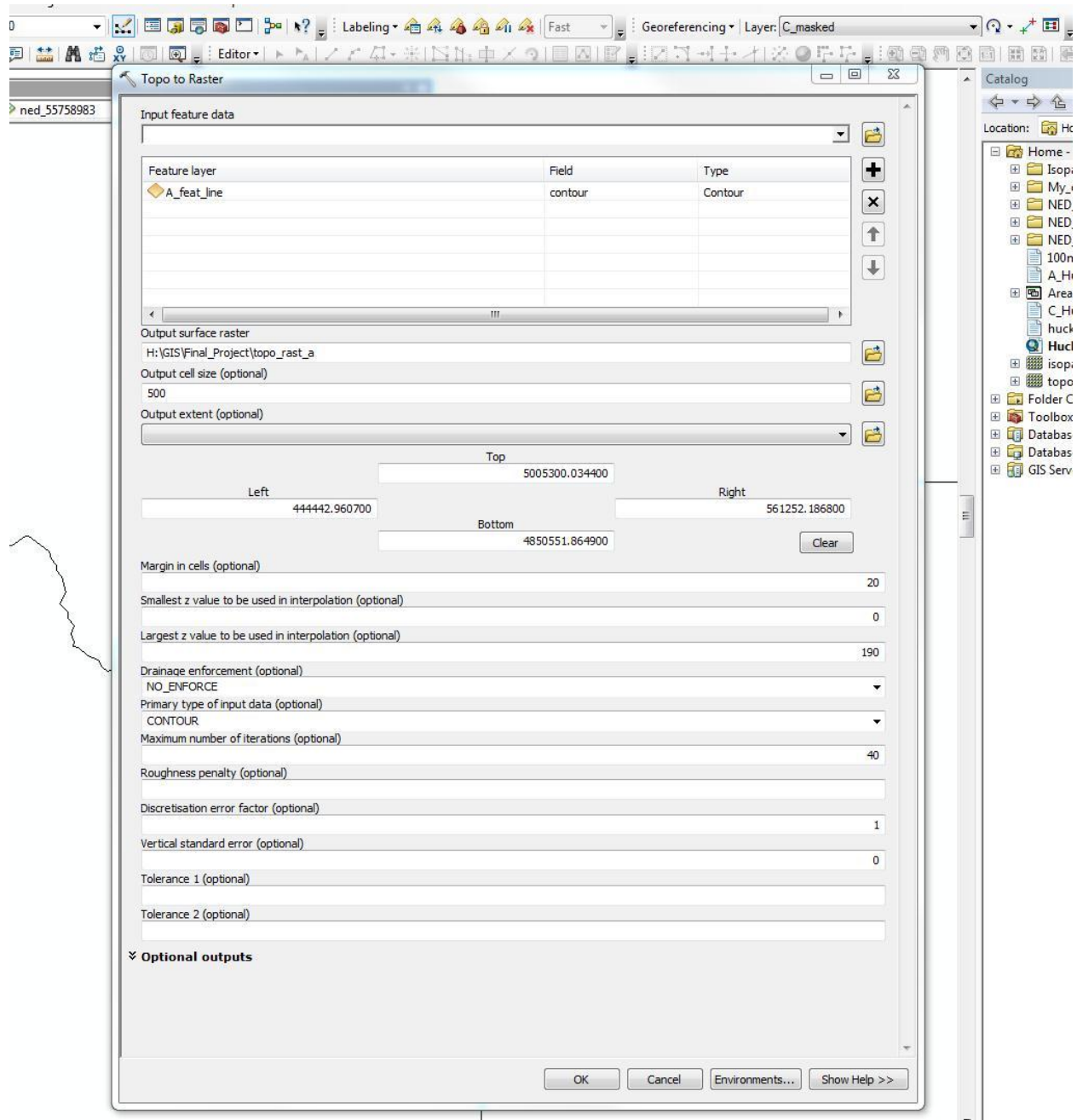


Figure 11 – tool for converting isopach lines to thickness rasters

Figure 12 shows the raster produced for member A.

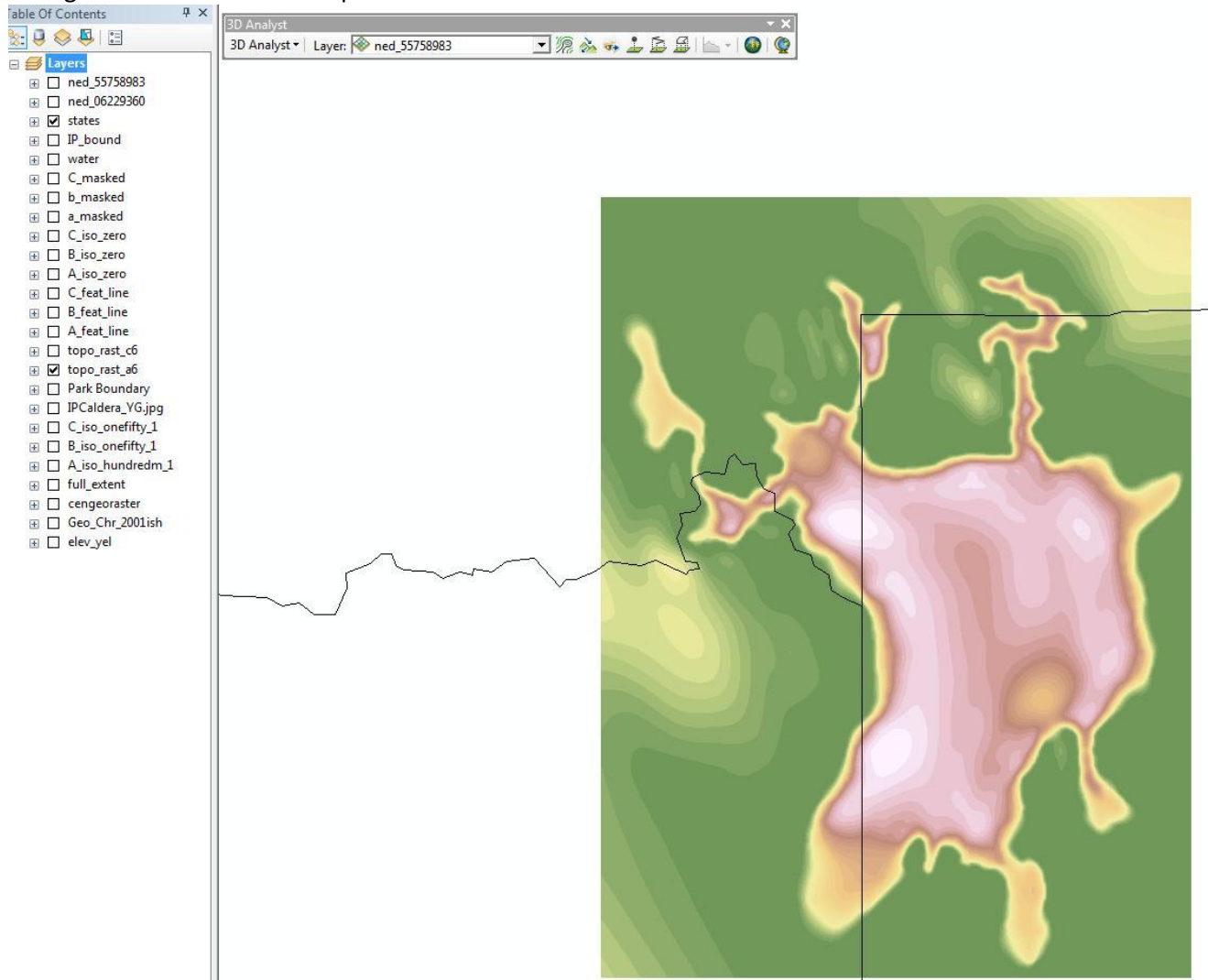


Figure 12 – thickness raster created from isopach maps

The rasters created in the previous step included thicknesses extrapolated beyond the borders of the 0 meter isopachs. To remove this excess area outside the 0 meter line, I merged all of the topo lines corresponding to member A into a single feature, which I converted into a polygon. This polygon represents the extent of the mapped ash-flow deposit of member A. The outside border of this line represents the 0 m isopach.

To remove the excess raster data, I activated the spatial analyst extension and opened ArcToolbox>Spatial Analyst tools>Extraction>Extract by Mask tool. The Input raster is the raster created using the topo to raster tool (see figure 13). The Input raster or feature mask data is the polygon created in the previous step. I assigned the Output raster to be A_masked. A raster showing thicknesses throughout the deposit and within the deposit boundaries was thus created (shown below in figure 14).

- ned_55758983
- ned_06229360
- IP_bound
- C_masked
- b_masked
- a_masked
- C_iso_zero
- B_iso_zero
- A_iso_zero
- C_feat_line
- B_feat_line
- A_feat_line
- topo_rast_c6
- topo_rast_a6
- topo_rast_b5
- Park Boundary states
- water
- C_iso_onefifty_1
- B_iso_onefifty_1
- A_iso_hundredm_1
- full_extent

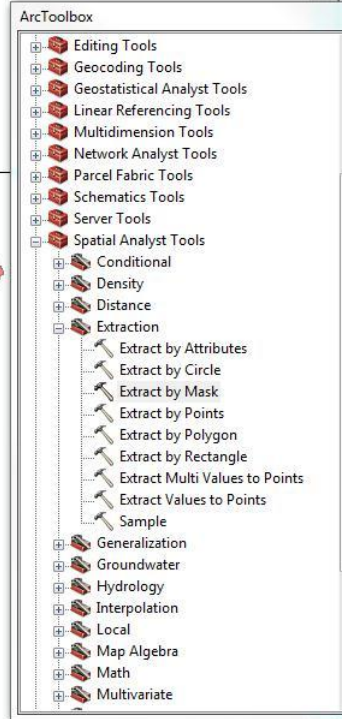
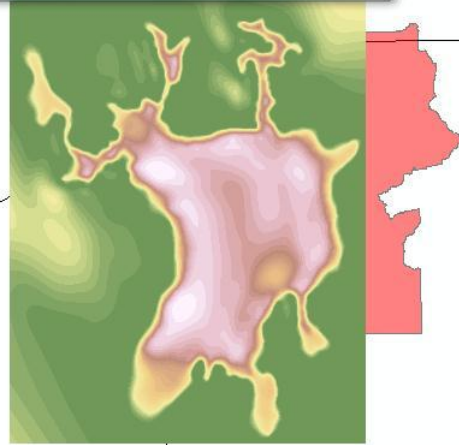
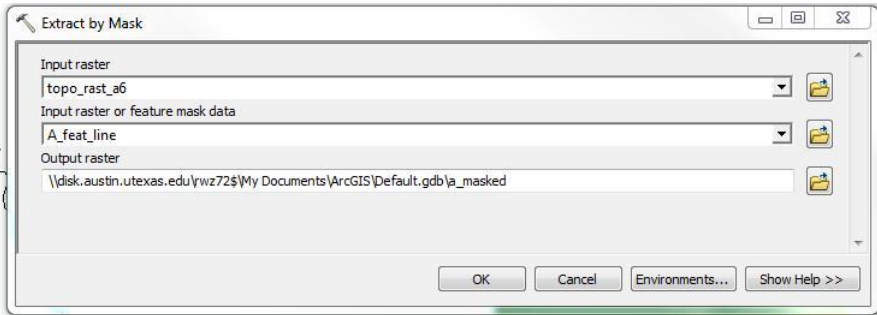


Figure 13 – extracting relevant parts of each raster using a mask

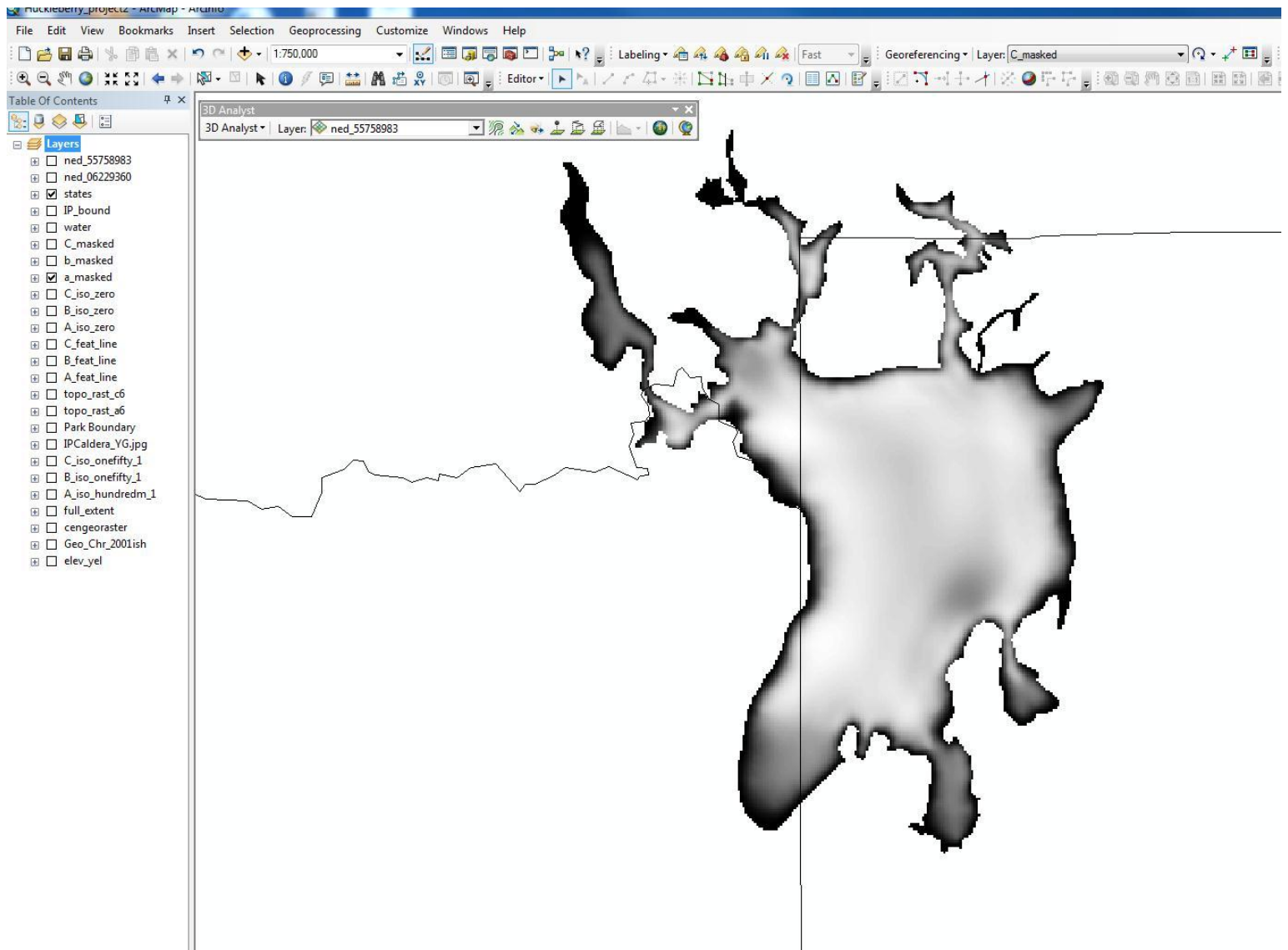


Figure 14 – thickness raster extracted by mask

I repeated the previous two steps for members B and C.

There are now three separate rasters (for members A, B, and C) showing the extent and interpolated thicknesses of the deposits. We now want to calculate the volumes of each of these members. For this step, I opened the Surface Volume tool from ArcToolbox>3D Analyst Tools> Functional Surface. For member A I set the Input Surface to A_masked (from the masked raster of member A) and set the output file to an appropriately named text file. The other options I left as default (shown in figure 15). This tool creates a table in the Table of Contents (left side of the screen). I opened this table by right-clicking on it and selecting “Open.” The 3D volume was given in meters. Figure 16 shows the opened table of information, including volume in cubic meters.

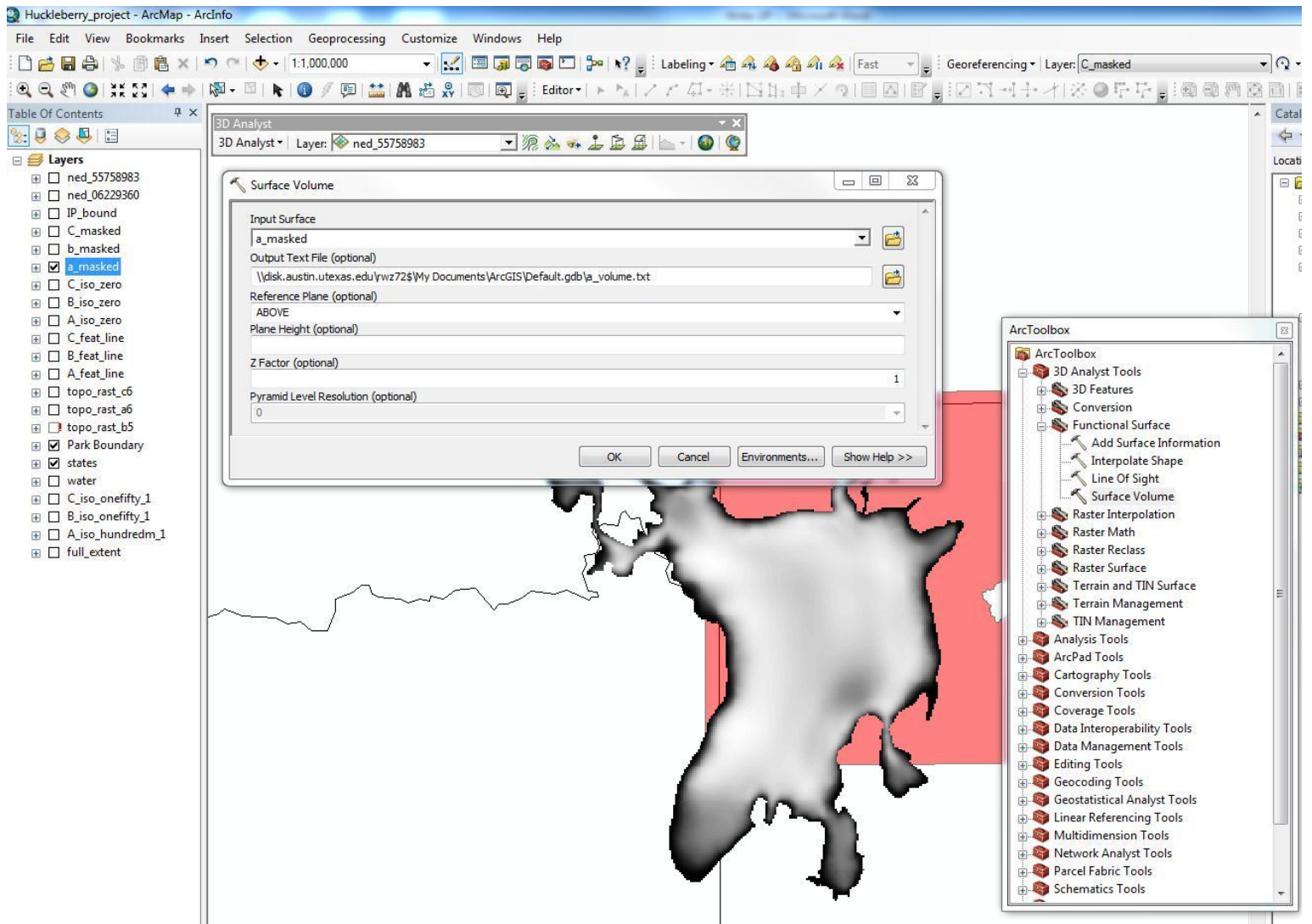


Figure 15 – volume calculation from thickness raster

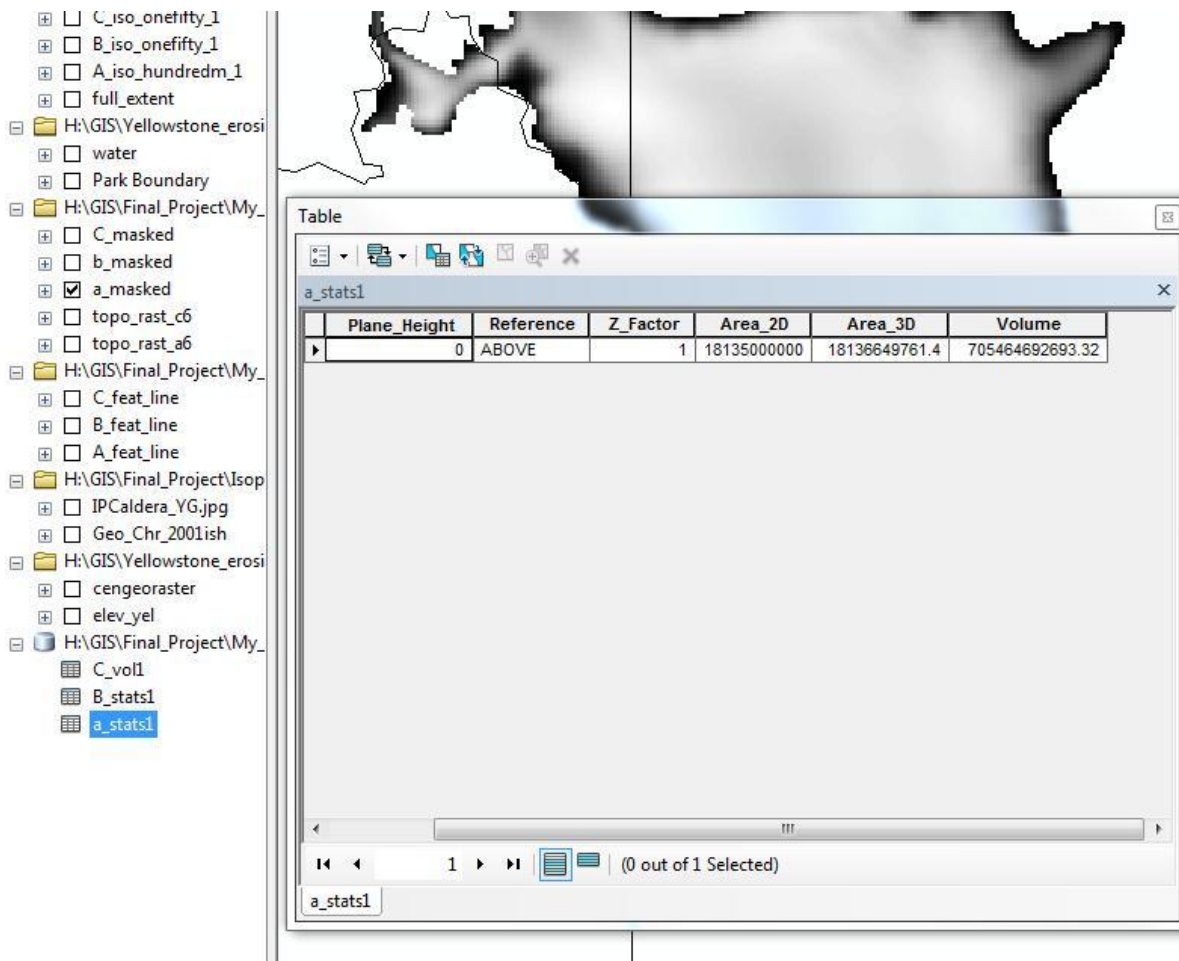


Figure 16 – volume of ash-flow deposit in a text file

Doing this for all three members, I calculated a sum total volume of ash-flow deposits associated with the Huckleberry Ridge Tuff. Results are shown below.

To make the map visually intuitive and aesthetically pleasing, I labeled the states by right-clicking on “states” in the table of contents and selecting the Label Features option. The state names interfered with the ash-flow symbols, so I converted them to annotation and relocated them. I also changed the symbology of the state outlines to reflect a common state boundary pattern.

I raised the transparency of the national park area using the Display tab in the “Park Boundary” properties, and labeled the feature accordingly using the method above.

The deposits themselves overlap and are therefore difficult to visualize all at once. To represent them all simultaneously, I made each of them 60% transparent and used colors bands that transitioned from light to dark in more or less a single color (yellow for member A, green for member B, and blue for member C). Figure 17 shows a nearly finished product.

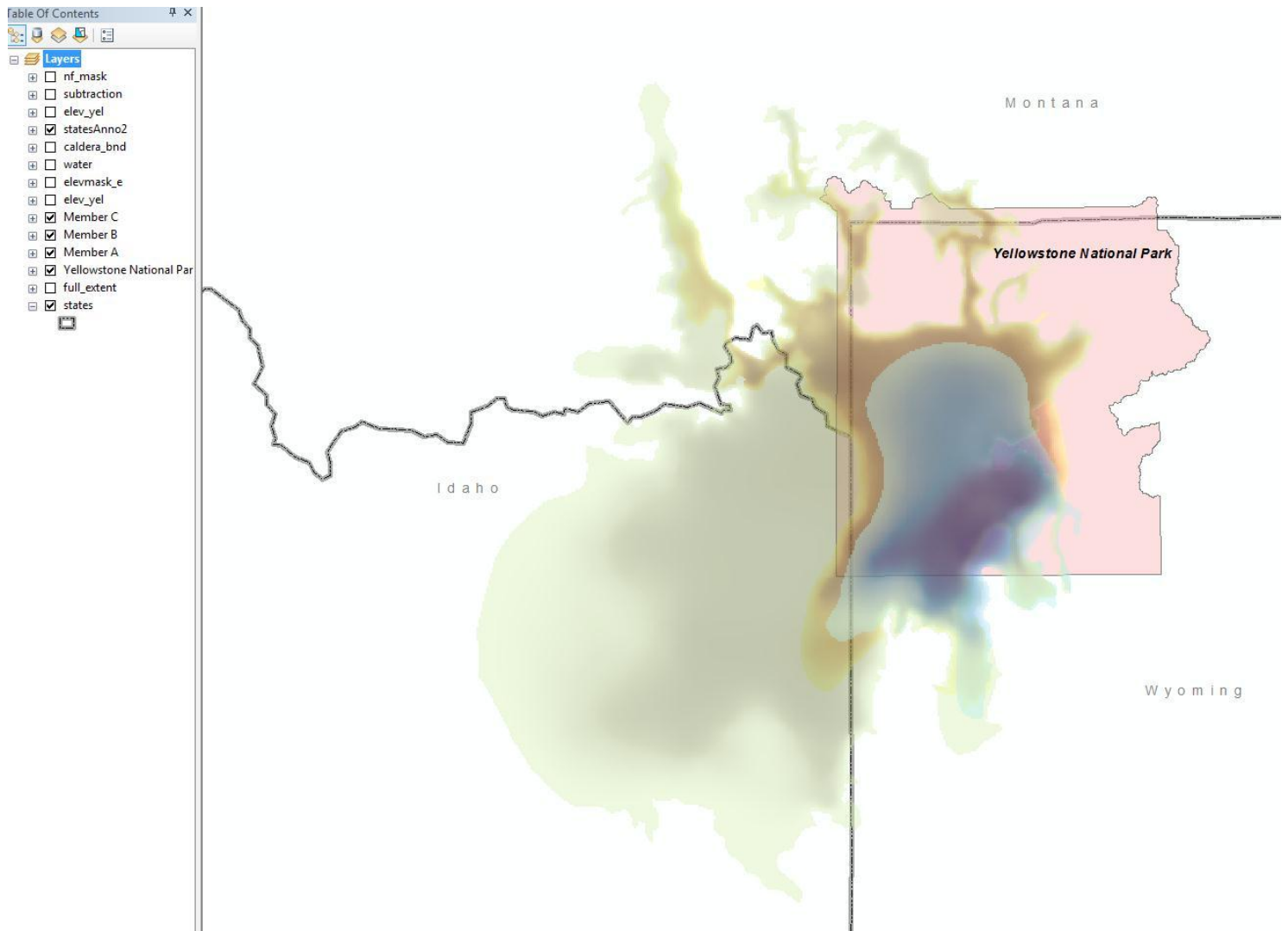


Figure 17 – rasters of members A, B, and C of the Huckleberry Ridge Tuff

I next wanted to show the elevation drop in the present Yellowstone Caldera floor if this amount of material were to erupt within the near future. To do this, I assumed a perfect piston model (a very large assumption!) in which the entire caldera floor drops uniformly and in proportion to the amount of material erupted. The volume of magma erupted was calculated based on an approximate density of welded tuff, such as that seen at Huckleberry Ridge (Christiansen, 2001), an approximate density of the magma beneath Yellowstone (Magn'us and Th'ord'is, 2006) and the volume of the tuff calculated above. I calculated the volume of magma to be 2236 cubic kilometers.

The present Yellowstone Caldera lies within the Yellowstone National Park boundaries. I used the shapefile of its boundary provided in a previous lab R:\geo-class\GEO327g_386g\Yellowstone_erosion_demo\Caldera_bndry. I traced over the caldera boundary with a new polygon (with projected coordinate system UTM zone 12) named "caldera_bnd." In the attributes table of this polygon I calculated the area of the caldera, in a similar manner to which I calculated the area of each

ash-flow tuff unit. I found this area to be 2471 square kilometers. Figure 18 shows the caldera boundary in ArcMap. Figure 19 shows a polygon representing the caldera and the calculated area in the attribute table.

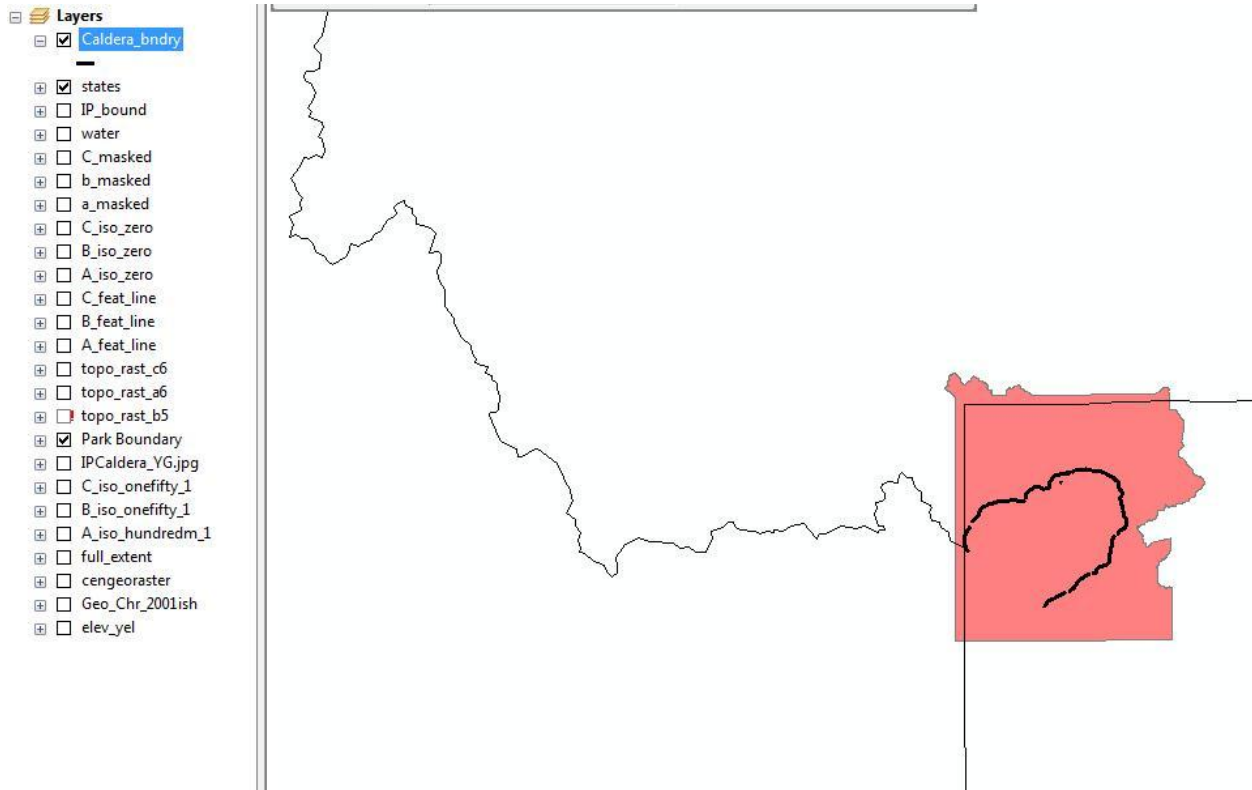


Figure 18 – Yellowstone caldera boundary

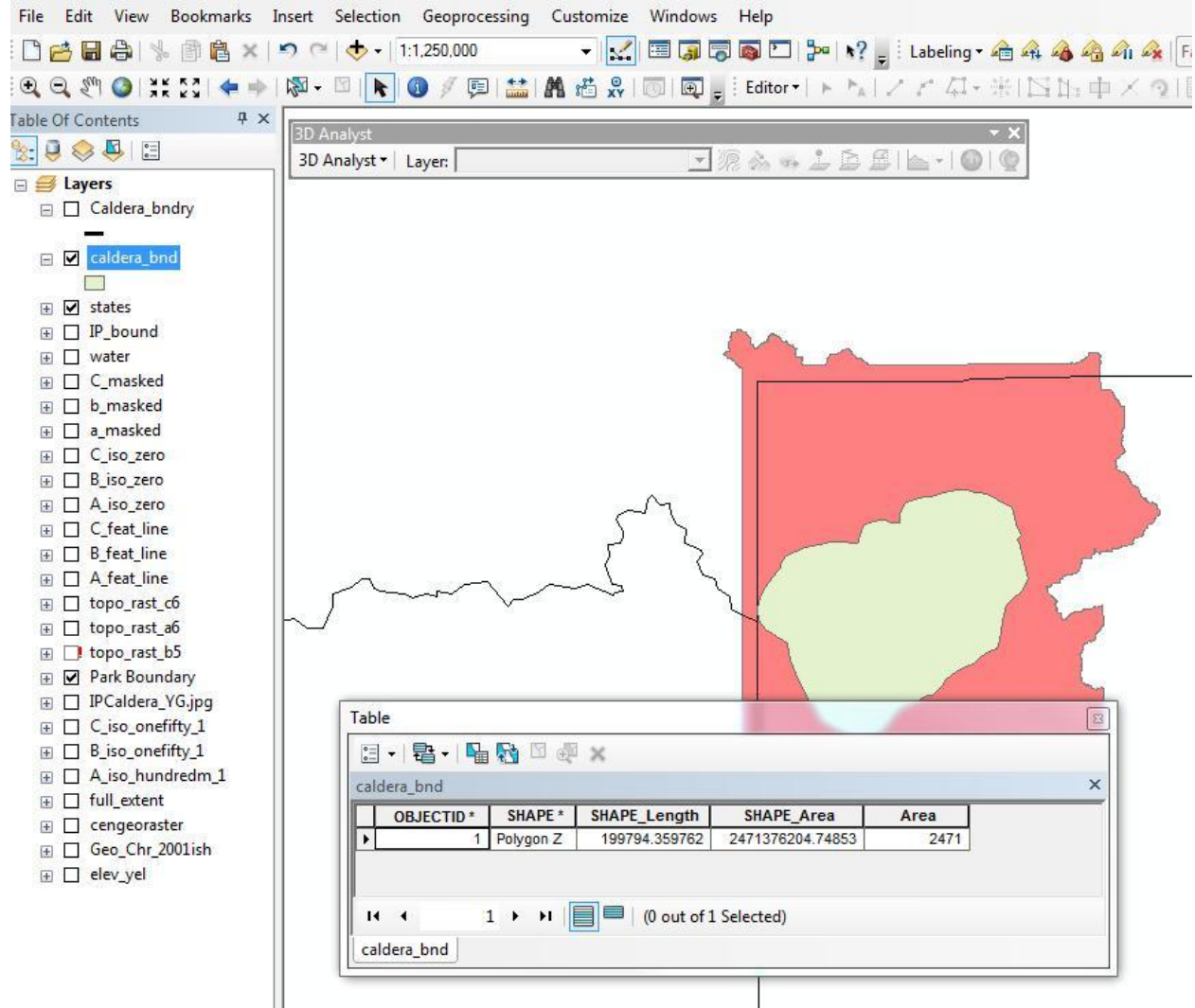


Figure 19 – polygon of the Yellowstone Caldera

If the next super eruption of the Yellowstone hotspot were to erupt from a caldera the size of the present Yellowstone caldera with the volume of the Huckleberry Ridge Tuff (the largest eruption produced by the Yellowstone hotspot), what would the drop in the caldera floor be assuming the caldera floor drops like a piston?

I used the calculated volume of magma and the area of the caldera (2338 cubic km/2471 square kilometers) to find a drop in elevation of 0.95 km.

To show this drop using ArcGIS, I added a raster of the present topography of Yellowstone National Park and its immediate surroundings from R:\geo-class\GEO327g_386g\Yellowstone_erosion_demo\elev_yel. This raster is shown in figure 20.

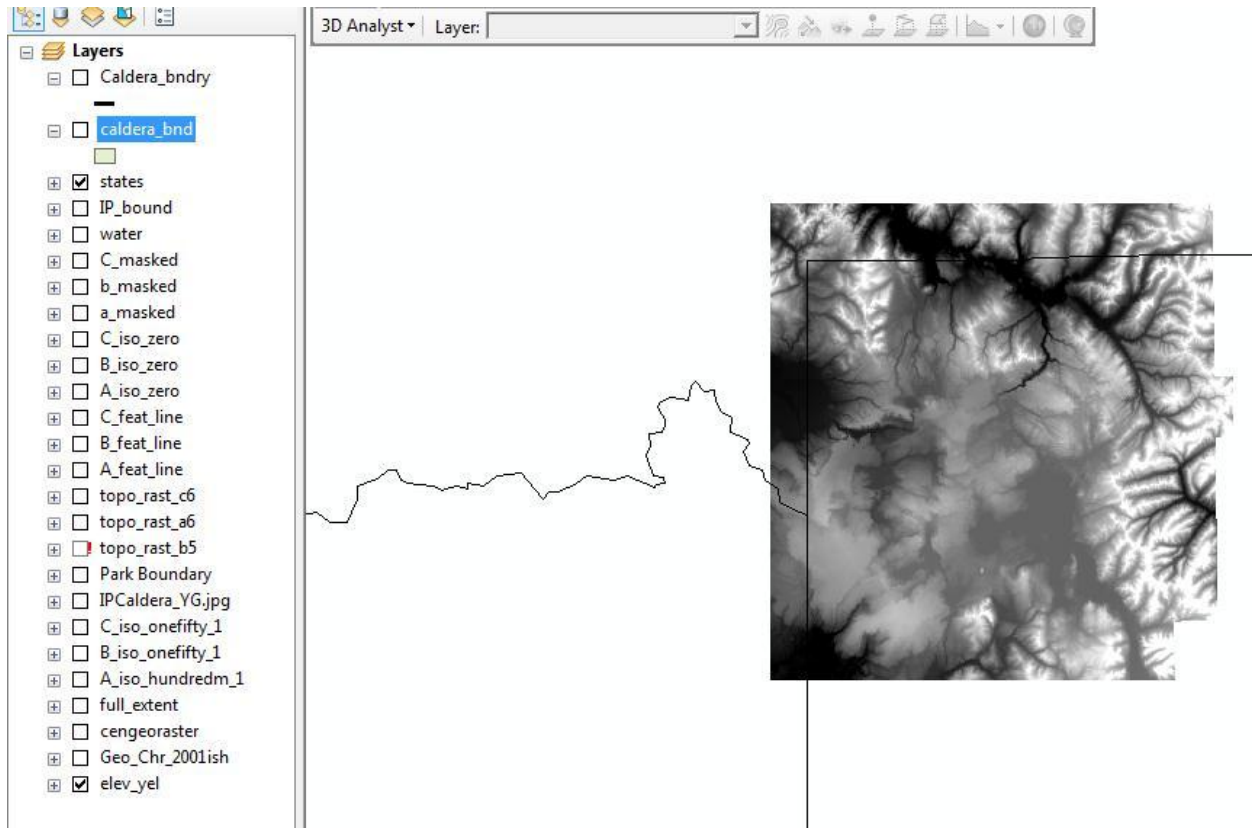


Figure 20 – elevation raster of Yellowstone National Park

To create a raster of the dropped caldera floor, I created a new raster using ArcToolbox>Spatial Analyst>Raster Creation>Create Constant Raster and created a raster called “ninefitym” that was a constant 950 meter surface (the amount of drop of the caldera). This surface is shown in figure 21.

- ninefifty
- 950
- subtraction
- elev_yel
- statesAnno2
- caldera_bnd
- water
- elevmask_e
- elev_yel
- Member C
- Member B
- Member A
- Yellowstone National Par
- full_extent
- states

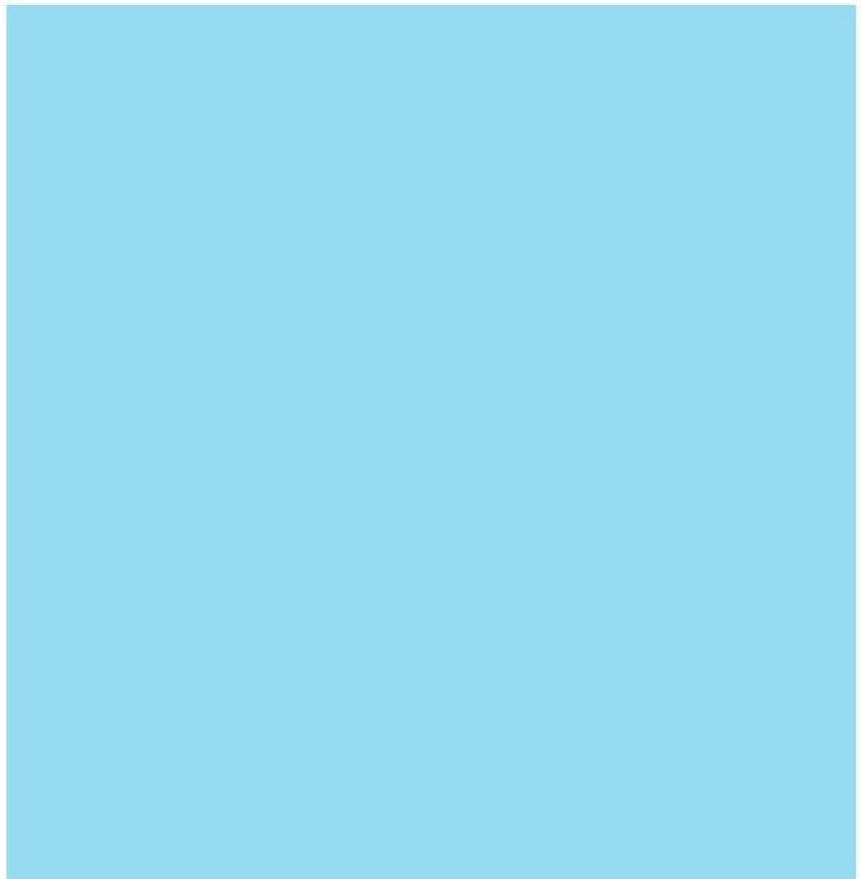


Figure 21 – a constant elevation surface

I masked the constant surface to the shape of the caldera boundary in a process similar to the masking processes described above. I named it “nf_mask” for 950 masked raster (see figure 22 below).

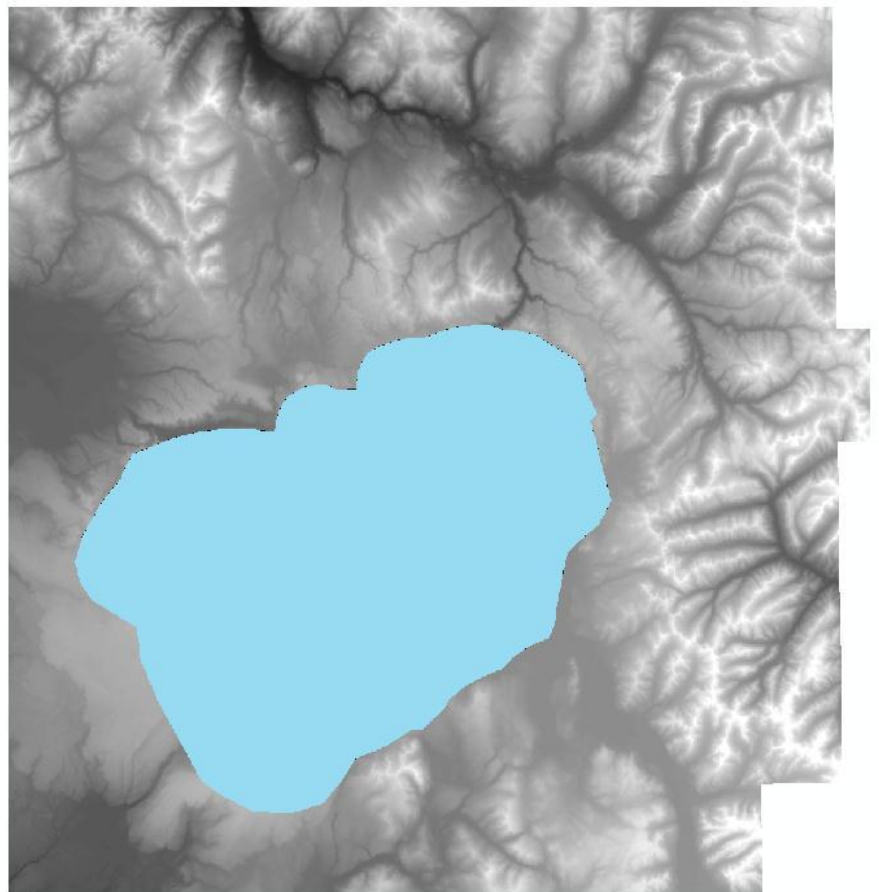
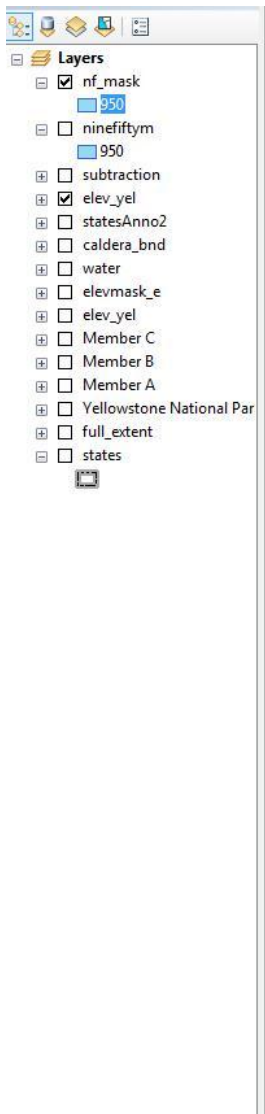


Figure 22 – masking area of the constant elevation surface over the Yellowstone elevation raster

I used the raster calculator under Map Algebra to subtract the 950 meter masked raster from the original elevation raster. The output is a raster similar to the original elevation raster, “elev_yel,” but 950 meters lower and with the dimensions of the caldera. I named this raster “subtraction.”

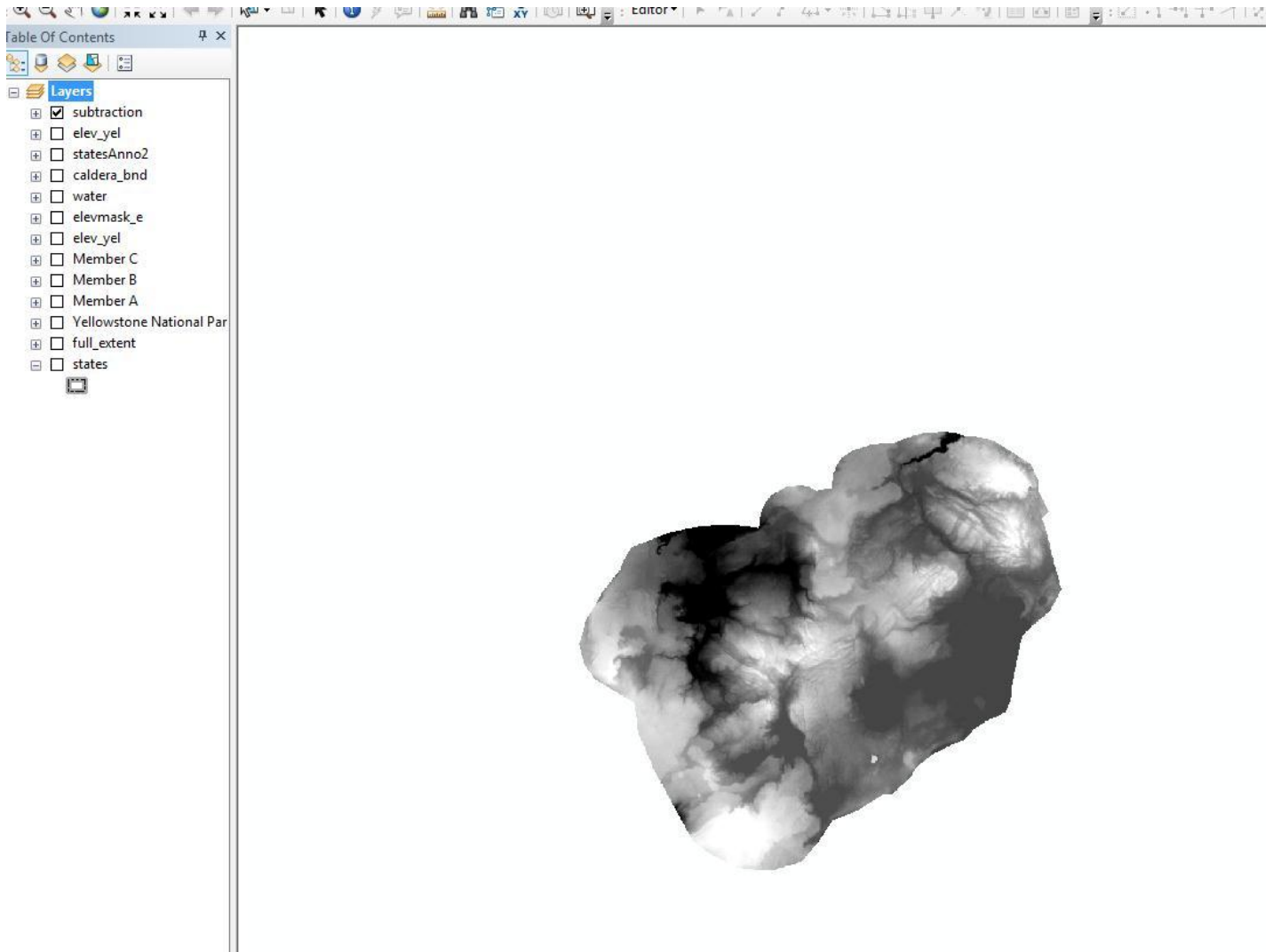


Figure 23 – “subtraction,” showing the elevation of the caldera after a 2,300+ cubic kilometer eruption

In order to combine this “dropped” raster with the original elevations, I used the Append tool under ArcToolbox>Data Management Tools>General>Append. I appended the “subtraction” raster to the “elev_yel” raster as shown in figure 24. This produced a raster with the present elevation around the

caldera rim and a downdropped “piston” caldera floor. I colored the raster according to elevation values and labeled features accordingly, as described above. Figure 24, below, shows the Append tool. Figure 25 shows the appended raster with the dropped caldera floor, shown in darker (lower) colors.

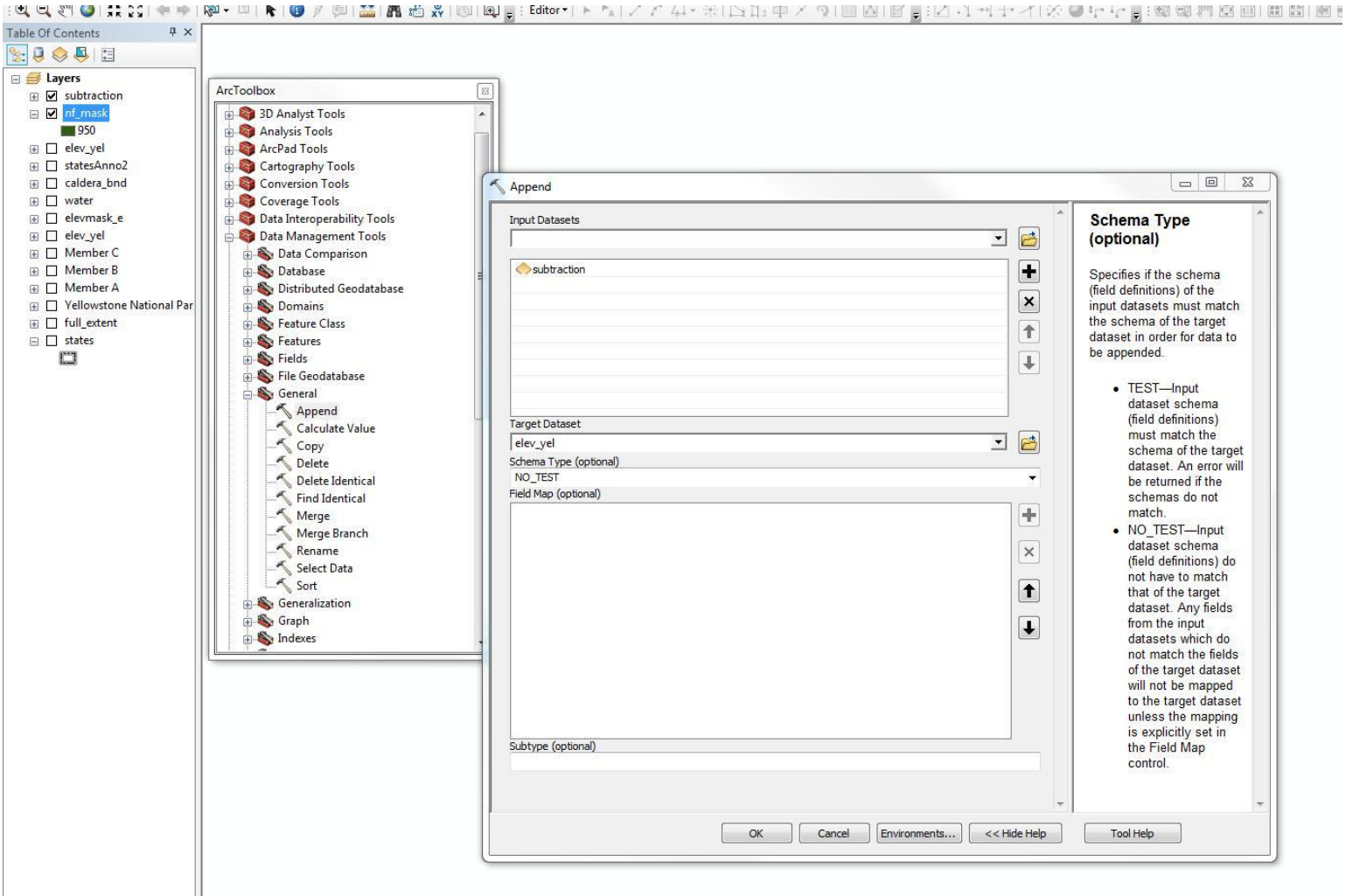


Figure 24 – inputs into the append tool

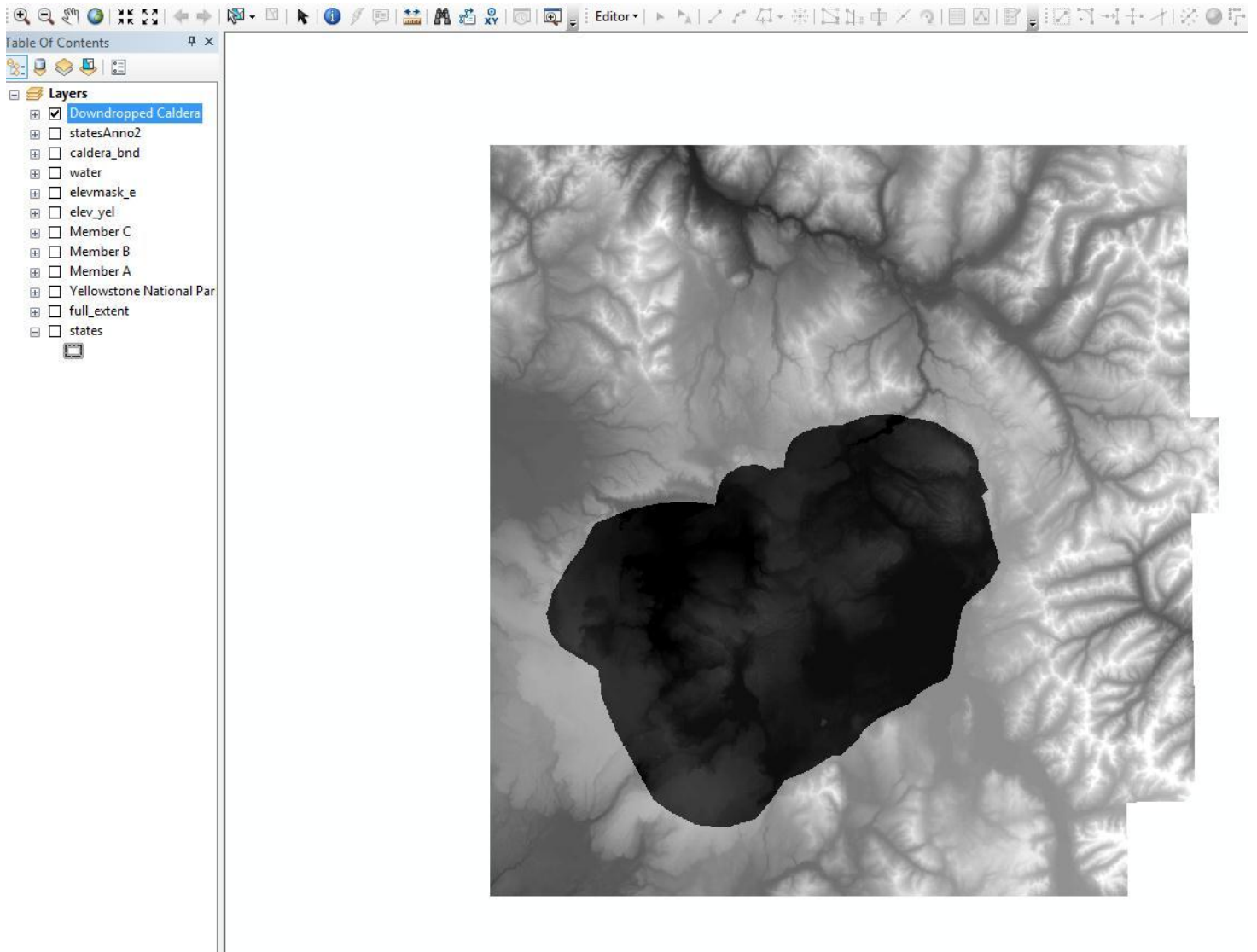


Figure 25 – appended rasters of the current elevation of Yellowstone and the caldera floor after a hypothetical eruption

To better show the current topography, I created a hillshade raster of the "elev_yel" raster through ArcToolbox>Spatial Analyst Tools>Surface>Hillshade. The input was simply the "elev_yel" raster and the output I assigned to be "yel_elev_hs." I placed the hillshade under the "elev_yel" in the table of contents and made "elev_yel" 40% transparent to see the new hillshade. Figure 26 below shows a nearly finished product. I later added the necessary elements to the maps in Layout View in ArcGIS.

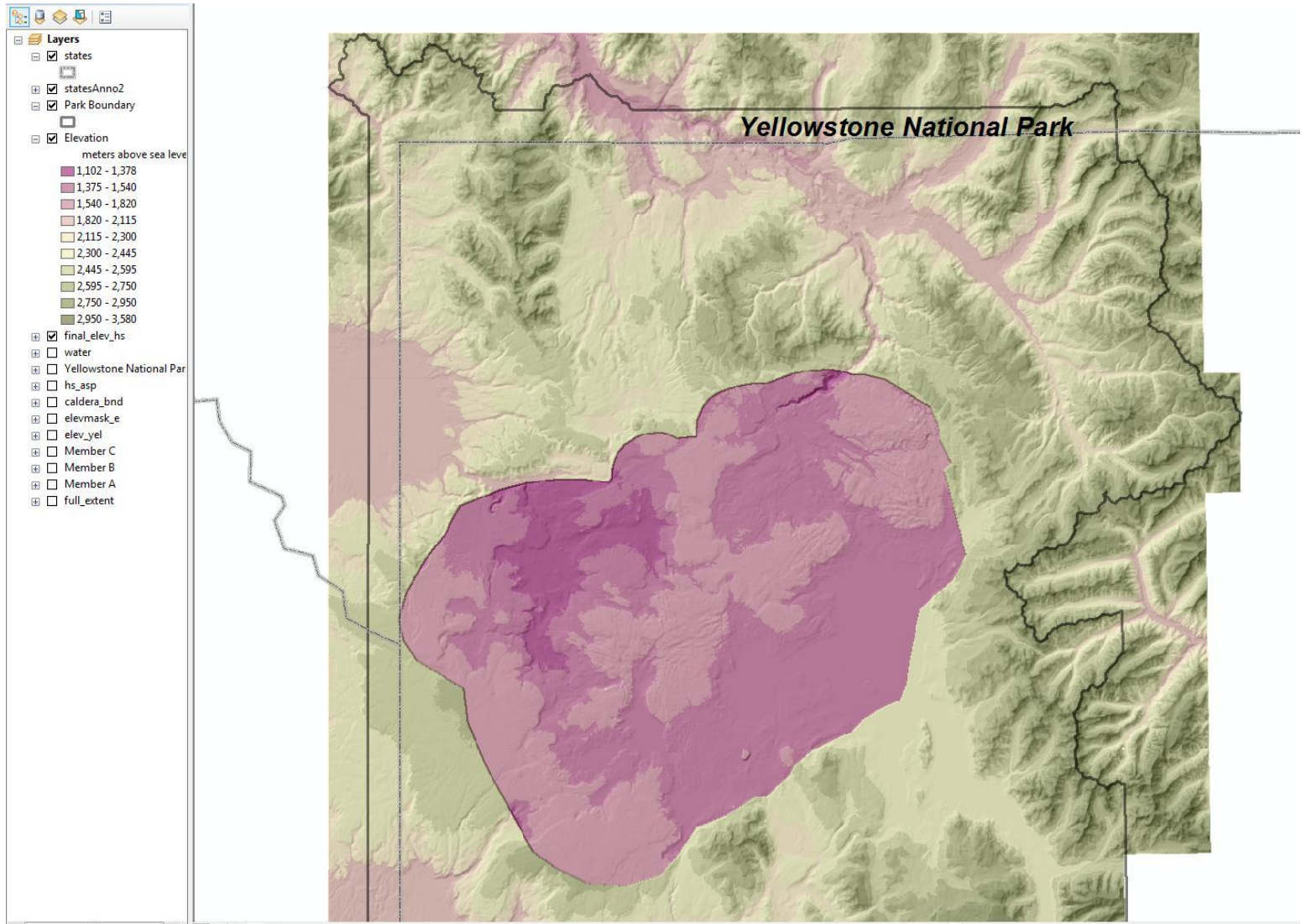


Figure 26 – a raster showing elevations of Yellowstone N.P. after a hypothetical eruption

Finally, to aide in the 3D visualization of the possible amount of caldera drop, I created an ArcScene image of the caldera. To do this, I simply opened ArcScene, clicked the Add Data icon and selected the “elev_yel” layer from above. I colored this layer in a scheme similar to my caldera map and changed to view so that it best showed the change in topography. The view looks over the area toward the northwest. To further enhance this view, I selected 2x vertical exaggeration by right-clicking on Scene Layers in the table of contents and clicking on the vertical exaggeration tab. Figure 27 below shows the result.

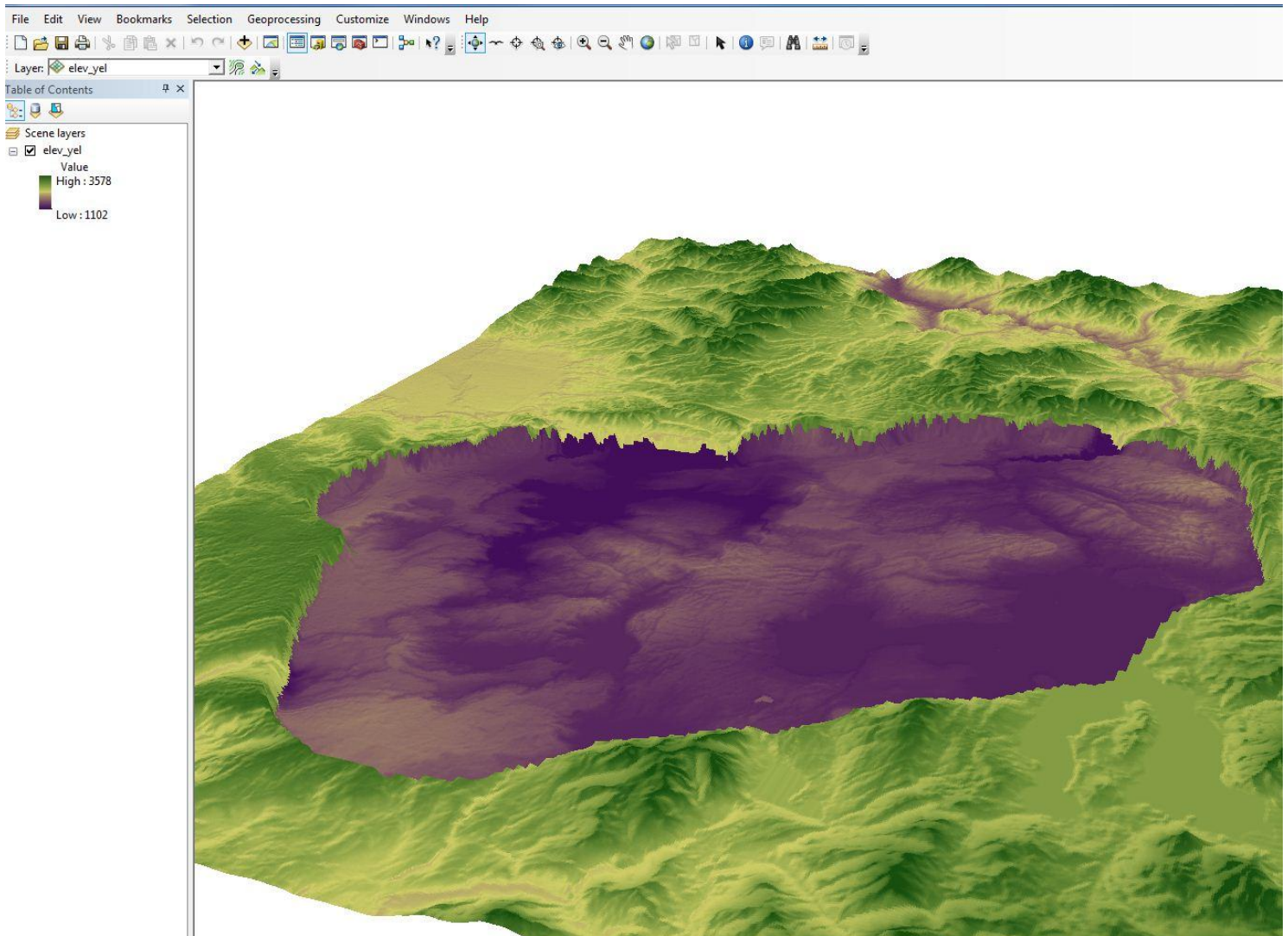


Figure 27 – looking NW across the caldera in ArcScene with 2x vertical exaggeration

Results

I successfully calculated the areas and volumes of member A, B, and C of the ash-flow deposits associated with the Huckleberry Ridge Tuff. The results are summarized in table 1 below.

	My results	Published results*	My results	Published results*
Member	Area (km ²)	Area (km ²)	Volume (km ³)	Volume (km ³)
A	6297	6297	705	820
B	18060	15400	1406	1340
C	3699	3690	226	290
Total	28056	25387	2338	2450

* Published results from Christiansen, 2001

Table 1

I calculated the equivalent volume of magma erupted as

$$(\text{Volume}_{\text{erupted material}} * \text{density}_{\text{erupted material}}) / (\text{density}_{\text{molten rhyolite}}) = 2,236 \text{ km}^3$$

I then was able to use ArcGIS to calculate an area of the most recent caldera (Yellowstone caldera):
~ 2,470 km².

Dividing the magma volume by the area above it, I determined that the maximum amount caldera floor dropped was approximately 950 m.

ArcScene was able to successfully render a 3D image of the surface that I created.

Conclusions

Overall, my total volume estimate (combining members A, B, and C) is within 5 % of the published estimate. This shows that ArcGIS software can calculate areas and volumes of erupted volcanic material on par with any of our current techniques.

Modeling the topography after a caldera-forming eruption is not possible. Calderas do not form by an abrupt and sharp change in elevation; the topography inside the caldera is not perfectly maintained; and the caldera is often filled by sediments. However, ArcGIS is able to effectively show changes and contrasts in topography, especially by the use of shaded rasters and hillshade rasters. Furthermore, given proper measurements and valid assumptions, ArcGIS is capable of modeling predicted changes based on geologic phenomena, such as volcanic eruptions.

The map of the caldera drop I created used techniques that could be greatly expanded and improved upon to show a more realistic scenario of what would happen to an area after a volcanic eruption.