

ABSTRACT

The first deep imaging of the southern Appalachians has revealed a double Moho from the Blue Ridge Escarpment towards the North Carolina Piedmont, raising questions of what material is convoluting the crust-mantle boundary (Wagner et al. 2012). We're presenting work that seeks to test if an eclogite root situated between 40 and 60km depth is permitted with the Bouguer gravity anomaly in this region. Results from this gravity modeling show that two profiles from Tennessee to North Carolina and from West Virginia to Virginia can include such a root, although small adjustments can be made to support a model without eclogite. We favor the eclogite models over the latter due to their ability to explain the seismic discontinuity found in Wagner et al. (2012) and the density anomaly found in Mooney and Kaban (2010).

INTRODUCTION

Previous tomography in the southern Appalachians by Wagner et al. (2012) reveals a deviation in the expected Mohorovičić (Moho) discontinuity (Figure 1). The authors concluded that an eclogite slab could explain the discontinuity observed in this area due to its density and its associated geologic story. The two current models for the deep structure of the Appalachians that came from this study show a complicated architecture with differing interpretations of how the continental plates merged together. A map of the region published by GSA (1991) also provides several suggested models for the crust and upper mantle in its cross-sections along this transect. In addition to these interpretations, gravity modelling of North America by Mooney and Kaban (2010) has revealed an unexplained density anomaly underneath the southern Appalachians after controlling for topography, sedimentary basins, crustal structure, and thermal expansion.

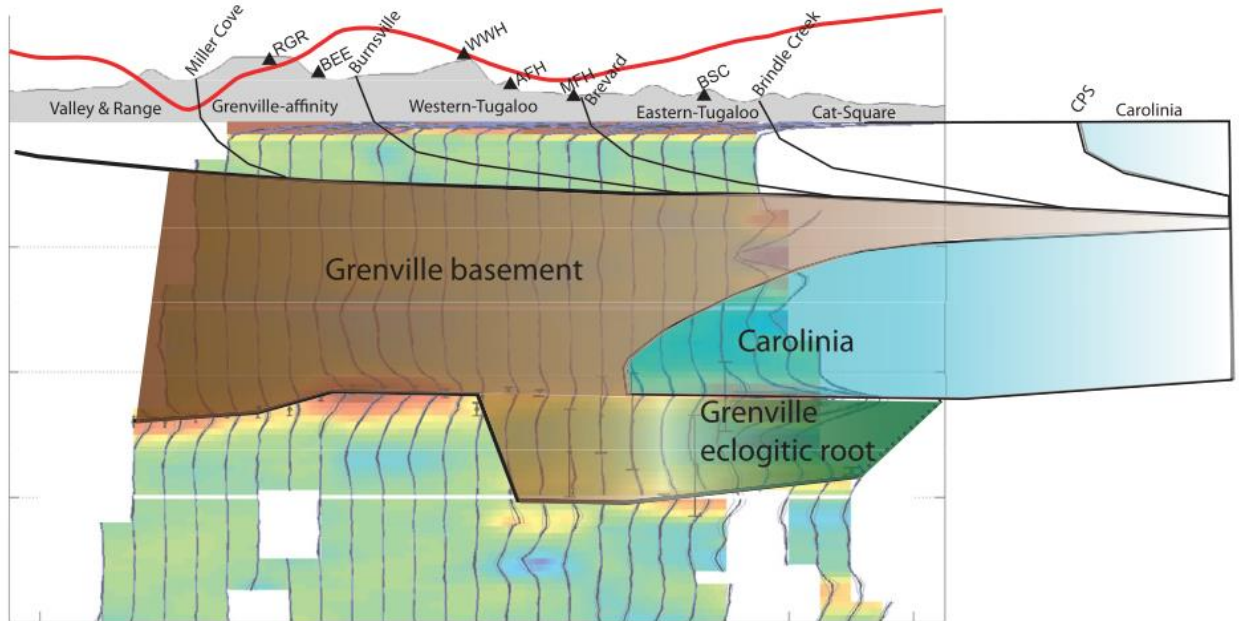


Figure 1. Proposed cross-section A – A' given in Wagner et al. (2012). The doubled Moho can be seen at the base of the Grenville eclogitic root.

These studies have all shown hypothesized structures at the Moho, but no work has been done yet to test if an eclogite root is consistent with the gravity anomaly in the area. This study seeks to improve these models by building crustal and mantle structures to match the Bouguer gravity anomaly profiles along two different transects of the southern Appalachians. Testing these models by looking at their generated gravity profiles will show if a large eclogite slab can exist between 40 and 60 km depth or if a homogenous mantle can fully explain the regional gravity anomaly.

GEOLOGIC SETTING

This study looks at the gravity along two different transects across the southern Appalachians. Cross-section A extends from northeastern Tennessee to western North Carolina, while cross-section B covers from central West Virginia to central Virginia, shown in Figure 2.

Cross-section A is the transect that Wagner et al. (2012) imaged the double Moho down to 60km depth, distinguishing this as the location of a possible eclogite root.

During the Appalachian orogeny, the closing of the Iapetus Ocean trapped a subducting oceanic plate underneath Laurentia. While descending, this oceanic slab would experience greater pressures and temperatures to partially eclogitize it, possibly confining it under the existing Grenville basement rocks. At a depth of 60km, the eclogite would have a density of approximately 3.35g/cm^3 (Groppo and Castelli 2010). If this did not happen, the plate would have continued descending deeper into the mantle and wouldn't have much of an effect on the gravity profiles.

Figure 3 shows the interesting topography of this region. The thicker crust towards A' has a lower corresponding surface elevation than the 46km crust beneath A, the higher-elevation Appalachian Plateau (Wagner et al. 2012). This isostatic compensation in this area does not intuitively make sense with a shallower crust supporting the weight of higher surface elevation. This would make sense with the eclogite root, since the dense material will pull down the lower-density rock above it.

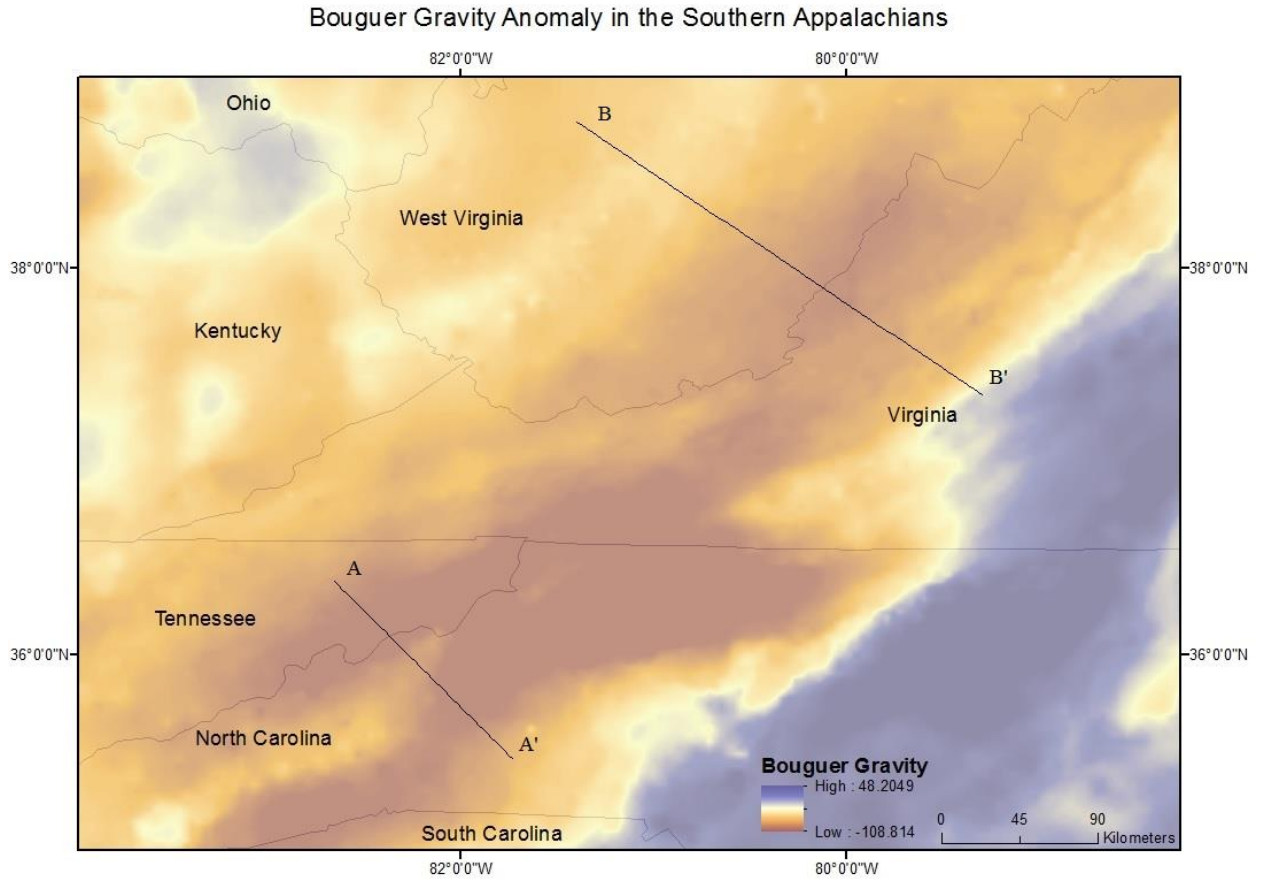


Figure 2. Locations of the cross-sections and Bouguer gravity. (A) is approximately 150km in length, (B) is approximately 250km.

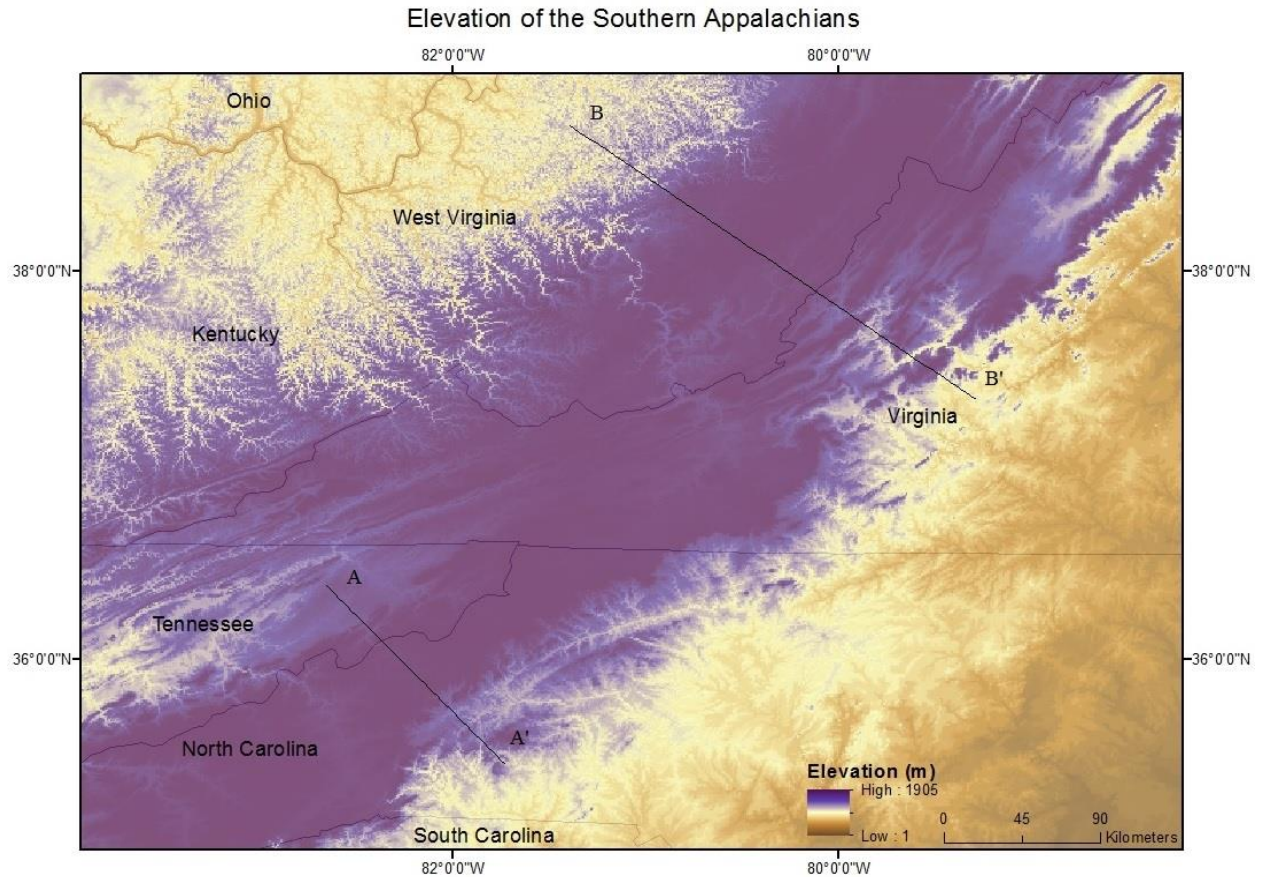


Figure 3. Relatively higher elevation in the southern Appalachians exist where the crust is thinner, which can't be explained with traditional isostatic compensation models if the crust is homogenous down to 60km.

METHODS

Gravity data for this study was procured from the Gravity Database of the US by Aldouri (2003) and Talwani 2.2 was used to construct the crustal structures in Figures 4 and 5. The densities and locations of the various rock units came from several different sources. The depth to the basement rock was located with Wilson (2000), King et al. (1998), and GSA (1991), each contributing the rock record down to 7 to 10km. Wagner (2012) provided the seismic data to derive depths of the Moho and possible eclogite root, while the Moho depth for transect B – B' was gathered from sediment loading models given in Wilson (2000).

I looked at the general shape of the gravity profiles in this area since that was more informative to the deep structure than seeking to explain every small-wavelength deviation in the profile. Kaban (2010) showed that generalized interpretations of the upper crust are adequate to image deeper structures, but the largest sources of error in this study likely come from an inability to determine precise locations of the different rock units and their corresponding densities. Even small ($<0.05\text{g/cm}^3$) changes in a rock unit's density can substantially alter the experimental gravity curve in that area. Using densities close to the average crustal density of 2.67g/cm^3 with informed nonconformities to that average minimized this error. The Carolina interpretation of the basement rock as explained in Wagner (2012) was used in cross-section A – A' to illustrate this region's gravity profile as it was the favored explanation of the tectonic history. Models with a consistent 2.73g/cm^3 , a lateral extension of the interpreted density for the Grenville basement, also supported the presence of eclogite.

Kaban et al. (2010) cautions that even with ideal data coverage, the standard deviations of residual gravity sources can be over 30mGal. This could substantially impact the accuracy of models where the amplitude of the profiles is small, such as in this field area (50-60mGal). Keeping a consistent upper-crustal structure between the various models helps to mitigate these errors, especially since they would likely be a shorter wavelength than we are interested in here.

See Appendix A for step-by-step instructions to replicate this study.

RESULTS

The eclogite models are consistent with the Bouguer gravity profile across both A – A' and B – B'. The higher density of the eclogite increases the gravitational pull of this area, raising the modeled curve above. While it is necessary to produce a steadily-increasing Bouguer gravity signature toward both A' and B', this same effect can be achieved with adding more dense

mantle in the area by raising the Moho less than a kilometer. The high density contrast between the crust and mantle compared to the low density contrast between the mantle and eclogite means that the Moho location has much more influence on the gravity signature.

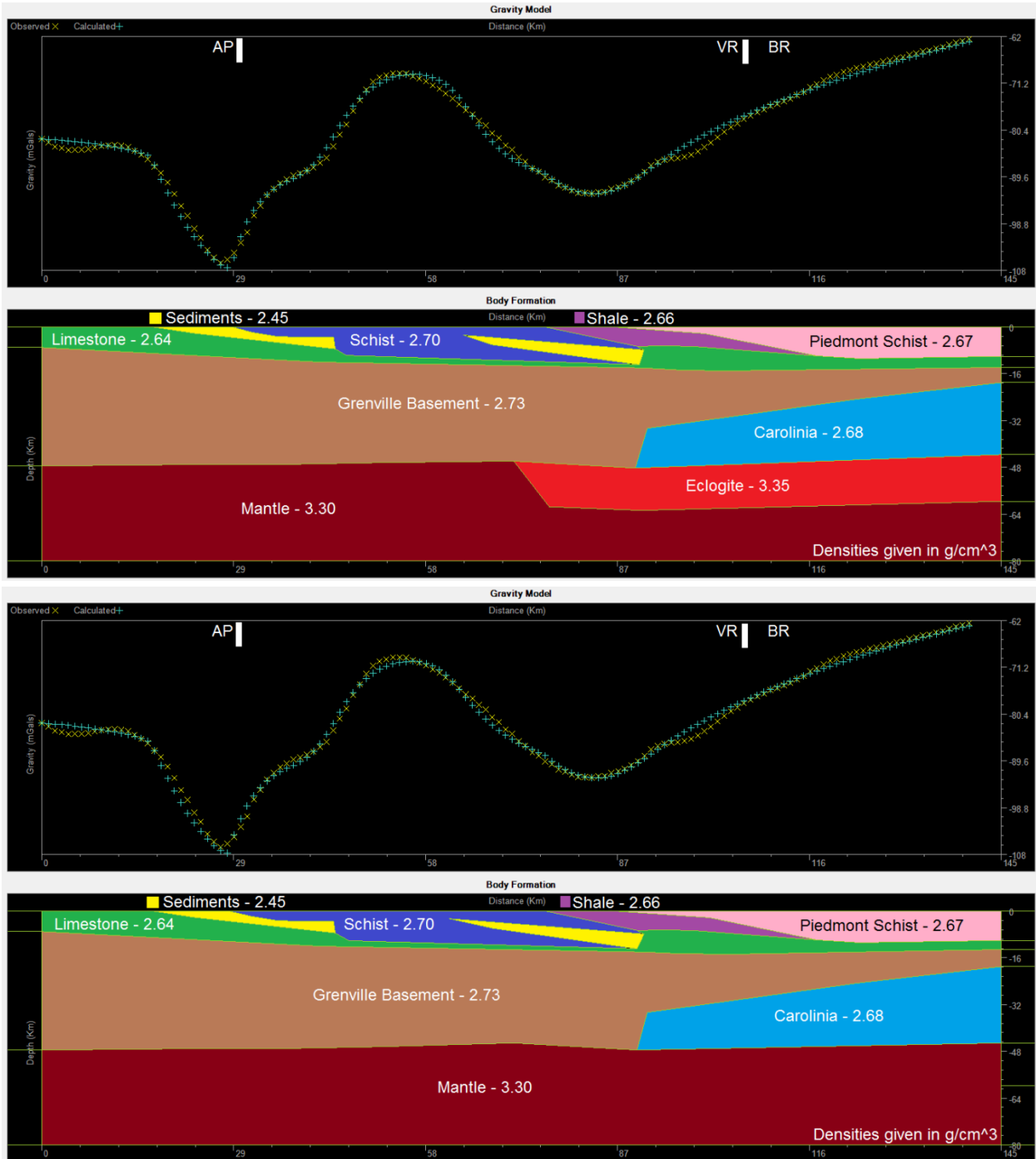


Figure 4. Cross-section A – A'. The Appalachian Plateau is labeled AP, the Valley and Ridge area is VR, and the Blue Ridge area is BR. The eclogite root fits the proposed models in Wagner

et al. (2012) and Mooney and Kaban (2010). The lower model shows that we can match the gravity profile without an eclogite root. The depth of the Moho near A' was changed less than a kilometer to provide the lower profile.

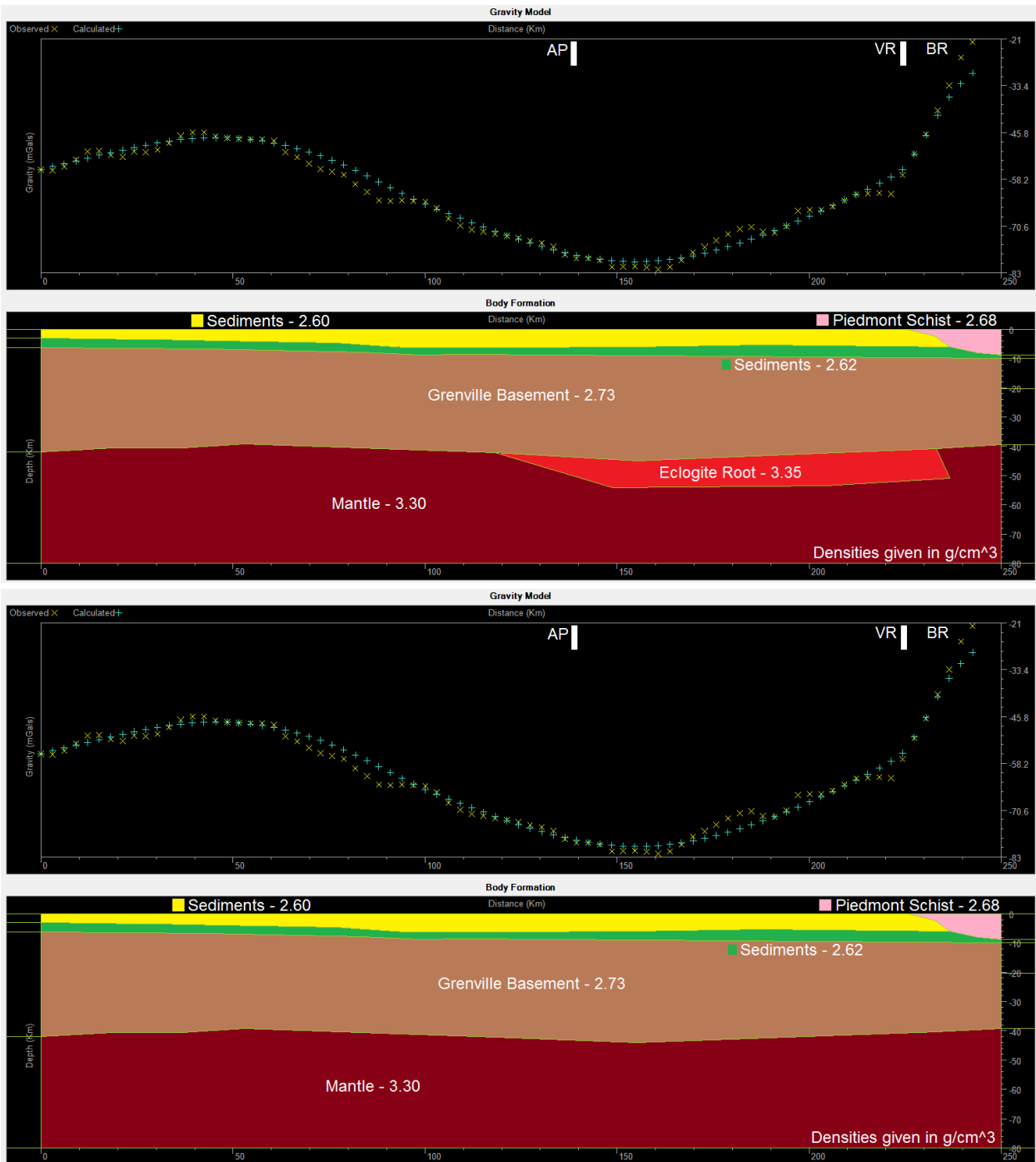


Figure 5. Cross-section B – B'. Similar to Figure 4, the gravity along this transect is consistent with an eclogite root between the Appalachian Plateau and Valley and Ridge. The homogenous-mantle diagram (lower) shows a Moho that is 0.8km higher than the eclogite model.

We tested these models by replacing the eclogite root with mantle to see how difficult it was to explain the Bouguer gravity in the area. Adjusting the Moho upward by less than a kilometer allows the relatively dense mantle material to displace the lighter crustal material, providing sufficient gravitational pull to match the observed gravity. This illustrates that the Bouguer gravity anomaly does not provide a unique solution to the regional gravity.

DISCUSSION

While the gravity models can support a deep structure with or without an eclogite root, we favor the models that include this root for their ability to explain the double Moho found in Wagner et al. (2012), the density anomaly found in Mooney and Kaban (2010), and the regional isostatic compensation. Figure 1 shows the double Moho underneath the proposed eclogite root, and the density anomaly described in Mooney and Kaban (2010) is shown in Figure 6. Its calculated 0.04 to 0.06 g/cm³ density increase fits the eclogite models for this region. Neither of the gravity models without this root can explain these geophysical signatures. The eclogite root's increased density would show up with the experiment conducted by Mooney and Kaban (2010) and alter wave speeds used in Wagner et al. (2012) enough to show the double Moho.

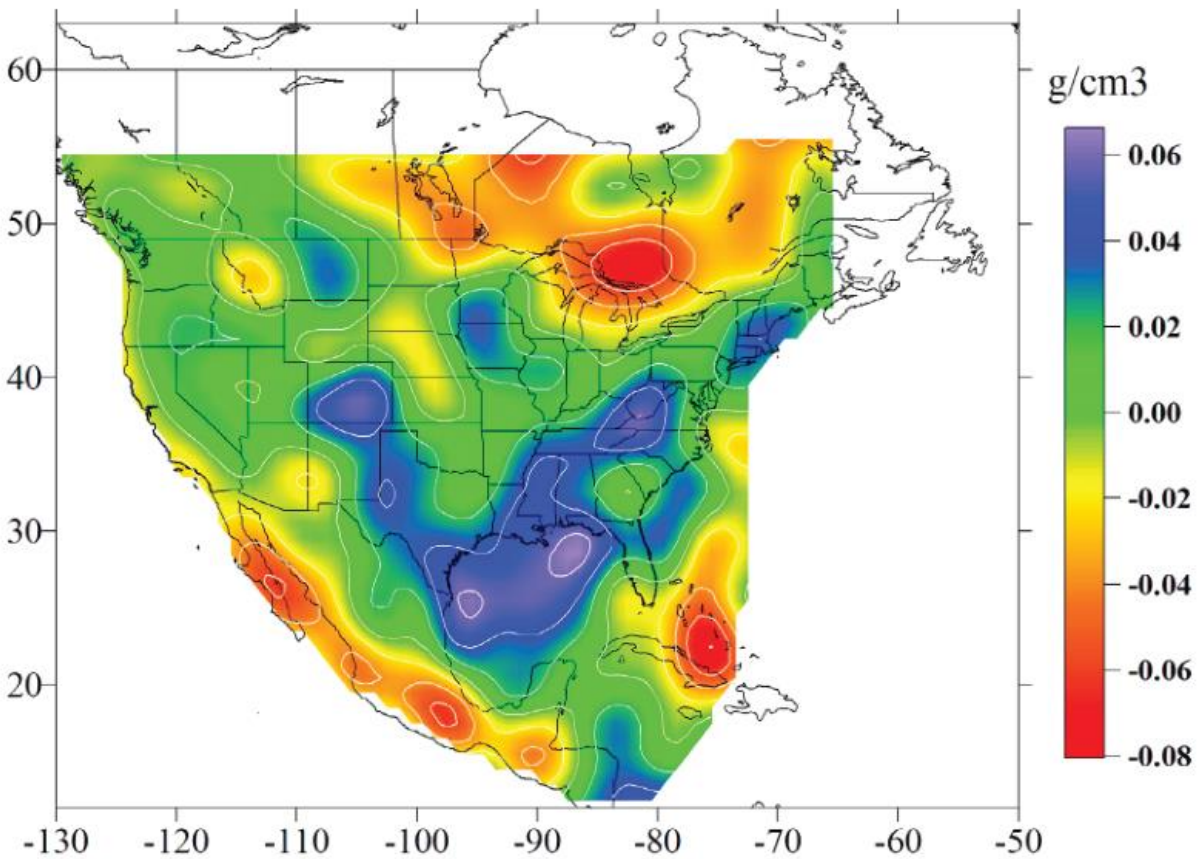


Figure 6. Taken from Mooney and Kaban (2010), this density anomaly map shows the location of a 0.04 to 0.06 g/cm^3 density increase underneath the southern Appalachians.

In addition to the geophysical evidence, an eclogite root would help to explain the regional isostatic compensation. The additional dense material wedged together with the lower crust would pull down on the rest of the plate, significantly lowering the surface elevation. The thinner crust towards A has no such root in these models, and it follows that this lack of dense material pulling it down corresponds to a higher elevation.

CONCLUSION

Overall, these models show that the Bouguer gravity anomaly permits an eclogite root in the deep structure of the southern Appalachians. Combining these models with the geophysical

results of Wagner et al. (2012) and Mooney and Kaban (2010) and the isostatic compensation of the area, we have good evidence to believe that this eclogite root exists at 40 to 60km depth along strike of the Appalachians. The Bouguer gravity profiles could support interpretations of a homogenous mantle on their own, but they would not be able to explain the other phenomena mentioned above.

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APPENDIX A

Gravity Modeling How-To

Programs needed, with recommended version:

- ArcGIS 10.1 (Through school)
- R 3.0.3 (<http://www.r-project.org/>)
- Talwani 2.2 (<http://research.utep.edu/Default.aspx?tabid=45290>)
- Notepad ++ 6.5 (<http://notepad-plus-plus.org/>)

1. Go to the “new application” for downloading gravity and magnetic data here:

<http://research.utep.edu/default.aspx?tabid=37229>

-Download up to 150,000 points at a time. You can download about 8 states’ worth of gravity data at a time.

2. Open the gravity data with excel

-copy the nad83 lat and lon columns, as well as the Bouguer anomaly column

-open a new Excel document, fill the first three columns with all the data like this:

Lon	Lat	Bouguer
83.873219	36.83273	-47.39

-save as .csv

3. Open ArcMap

-Connect to the folder with this file in it

-File>Add Data>Add X Y Data

-Lon and Lat should be filled out automatically, select Bouguer as your z value

-Select Nad83 as your projected coordinates if not automatically selected

-Hit OK

4. Now we need to rasterize the data

-ArcToolbox window > 3D Analyst > Raster Interpolation > IDW (or your favorite raster)

-Input point features: (Yourfilename.csv) from drop-down menu

-z value field: Bouguer

-Output raster: Choose a location for the file

-Hit OK, and your file should be added. Right click it and go to Properties > Symbology to play with the color ramp and classification

5. In ArcMap, click "Interpolate Line" from the 3D Analyst toolbar. Click on the starting point of the gravity cross-section that you want to extract, double click at the endpoint. This will draw a line that you can extract with the Profile Graph button, found on the drop-down menu of the point profile button.

-Right click on the graph > Export > Data > Excel > Save

-Right click on the line itself > Length

-Check that this is in decimal degrees, then copy the start point and end point locations. We will use this to calculate the true distance between the points.

6. Open up a new excel document and copy in the values like so:

pt1lon	pt1lat	pt2lon	pt2lat
-82.9831	36.13213	-81.3425	35.2438

-Save as a .csv file you will replace in the code below

7. Open up the data you saved from the profile graph in Excel

-Delete the title and organize it like so:

X	Y
0	-45.327
0.07213	-48.213

-Save this as a .csv file that you will replace in the code below

8. Open Notepad++

-Add the following code and save it somewhere:

```
##You need to install the geosphere package. Do this with Packages > Install Packages in R.
```

```
This only needs to be done once.
```

```
##Should be 3 files you need to change each time here
```

```
##Set your working directory in the line below, where you have stored all your files you will load in. This will not need to be changed again once it has been set. To find this, navigate to the file in your computer and copy the pathway to that folder in Properties.
```

```
setwd("C:/") ##Add your working directory here
```

```
library(geosphere)
```

```
##Your data file from step 8 goes here, with .csv, in the quotes
```

```
A=read.csv("",head=TRUE)
```

```
##Your point file from step 7 goes here, with .csv, in the quotes
```

```
pt=read.csv("",head=TRUE)
```

```
B=data.frame(A)
```

```
ptd=data.frame(pt)
```

```
#Gather variables
```

```
P=A$X
```

```
G=A$Y
```

```

p1n=pt$pt1lon
p1t=pt$pt1lat
p2n=pt$pt2lon
p2t=pt$pt2lat
nr=nrow(B)

##Make two matrices
M1=matrix(
  c(p1n,p1t),
  nrow=1,
  ncol=2)
M2=matrix(
  c(p2n,p2t),
  nrow=1,
  ncol=2)

##Calculates the true distance between points, using the radius of the earth set below
dH=distHaversine(M1, M2, r=6378137)

##Divide into equidistant segments, convert to km. Talwani uses km for units
E=(dH/(nr-1))/1000
DF=data.frame(X=c(E*seq(0,nr-1,1)))
Gp=data.frame(G=c(G))

#combine the columns
Fin=c(DF,Gp)

##In the quotes, change this to the output file name you like with .csv in the title
write.csv(Fin,"",row.names=FALSE)

```

8. Now that you have saved this file and changed the three file names, copy it into R. If the `setwd()` command didn't work (it can be finicky sometimes), do it manually through File > Change Dir.

- All the code should run, hit enter to get your final file
- If you get errors, the most likely reason it the files are not set up correctly. Check to make sure you have actually saved them as .csv files through excel and you're not loading the .xls files. See if your working directory is set correctly.

9. Open up your new file with the correct distances in km.

Load up Notepad again and make a new file, copy this information into it. This will be your gravity file, and it needs to be saved as a text document. When you enter a file name, it has to have .grav.tal at the end of it (Example: 6WVgravity.tal.grav). But before you do that...

- Open the Talwani example gravity file and look at how the text file is structured. Erase your heading on your file and copy theirs (Two lines with an asterisk before each one)
- Open up the Talwani example input file.
 - Copy this into a new file, save it as a text file with .tal at the end (Example: 6WVcs.tal).
 - There are a several things you need to change here, discussed in part 11.

10. Variables worth changing in the example Talwani file

RMAX – how long (in km) the cross section is. Make this a little bit bigger than your highest distance in your gravity file

ZMAX – how deep the cross-section goes. Depending on how deep you need to go, -80 is about good.

GMIN, GMAX – range of gravity values. Set these a little lower and a little higher than your minimum and maximum gravity values, respectively. This will be changed again once you're in Talwani.

NOBS – Look at your gravity file. This should be how many gravity observations there are (last line number minus 2 for the heading). If this number is wrong, you will get an error trying to load it into Talwani

NUMBODS – come back to this after you have entered your structure. It is the total number of units for the program to load in

* Gravity observations at external file – This is where you put in your gravity file. Example:
@6WVgravity.tal.grav

Delete all the example structure except for one of them.

The all-caps title is what will be displayed in the program

Then there are 5 numbers like so:

```
14 2.7 1000 1000 0
```

Only change the first two numbers here; the first number (14) is the number of points, the second (2.7) is the density in g/cm³

The points you put in must be in the form X (Tab) –Y and they have to be in a logical order.

Construct the geologic units in clockwise or counterclockwise order. Example:

```
0      0
0      -5.9
42     -12.9
91     -14
98     0
```

This example has 5 points in it, and let's say it is all granite.

The final section would read

```
GRANITE
5 2.67 1000 1000 0
```

0	0
0	-5.9
42	-12.9
91	-14
98	0

Make several more of these, using the same points for where you want two neighboring structures to share a boundary. This makes sure that when you move a point there is no gap left behind. This can be very tricky to get right when you have lots of points in one file, so be careful when you go back and edit the file to include more structures. Always remember to change the NUMBODS at the start of the file and the number of points in each structure's heading to reflect the structures in the file. This is where most errors will come from.

11. Load Talwani

- Open the .tal file you made
- Go to Tools > Options and check "Define End-Bodies automatically", and set the Extension amount to 1000
- Check Adjust G-scale automatically
- Once you feel comfortable with the program, you can adjust the other settings to your liking

12. Observe the differences between the blue (calculated) and yellow (observed) gravity values.

- Drag the points on the lower portion (the structure) around to see how it changes the gravity profile. Right clicking on the bodies will allow you to edit their densities. If you need to add another unit, you must save, exit, and load the saved file into Notepad++ and add it from there.

13. For this study specifically, the density values used for each section of the structures can be seen in figures 2 and 3.