**Using ArcGIS to understand the interplay of metamorphic core complex formation, isostatic rebound, and elevation**

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**Problem Formulation**

Metamorphic core complexes (MCCs) are geologic structures in which one or more low-angle normal faults exhume deep-seated metamorphic and mylonitized crustal blocks in their footwalls from beneath a younger, non-metamorphic upper plate (i.e. the hangingwall). The Whipple Mountains metamorphic core complex (MCC) is one within a belt of MCCs spanning the Colorado River extensional corridor (CREC) in the southern extent of the Basin & Range province. These MCCs expose middle to lower crust in their centers and give geoscientists the opportunity to study the structures and rheology of deep regions of the Earth's crust, albeit overprinted by extensional fabrics.

Importantly, work over the past few decades has produced various models to explain the formation of metamorphic core complexes. These models employ the aid of isostasy to bring lower plate rocks to the Earth's surface. The conservation of mass (therefore energy) implies that at an arbitrary stationary point in the upper Mantle, the pressure must remain constant even after upper plate rocks are removed from above it. The influx of more mantle material above the point than there was before any crust was removed satisfies the constant pressure requirement. Typically, isostatic equations are applied to the erosion of mountain belts and the removal of ice sheets, but this study applies them to the removal of rock via detachment faulting (i.e. tectonic processes) to calculate the surface elevation, the depth to the Mohorovičić discontinuity (Moho), and the elevation of the lower plate (basement rocks) before the metamorphic core complex formed and brought the lower plate rocks to the surface. **Figures 1&2** are complimentary to the mathematical process, described below.

*Project Goal:*

This study aims to present the paleo-elevation of the region that is now the Whipple Mountains MCC, contained within the Whipple Mountains Wilderness Area, before detachment faulting (i.e., the MCC's formation), without taking erosion into account. By calculating isostasy-determined variables and applying them in raster calculations (Map Algebra), a digital elevation model (DEM) of the study area can be produced to represent these various variables. This will aid in reconstructions of the Colorado River Extensional Corridor, an area previously affected by on-going contractional strain and tectonic convergence, before the onset of Basin and Range extension.
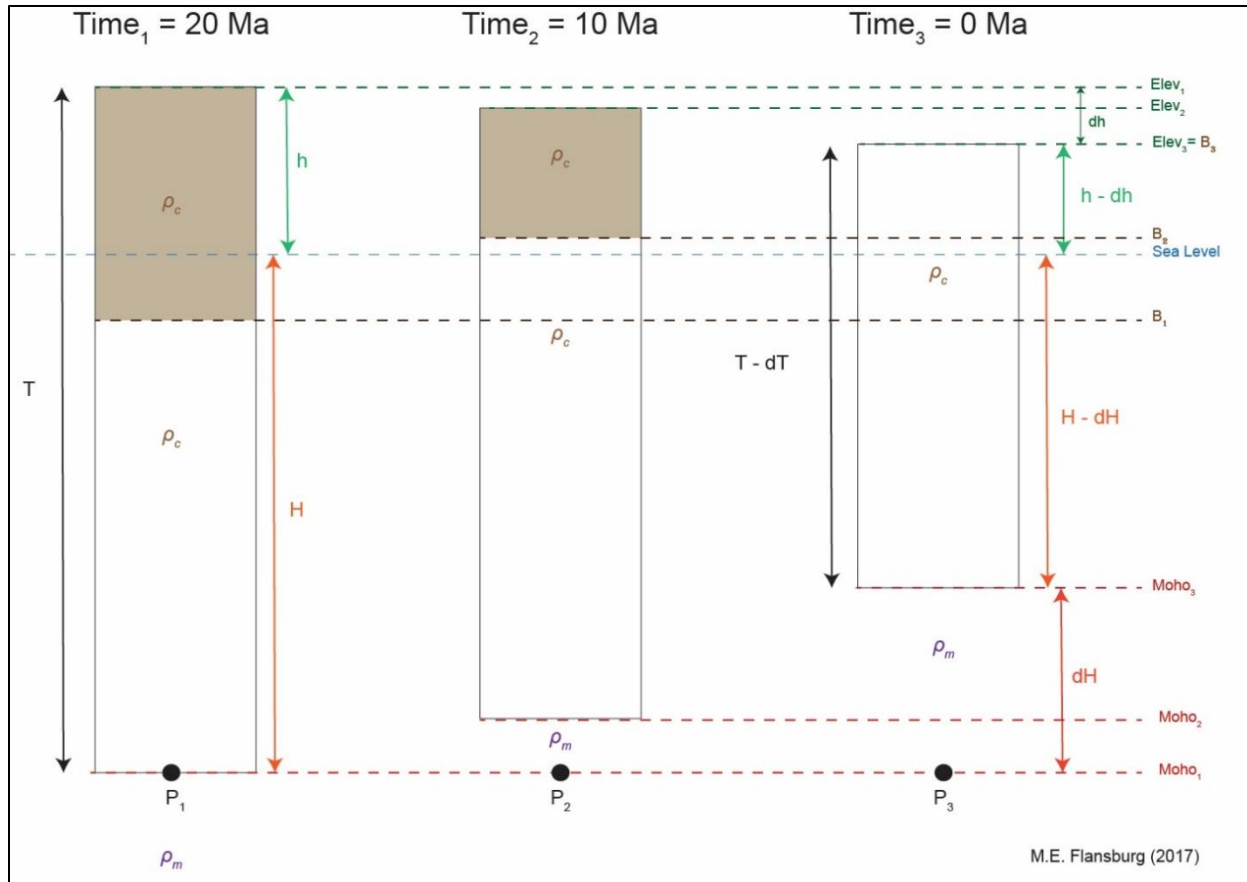
**Figure 1**. Schematic diagram depicting isostatic rebound of the Earth's crust and the Mohorovičić discontinuity from the removal of a given load (via surface or tectonic processes). Points $P_1$, $P_2$, and $P_3$ are the exact same location within the Earth (a fixed depth below sea level, but can be any other constant datum). Refer to **Figure 2** for these stages during metamorphic core complex formation as it applies to this study, and *Tables 1 and 2* for an explanation of the variables.
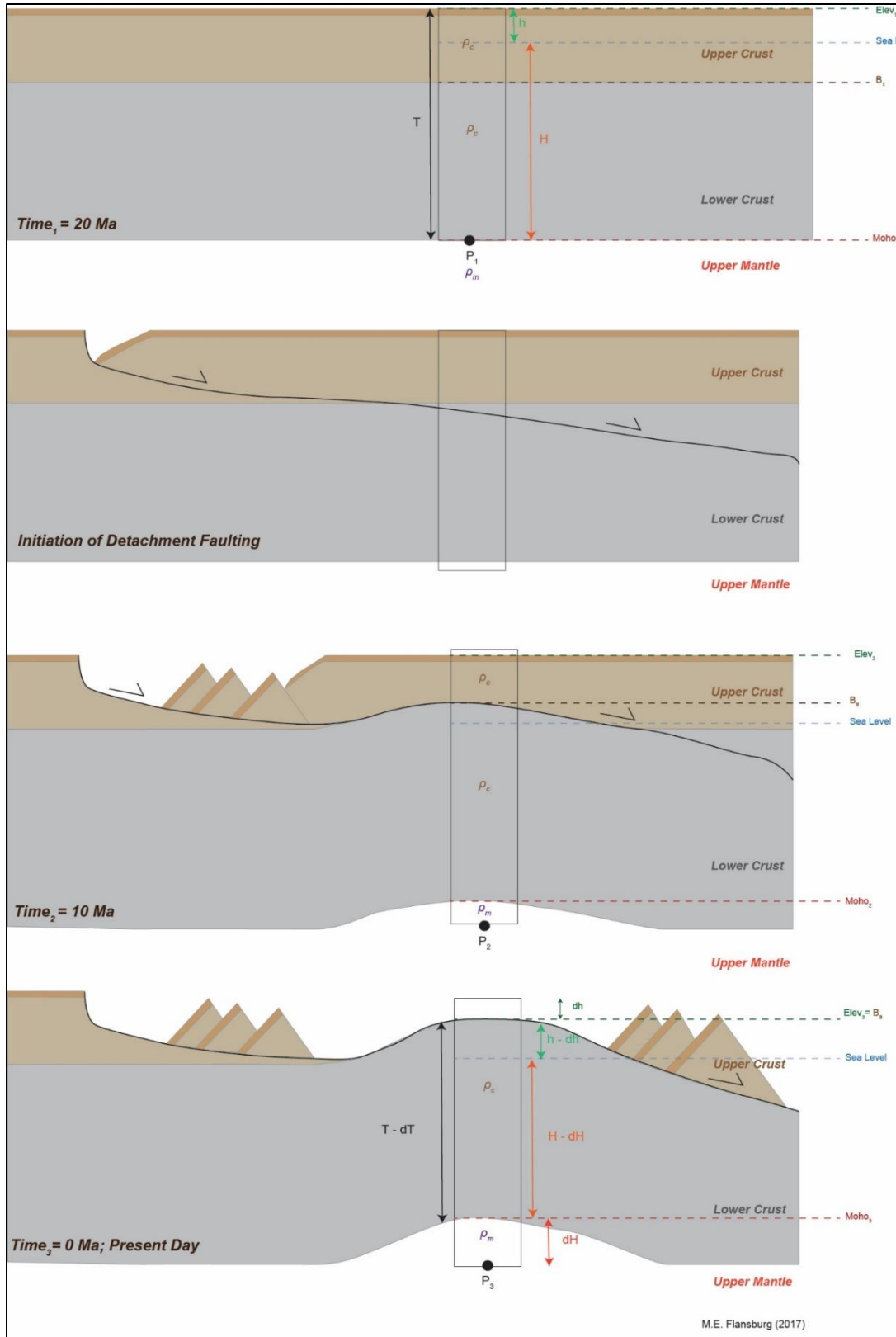
**Figure 2**. Schematic diagram depicting how the principles of isostasy apply to the formation of metamorphic core complexes. Columns and labels correspond to **Figure 1** and *Tables 1 and 2*.

***Problem Set-Up:***

To tackle this problem, application of the conservation of mass to the isostatic rebound of the upper mantle and the crust following the removal of a significant load (i.e. the upper crust) can generate estimates of pre-MCC formation elevations. This requires some algebraic set-up, with variables following the labeling in **Figures 1 and 2**, before it can be applied in ArcGIS software with the *Raster Calculator tool*.

*Table 1*. Known observations and variables. **Figures 1 and 2** contain a visual description of the variables.

| Observation | Variable | Value | Reference |
|---|---|---|---|
| Present-day crustal thickness | $(T - dT)$ | 28 km | Gilbert (2012) |
| Average thickness of pre-detachment upper plate (non-metamorphic rocks) | $dT$ | 15 km | Platt et al. (2014) |
| Present-day elevation | $(h - dh)$ | Depends on location | National Elevation Dataset (USGS) |
| Average density of the crust | $\rho_c$ | 2700 kg/m$^3$ | -- |
| Average density of the mantle | $\rho_m$ | 3300 kg/m$^3$ | -- |
| Acceleration due to gravity | $g$ | 9.8 m/s$^2$ | -- |

*Table 2*. Unknown variables to be represented as new raster files created in ArcGIS. **Figures 1 and 2** contain a visual description of the variables.

| Unknown | Variable | Value |
|---|---|---|
| Pre-detachment elevation of surface | $h$ | ? |
| Change in depth to the Moho | $dH$ | ? |
| Pre-detachment depth to the Moho (below sea level) | $H$ | ? |
| Pre-detachment thickness of the crust | $T$ | ? |
| Pre-detachment elevation of lower plate (i.e. top of metamorphic rocks) | $B_1$ | ? |

However, there are assumptions which go into these calculations:

- Sea level has remained constant since before the metamorphic core complex formed.
- Over an area of interest (either the entire WMWA or the Zones, described later), a uniform thickness of upper crust has been removed.
- The average crustal density accurately represents the density of both the upper and the lower crust.
- The average mantle density accurately represents the density of the upper mantle.
- The removal of crust is purely a cause of detachment faulting. Since the focus is solely on effect of metamorphic core complex formation on topography, the effects of erosion can be ignored and occurred at a constant rate over the time of the study (~20 Ma and present). Ideally, this would be a separate, additional isostatic balance, but even adding it to the end is inaccurate, since erosion is occurring constantly through the formation of the metamorphic core complex and does not simply carve out the topography at the end.

The end goal is to reconstruct the surface and lower plate elevation pre-MCC formation, two of the unknowns above. Because of the conservation of energy (mass), an energy balance equation of the pressure in the upper mantle below the Whipple Mountains MCC pre- and post-MCC formation is used to solve for the unknowns. In the equation below, $P_1$ and $P_2$ are pressures at a point of constant location through time (See **Figures 1 and 2**):

*Pressure before removal of the upper plate must be equal to the pressure after the removal of the upper plate.*

$$P_1 = P_2$$

$$\rho_c T g = \rho_c (T - (dT))g + \rho_m (dH)g$$

$$\rho_c T = \rho_c (T - (dT)) + \rho_m (dH)$$

$$\rho_c T - \rho_c (T - (dT)) = \rho_m (dH)$$

$$\rho_c (T - (T - (dT)) = \rho_m (dH)$$

$$\rho_c (dT) = \rho_m (dH)$$

$$dH = \frac{\rho_c}{\rho_m} (dT)$$

$$dH = \frac{2700 \,{}^{kg}/_{m^3}}{3300 \,{}^{kg}/_{m^3}} (15000 \, m) = (0.8181) * 15000 \, m = 12{,}272 \, m$$

This value, the change in the depth to the Moho from any reference point, is constant for any region which has experienced the removal of 15 km of material and only two layers of different density.

Next, it is possible to solve for the pre-detachment depth to the Moho below sea level for any given point on the Earth's surface if it has a known current elevation. As an example, the following equations solve for this value below the peak elevation in the Whipple Mountains MCC (~1200 m).

$$H - dH = (T - dT) - (h - dh)$$

$$H = (T - dT) - (h - dh) + dH$$

$$H = (28000\ m) - (1200\ m) + 12272\ m = 39072\ m$$

Now that there is a known depth to the Moho, $H$, before the metamorphic core complex formed, it is simple to solve for the surface elevation, $h$, at that time.

$$h = T - H$$

$$h = 43000\ m - 39072\ m = 3{,}928\ m$$

Note that while 15 km of crust was removed from the surface, this does not mean the surface was 15 km higher in elevation than it is today. As the energy balance shows, it was only about 2 km higher. This is because when the crust was thicker, it sat lower in the mantle, increasing the depth to the Moho. Because of the density contrast between the crust and the mantle is 0.8181, decreasing the depth to the Moho accounts for approximately 80% of the change in crustal thickness, while decreasing the surface elevation makes up only ~20%.

These findings can also calculate the elevation of the lower plate rocks before detachment faulting occurred throughout the area.

$$B = h - dT$$

$$B = 3928\ m - 15000\ m = -11{,}072\ m$$

### Data Collection and Sources

*Present-day surface elevation of the Whipple Mountains area:*
Elevations across the United States are readily accessible via the National Elevation Dataset (NED) produced by the United States Geologic Survey (USGS). These data come in raster format tiles bound by lines of latitude and longitude and at various resolutions. The tile used for this study is bound by 35°S and 113° to 115°W.

> DEM online: www.nationalmap.gov/viewer or www.ned.usgs.gov
> NED tile name: grdn35w115_13
> Spatial Reference: GCS_North_American_1983
> Linear Unit: undefined
> Datum: D_North_American_1983
> Resolution: 1/3 Arc Second (10 m)

*Limiting the study area:*

To place relatable boundaries on this study, limiting the region to the boundaries of the Whipple Mountain Wilderness Area, managed by the U.S. Bureau of Land Management sufficiently encompasses the MCC itself, particularly its center (core).

Whipple Mountain Wilderness Area boundary shapefile: Wilderness.net

Dataset compiled by: Lisa Eidson at the University of Montana's Wilderness Institute

Larger dataset sources: Individual wilderness boundaries obtained from the Fish and Wildlife Service (FWS), Bureau of Land Management (BLM), National Park Service (NPS), and the Forest Service (USFS). FS data has been obtained from the Automated Lands Project, or from regional or national forest GIS staff. BLM data is from a national dataset from field inventories. FWS and NPS data have been obtained from National Park or Refuge offices. For a history of updates, contacts from whom the data were obtained can be cross-referenced using the WID in the spreadsheet at http://www.wilderness.net/GIS/WildernessUpdates.xls.

Geographic Coordinate System: GCS_WGS_1984_Major_Auxiliary_Sphere

Datum: D_WGS_1984_Major_Auxiliary_Sphere

Spheroid: WGS_1984_Major_Auxiliary_Sphere

Projection: Mercator

Linear Unit: Meter

*Geology of the MCC:*

For the purpose of this study, a regional geologic map for the state of California is sufficient to create appropriate boundaries for lower plate and upper plate rocks at the surface today. Google Earth .kml files are available from the Mineral Resources On-Line Spatial Data at the USGS.

.kml polygon files online: https://mrdata.usgs.gov/geology/state/state.php?state=CA

File name: cageol.kml

Spatial Reference: GCS_North_American_1983

Metadata stored: Geologic unit names, abbreviations, and descriptions

## Data Pre-Processing

As shown in the information detailed above, the downloaded files different geographic coordinate systems and/or projections. **Note: The Whipple Mountains shapefile from Wilderness.net presented a problem, however, and would not place in the correct location when converted into the NAD83 coordinate system and then projected into UTM Zone 11 N. The DEM file and the .kml file would not encounter any errors with the projection tool or with "projecting on the fly" in the Data Frame in ArcGIS, but since the shapefile failed to project, I chose to project the files into the spatial reference the shapefile was originally. This worked, and all three files showed up in the correct location.**

1. In ArcCatalog, right click on the grdn35w115_13 DEM raster file and select properties. In the XY Coordinate System tab browse to Projected Coordinate Systems -> World -> GCS_WGS_1984_Major_Auxiliary_Sphere. This automatically assigns the file to a Mercator-type projection with linear units in meters and the GCS 84 coordinate system.
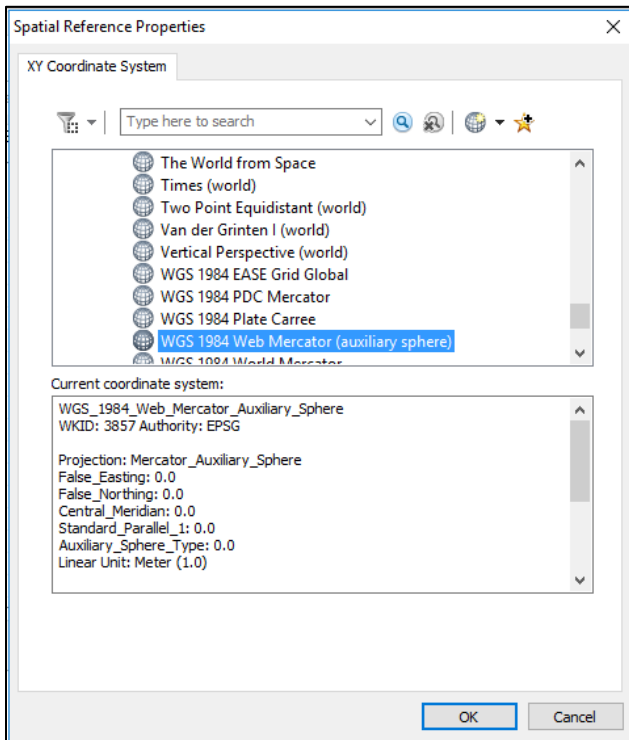
**Figure 3**. This window changes the spatial reference of the raster and .kml file to match that of the WMWA shapefile in ArcCatalog.

2. Next, pre-process the Google Earth file containing polygons of the geologic units so it can be viewed and used in ArcMap. With a new map document open in ArcMAP, add the DEM raster file and the Whipple Mountain Wilderness Area (WMWA) shapefile (now in the same projections). Set the Data Frame spatial reference to GCS_WGS_1984_Major_Auxiliary_Sphere as well (right-click on the Data Frame's name, select Properties, Coordinate system tab, and set it to the same as **Figure 3**).

3. Open the *KML to Layer* tool. Fill out the information as shown in **Figure 4**, with the Google Earth .kml file as the input. Save it to the appropriate workspace and give it a name.

4. Add the file as a .lyr file containing both polygon and polyline shapefiles for the geologic units and contacts, respectively.
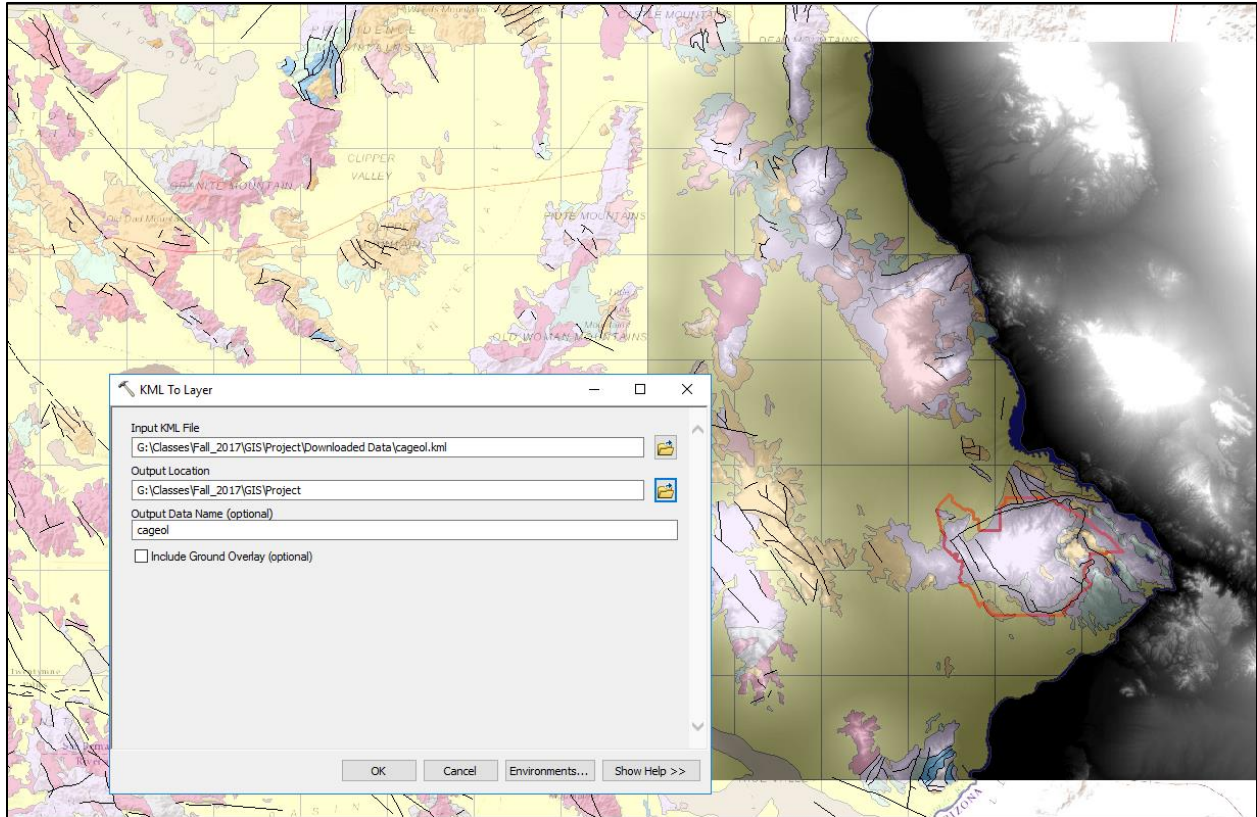
**Figure 4**. The layers as they appear in ArcMap after the pre-processing steps outlined above, highlighting the KML to Layer tool which converts the Google Earth geologic map into a .lyr file with polygons and polylines (seen in the background).

### ArcGIS Processing

Now that all data is within the map document and in the same spatial reference (**Figure 4**), begin to process the data.

5. To limit the DEM to the area we're interested in, and therefore avoid calculating values for an entire DEM tile, open the *Extract by Mask* tool. Select from the dropdown the downloaded DEM tile as the input raster and the WMWA shapefile as the feature mask data. Name it something simple like Whipple_DEM and save it to a Created Files folder for the project. Click Okay.

6. To limit the geology layers, open the *Clip tool* (since these are shapefiles and not raster files). Input Features should be cageol\polygons and Clip Features is the WMWA shapefile, as in **Figure 5**. Click Okay. Do the same to clip the geologic contacts (cageol\polylines).
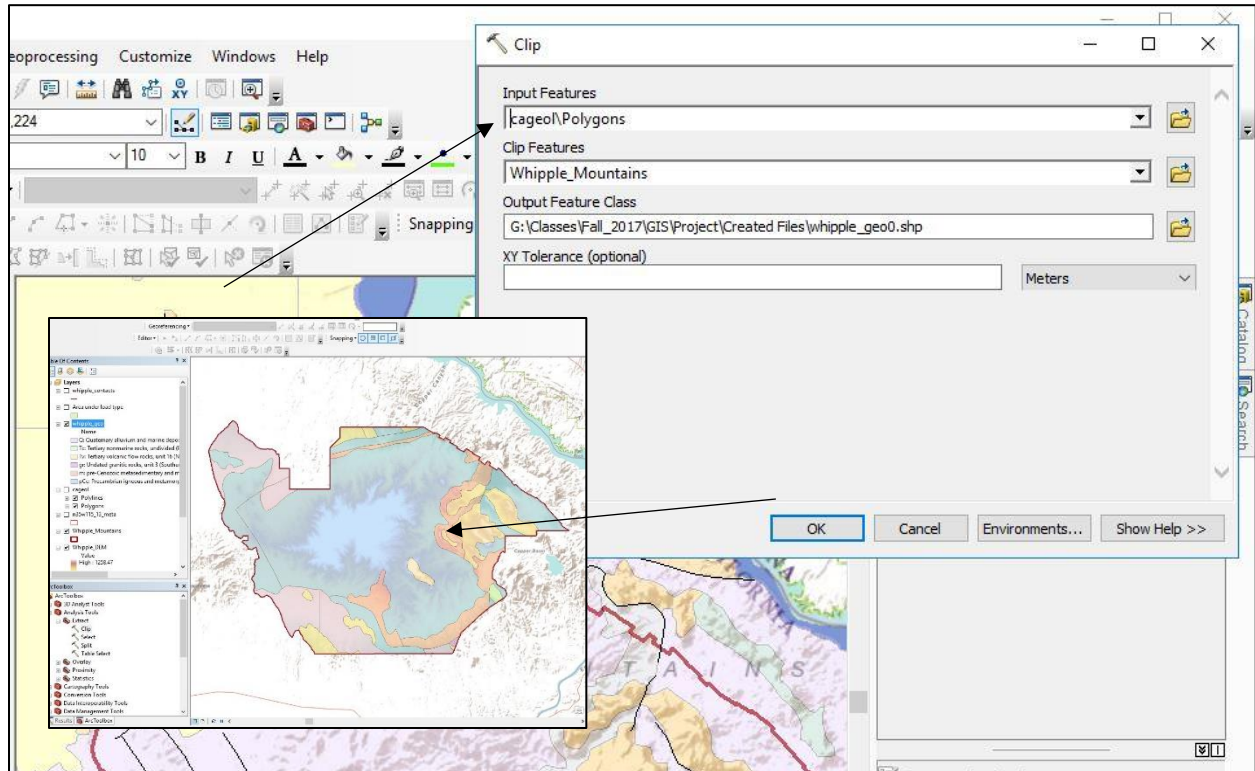


**Figure 5**. The *Clip tool* is used *twice* to create a polygons shapefile for the geologic units and a polylines shapefile for the geologic contacts and faults.

7. Add a Basemap for easy referencing, like the World terrane map shown in **Figure 5**.
8. Now that the DEM is limited just to the Whipple Mountains MCC region, we can begin to use the *Raster Calculator tool*.

### *Performing the Isostatic Energy Balance with Map Algebra*

9. Open the *Raster Calculator tool*. The first new raster we want to create is a DEM of the present-day depth to the Moho below sea level. Following the algebra detailed earlier, this raster is equal to 28 km (the thickness of the crust today) minus the current surface elevation: 28000 – "Whipple_DEM". I called this new raster "modern_dslmo".
10. The *Raster Calculator tool* is then used for the rest of the algebraic steps, following the math below to create different DEMs. Part *a* is shown in **Figure 6**.
    a. Pre-detachment faulting depth to the Moho below sea level, "paleo_dslmo":
       i. "modern_dslmo" + (0.8181)*15000
    b. Pre-detachment faulting surface elevation, "paleo_elev":
       i. 43000 - "paleo_dslmo"
    c. Pre-detachment faulting elevation of the lower plate, "paleo_dbase":
       i. paleo_elev – 15000
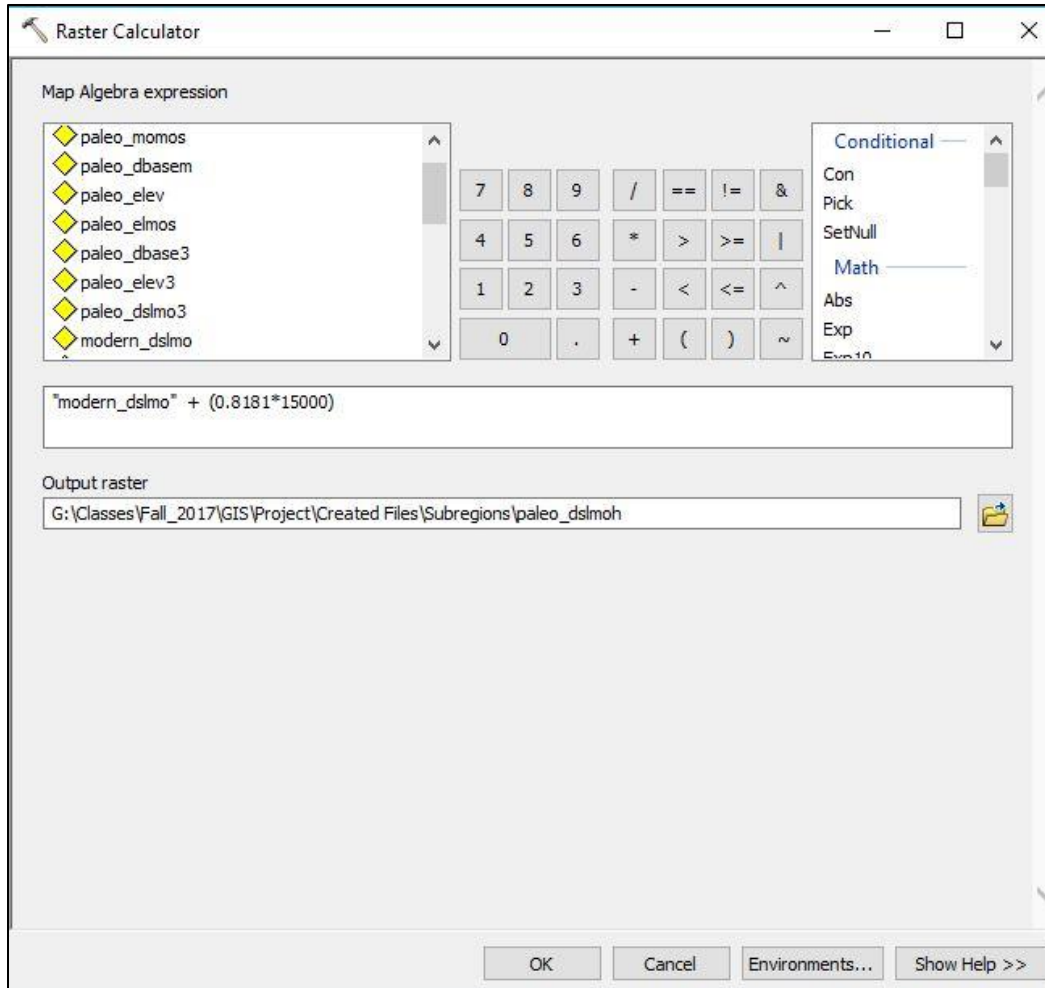
**Figure 6**. The *Raster Calculator tool* creates new rasters by performing mathematical operations on the values contained within each cell of the input raster.

This process creates final DEMs from applying the same isostatic parameters across the entire study area (see **Plate 1**), with 15 km of crust removed.

### *Muting the effect of present-day topography*

However, it would be nice to create a DEM of the region that didn't directly replicate the relief of the present-day topography, such as the pre-MCC formation surface elevation in **Plate 1**. In reality, the core of the metamorphic core complex has been exhumed from deeper depths, with decreasing exhumed-depth downdip along the flanks of the MCC. To crudely replicate this, I divided the DEM into three zones based on the current elevation profile (i.e. topographic contours), which closely mirrors the geology. See **Plates 4 and 5** for a visual representation of these zones and **Plates 2, 3, and 5** for final products created from them.

*Table 3.* Zones used to divide up the Whipple Mountains area by different crustal thickness and therefore different isostatic effects.

| Zone | Elevation | Thickness of Upper Plate (dT) |
|---|---|---|
| Outer | <650 m | 10,000 m |
| Middle | >650 m and <800 m | 12,500 m |
| Core | >800 m | 15,000 m |

11. The DEM needs to be contoured by these parameters using the *Contour tool*. I chose the 800 m contour to bound the Core Zone, since this encompasses the highest topography neatly into one place and Precambrian basement rocks is the only geologic unit exposed within it. For the Middle Zone, I chose the 650 m contour, which follows the 800 m contour pattern and also encompasses only lower plate rocks. The remaining DEM (below 650 m) contains all other geologic units as well as some basement rocks. Each of these contours (and associated interval, shown in **Figure 7**) creates just one elevation contour, since neither 650 nor 800 go into the elevation range (~1000 m) more than once.
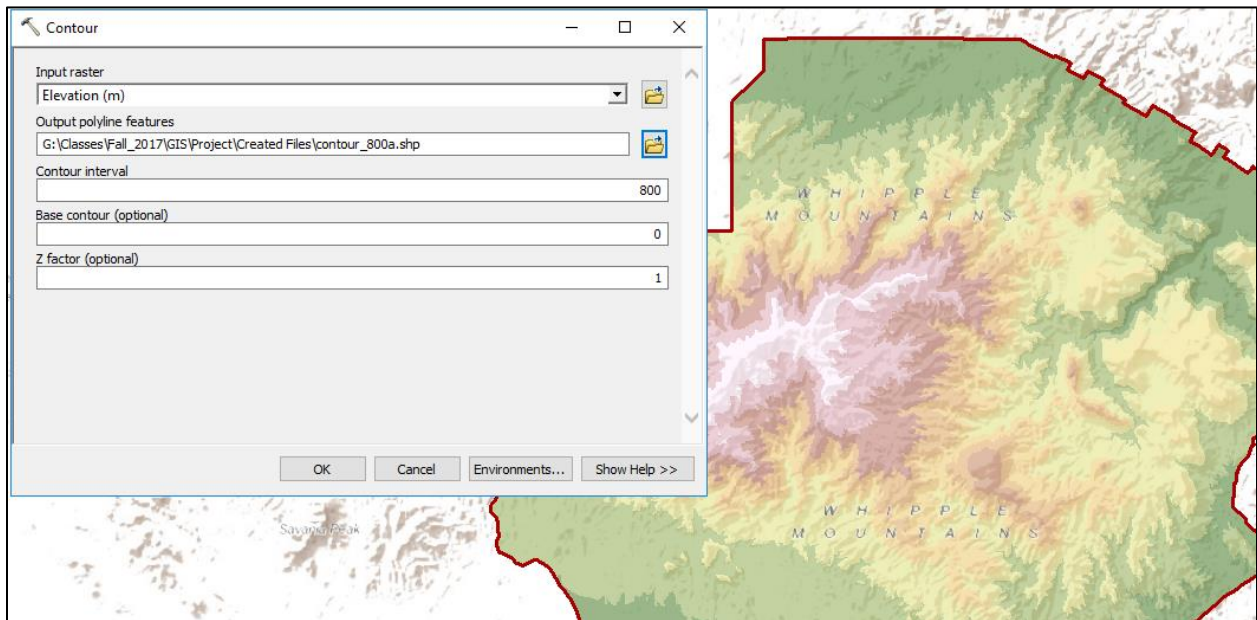


**Figure 7**. The input window for the *Contour tool* showing an 800 m contour interval. Because the DEM in the Whipple Mountains Wilderness Area ranges from ~200-1250 m, this will create a single contour at 800 m.

12. However, we can't apply *Extract by Mask* to the DEM just yet, since this will create a line of tiles rather than all the tiles enclosed within this contour. Open the *Feature to Polygon* tool, choose the appropriate contour polyline, and save it to the Created Files folder (**Figure 8**).
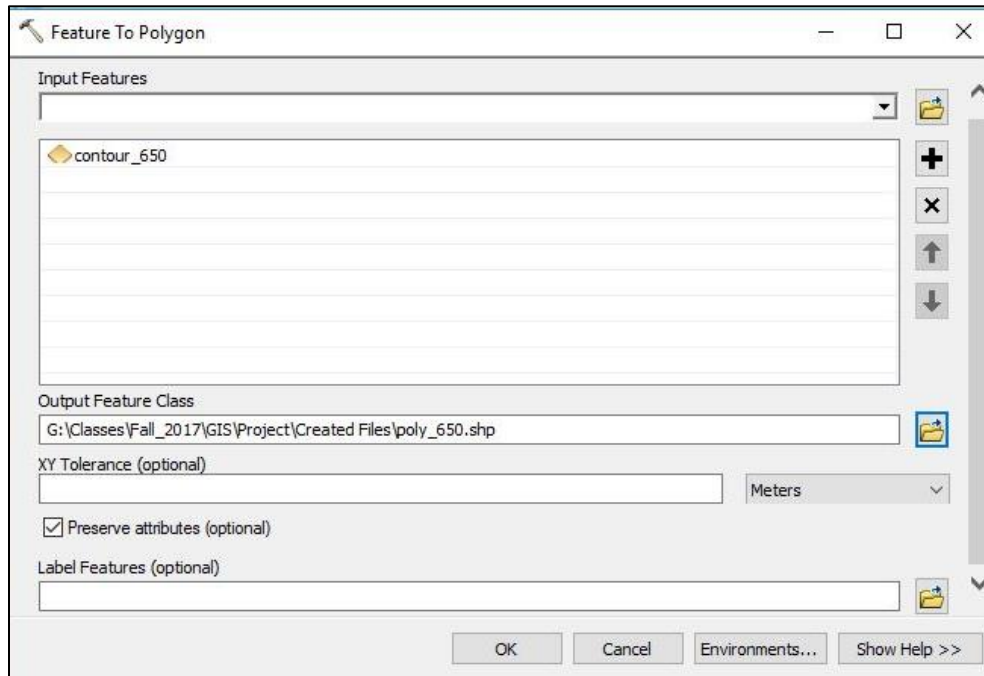
**Figure 8**. The *Feature to Polygon tool* creates a polygon from the polylines created by the *Contour tool* in **Step 11**.

13. Now, the polygon still needs come cleaning up if we want to apply different isostatic parameters to these discrete zones. From the Data Frame, right click on the poly_650 shapefile and select Edit Features and Start Editing.
14. Once editing, open the attribute table and delete all polygons outside the main 650 m contour. Save edits and stop editing once only the central large polygon remains.
15. Do the same for the 800 contour.
16. Now that these polygons have been created, use the *Extract by Mask* tool (*Step 5*), to create DEMs of these zones individually. (The original, "Whipple_DEM", is used for the Outer Zone).
17. Do *Steps 9 and 10* again, this time with 15000 applied to the Core, 12500 applied to the Middle, and 10000 to the Outer Zone in all calculations where the thickness of crust removed was necessary.
18. Finally, these three separate DEMs of pre-detachment surface elevation (or depth to the Moho or elevation of the lower plate) need to be merged into one again. Open the *Mosaic to New Raster* tool and input the three surface elevation DEMs (just created in *Step 17*). Give it a new name and save it with the correct spatial reference. The number of bands should be 1. All other defaults are okay, as in **Figure 9**.
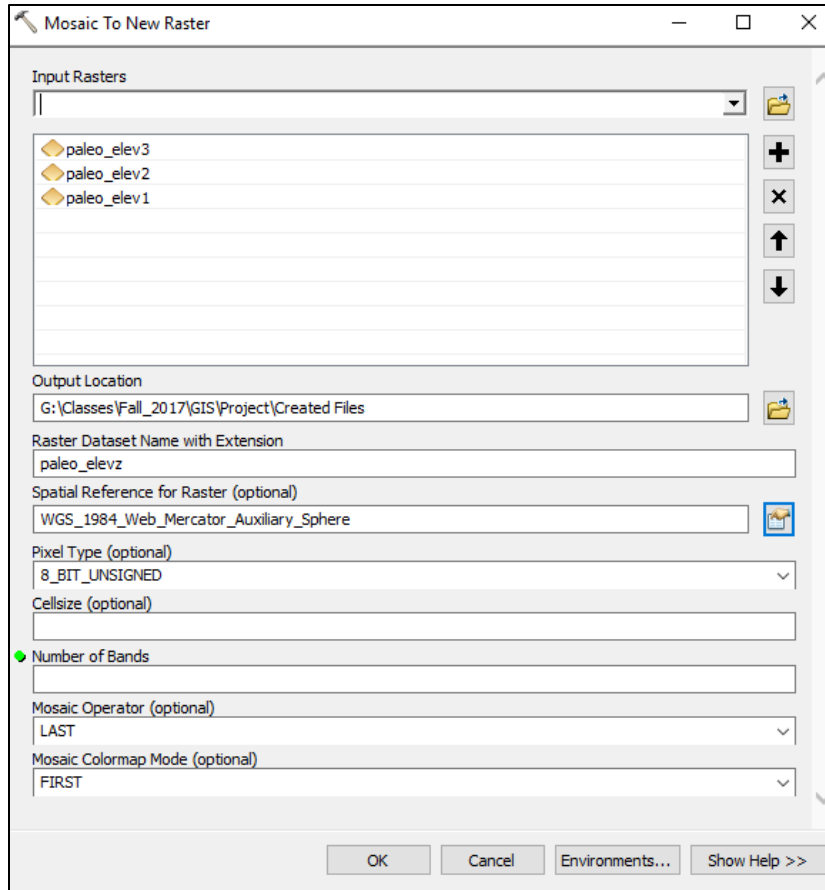
**Figure 9**. The *Mosaic to New Raster tool* will create a new seamless raster from the individual rasters of each zone. Be careful to choose the correct spatial reference. Number of bands should be 1.

This tool can also be used to mosaic DEMS for the separate zones of depth to the Moho and lower plate (See **Plates 2, 3, and 5** for the final products).

*Comparing the modern and pre-detachment lower plate elevation*

While the lower plate is essentially at the surface today, in some areas of the Whipple Mountains Wilderness Area the basement rocks are still covered by Tertiary and Mesozoic sedimentary rocks. It would be nice to create a present-day DEM of lower plate elevation to compare to the pre-detachment DEM (see **Plate 3**).

19. In the table of contents, turn on the Geology polygons created in *Step 6*. Use the *Select pointer* to select all the polygons that are not mapped as Precambrian basement rocks. See **Plate 6** for the geology and the inset on **Plate 3** for the two groupings. Once this is done, right click on the geology layer in the Table of Contents and select Data, then Export Data.
20. Choose to Export only selected features and keep the spatial reference the same as the source layer.
21. Use this new polygon to apply another *Extract by Mask* to the Whipple_DEM and call it "dem_cover" or something similar.

22. Assume that approximately 1 km of sedimentary and volcanic rocks cover the basement in these regions of the map. Refer to *Steps 9 and 10* and **Figure 6**. Open the *Raster Calculator*:
    a. Create a new raster of the modern lower plate elevation under sedimentary cover and give it a new name. Use this equation in the Raster calculator:
        i. "dem_cover" – 1000
23. Mosaic this raster with the "Whipple_DEM" raster to merge the two datasets using the *Mosaic to New Raster tool* (*Step 18*, **Figure 9**).

<div align="center">

**Data Presentation/Results**

</div>

All of these steps were used and integrated in a variety of ways to display estimates of both the surface and the lower plate elevation as they were before the Whipple Mountains metamorphic core complex formed. Outlined below are descriptions of the six plates created to showcase the important steps or features of this conservation of energy system.

*Plate 1: Surface elevation both today and pre-MCC formation*
- Pre-MCC formation surface elevation calculated by removing 15 km of crust across the entire area.
- Both DEMs are displayed with 30% transparency to showcase the terrain underneath.
- The color schemes closely blend into one another, since the modern elevation is everywhere less than the pre-MCC elevation.
- The color breaks are Equal Intervals, since this is an intuitive way to visualize elevation data (like topographic contours).

*Plate 2: Depth to the Moho below sea level by zone today and pre-MCC formation*
- From geophysical data (Gilbert, 2012) it is safe to assume that the present-day depth to the Moho (thickness of the crust) is constant throughout, so the top map is not a mosaic of the Zones.
- The bottom map is a mosaic of DEMs calculated by Zone.
- The two maps use an identical color scale, with cooler colors representing deeper areas (higher values). Note that the values are significantly greater in the ~20 Ma map (as confirmed by hand-calculation).
- The color breaks are Natural Breaks, since Equal Intervals lends disproportionate weight to each Zone boundary and masks the value variability within each Zone.

*Plate 3: Elevation of the lower plate by zone today and pre-MCC formation*
- The two maps use an identical color scale, but with different values.
- The color breaks are Natural Breaks, since Equal Intervals lends disproportionate weight to each Zone boundary and masks the value variability within each Zone.

*Plate 4:  Changes in surface elevation and in depth to the Moho by zone*
- Map patterns are the same since the calculations are by zone.  (Performed by subtracting a present-day DEM from its corresponding pre-MCC DEM in the *Raster Calculator tool*).
- Note that the greatest change is seen in the depth to the Moho value, rather than in the surface elevation.

*Plate 5:  The principles of isostasy as they apply to MCC formation*
- This plate guides the viewer through the calculations necessary to create maps of pre-MCC elevation of the lower plate and the surface based on isostatic principles and the conservation of energy.
- Maps are mosaics from map algebra applied to Zones.
- Surface elevation maps (**Maps 1 and 4**) displayed with 30% transparency.  The 20 Ma surface elevation map here is different than on **Plate 1**, since it was created from a mosaic of DEMs calculated by Zone (each Zone with a different thickness of crust removed, see *Table 3*).  Note the muted topography (it is no longer an exact, although higher, replica of modern topography as in **Plate 1**).  Color breaks are Equal Intervals.
- **Maps 2, 3, and 4** have color breaks defined as Natural Breaks.

**Plate 6:  Geology of the Whipple Mountains Wilderness Area**
- Used to divide the surface exposure into present-day lower and upper plate rocks for **Plate 3**.
- An annotation group was created for labeling purposes, since the Google Earth file contained the unit description within the labels.
- Colors changed in ArcGIS from those imported from the original Google Earth file.

# References

Gilbert, H., 2012, Crustal structure and signatures of recent tectonism as influenced by ancient terranes in the western United States: Geosphere, v.8, p.141–157. https://doi.org/10.1130/GES00720.1

Model: *Crustal thickness values within the western United States derived from receiver functions observations*

Platt, J.P., Behr, W.M., and Cooper, F.J., 2014, Metamorphic core complexes: windows into the mechanics and rheology of the crust: Journal of the Geological Society, v.172, p. 9-27, doi:10.1144/jgs2014-036

All guidance for ArcGIS processing and pre-processing comes from labs associated with Dr. Mark Helper's GEOL 386G: GIS & GPS Applications in Earth Sciences course in the Fall 2017 semester. Labs 8 and 10 were particularly useful references.

# Plate 1: Present-Day and Paleo-Elevation of the Whipple Mountains Wilderness Area

## Uniform Isostatic Adjustment



**Present Day**

Source:
National Elevation Dataset
1/3 arc second DEM
Bureau of Land Managment
(BLM) shapefiles

☐ BLM Border

**Elevation (m)**

| | |
|---|---|
| | 215 - 375 |
| | 376 - 444 |
| | 445 - 514 |
| | 515 - 588 |
| | 589 - 661 |
| | 662 - 739 |
| | 740 - 825 |
| | 826 - 923 |
| | 924 - 1,038 |
| | 1,039 - 1,258 |

Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

0   2.5   5   10
Km

**~20 Ma**
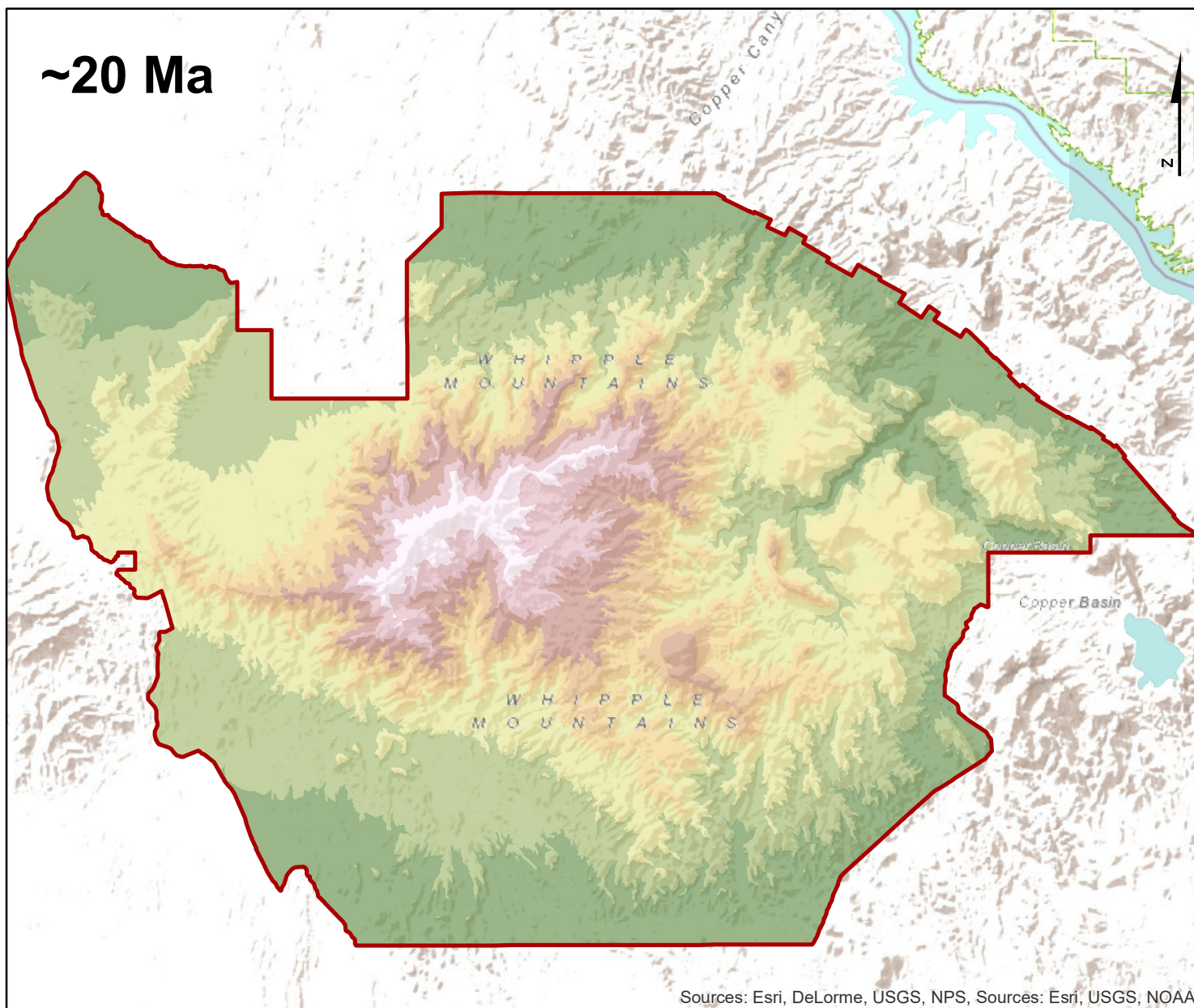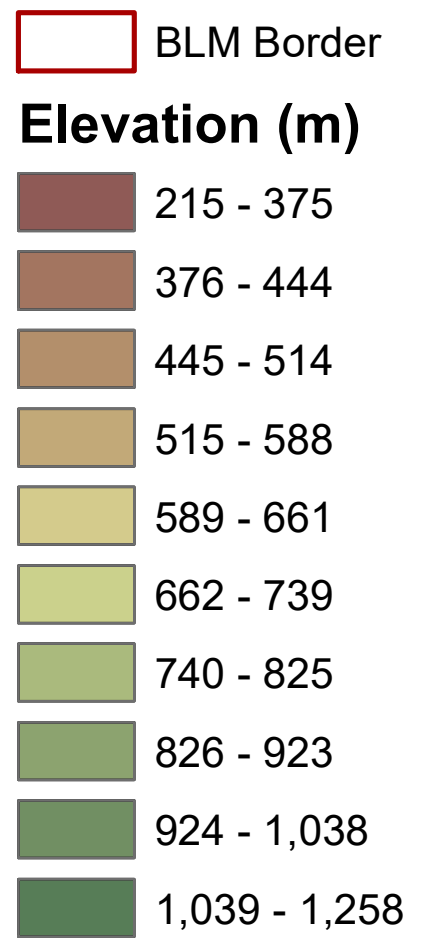
Assumptions:
1. Homogenous,15 km of upper crust added
2. Isostatic adjustments the same throughout

☐ BLM Border

**Elevation (m)**

| | |
|---|---|
| | 2,034 - 2,253 |
| | 2,254 - 2,361 |
| | 2,362 - 2,494 |
| | 2,495 - 2,737 |
| | 2,738 - 2,995 |
| | 2,996 - 3,103 |
| | 3,104 - 3,298 |
| | 3,299 - 3,629 |
| | 3,630 - 3,751 |
| | 3,752 - 3,987 |

Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

# Plate 2: Present-Day and Paleo-Depth to Mohorovičić Discontinuity of the Whipple Mountain MCC

## Isostatic Adjustment Partitioned into Three Zones (Core, Middle, Outer) of the MCC



**Present Day**

Nevada

California          Arizona
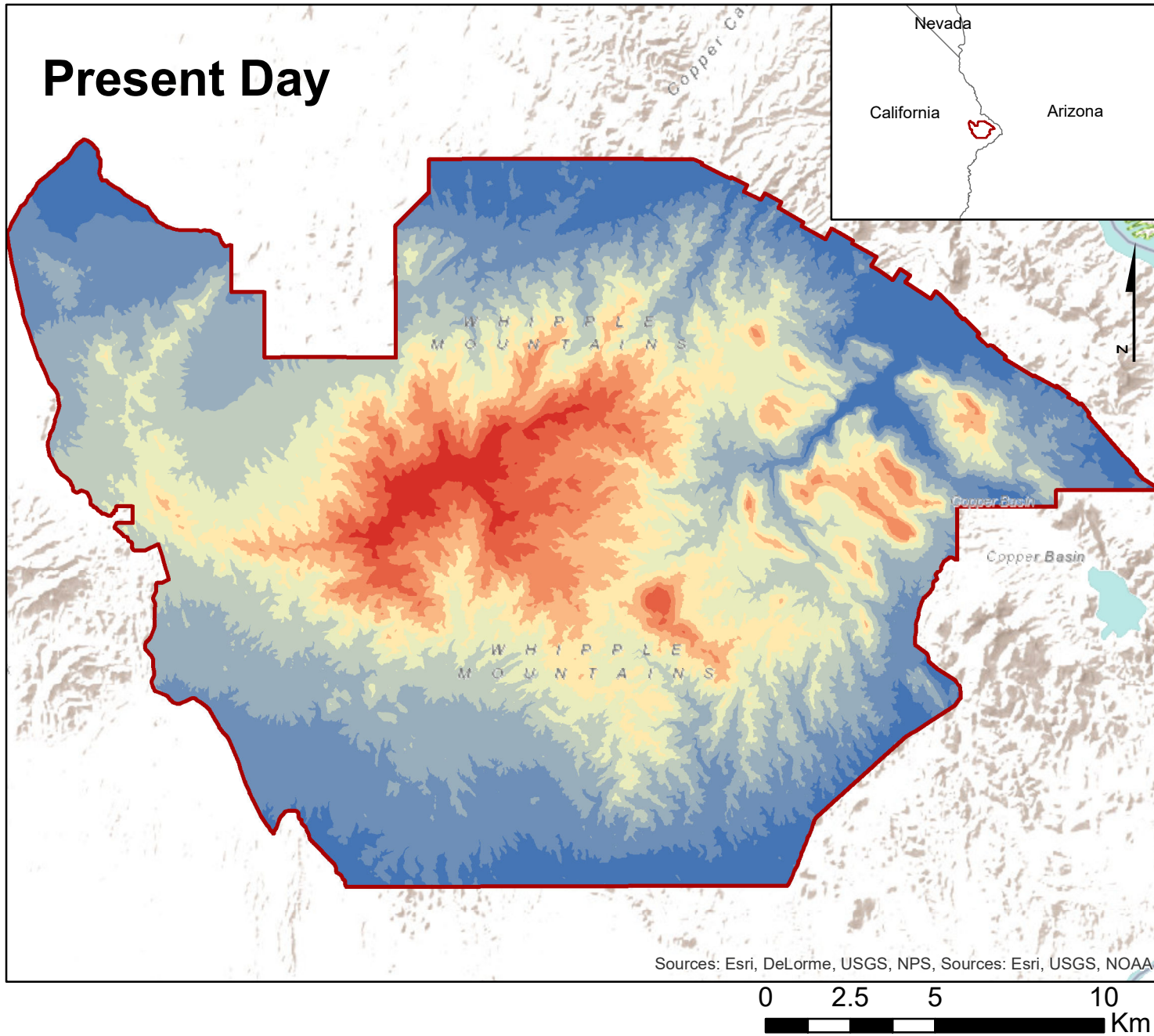
Source:
National Elevation Dataset
1/3 arc second DEM
Bureau of Land Managment
(BLM) shapefiles

Assumption:
The crust is evenly
28 km thick today

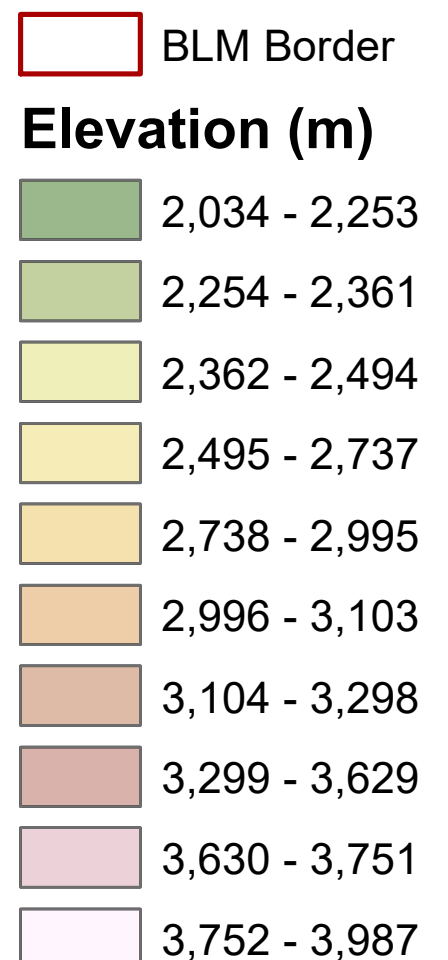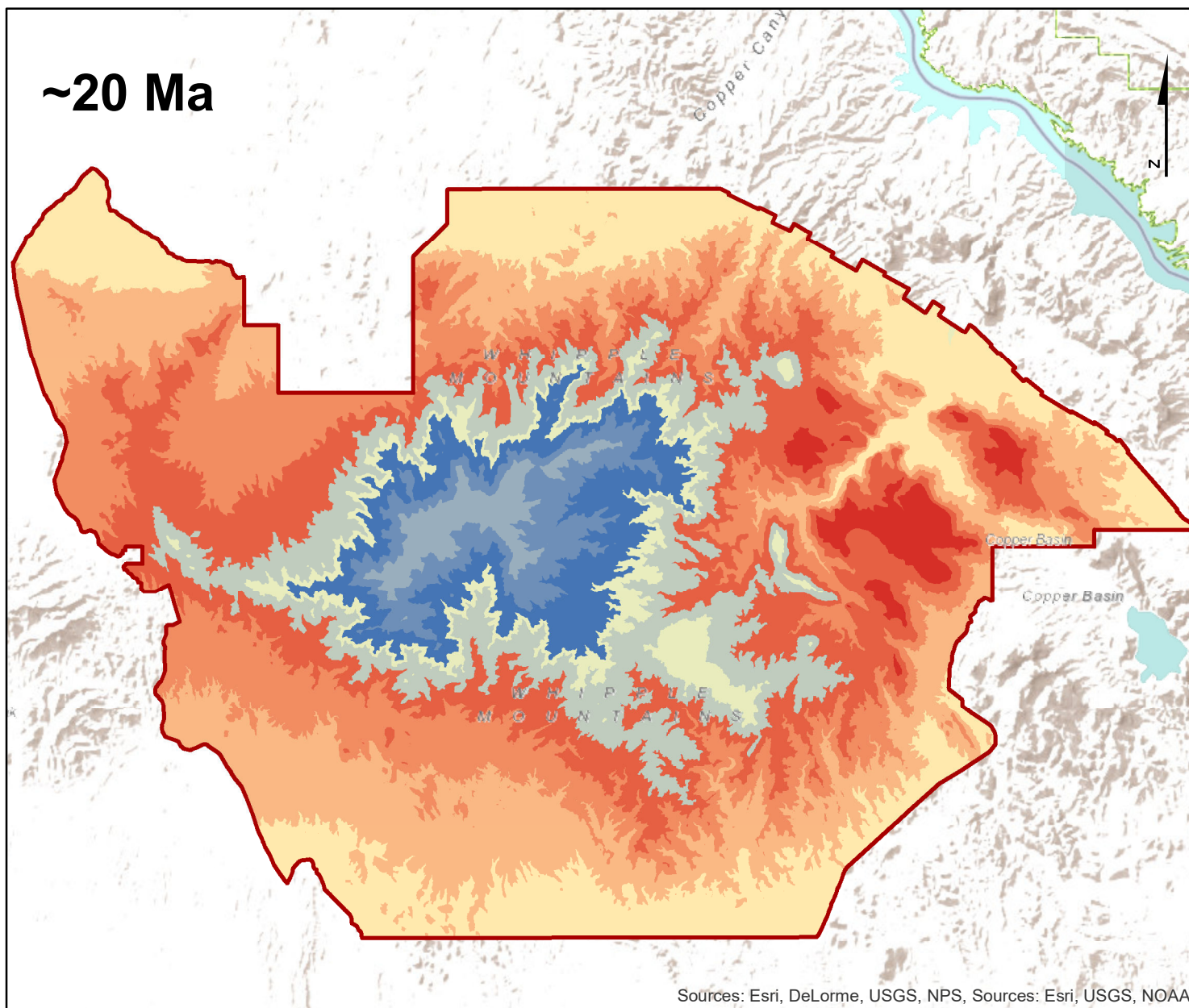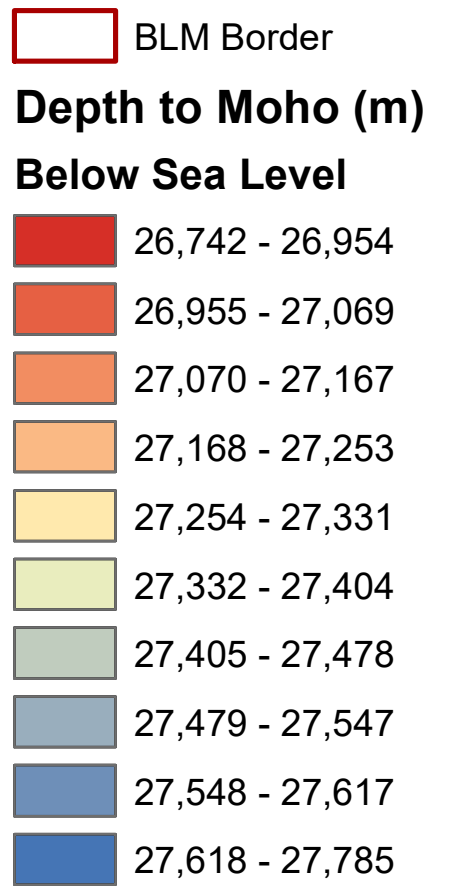☐ BLM Border

**Depth to Moho (m)**

**Below Sea Level**

| | |
|---|---|
| ■ | 26,742 - 26,954 |
| ■ | 26,955 - 27,069 |
| ■ | 27,070 - 27,167 |
| ■ | 27,168 - 27,253 |
| ■ | 27,254 - 27,331 |
| ■ | 27,332 - 27,404 |
| ■ | 27,405 - 27,478 |
| ■ | 27,479 - 27,547 |
| ■ | 27,548 - 27,617 |
| ■ | 27,618 - 27,785 |

Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

0    2.5    5        10
━━━━━━━━━━━━━━ Km

**~20 Ma**

Assumptions:
1. Upper Plate is:
   15 km thick above Core
   12.5 km thick above Middle
   10 km thick above Outer
2. Isostasy makes adjustments
   evenly according to zone

☐ BLM Border

**Depth to Moho (m)**

**Below Sea Level**

| | |
|---|---|
| ■ | 35,263 - 35,478 |
| ■ | 35,479 - 35,610 |
| ■ | 35,611 - 35,693 |
| ■ | 35,694 - 35,775 |
| ■ | 35,776 - 35,957 |
| ■ | 35,958 - 37,477 |
| ■ | 37,478 - 37,576 |
| ■ | 37,577 - 39,244 |
| ■ | 39,245 - 39,360 |
| ■ | 39,361 - 39,475 |

Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

# Plate 3: Present-Day and Paleo-Elevation of the Top of the Lower Plate of the Whipple Mountain MCC

## Isostatic Adjustment Partitioned into Three Zones (Core, Middle, Outer) of the MCC



**Present Day**

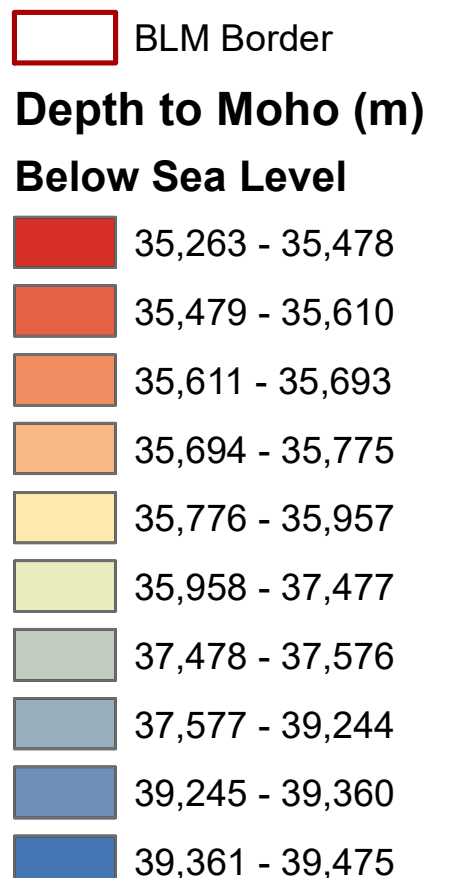Lower Plate Rocks

Upper Plate Rocks

Assumptions:
1. Present-day geologic map units correspond to Upper and Lower Plate (see Plate 6)
2. All Upper Plate Rocks (non-basement) are1 km thick.

Negative values are below sea level

BLM Border

**Elevation (m)**

- -780 - -580
- -579 - -460
- -459 - -308
- -307 - 19
- 20 - 435
- 436 - 547
- 548 - 651
- 652 - 779
- 780 - 939
- 940 - 1,250

Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

0   2.5   5   10   Km

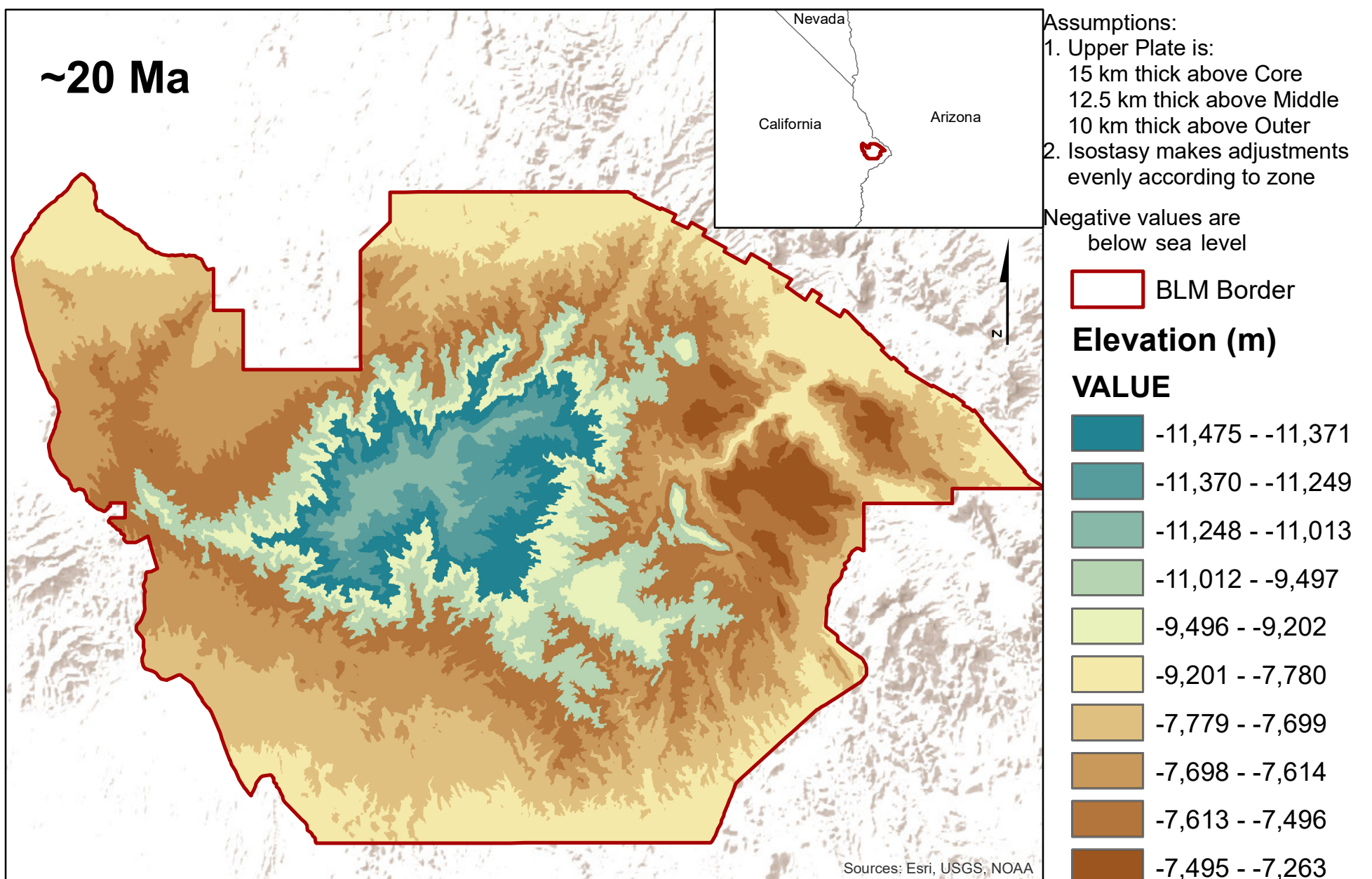**~20 Ma**

Nevada

California        Arizona

Assumptions:
1. Upper Plate is:
   15 km thick above Core
   12.5 km thick above Middle
   10 km thick above Outer
2. Isostasy makes adjustments evenly according to zone

Negative values are below sea level

BLM Border

**Elevation (m)**

**VALUE**

- -11,475 - -11,371
- -11,370 - -11,249
- -11,248 - -11,013
- -11,012 - -9,497
- -9,496 - -9,202
- -9,201 - -7,780
- -7,779 - -7,699
- -7,698 - -7,614
- -7,613 - -7,496
- -7,495 - -7,263

Sources: Esri, USGS, NOAA

Source: National Elevation Dataset (1/3 arc second DEM); Bureau of Managment (BLM) shapefiles

# Plate 4: Difference in Elevation and Depth to Moho within the Core, Middle, and Outer Zones of the Whipple Mountains MCC

## Decreasing the Depth to the Moho Accomodates 80% of Upper Plate Removal



**Difference between ~20 Ma and Present-Day Elevation**
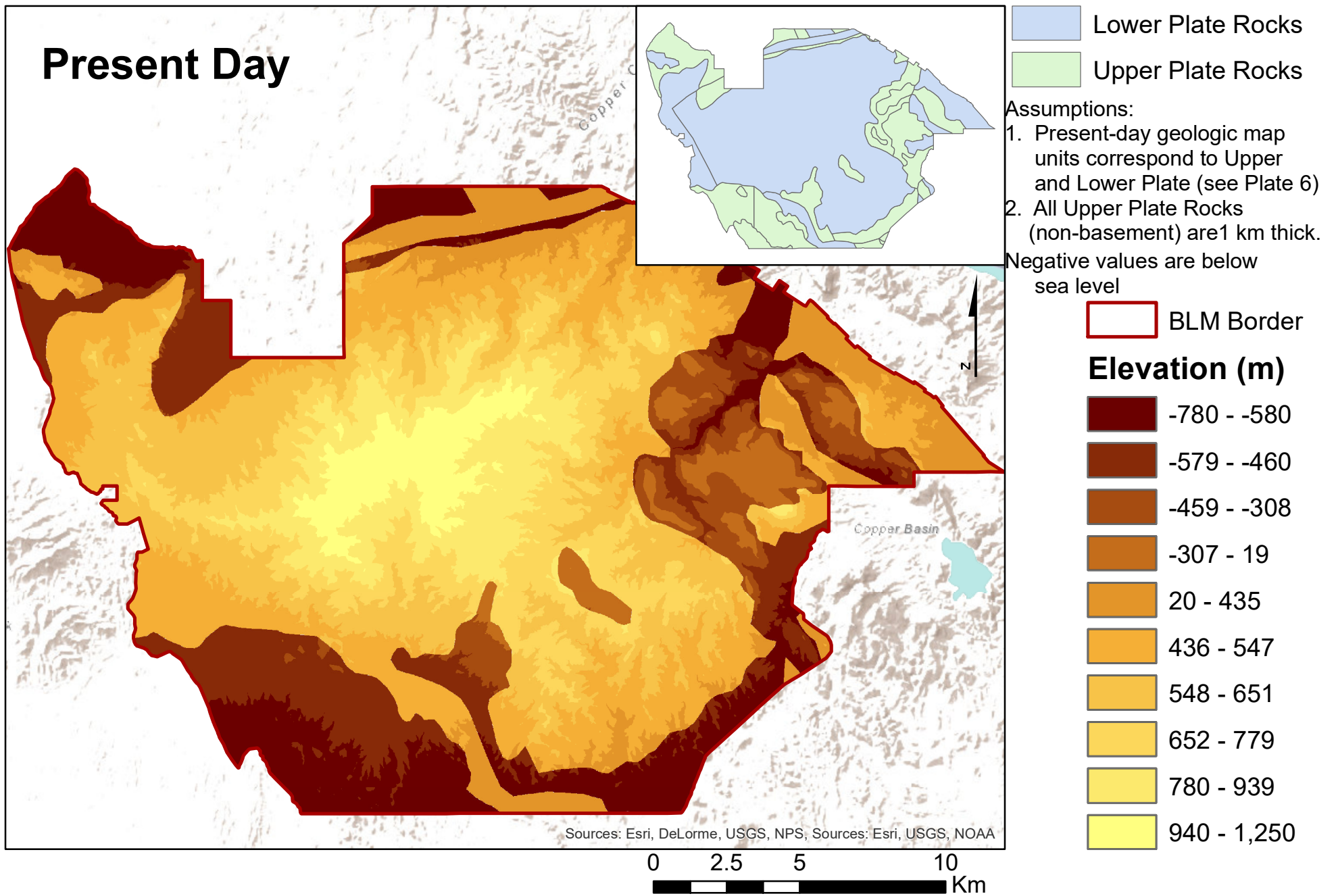
Assumptions:
1. Upper Plate is:
   15 km thick above Core
   12.5 km thick above Middle
   10 km thick above Outer
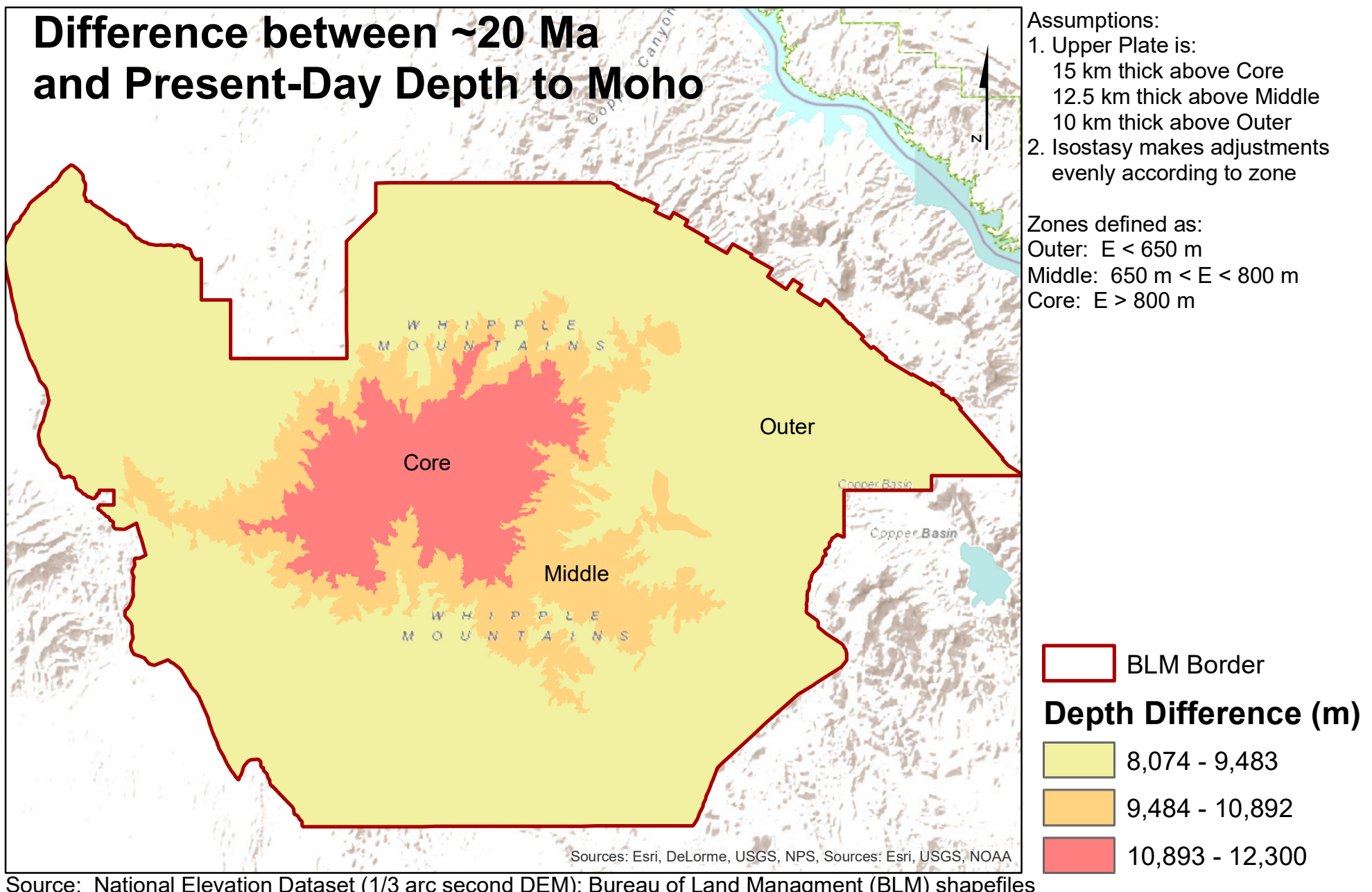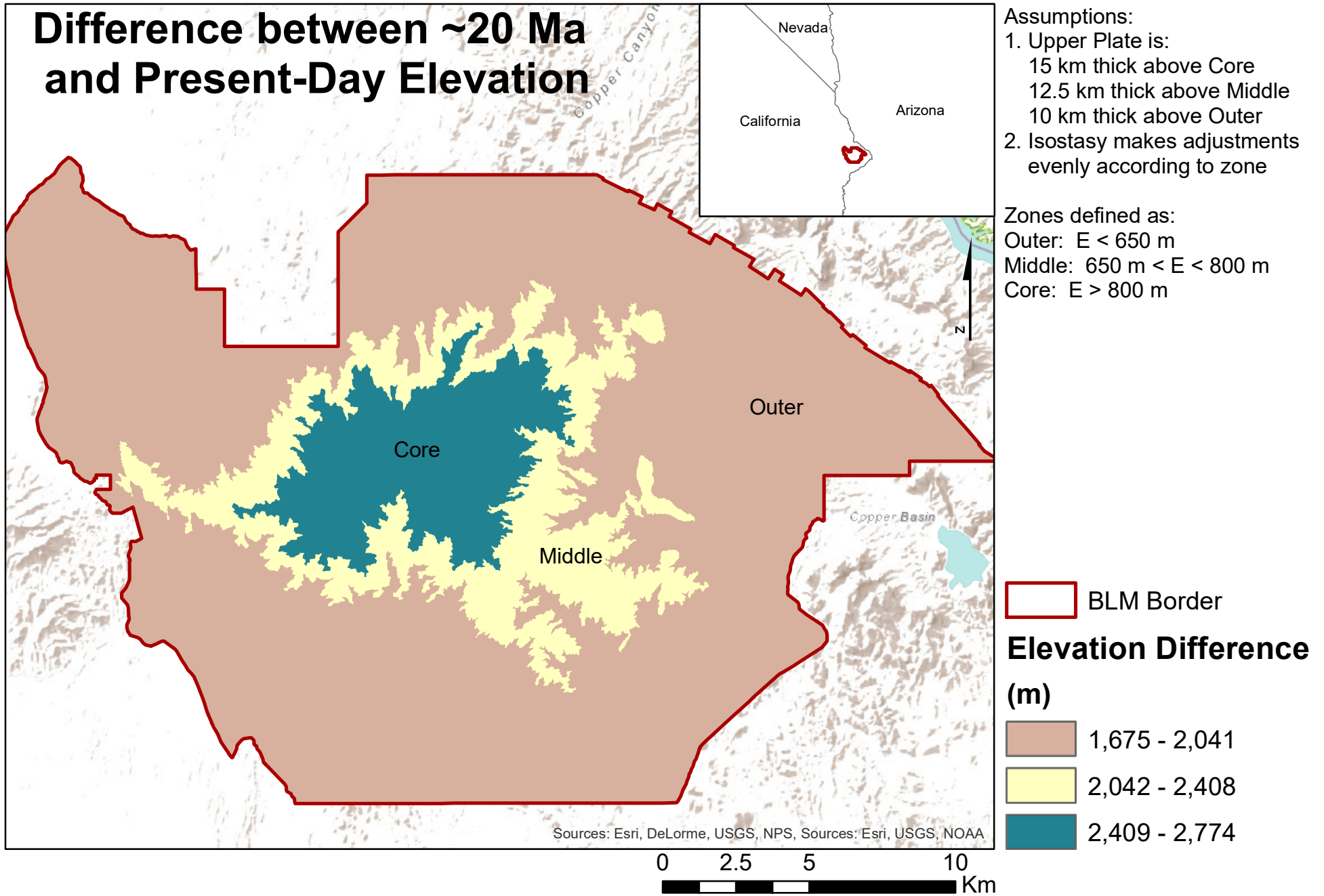2. Isostasy makes adjustments evenly according to zone

Zones defined as:
Outer: E < 650 m
Middle: 650 m < E < 800 m
Core: E > 800 m

Outer

Core

Middle

Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

☐ BLM Border

**Elevation Difference (m)**

| | |
|---|---|
| | 1,675 - 2,041 |
| | 2,042 - 2,408 |
| | 2,409 - 2,774 |

0    2.5    5    10
━━━━━━━━━━━━ Km



**Difference between ~20 Ma and Present-Day Depth to Moho**

Assumptions:
1. Upper Plate is:
   15 km thick above Core
   12.5 km thick above Middle
   10 km thick above Outer
2. Isostasy makes adjustments evenly according to zone

Zones defined as:
Outer: E < 650 m
Middle: 650 m < E < 800 m
Core: E > 800 m

WHIPPLE MOUNTAINS

Outer

Core

Middle

WHIPPLE MOUNTAINS

Copper Basin

Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

☐ BLM Border

**Depth Difference (m)**

| | |
|---|---|
| | 8,074 - 9,483 |
| | 9,484 - 10,892 |
| | 10,893 - 12,300 |

Source: National Elevation Dataset (1/3 arc second DEM); Bureau of Land Managment (BLM) shapefiles

Plate 5

Megan E. Flansburg
12/7/2017
GEOL 386G Final Project

# The Whipple Mountains Metamorphic Core Complex and Paleo-Elevation

## Applying the principles of isostatic equilibrium to detachment faulting and removal of the upper plate.

*Assumptions*
1. Thicknesses within zones as defined on Plate 4.
2. Isostatic principles apply equally across these zones.
3. No erosion has taken place.

Source:
National Elevation Dataset
1/3 arc second DEM
Bureau of Land Managment
(BLM) shapefiles

Coordinate System: GCS_WGS_1984_Major_Auxiliary_Sphere
Projection: WGS_1984_Web_Mercator

### Present-Day Surface Elevation
Map 1
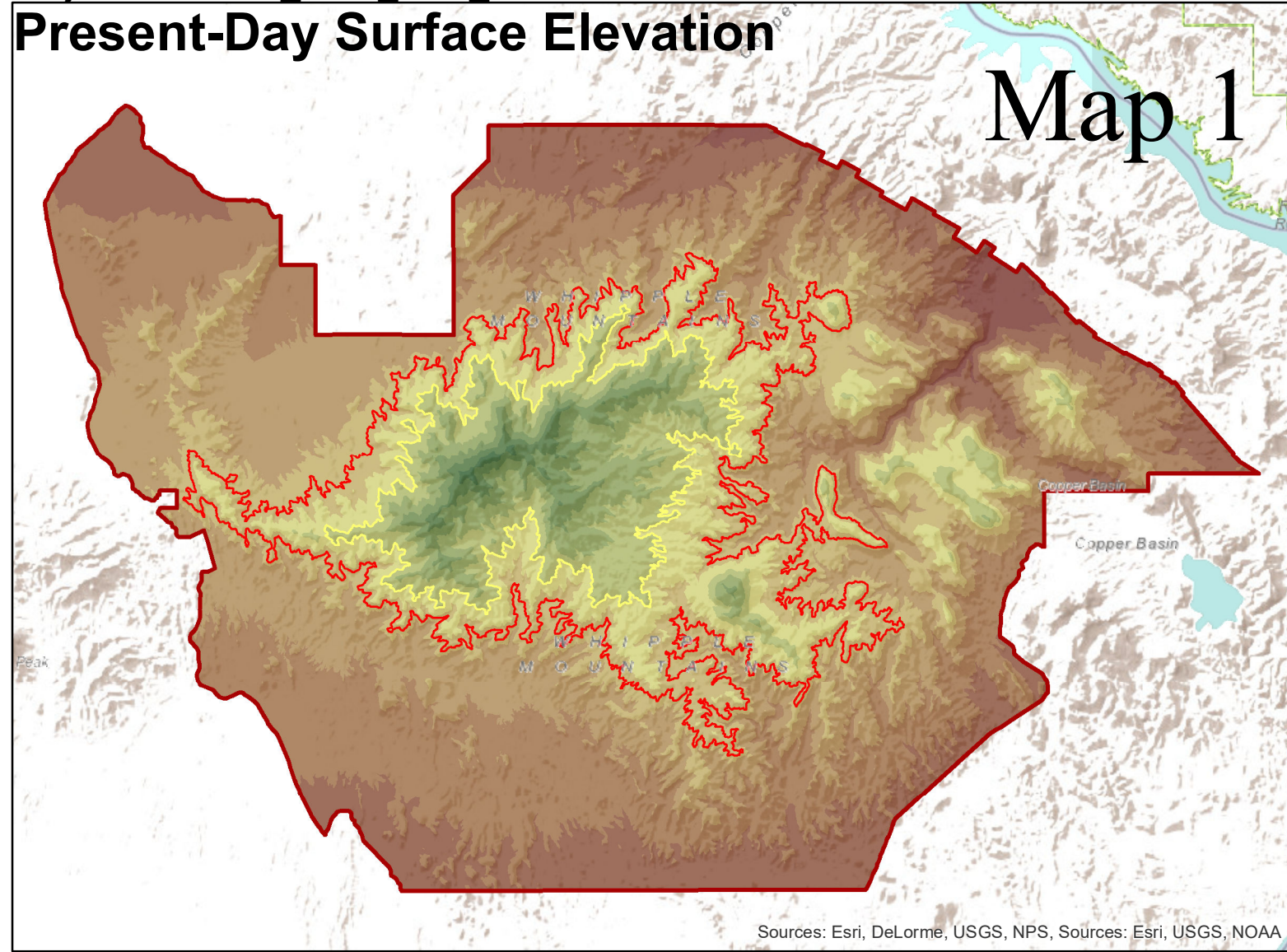
BLM Border
Core Zone (>800 m)
Middle Zone (>650 m)

**Elevation (m)**
- 215 - 300
- 301 - 400
- 401 - 500
- 501 - 600
- 601 - 700
- 701 - 800
- 801 - 900
- 901 - 1,000
- 1,001 - 1,100
- 1,101 - 1,200
- 1,201 - 1,300

Map Algebra (Raster Calculations)

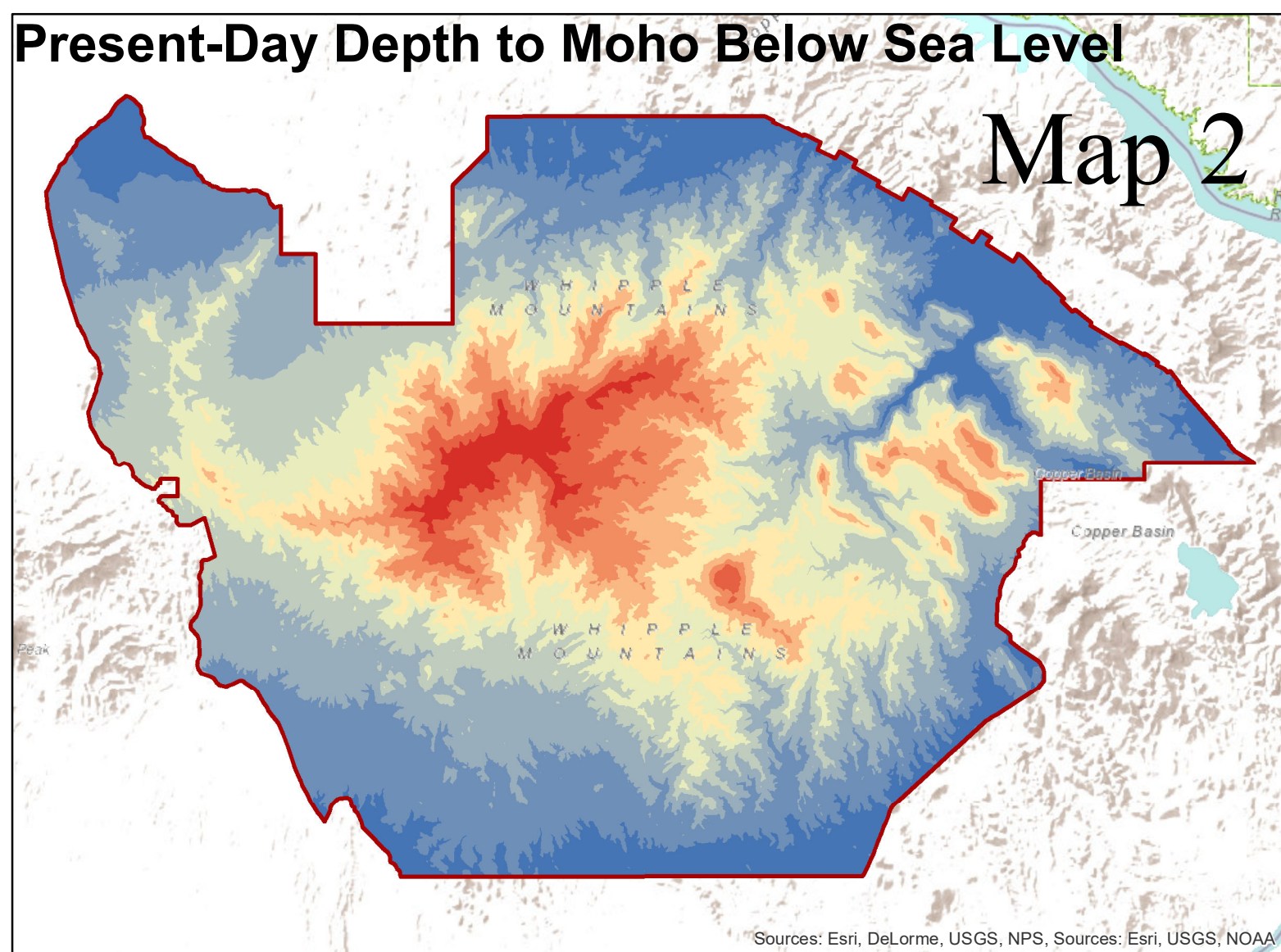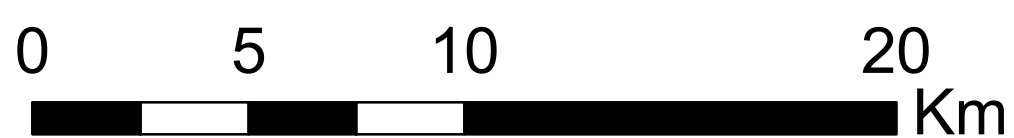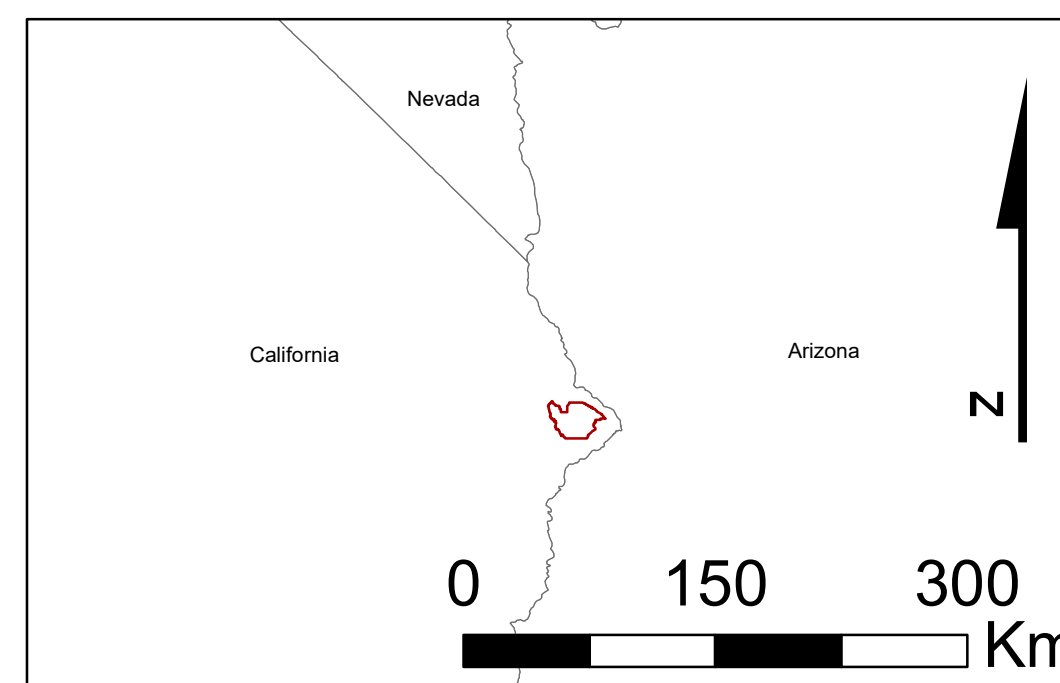Map 1 is National Elevation Dataset 1/3 arc second DEM

Map 2 = 28000 - Map 1

Core Zone:
Map 3 = Map 2 + (15000 * 0.8181)
Map 4 = Map 1 + (15000 *.1819)
Map 5 = Map 4 - 15000

Middle Zone:
Map 3 = Map 2 + (12500 * 0.8181)
Map 4 = Map 1 + (12500 *.1819)
Map 5 = Map 4 - 12500

Outer Zone:
Map 3 = Map 2 + (10000 * 0.8181)
Map 4 = Map 1 + (10000 *.1819)
Map 5 = Map 4 - 10000

Maps 3, 4, and 5 presented here are new rasters
created from Mosaic of calculated rasters above.

0  150  300  Km

0  5  10  20  Km

Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

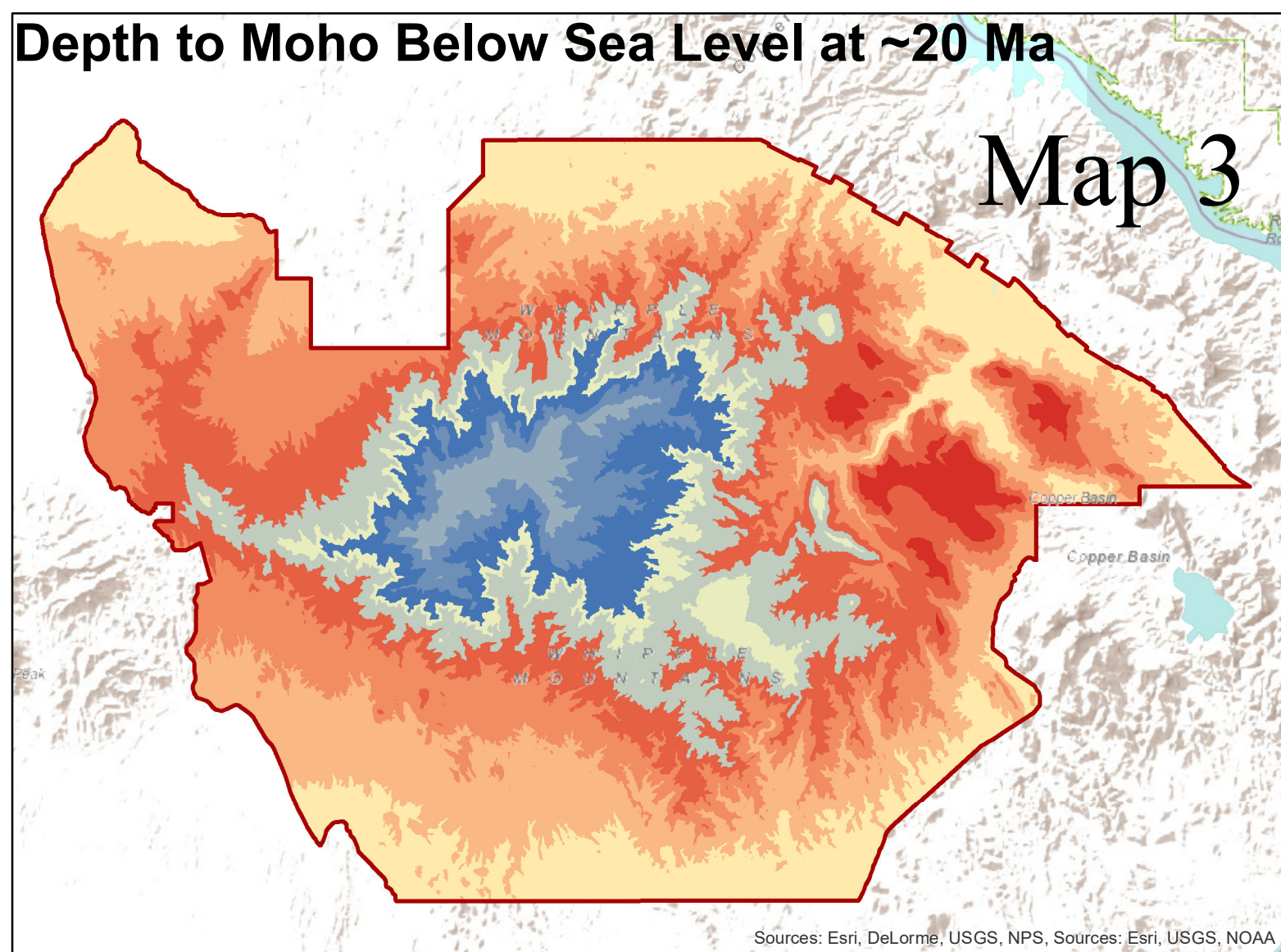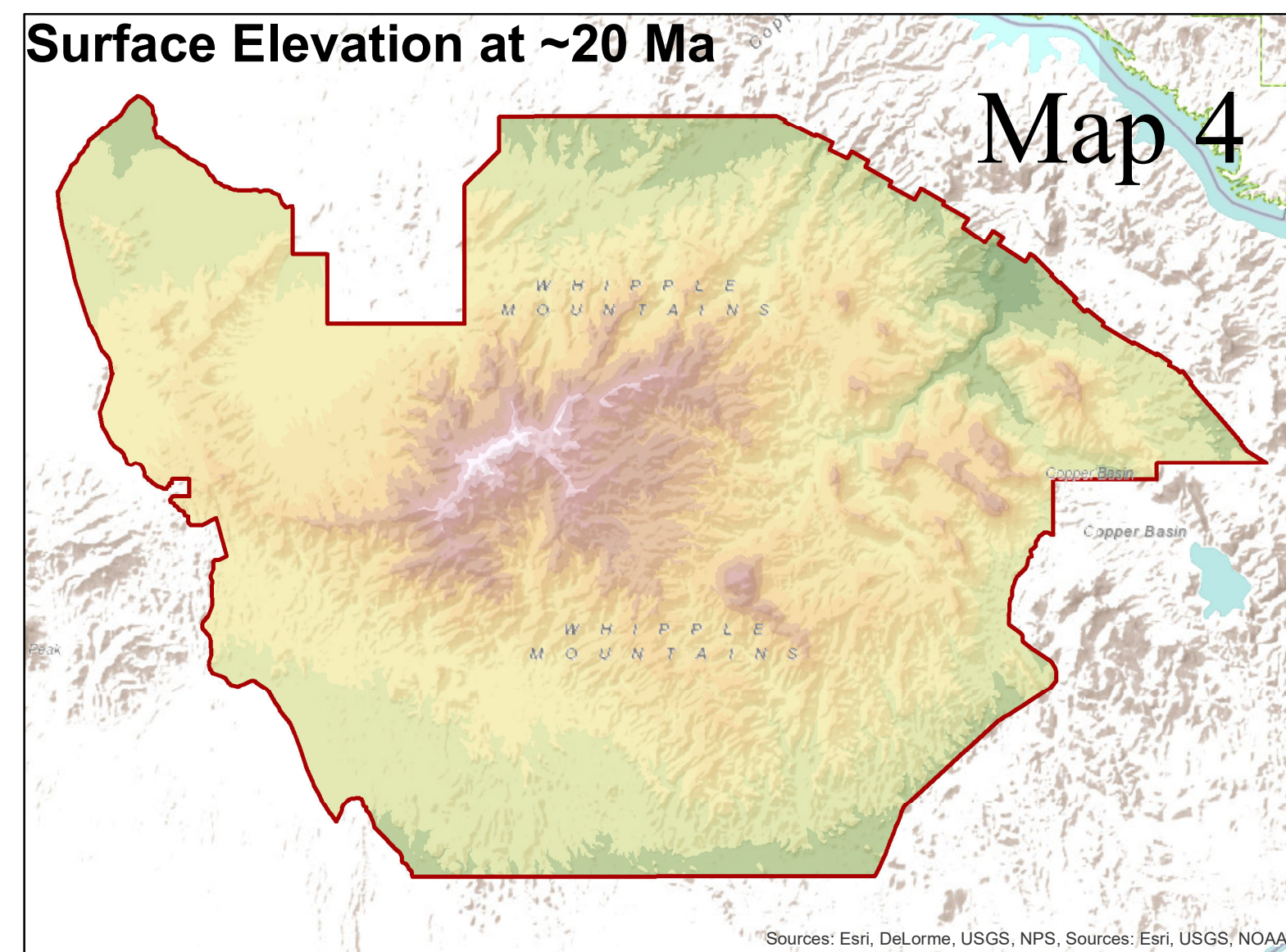### Present-Day Depth to Moho Below Sea Level
Map 2

**Depth to Moho (m)**
**Below Sea Level**
- 26,742 - 26,954
- 26,955 - 27,069
- 27,070 - 27,167
- 27,168 - 27,253
- 27,254 - 27,331
- 27,332 - 27,404
- 27,405 - 27,478
- 27,479 - 27,547
- 27,548 - 27,617
- 27,618 - 27,785

**Elevation (m)**
- 2,944 - 3,000
- 3,001 - 3,100
- 3,101 - 3,200
- 3,201 - 3,300
- 3,301 - 3,400
- 3,401 - 3,500
- 3,501 - 3,600
- 3,601 - 3,700
- 3,701 - 3,800
- 3,801 - 3,900
- 3,901 - 4,000

Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

### Surface Elevation at ~20 Ma
Map 4

Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

### Depth to Moho Below Sea Level at ~20 Ma
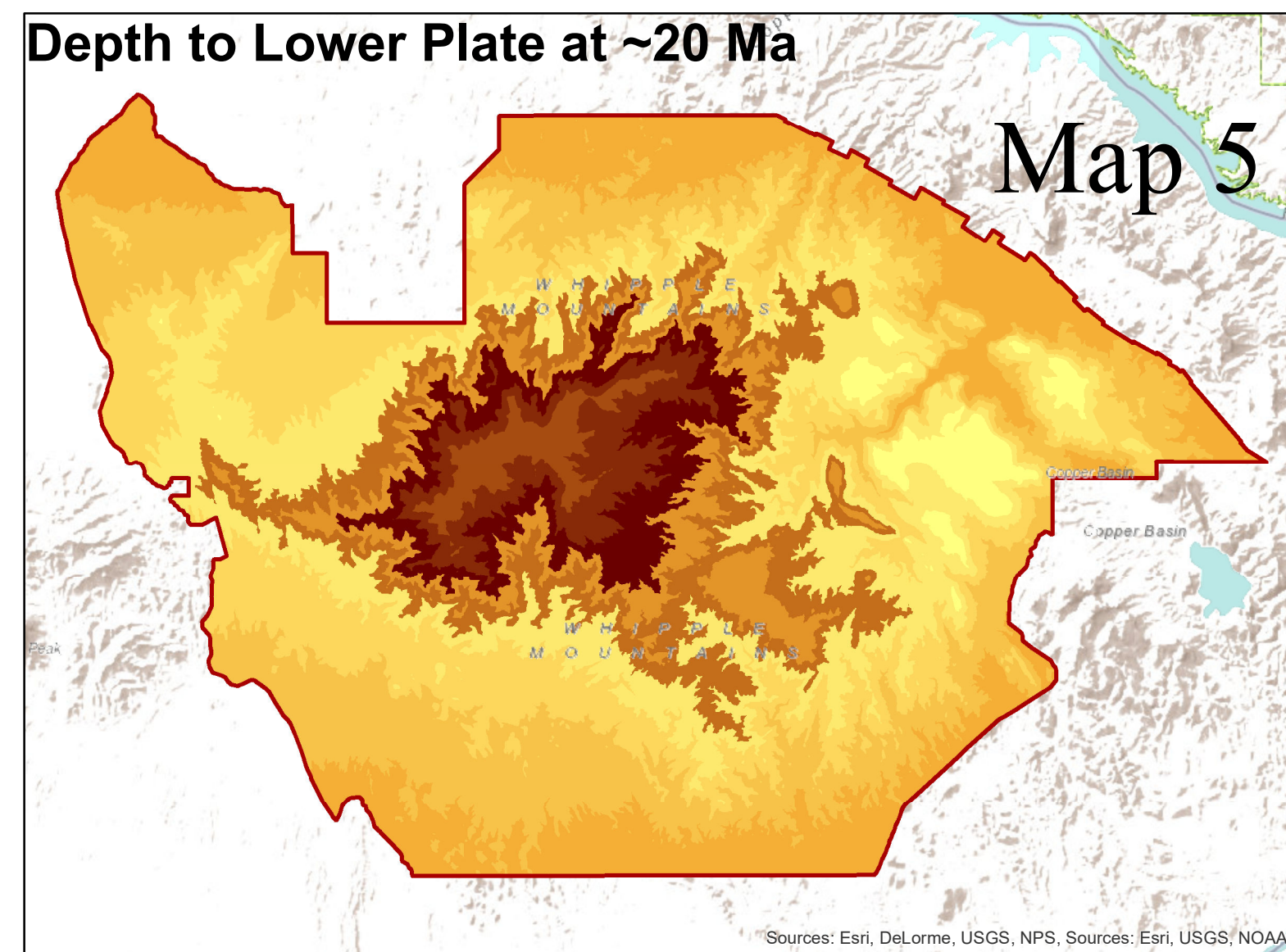Map 3

**Depth to Moho (m)**
**Below Sea Level**
- 35,263 - 35,478
- 35,479 - 35,610
- 35,611 - 35,693
- 35,694 - 35,775
- 35,776 - 35,957
- 35,958 - 37,477
- 37,478 - 37,576
- 37,577 - 39,244
- 39,245 - 39,360
- 39,361 - 39,475

Negative values
are below sea level

**Elevation (m)**
- -11,475 - -11,371
- -11,370 - -11,249
- -11,248 - -11,013
- -11,012 - -9,497
- -9,496 - -9,202
- -9,201 - -7,780
- -7,779 - -7,699
- -7,698 - -7,614
- -7,613 - -7,496
- -7,495 - -7,263

### Depth to Lower Plate at ~20 Ma
Map 5

Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA

Nevada
California
Arizona
N

Megan E. Flansburg
12/7/2017
GEOL 386G Final Project

# Plate 6:  Geology of the Whipple Mountains Wilderness Area

Whipple Mountains Metamorphic Core Complex

Inset on Plate 3:
Precambrian unit assigned as Lower Plate (bound by detachment fault).
All other units assigned as Upper Plate.
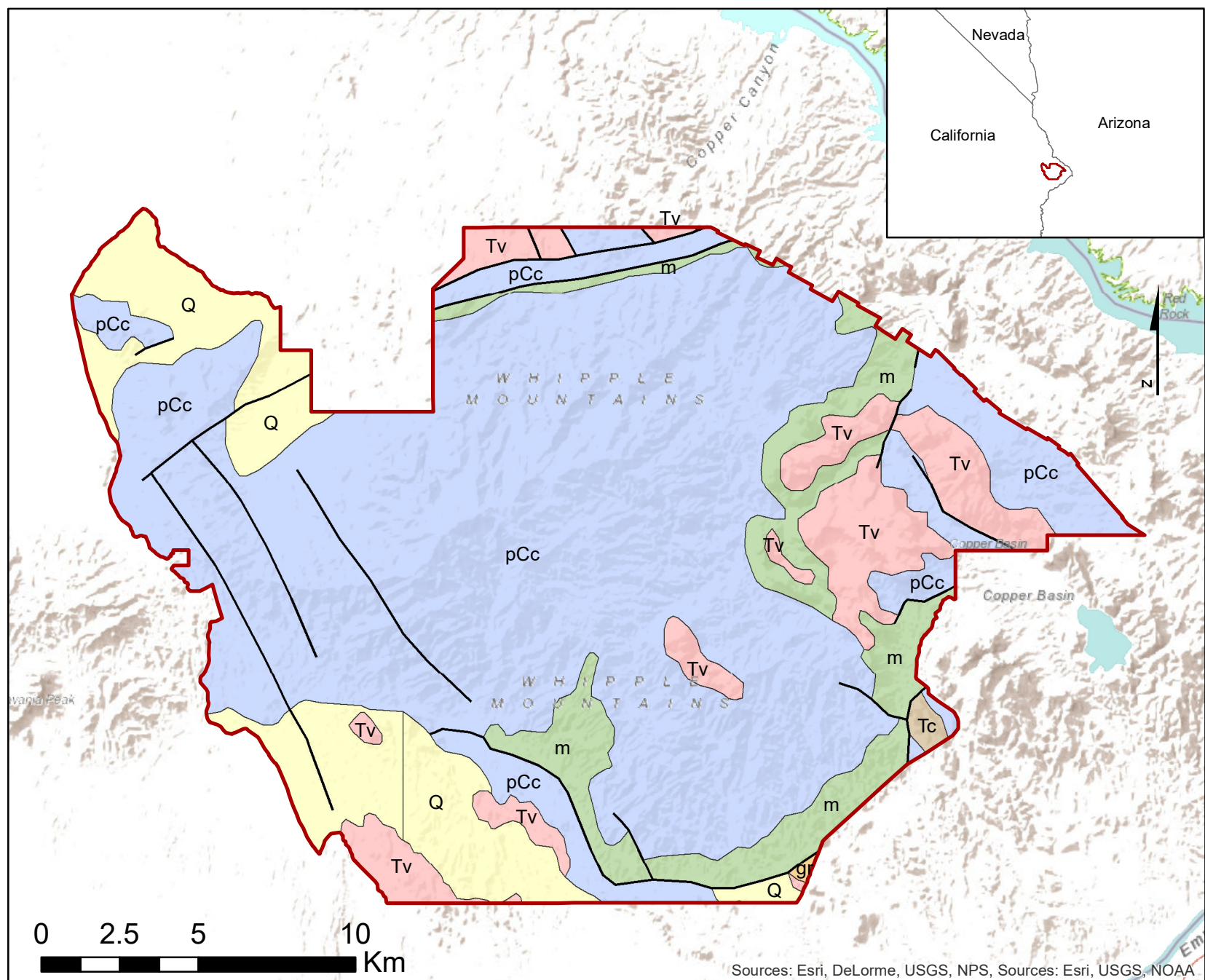


Coordinate System:  GCS_WGS_1984_Major_Auxiliary_Sphere
Projection:  WGS_1984_Web_Mercator

☐ BLM Border

—— High-Angle Faults

## Units

☐ Q: Quaternary alluvium and marine deposits (Pliocene to Holocene)

☐ Tc: Tertiary nonmarine rocks, undivided (Paleocene to Pliocene)

☐ Tv: Tertiary volcanic flow rocks (Tertiary (4-22 Ma))

☐ gr: Undated granitic rocks (Jurassic(?) to Cretaceous(?))

☐ m: pre-Cenozoic metasedimentary and metavolcanic rocks undivided (Early Proterozoic to Cretaceous)

☐ pCc: Precambrian igneous and metamorphic rock complex (Early Proterozoic to Miocene)

Source:  National Elevation Dataset (1/3 arc second DEM); Bureau of Land Managment (BLM) shapefiles;
USGS Mineral Resources On-line Spatial Data California Geologic Map