Gravity and magnetic modeling of basement beneath the Appalachian Plateau, Valley and Ridge, and Piedmont provinces, Alabama

by

Robert Frank Singleton III

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
August 6, 2016

Approved by

Lorraine W. Wolf, Chair, Professor of Geosciences
Mark G. Steltenpohl, Professor of Geosciences
Ashraf Uddin, Professor of Geosciences

Abstract

Despite the significance of regional geophysical anomalies and the economic potential of the area, central Alabama has lacked detailed crustal gravity and magnetic models. The southeastern United States has undergone at least two complete successions of Wilson cycles, making the geology of the region complex. This study focuses on creating tectonic and geologic models of this region in Alabama, specifically targeting the New York – Alabama lineament and what is interpreted as the southern continuation of the Amish Anomaly. These anomalies and the basement rock beneath Alabama are difficult to study due to the presence of overlying Appalachian rocks. In northwest Alabama, the Appalachian/Cumberland Plateau is comprised mainly of the Black Warrior basin, a thick package of Paleozoic sedimentary rocks that display minor evidence of Alleghanian deformation. In central Alabama, Paleozoic sedimentary rocks of the Valley and Ridge province cover the basement rocks to even greater depths. To the southeast, sedimentary rocks abruptly transition to metamorphic rocks of the Talladega slate belt and the Piedmont province. These provinces were sutured onto Laurentia during the Acadian orogeny, further obscuring the basement from study.

In this study, airborne-gridded gravity and magnetic data were used to produce a detailed crustal model for this region of Alabama. These transects cross major tectonic boundaries, geophysical anomalies, and Grenville-aged structures. Geologic maps, well-logs, and interpreted cross-sections were used to constrain these models to make them as accurate as possible.

However, these constraints only apply to the upper few kilometers of the crust, and much is unknown about the basement beneath Alabama. Previous geophysical studies from adjacent areas in Mississippi, Georgia, and Tennessee, and Alabama further constrain this study's models and help add to their validity.

Results support interpretations that the New York – Alabama lineament and Amish Anomaly mark the northwestern and southeastern boundaries of a westward dipping terrane with relatively high density and magnetic susceptibility. This finding is consistent with other studies done on the New York – Alabama lineament in Tennessee and Ohio, and suggests that a previously unknown Grenville-aged tectonic terrane may be present in the basement beneath Alabama.

Acknowledgments

I would like to take this time to show my deepest gratitude and thanks to my thesis adviser, Dr. Lorraine Wolf, whose kind and constant support of this project was the key to its completion. Without her consistent guidance and expertise, I would still be stalled. Thank you for making me a better scientist and person. I also want to thank my other committee members who were, at other times during my graduate tenure, also my advisers. Dr. Mark Steltenpohl is the reason I pursued a graduate degree in geology, while Dr. Ashraf Uddin is one of the most helpful and genuine professors I have ever had the fortune to study under. Thank you all for your patience, expertise, support, and contribution to this project.

My gratitude also extends to the rest of the faculty and staff in the Geosciences Department at Auburn University. Your constant guidance throughout my undergraduate and graduate degrees will be crucial to my success as a geoscientist.

I would like thank other people who helped me at various times throughout my project. Thank you to Dr. Dave Daniels for providing the gravity and magnetic data, and to Dr. Jack Pashin and Dr. Heather DeShon for commenting on my research. I would like to especially thank everyone at the Geologic Survey of Alabama and State Oil and Gas Board: Dr. Nick Tew, Dr. William Thomas, Dr. Sandy Ebersole, Ms. Denis Hills, and Ms. Camilla Musgrove. Your willingness to speak with me and provide me with resources was crucial to this research.

Last but not least, I would like to send out all of the love and appreciation that I can for my parents, Bob and Tracy Singleton, as well as my brother Gregory. The support they have shown me throughout my life will never be eclipsed, and my gratitude is endless. Thank you so much.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AA – Amish Anomaly

AL – Alabama

BMA – Brunswick Magnetic Anomaly

BMW – Bessemer “mushwad”

COCORP – Consortium for Continental Reflection Profiling

EARS – EarthScope Automated Receiver Survey

HF – Helena fault

HLF – Hollins Line fault

IRIS – Incorporated Research Institutions for Seismology

Ma – Mega-annum, 1 million years

NGDC – National Geophysical Data Center

NOAA – National Oceanic and Atmospheric Association

NY-AL lineament – New York-Alabama lineament

OJF – Opossum/Jones Valley fault

PCF – Pell City fault

PMW – Palmerdale “mushwad”

SI – Systéme Internationale (International System)

TCF – Talladega/Cartersville fault

TPS – Total Petroleum System

Introduction

Rocks underlying the southeastern United States have undergone multiple orogenic events and created a complex geologic setting. The key tectonic events include the Precambrian Grenville orogeny, the opening of the Iapetus ocean, multiple Appalachian orogenic episodes, and Mesozoic rifting that led to the opening of the Atlantic Ocean. Structures associated with these tectonic events are preserved in central and north Alabama, the location of this study. Some structures associated with various episodes of orogenesis can be observed at Earth's surface. However, many Appalachian structures and deeper Grenville structures are hidden within transported terranes or buried beneath Coastal Plain sediments that are up to 8 km thick. Although regional gravity and magnetic data are available, the nearest seismic studies are from the 1980's Consortium for Continental Reflection Profiling (COCORP) campaign in adjacent Georgia and Tennessee. A lack of deep seismic data in Alabama has limited our ability to interpret the nature of the deeper crust.

The Black Warrior, Cahaba, and Coosa basins are deformed foreland sedimentary basins contained within multiple geologic provinces in central and north Alabama (Figure 1). These basins have long been recognized for their deposits of high-grade bituminous coal and carbon sequestration potential of the Pennsylvanian Pottsville Formation (Carroll et al., 1995; Carroll and Pashin, 2003). Although the Birmingham area in central Alabama is historically known for the forging of steel and iron during the Industrial Revolution, this industry has long since left the area. However, the Pottsville Formation has stimulated interest in the extraction of natural gas and the potential for CO_2 sequestration. The Pottsville Formation is one of the thickest successions of Lower Pennsylvanian siliciclastic strata in North America with sorption capacity estimates on the

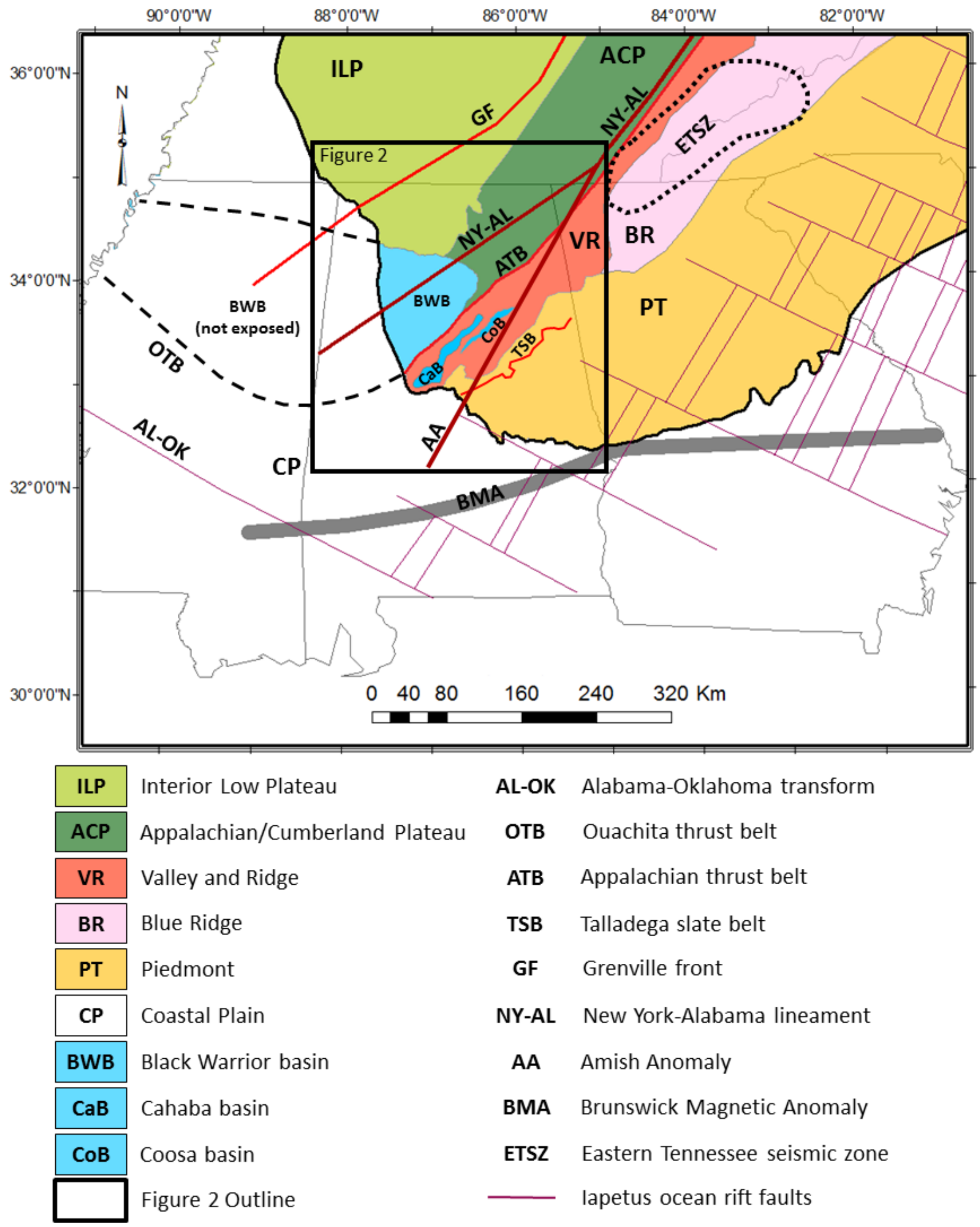


Figure 1. Map of physiographic provinces, individual Carboniferous basins, tectonic structures, and geophysical anomalies in the southeastern United States. The Black Warrior basin's (BWB) approximate extent beneath the Coastal Plain is shown by the dashed line. The Eastern Tennessee seismic zone (ETSZ) is outlined by the black dotted line. Physiographic province and basin locations from Sapp and Emplaincourt (1975); BMA from McBride and Nelson (1991); AL-OK transform and rift structures from Thomas (2006); GF, NY-AL lineament, AA, BMA, and ETSZ from Raymond et al. (2008); Steltenpohl et al. (2010).

scale of gigatons and approximately 3 to 4 billion cubic meters of gas production volume per year between 1999 and 2007 (Carroll and Pashin, 2003; Hatch and Pawlewicz, 2007; Hall and Bolin, 2009). Its potential economic value motivates the need for continuing research to understand the region's tectonic and depositional history.

Central and northern Alabama also contain prominent local and regional geologic structures and geophysical anomalies such as the New York – Alabama (NY-AL) lineament (Figure 1). This northeast-trending magnetic anomaly can be traced from New York to Alabama, terminating at an unknown depth beneath the Coastal Plain (King and Zietz, 1978; Steltenpohl et al., 2010). The lineament has been interpreted as a buried crustal-scale strike-slip fault that is a remnant of the suture between a large continental block with Laurentia during the Grenville orogeny. This fault is thought to be a possible contributor to modern seismicity in the Eastern Tennessee seismic zone and to have offset the Amish Anomaly (AA), another significant magnetic anomaly in the study area (Figure 1) (Steltenpohl et al., 2010).

This study will make use of existing aeromagnetic and gravity data to create tectonic models for central and north Alabama, focusing on basin faults, deep crustal structures, the NY-AL lineament, and the AA. This model will provide insight on the origin and geometry of the NY-AL lineament, including its relationship to previous and ongoing tectonic events, and the depositional and tectonic history of basins in the study area. Results will be compared to models derived from the COCORP seismic transects in Georgia and Tennessee, as well as to previously developed models (Harry et al., 2003; Savrda, 2008; Bajgain, 2011). Combined with previous work, this study addresses questions about the tectonic evolution of the southeast United States that have not been revealed by drilling and seismic profiles.

Background

Tectonic History

The southeastern United States has a complex tectonic history despite its current location on a passive margin. Rocks and structures of the region indicate at least two complete supercontinent "Wilson" cycles, beginning with the Grenville orogeny (ca. 1350-980 Ma) (Figure 2) (Wilson, 1966; Pindell and Dewey, 1982; Hatcher, 1978, 1987; Salvador, 1991; Thomas 2006). The Grenville orogeny was responsible for the formation of the supercontinent Rodinia (Thomas, 2006) and has particular importance in regards to the current study. During rifting of Rodinia in the late Proterozoic to early Paleozoic (ca. 760-530 Ma), deep crustal rift structures formed, like the Alabama-Oklahoma transform (Figures 1 and 2) (Harry et al., 2003; Thomas, 2006). After the breakup of Rodinia, a second series of collisional orogenic events began in the Ordovician and lasted into the Permian, creating the supercontinent of Pangaea (Thomas, 2006). The break-up of Pangaea and the opening of the Atlantic Ocean left behind the tectonically inherited terranes of Appalachia, superimposed on Grenville-aged crust (Figures 1-3) (Thomas, 2006).

Three distinct mountain-building events are recorded in the Appalachian orogenic belt: the Taconic orogeny (Ordovician), the Acadian orogeny (Devonian-Mississippian), and the Alleghanian orogeny (Pennsylvanian – Permian) (Figure 2) (Hatcher, 2010). The Taconic orogeny (ca. 470-450 Ma) reflects the collision of a system of island arc terranes with Laurentia in eastern Canada and the northeastern United States (Horton et al., 1989; Drake et al., 1989; Hatcher, 2010). In the southeasternmost United States relatively little is known about the Taconic event because evidence for it is sparse (Steltenpohl, 2005). The Acadian orogeny (ca. 380-350 Ma), which involved the accretion of a system of peri-Gondwana volcanic island arc

Ma	Period	Orogenic Event	Description
208	Jurassic		Opening of Atlantic Ocean basin
245	Triassic		
286	Permian	Alleghanian	Gondwana and Laurentia collide Closing of ocean basin Assembly of Pangea
320	Pennsylvanian		
360	Mississippian		
408	Devonian	Acadian	Emplacement of Piedmont terrane
438	Silurian		
505	Ordovician	Taconic	Emplacement of system of island arc
570	Cambrian		Iapetus ocean basin begins closing Creation of transform fault system i.e. AL-OK transform Destruction of Rodinia
600	L. Proterozoic		Opening of Iapetus Ocean basin
1000 1200	M. Proterozoic	Grenville	Assembly of Rodinia

Figure 2. Major orogenic events affecting the southeastern United States. Modified from Hatcher, 1987; Bajgain, 2011.

terranes to Laurentia, resulted in the formation of the metamorphic terranes of the Piedmont province (Figure 2 and 3) (Tull, 1980; Glover et al., 1983; Hatcher, 2010). The Alleghanian orogeny (ca. 325-250 Ma) records the closing of the Iapetus ocean basin and the collision of Gondwana with Laurentia to form Pangaea (Hatcher, 2005; Thomas, 2006). This orogeny was prevalent in the southeast and strongly shaped the crust, reactivating many older faults and creating thin-skinned foreland fold-and-thrust belt structures including the Birmingham anticlinorium and “mushwads” in Alabama (Figures 2 and 3). (Thomas, 2007; Hatcher, 2005, 2010).

In the Late Triassic to Early Jurassic, Pangaea began to rift apart (ca. 180 Ma) (Figures 1 and 2). Rifting evolved to create the modern day Gulf of Mexico and Atlantic Ocean as large amounts of sediments derived from the erosion of the Appalachians were deposited along the Coastal Plain. Today, many rocks and structures related to this plate tectonic history are now buried beneath sediments of the Appalachian basin and the Coastal Plain sediments.

Geologic Setting and Stratigraphy

Based on topographic relief, provenance, and geologic structure, Alabama is broadly divided into five major physiographic provinces (Figure 1 and 3) (Sapp and Emplaincourt, 1975). In northwest Alabama, the Interior Low Plateau province is capped by carbonate and siliciclastic sedimentary rocks deposited as Gondwana and Laurentia were colliding in the Carboniferous and Permian (ca. 330-250 Ma). The Black Warrior basin lies within the Appalachian/Cumberland Plateau and consists predominantly of Pennsylvanian coal-bearing siliciclastic rocks of disputed provenance (Mack et al., 1983; Pashin, 1999; Gomes, 2012). The Black Warrior basin is bordered on the southwest by Ouachita thrust belt and on the southeast by the Appalachian thrust belt (Figure 1) (Guthrie and Raymond, 1992; Cates and Groshong, 1999; Thomas, 2004).

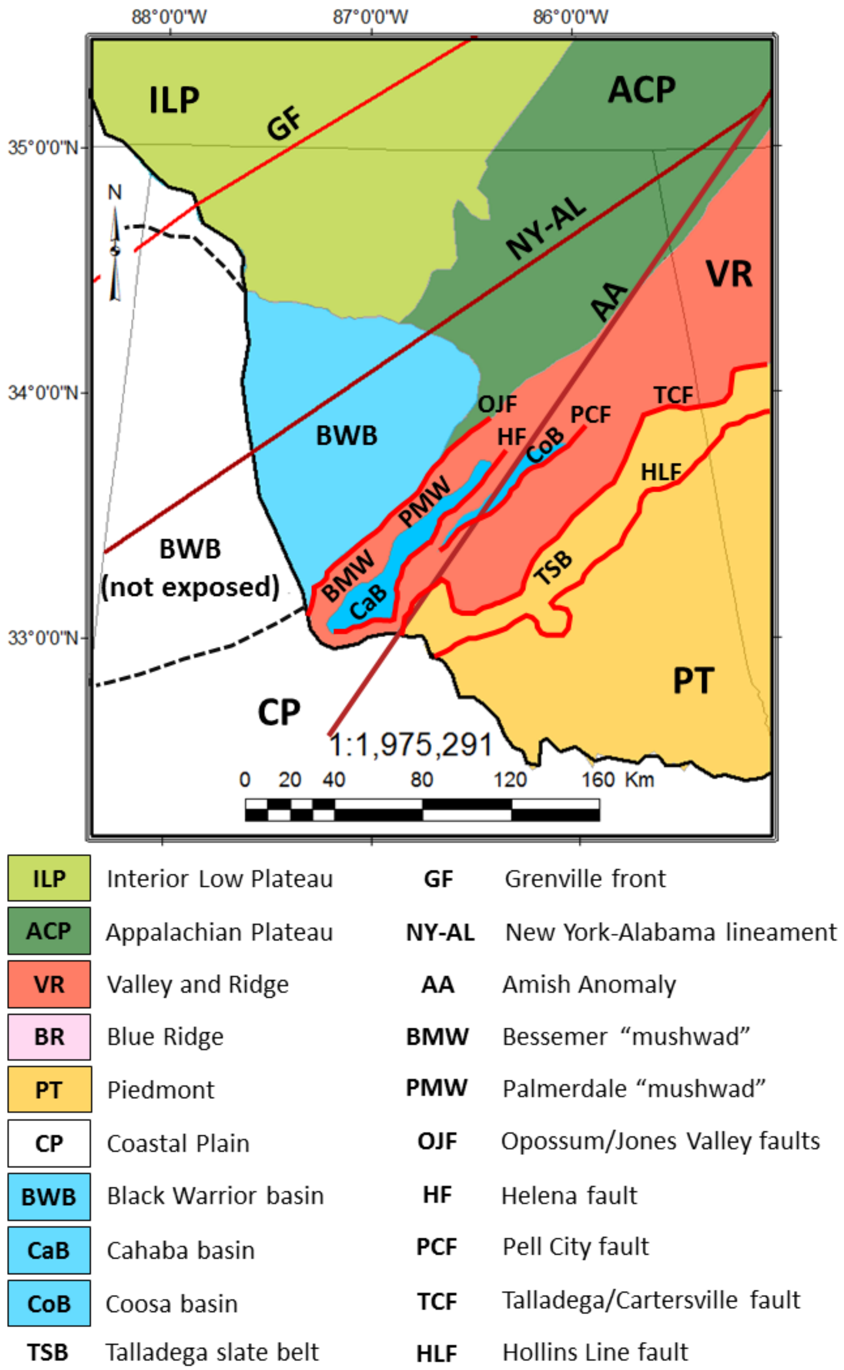


Figure 3. Major structures in study area superimposed on physiographic provinces and restricted Carboniferous basins. The Black Warrior basin's (BWB) approximate extent beneath the Coastal Plain is shown by the dashed line. Physiographic province and basin locations from Sapp and Emplaincourt (1975); fault and mushwad locations from Thomas (2007); geophysical anomaly locations from Steltenpohl et al. (2010).

The Valley and Ridge province is composed mainly of Cambrian to Pennsylvanian sedimentary rocks that were folded and thrust during late Paleozoic suturing of Laurentia and Gondwana (Thomas, 2006) and contains the Carboniferous Cahaba and Coosa basins. These two basins are similar in structure and stratigraphy and occur with synclinoriums. The Coosa basin is located southeast of the Helena fault (HF), slightly northeast of the Cahaba basin, and bounded to the southeast by the Pell City fault (PCF) (Figure 3). Valley and Ridge rocks within the study area outcrop as the Birmingham anticlinorium, a northeast-trending exposure of formations deposited from the Cambrian to Mississippian, separated from the Black Warrior basin to the northeast by the Opossum/Jones Valley fault system (OJF) and formed as a result of northwestward-propagating thrusting during the Alleghanian orogeny (Thomas, 1995; Cates and Groshong, 1999). In the study area, the OJF is near vertical in surface exposures. The units in the anticlinorium have been deformed in a ductile fashion, with thick, weaker layers uplifting stronger, stiff overlying layers (Thomas, 2001; Pashin et al., 2012). Thomas (2001) called the structure associated with this type of deformation a "mushwad." In the study area, there are two major "mushwad" structures, the Bessemer "mushwad" (BMW) and the Palmerdale "mushwad" (PMW) (Figure 3). To the south, units of the Valley and Ridge partly provide basement for the younger sediments of the Coastal Plain.

The Talladega slate belt in Alabama is a structural block bounded to the north by the Talladega-Cartersville fault system (TCF) and to the south by the Hollins Line fault (HLF) (Figure 3). It is part of the Piedmont and contains low-grade (greenschist facies) metasedimentary and metavolcanic rocks. The lithologies of the Talladega slate belt consist mostly of phyllite, marble, and slate (Thomas and Neathery, 1980; Raymond et al., 1988).

The Black Warrior basin is a foreland basin located in the gap between the Appalachian orogenic belt to the southeast and the Ouachita orogenic belt to the southwest (Figure 1) (Hatch and Pawlewicz, 2007). The basin has a surface area of approximately 91,000 km^2, and depth to basement increases from approximately 5 km in the north to approximately 25 km in the south, beneath the Ouachita orogenic belt, within a 400 km horizontal distance (Harry and Londono, 2003). The basin is composed primarily of Pennsylvanian sedimentary rocks, though ages range from Early Paleozoic to Early Cenozoic (Hatch and Pawlewicz, 2007).

Stratigraphic succession differs only slightly between the Black Warrior basin region and the Appalachian Valley and Ridge province (Figure 4). The oldest stratigraphic units are Cambrian in age, starting with the Rome Formation, a mostly fine-grained shale. Above the Rome is the Conasauga Formation, which is mainly composed of fine-grained clastic and carbonate rocks associated with extension that interrupted the growth of a significant carbonate platform (Thomas, 1989, 2007; Rutter, 2012). Gaseous shales generated by “mushwad-style” deformation are associated with the Rome and Conasauga formations (Pashin et al., 2012). The Conasauga is overlain by the Ketona Dolomite and Knox Group, the latter composed primarily of limestone and dolostone. The Knox Group is known for significant gas recovery (Osborne and Raymond, 1992; Hatch and Pawlewicz, 2007), and constituted a rigid layer that resisted Alleghanian deformation, instead sliding over the underlying Conasauga and Rome formations (Thomas, 2007). The Stones River Group and a unit of undifferentiated shales and cherty limestone follow the Knox Group in the Black Warrior basin. Little to no natural gas exploitation is reported for these units. In the Valley and Ridge province, these units are replaced with two sandstone units, the Red Mountain Formation and the Frog Mountain Sandstone. The Devonian-aged Chattanooga Shale lies above

Time: Era	Period	Epoch	Geologic Unit (Black Warrior basin)	Geologic Unit (Valley and Ridge)	Lithology
Paleozoic	Pennsylvanian	L	Pottsville Formation		Thick succession of strata, sandstone, siltstone, coal beds, conglomerate at top, quartzarenite sandstone at base
Paleozoic	Pennsylvanian / Mississippian	?	Parkwood Formation		Fine- to medium-grained sandstones, some interbedded shale, very little carbonate rock
Paleozoic	Mississippian	U	Floyd Shale		Interbedded shale, limestone, some silty to sandy beds, capped by Hartselle Sandstone
Paleozoic	Mississippian	U	Tuscumbia Limestone		Oolitic limestone, crystalline to microcrystalline, fossiliferous in parts
Paleozoic	Mississippian	L	Fort Payne Chert		Chert and cherty limestone, thin shale beds and lenses
Paleozoic	Devonian		Chattanooga Shale		Shale, phosphatic inclusions, pyrite, thinly bedded
Paleozoic	Devonian		Undiff.	Frog Mountain Sandstone	Undifferentiated – cherty limestone Frog Mountain Sandstone – sandstone, coarse-grained, cherty, locally conglomeratic
Paleozoic	Silurian		Undiff.	Red Mountain Formation	Undifferentiated – limestone Red Mountain Formation – Sandstone, siltstone, shale, hematite beds, minor limestone
Paleozoic	Ordovician	U	Undiff.	Sequatchie Formation	Undifferentiated – limestone Sequatchie Formation – shale, calcareous, fine- to coarse-grained limestone
Paleozoic	Ordovician	M	Stones River Group	Chickamauga Limestone	Stones River Group – limestone, locally sandy, some silt Chickamauga Limestone – limestone, thick-bedded, fossiliferous
Paleozoic	Ordovician / Cambrian	L / U	Knox Group		Dolomite, limestone, cherty, fine- to medium-grained, well-rounded sand at top
Paleozoic	Cambrian	U	Ketona Dolomite		Dolomite, finely crystalline
Paleozoic	Cambrian	M	Conasauga Formation		Limestone, shale, argillaceous in parts, less competent, part of "mushwad"
Paleozoic	Cambrian	L	Rome Formation		Shale and siltstone, sandstone, very fine- to fine-grained, phosphatic, glauconitic, part of "mushwad"
Precambrian			Basement		Metamorphic and/or igneous rocks

Figure 4. Generalized stratigraphic column of the Appalachian fold and thrust region and the Black Warrior basin. The blue box indicates units present only in the Black Warrior basin, and the red box indicates units present only in the Valley and Ridge. Modified from Hall and Bolin (2009).

these undifferentiated zones, and constitutes the producing unit in the Chattanooga Shale/Floyd Shale – Paleozoic total petroleum system (TPS) of Hatch and Pawlewicz (2007). Natural gas migrates vertically from the Chattanooga Shale and Floyd Shale to fractures and cavities in the Fort Payne Chert and Tuscumbia Limestone, where the gas is stored in sand layers and sand lenses. The Parkwood Formation overlies the Chattanooga Shale/Floyd Shale – Paleozoic TPS and is composed primarily of shale and limestone (Rutter, 2012). The Pottsville Formation overlies the Parkwood. With thicknesses greater than 3000 m in some areas, the Pottsville is a coal-bearing clastic wedge that overlies older carbonates and clastic units (Rutter, 2012). The Pottsville Formation is the sole unit in the Pottsville Coal TPS (Hatch and Pawlewicz, 2007). Unconformably overlying the Pottsville Formation at a pronounced angular unconformity are horizontal Mesozoic and Cenozoic siliciclastic and carbonate rocks deposited in the Gulf Coastal Plain (Pashin, 1999).

The Cahaba basin is a synclinorium that was part of a foreland basin; it is localized on the southeastern side of the Birmingham anticlinorium (Figure 3). Similar to the Black Warrior basin, the majority of basin fill is composed of Pennsylvanian coal-bearing Pottsville Formation. The same units present in the Black Warrior basin make up the Cahaba basin (Pashin, 1999; Gomes, 2012). Locally the Pottsville reaches depths of approximately 2500 m, and has more than 20 coal zones (Pashin 1999). These coal zones were deposited in tidal zones and near-shore swamps, and have significant bituminous coalbeds associated with coalbed methane in the subsurface (Carroll et al., 1995). The geographic extent of the Cahaba basin is much smaller than the Black Warrior basin, and is situated between the Helena fault and the Birmingham anticlinorium of the Valley and Ridge province (Figure 3) (Pashin, 1999).

Geophysical Anomalies

Two major geophysical anomalies are present in Alabama: the Brunswick Magnetic Anomaly (BMA) and the NY-AL lineament (Figure 5). The BMA is a prominent linear magnetic low that trends east-west through Alabama and into Georgia, continuing north along the east coast of the United States. The BMA marks the late Paleozoic Suwannee suture between Laurentia and Gondwana (Nelson et al., 1985b; Savrda, 2008; Bajgain, 2011). The NY-AL lineament is a major magnetic anomaly that stretches from Alabama to central New York (Figure 6). The Amish anomaly (AA) is a significant splay off the NY-AL lineament which branches west from the main anomaly in West Virginia and trends north-northwest along the Pennsylvanian-Ohio border and into western New York. A possible continuation of the AA, offset by the NY-AL lineament, appears in the study area, deviating from the main lineament and trending southwest (Figure 6) (Steltenpohl et al., 2010). Between the splay of the NY-AL lineament and the main anomaly is a very high magnetic anomaly (> 500nT) which correlates with a zone of low gravity. This zone is sandwiched to the north and south by high gravity/low magnetic values, suggesting a significant change in crustal composition (Figure 5). Steltenpohl et al. (2010) suggested that the NY-AL lineament marks a crustal-scale dextral strike-slip fault that has displaced Grenville-aged anomalies (i.e. Amish Anomaly) by up to ~220km and is possibly associated with seismicity in Alabama and Tennessee. Traditionally, the lineament is thought to mark a major crustal boundary between a northwest block that behaved rigidly and a less competent southeast block (Steltenpohl et al., 2010). Timing of the latest movement of the fault is thought to be either (1) a late post-contraction stage of the Grenville orogeny, (2) late Neoproterozoic-Cambrian rifting of Laurentia, or (3) a right-slip reactivation during the late Neoproterozoic-Cambrian rifting (Steltenpohl et al., 2010). Modern earthquakes are spatially associated with metasedimentary gneisses, and low-

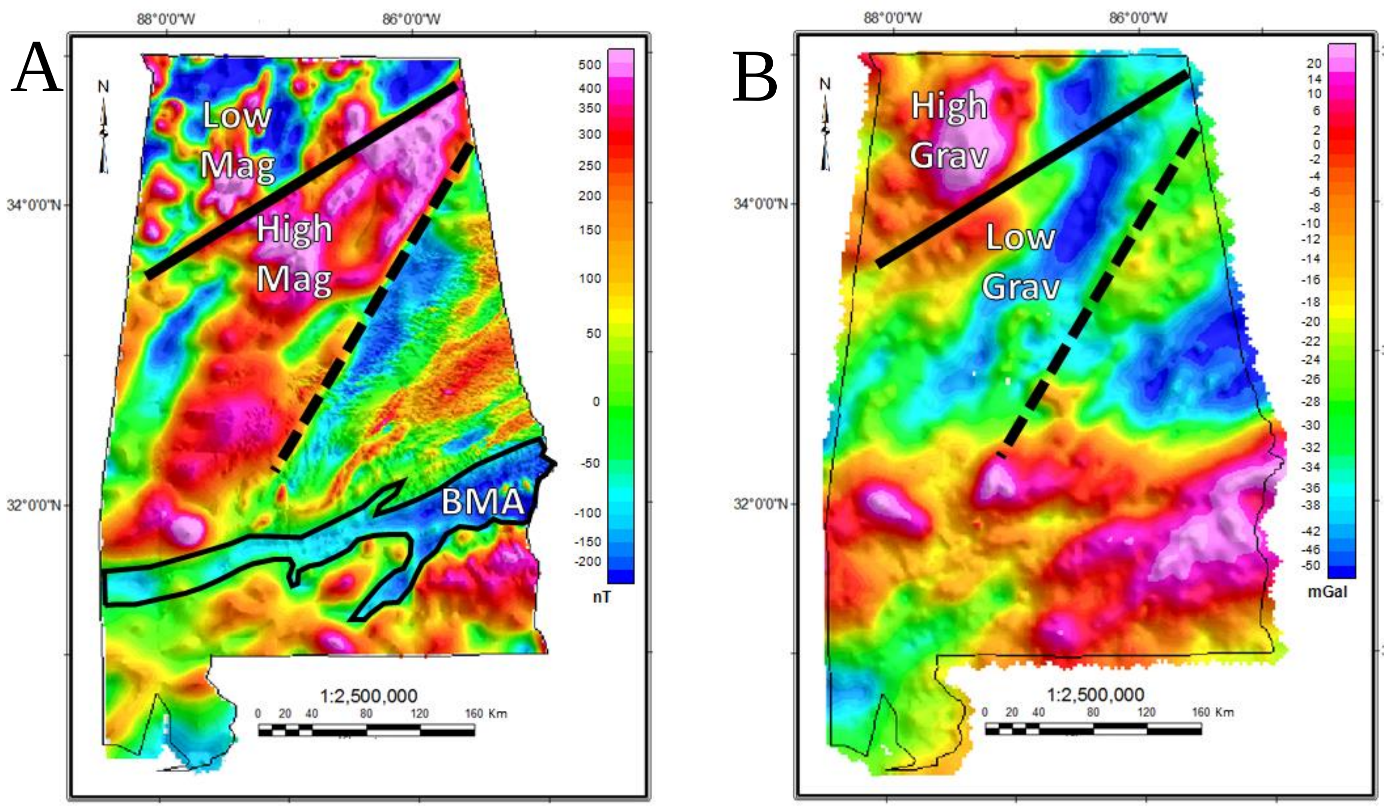


Figure 5. Approximate location of the NY-AL lineament (black line) and the Amish anomaly (dashed black line) on (A) reduced to pole total field magnetic anomaly map and (B) complete Bouguer gravity anomaly map. In (A), the lineament separates a zone of northeast-trending magnetic highs from magnetic lows. The Brunswick Magnetic Anomaly (BMA) is outlined in black. Although not as distinct, in (B) the NY-AL lineament and Amish anomaly bracket a northeast-trending gravity low. BMA location from McBride and Nelson (1991). Data from the National Geophysical Data Center (NGDC); Daniels, pers. communication (2007); NY-AL lineament and Amish anomaly locations from Raymond et al. (2008) and Steltenpohl et al. (2010).

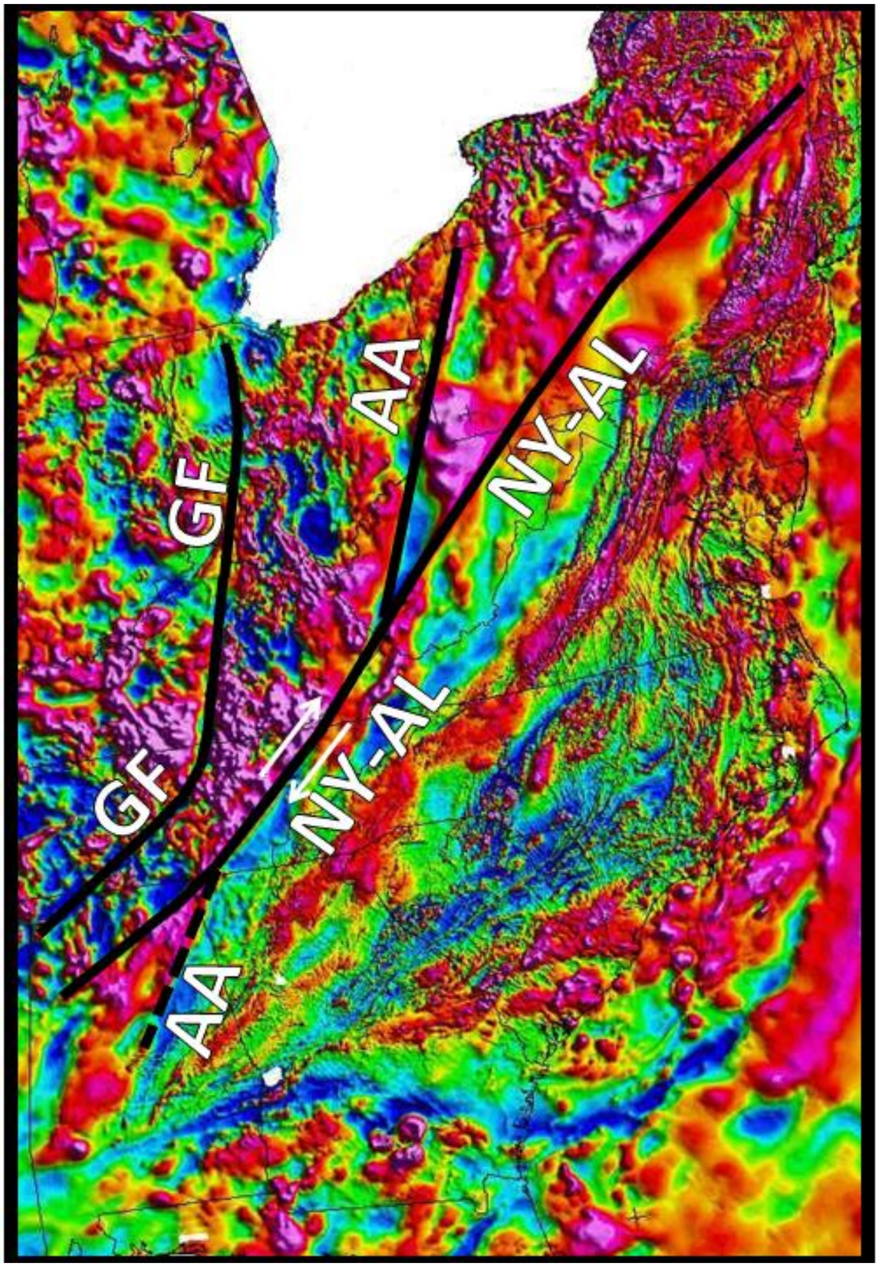


Figure 6. Magnetic map of the eastern United States. NY-AL lineament borders a continuous magnetic high beginning in eastern New York and terminating beneath the Gulf Coastal Plain. The Grenville front (GF) is also shown as a magnetic low and separates cratonic rocks to the west from rocks of the Grenville orogeny (Thomas, 2006). The Amish anomaly (AA), a splay off of the NY-AL lineament, is present in West Virginia, western Pennsylvania, and western New York (Culotta et al., 1990; Steltenpohl et al., 2010). A possible continuation of the AA in Alabama is shown by black dashes. Arrows indicate dextral movement of NY-AL lineament. Magnetic map modified from Bankey et al. (2002); Steltenpohl et al. (2010).

velocity earthquake focal mechanisms described by Powell et al. (1994; 2014) match the geometry and kinematics of the NY-AL lineament (Steltenpohl et al., 2010). The sources for this anomaly are not exposed, and drilling has not revealed its source.

Previous interpretations of the NY-AL lineament (Raymond et al., 2008) constrained the southern portion of the NY-AL lineament in Alabama as a magnetic anomaly trending approximately south 40° west with a northern splay trending south 70° west. Steltenpohl et al. (2010) determined the NY-AL lineament’s southern termination was the northern splay interpreted by Raymond et al. (2008), and the southern anomaly a possible continuation of the AA that was offset dextrally by the NY-AL lineament (Figure 6). The AA is present in West Virginia, eastern Pennsylvania, and eastern New York, and is thought to represent a belt of metasedimentary rocks (Culotta et al, 1990; King et al., 1998; Steltenpohl et al., 2010).

Previous Work

In the 1970's and 1980's several seismic lines were acquired by COCORP in Georgia to provide insight into crustal structure of accreted terranes and their continuation beneath the Coastal Plain (Figure 7). McBride et al. (1989) concluded that prominent seismic reflectors in the data corresponded to thick basalt and diabase sequences produced by magmatism during rifting. McBride and Nelson (1988) also pinpointed the Alleghanian (ca. 325-250 Ma) suture zone as a series of seismic reflectors located above the BMA, and using the same data, identified the depth to the Moho (approximately 40 km) in the southern Appalachians. McBride and Nelson (1991) reported a large decrease in crustal thickness from the Piedmont and Blue Ridge terranes to the crust beneath the Coastal Plain (Figure 8).

Culotta et al. (1990) used gravity, magnetic, and COCORP seismic data to model the Grenville front and the AA in Ohio and correlate these models to seismically imaged structures in Tennessee, New York, and Canada (Figure 9). They interpreted a pair of opposite dipping, crustal-scale shear zones between the Grenville Front and AA, and postulated that these shear zones occur hundreds of kilometers to the north and south. Their research also revealed evidence of a west-dipping zone of reflectors underlying the Appalachian basin that extends from northern Alabama to New York, west of the AA. They suggest a correlation between terranes containing surface-exposed magmatic-arc rocks in New York to the buried terranes beneath the Appalachian basement in Alabama. They speculate that the zone between the Grenville front and AA represents an intra-Grenville province suture zone.

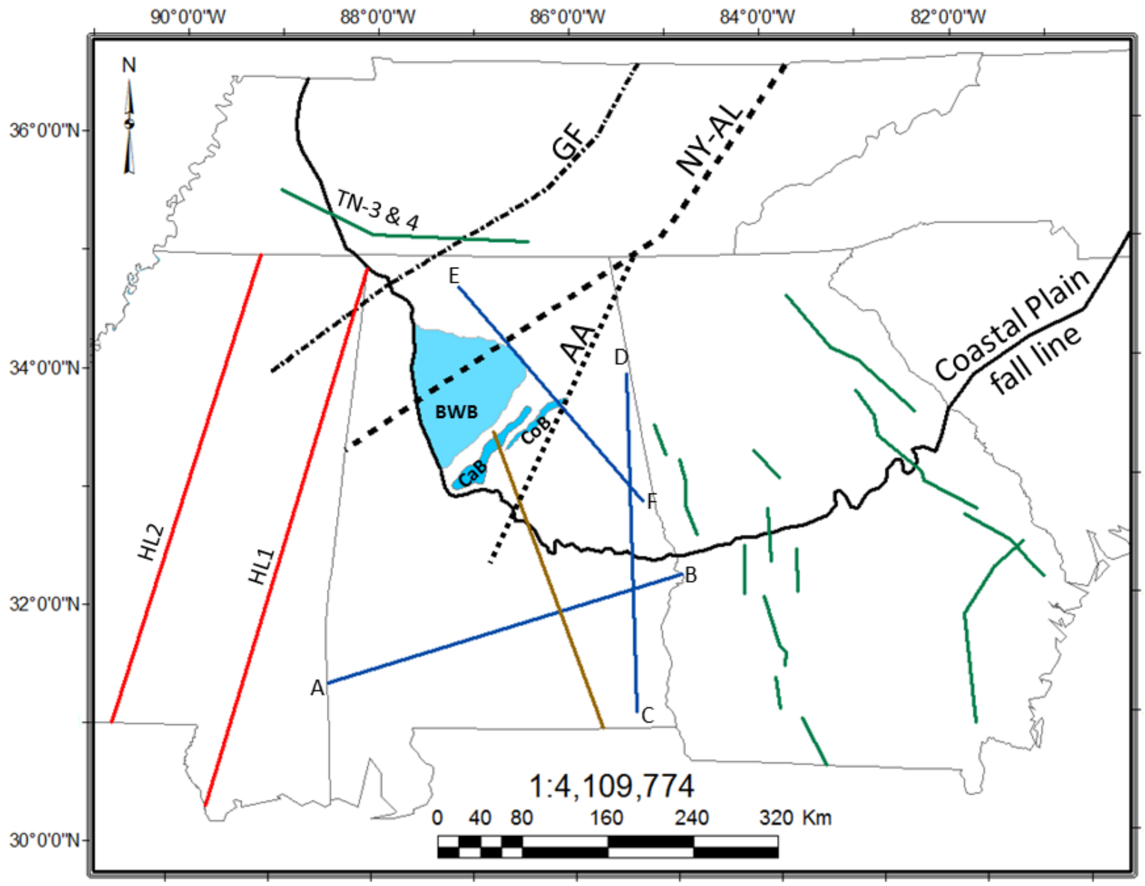


Figure 7. Map of previous crustal scale studies in and around the study area, including COCORP seismic lines (green lines), Harry and Londono's (2004) Mississippi gravity transects (red lines HL1 and HL2), Savrda's (2008) gravity transect (brown line), and Bajgain's (2011) magnetic and gravity transects (blue lines A-B, C-D, and E-F). Locations of NY-AL lineament, Grenville front (GF), Amish anomaly (AA), Coastal Plain fall line, Black Warrior basin (BWB), Cahaba basin (CaB), and Coosa basin (CoB) are shown. Modified from Sapp and Emplaincourt, 1975; McBride and Nelson, 1988 and 1991; McBride et al., 1989; Culotta et al., 1990; Harry and Londono, 2004; Thomas, 2006; Raymond et al., 2008; Savrda, 2008; Steltenpohl et al., 2010; Bajgain, 2011.

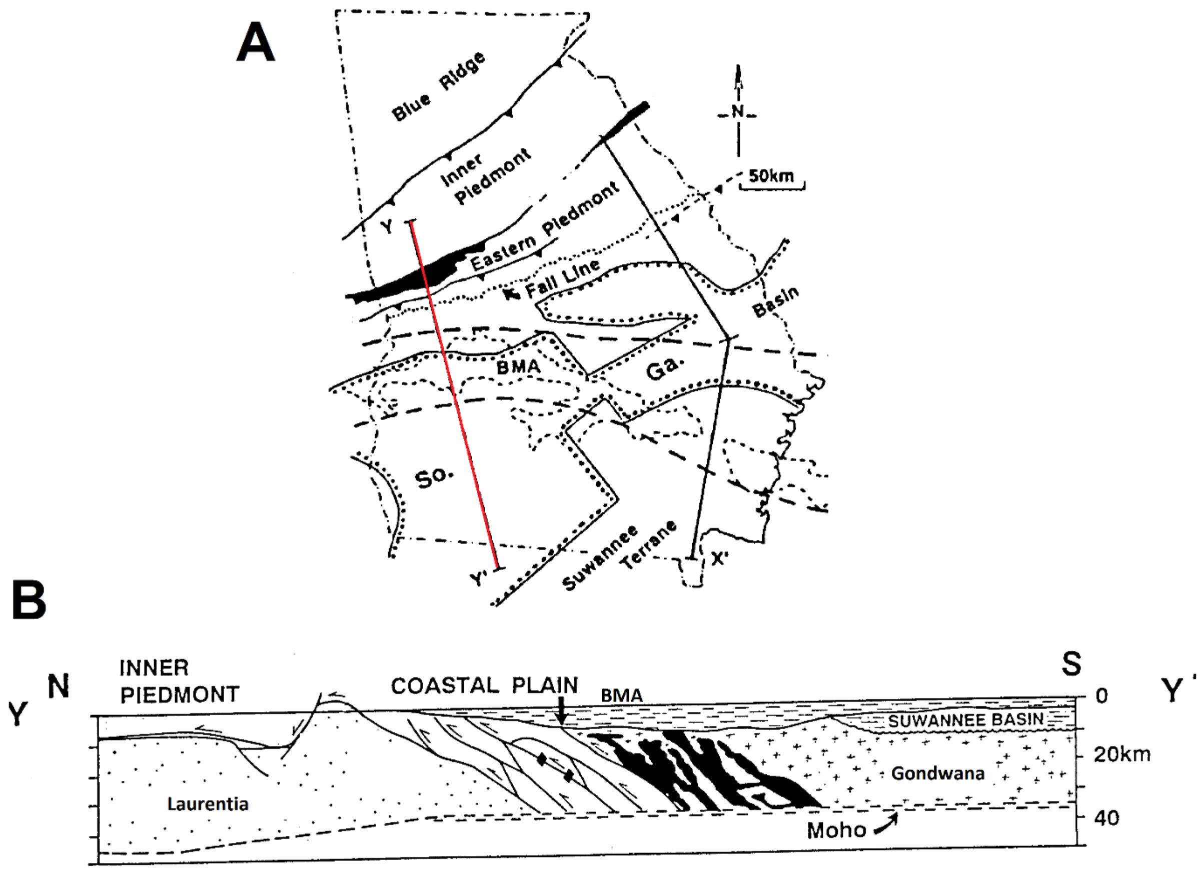


Figure 8. (A) Geologic interpretation of COCORP seismic reflection data. (B) Profile Y-Y′ (red line) crosses major structures such as the BMA, Coastal Plain onlap, contacts between Laurentian, peri-Gondwanan, and Gondwanan crust. From McBride and Nelson (1991).

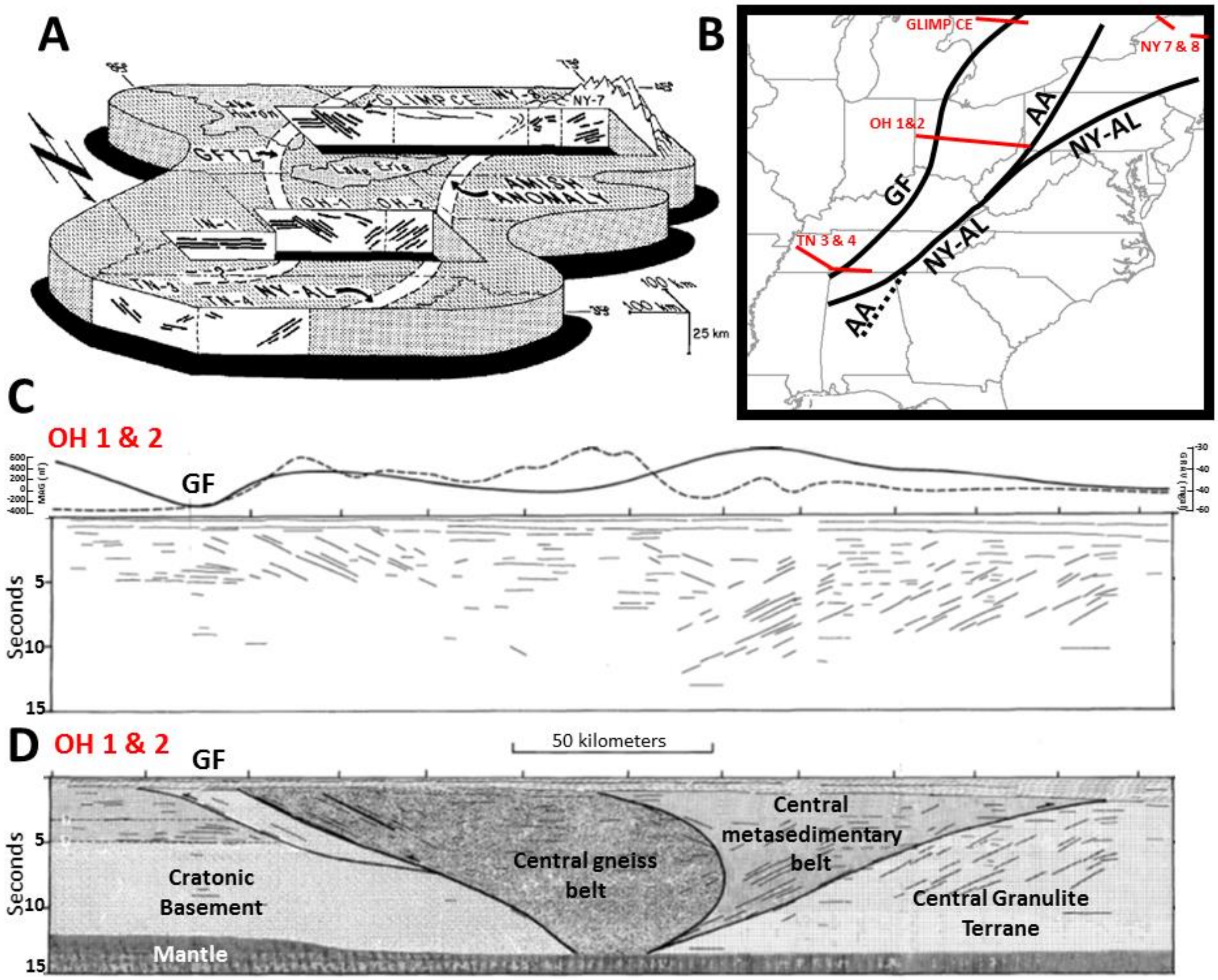


Figure 9. Results from COCORP seismic lines from southern Tennessee, Ohio, and New York. (A) Schematic correlation of reflectors seen along COCORP profiles; (B) map of the eastern United States with the locations of the NY-AL lineament (NY-AL), Grenville front (GF), Amish anomaly (AA) and its possible continuation in the study area (black dashes), and the location of COCORP profiles (red lines); (C) combined geophysical transects of OH 1 & 2 including gravity (solid line) and magnetic (dashed line) curves and reflections interpreted from seismic data; (D) interpreted cross section of (C) showing the Laurentian craton to the west of the Grenville front (GF) and metamorphic terranes to the east. Seismic lines TN 3 & 4 are shown in Figure 7. Modified from Culotta et al. (1990) and Steltenpohl et al. (2010).

Harry and Londono (2004) used gravity modeling, seismic refraction data, and subsurface density models to examine basement structures beneath Mississippi. In their study, they produced two north-south trending transects that covered the majority of eastern and western Mississippi and crossed both the Wiggins Arch and the Black Warrior basin (Figure 10). They postulated that loading of the Laurentian plate by the Ouachita orogeny in the late Paleozoic caused significant tectonic subsidence in the Black Warrior basin.

Thomas and Bayona (2005) examined the Appalachian thrust belt in Alabama and Georgia, specifically targeting basement faults and the role faults may have played in thin-skinned thrusting and the creation of "mushwads" (Thomas, 2001). The report included two plates with detailed fault maps, terrane boundaries, and 18 transects with generalized cross-sections (Figure 11). The cross-sections were created using well-log information and proprietary seismic data. Thomas (2007) also examined the role of the Birmingham basement fault in the Birmingham anticlinorium, a very prominent feature in this study area, and determined that the fault marks the termination of the leading edge of the shale-dominated "mushwad" (Figure 11).

Savrda (2008) constructed a crustal model of the Alabama Gulf Coastal Plain using well-log and gravity data. In her model, which extended from the Gulf of Mexico to Birmingham, AL, she inferred the possible location of the suture between the continental crust of ancient North America (Laurentian) and peri-Gondwana rocks beneath the Coastal Plain sediments (Figure 12).

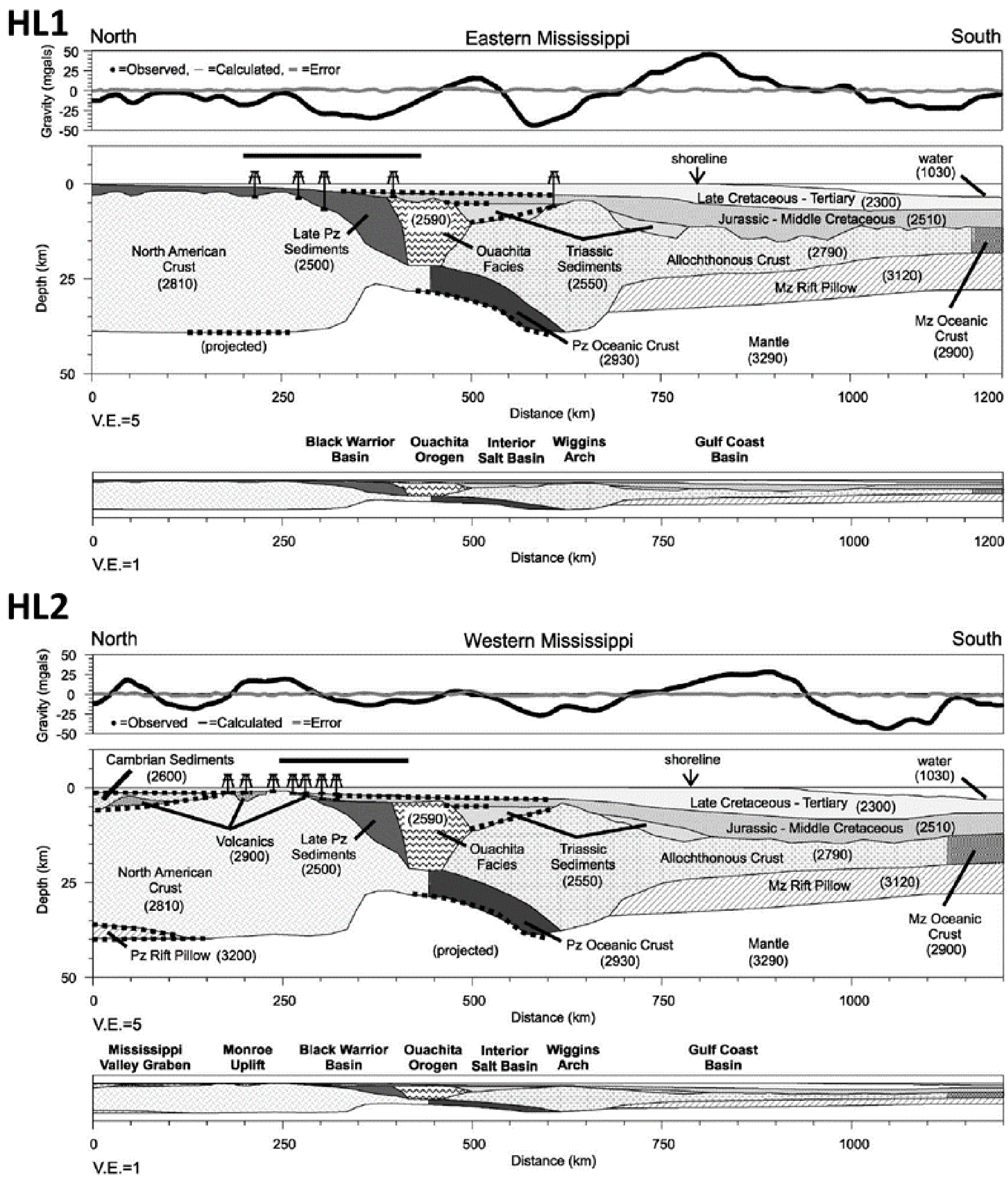


Figure 10. Schematic interpretations of complete Bouguer gravity data along two parallel north-south trending profiles in Mississippi. Harry and Londono (2004) suggested that the loading of the Laurentian plate via the Ouachita orogen caused subsidence beneath the Black Warrior basin, increasing the depth to basement from north to south. See Figure 14 for transect locations. Figure from Harry and Londono, 2004.

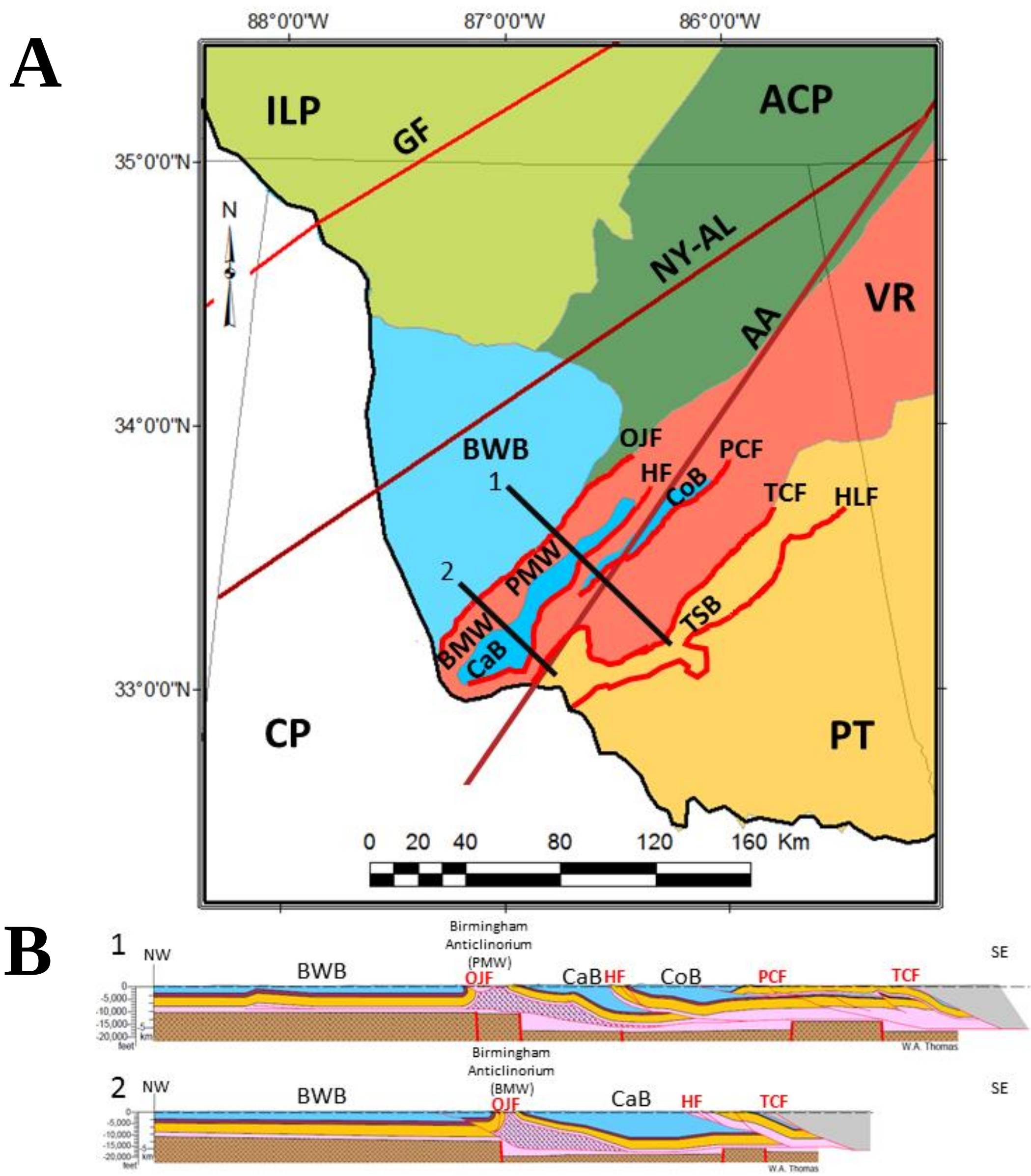


Figure 11. (A) Structural map of central Alabama, including the Birmingham anticlinorium, Bessemer “mushwad” (BMW), Palmerdale “mushwad” (PMW), Black Warrior basin (BWB), Cahaba basin (CaB), and Coosa basin (CoB). Major faults include the Opossum/Jones Valley fault system (OJF), Helena fault (HF), and Pell City fault (PCF). (B) Schematic cross-sections of two profiles from (A). TCF = Talladega/Cartersville fault; TSB = Talladega slate belt. Map modified from Sapp and Emplaincourt (1975), Thomas (2006), and Steltenpohl et al. (2010). Cross-sections modified from Thomas and Bayona (2005).

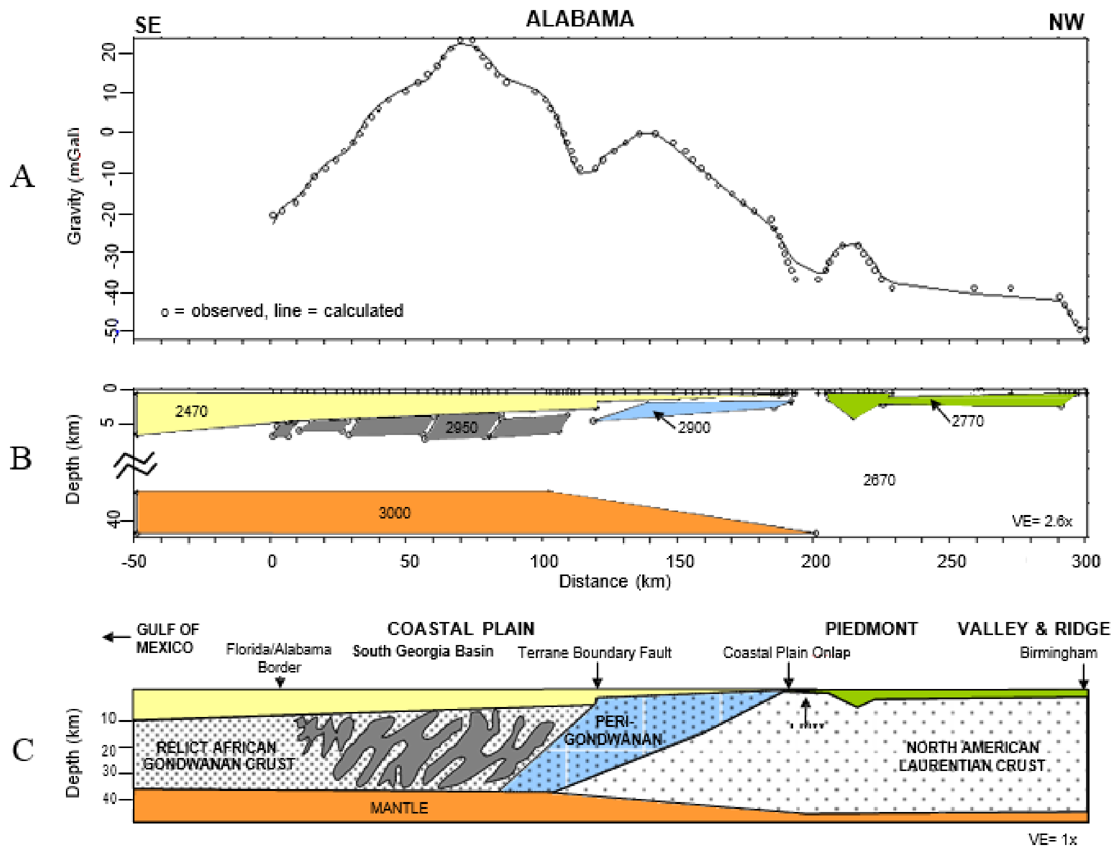


Figure 12. Gravity model of Savrda (2008) from Birmingham, AL, to the Gulf of Mexico. (A) Observed data compared with data calculated from model (B). (C) The geologic interpretation. See Figure 7 for profile location.

Building upon the previous results of Savrda (2008), Bajgain (2011) used gravity and magnetic data from Alabama to model deep crustal structure in northern, eastern, and southern Alabama (Figure 13). His study focused on terrane boundaries, geophysical anomalies, and the ancient Laurentian margin. Using two geophysical transects that crossed major crustal structures, he identified an east-west trending gravity low as the suture zone between Gondwanan and peri-Gondwanan crust. Piedmont and Valley and Ridge rocks correspond to moderate gravity highs. Both Savrda (2008) and Bajgain (2011) noted that Laurentian crust continued beneath the Alabama Coastal Plain sediments until it is truncated by the tectonic suture with Gondwanan-affiliated crust. This suture zone is located at the north side of the BMA. Their models showed crustal thinning from north to south in Alabama by approximately 3-5 km. Bajgain (2011) also suggests that the crust beneath the Wiggins Arch in southwest Alabama is similar to that of the Mississippi Gulf Coast, resembling a transform margin with an absence of rift-related volcanic rocks.

Although these previous studies provide insight into the large-scale crustal structures of Alabama, there has been little detailed work focused on the basement underlying the study area. In addition, the geophysical models of the NY – AL lineament in the study area are limited.

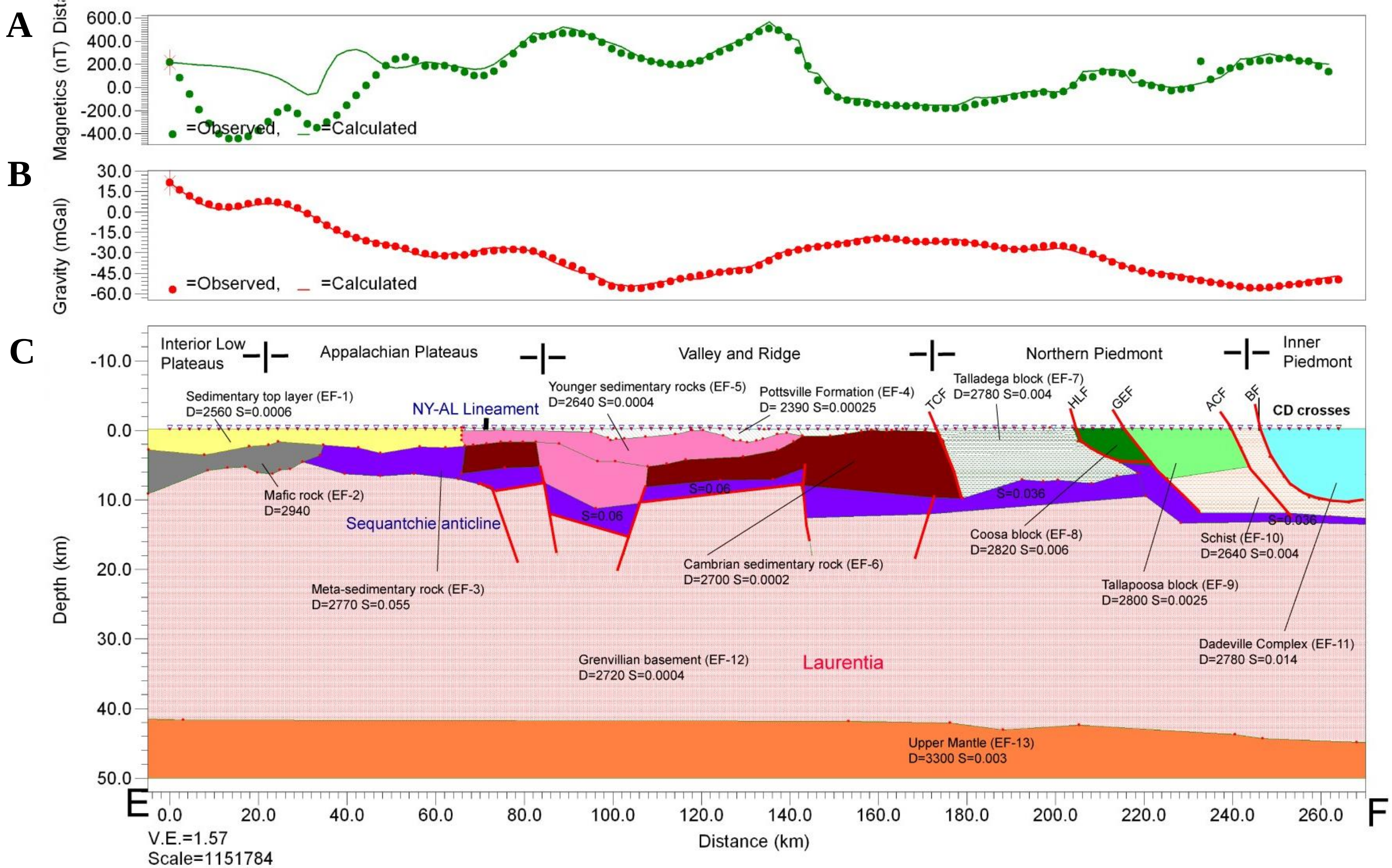


Figure 13. (A) Magnetic data, (B) gravity data, and (C) interpreted geologic cross-section from Bajgain (2011). This profile is located approximately 100 km northeast and subparallel to the current study's model transects. Note the poor fit of magnetic data in the northwest portion of the profile, near the NY-AL lineament. Locations Bajgain's (2011) profiles are shown in Figure 7.

Methodology

This section details, defines, and explains the data collection and processing methods used in the current study. Data collection consisted of obtaining existing gravity and magnetic data, gathering well-logs, collecting susceptibility measurements in the field, and accumulating other supporting data. Data processing included analyzing gravity and magnetic anomaly maps and constructing 2D crustal models along the transects.

Data Collection

The current study uses gravity data and magnetic data collected by the Defense Mapping Agency, and accessed from the U. S. Geological Survey and National Geophysical Data Center (NGDC) (https://www.ngdc.noaa.gov/ngdcinfo/onlineaccess.html). Both the magnetic and the gravity data have been reprocessed at a 2500-m grid interval (Daniels, pers. communication, 2007) to allow better correlation with surface features (Figures 14 and 15). The original magnetic map (Godson, 1986) was created by using digitized contours of the composite magnetic anomaly map of the United States (Zietz, 1982). Other data used in this study are from well logs, geological cross sections, and published literature.

Gravity Data

Gravity varies from place to place on Earth's surface due to a variety of variables, including but not limited to underlying rocks, latitude, elevation, and topography. For gravity modeling to be accurate, observed data need to be corrected so that anomalies created by the varying material in Earth's crust can be extracted ($\mathbf{g_{obs}}$). The free-air correction ($\mathbf{FA_{corr}}$) accounts for variation in elevation between gravity stations, adjusting these measurements to what would

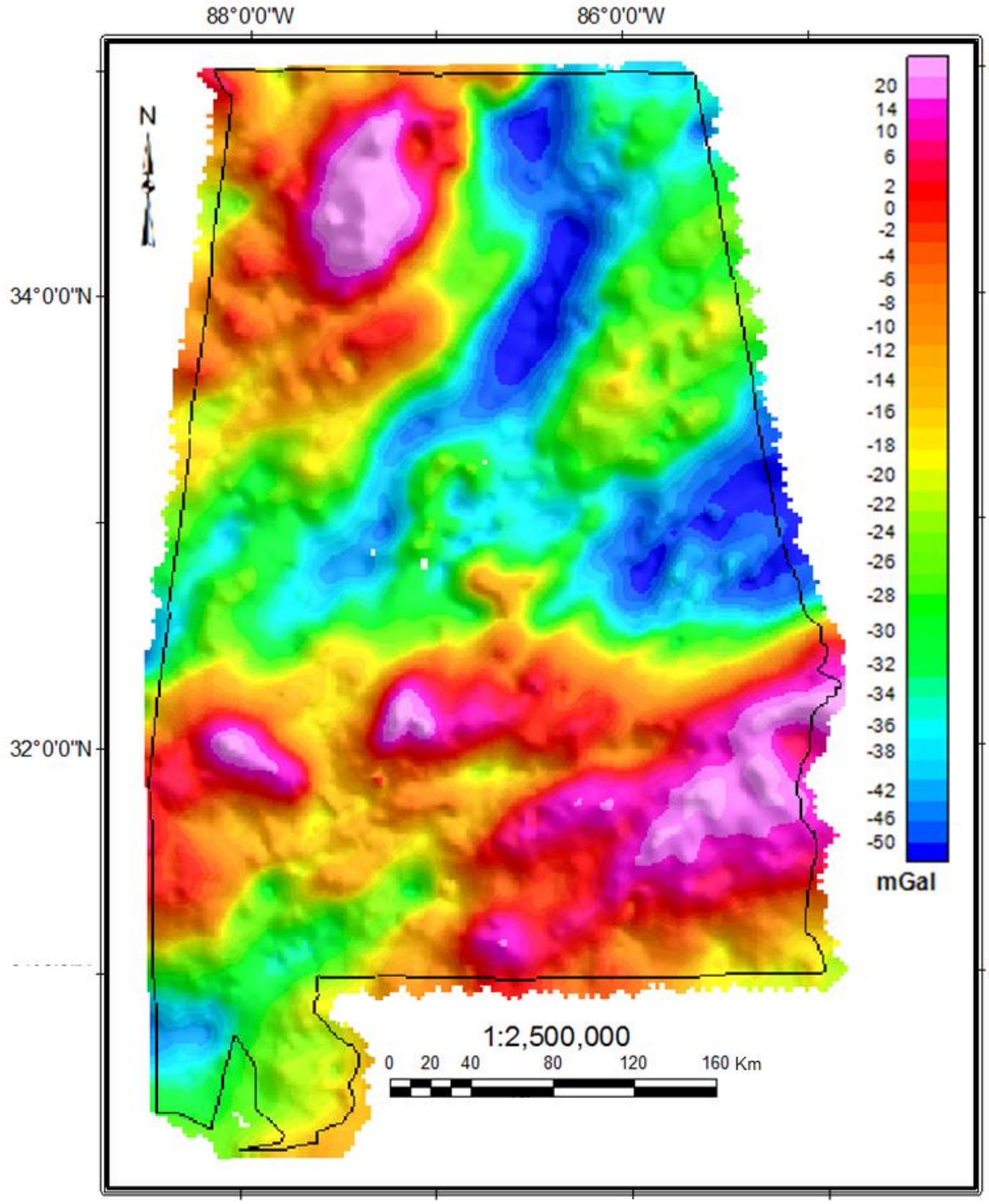


Figure 14. Complete Bouguer anomaly map of Alabama, reprocessed using a 2500-m grid interval (NGDC, 2007; Daniels, pers. communication, 2007; Bajgain, 2011).

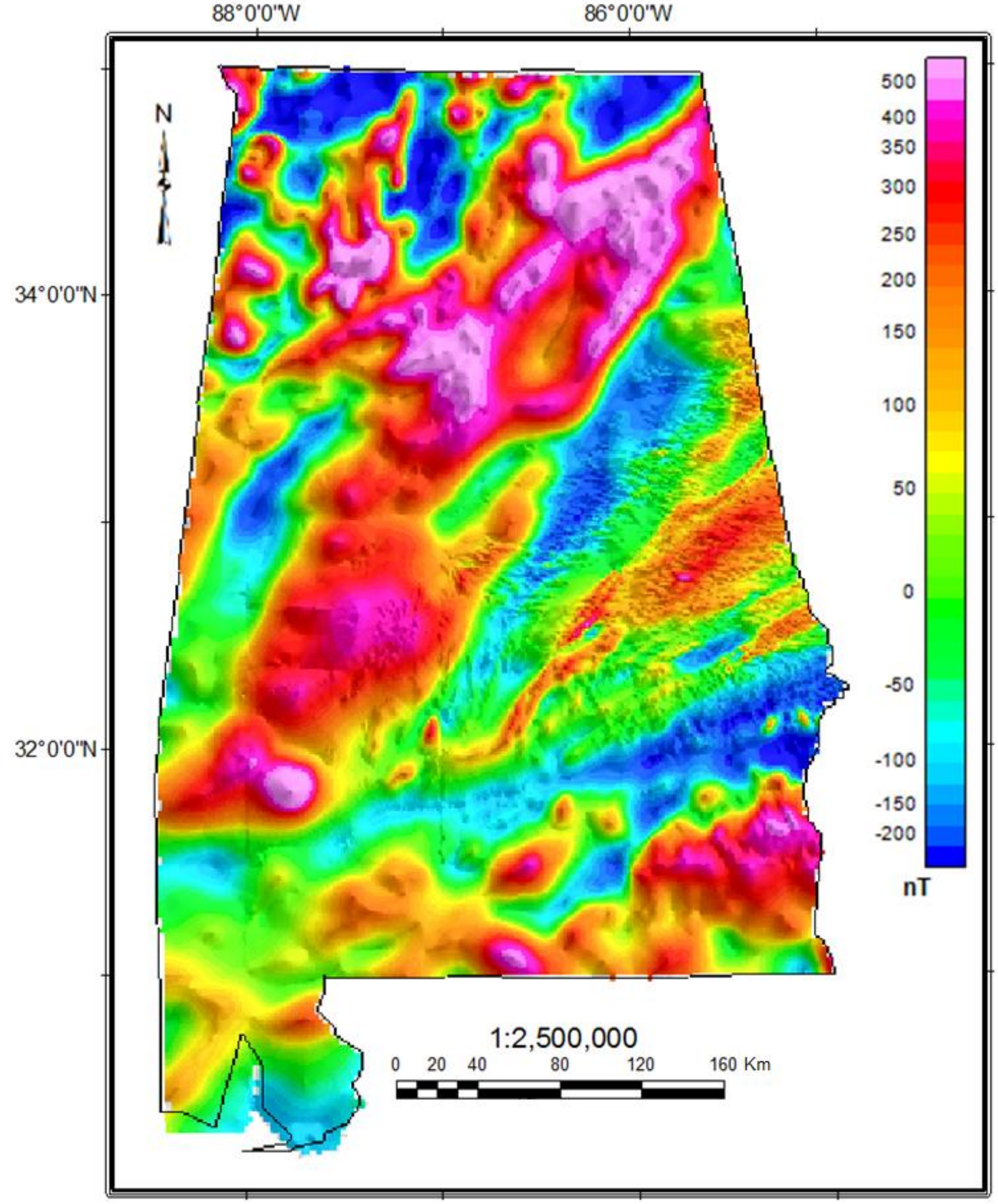


Figure 15. Magnetic map of Alabama complete with reduction-to-pole filter, reprocessed using a 2500 m grid interval (NGDC, 2007; Daniels, pers. communication, 2007; Bajgain, 2011).

have been measured at a reference level (i.e., sea level) (Burger et al., 2006). Terrain corrections (**TC**) account for variations in the observed gravity caused by variations in topography near each observed point, and have been applied here in areas with steep and/or changing elevation gradients (Phillips et al., 1993; Burger et al., 2006). Latitude ($\mathbf{g_n}$) is also corrected for, as centrifugal forces cause the earth to have an equatorial bulge which must be accounted for (Burger et al., 2006). The Bouguer correction ($\mathbf{B_{corr}}$), named after eighteenth century mathematician and geophysicist Pierre Bouguer, accounts for deficit or excess mass as estimated by a horizontal slab between the measuring station and sea-level (Burger et al., 2006). Maps used in this study were produced by applying corrections as given in Equation 1, resulting in a complete Bouguer anomaly map ($\mathbf{\Delta g_b}$) (Burger et al., 2006). The complete Bouguer-corrected gravity data used in the study assume a reduction density of 2670 kg/m^3 (Figure 14)

$$\Delta g_b = g_{obs} - g_n + FA_{corr} - B_{corr} + TC \qquad [1]$$

With these corrections applied, positive or negative anomalies can be assumed to be created by changes in density of subsurface rocks. High gravity gradients can be used to delineate faults, terrane boundaries, and contacts between rock units (Phillips et al., 1993; Burger et al., 2006).

Magnetic Data

Magnetic anomalies are the result of the distribution of magnetic minerals (e.g. magnetite, hematite, pyrrhotite) in the Earth’s crust. Typically, igneous and metamorphic rocks have a higher concentration of magnetic minerals when compared to sedimentary rocks, and therefore can create strong magnetic gradients. Fault zones and terrane boundaries can correlate with strong magnetic anomalies. This study uses magnetic data to delineate major geologic features in the crust and to infer basement composition.

Ancillary Data

Apart from the gravity and magnetic data, other data were gathered to help constrain the crustal models and their geologic interpretation (Table 1). Well-log information was obtained from the log library of the State Oil and Gas Board at the Geological Survey of Alabama in Tuscaloosa, AL (Table 2) (Figure 16). Magnetic susceptibility readings were obtained on exposed rock outcrops in the study area using a Terraplus KT-10 v2 magnetic susceptibility/conductivity meter. These were used to constrain values used in the magnetic modeling (Table 3) (Figure 16). Crustal thickness was derived from the EarthScope Automated Receiver Survey (EARS), a system that calculates bulk crustal properties of stations using receiver functions. Other data, such as published maps (Szabo et al., 1988), empirical data on the density and magnetic susceptibility of different rock types (Dobrin and Savit, 1988; Telford et al., 1990), and geologic cross-sections (Thomas and Bayona, 2005), were used to construct preliminary models and the geologic interpretation.

Table 1. Types of data and their sources.

Type of Data	**Data Source**
Bouguer gravity anomaly grid (.grd file)	NGDC, 2007; Daniels, Personal communication, 2007; Bajgain, 201l.
Magnetic data grid (.grd file)	NGDC, 2007; Daniels, Personal communication, 2007; Bajgain, 201l.
Well-logs	Geological Survey of Alabama and State Oil and Gas Board
Magnetic Susceptibility Measurements	Terraplus KT-10 v2 magnetic susceptibility/conductivity meter
Crustal thickness	EarthScope Automated Receiver Survey <http://ears.iris.washington.edu/index.html>
Geologic map of Alabama (ArcGIS), 1:24,000 geologic quadrangle maps	Geological Survey of Alabama and State Oil and Gas Board GIS online data; Szabo et al., 1988.
Geologic cross-sections	Thomas and Bayona, 2005.
Density and magnetic susceptibility of rocks	Dobrin and Savit, 1988; Telford et al., 1990.

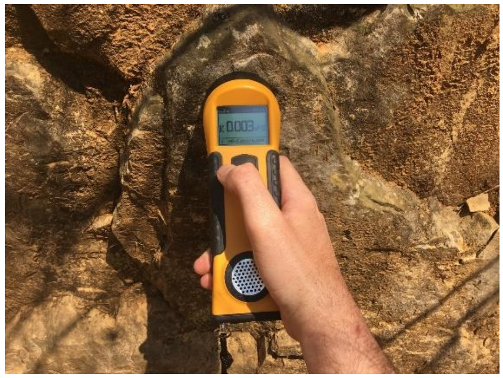
Table 2. List of wells whose interpreted lithologic logs were used for this study. For each well, the permit number, well name, location, and total depth drilled is provided. Well locations shown in Figure 16.

Permit #	**Well Name**	**Location**	**Total Depth (m)**
142	DL Wright 1	33.76098, -87.61353	1393.2
535	John B Deavours 1	33.71148, -87.63953	1229.6
782	JL Garrison #1	33.70566, -87.64774	1261.6
1148	Wiley 34-10 1	33.52120, -87.46552	3371.1
2307	RN Whitehurst 13-6	33.22169, -87.74551	2443.6
2423	Cleveland Lumber 1	33.78373, -87.57958	1383.5
3151	Loyal Baker 19-10 1	33.72927, -87.62080	1280.2
6754	Brown 8-7 1	33.14371, -87.39285	3352.8
12943	USS 2-12-01 (SWD)	33.23784, -86.93293	3509.8
13709	Ramsay 20-8 1	33.37182, -87.07784	1636.8
15498	Marchant 22-16 1	33.10497, -87.24802	3780.7
3518	Arco 15-11 1	33.28967, -86.52885	5183.1
3803	Harrell 26-13 1	33.87405, -86.93610	1219.5
16961	Crawford 4-14 2	33.93456, -86.96755	1484.4
1792	BE Turner 32-10	33.44293, -87.91381	2283.0
3097	Leroy Jones 14-10 1	33.66530, -88.07631	2133.6
4530A	John Goodson 9-7 1	32.90262, -87.17805	2416.2

Table 3. Complete list of susceptibility measurements on outcrops conducted using the KT-10 magnetic susceptibility/conductivity meter. The location, stop name, and unit information is provided, as well as the average magnetic susceptibility taken from the mean of five measurements per stop. Units are in the international system m^3/kg (SI). Stop locations shown in Figure 16

Location	**Stop Name**	**Unit**	**Average Magnetic Susceptibility (SI)**
33.165313, -86.277574	Allen's Food Mart	Talladega Block	0.00144
33.182263, -86.299921	1st Assembly of God	Talladega Block	0.00134
33.350980, -86.623875	Loading Dock/Sonic	Pottsville Formation	0.00023
33.390069, -86.665714	Cahaba Valley	Parkwood Formation	0.00019
33.257508, -87.078684	Tannehill State Park	Knox Group	0.00013
33.614421, -86.933607	I-22	Pottsville Formation	0.00019

A



B

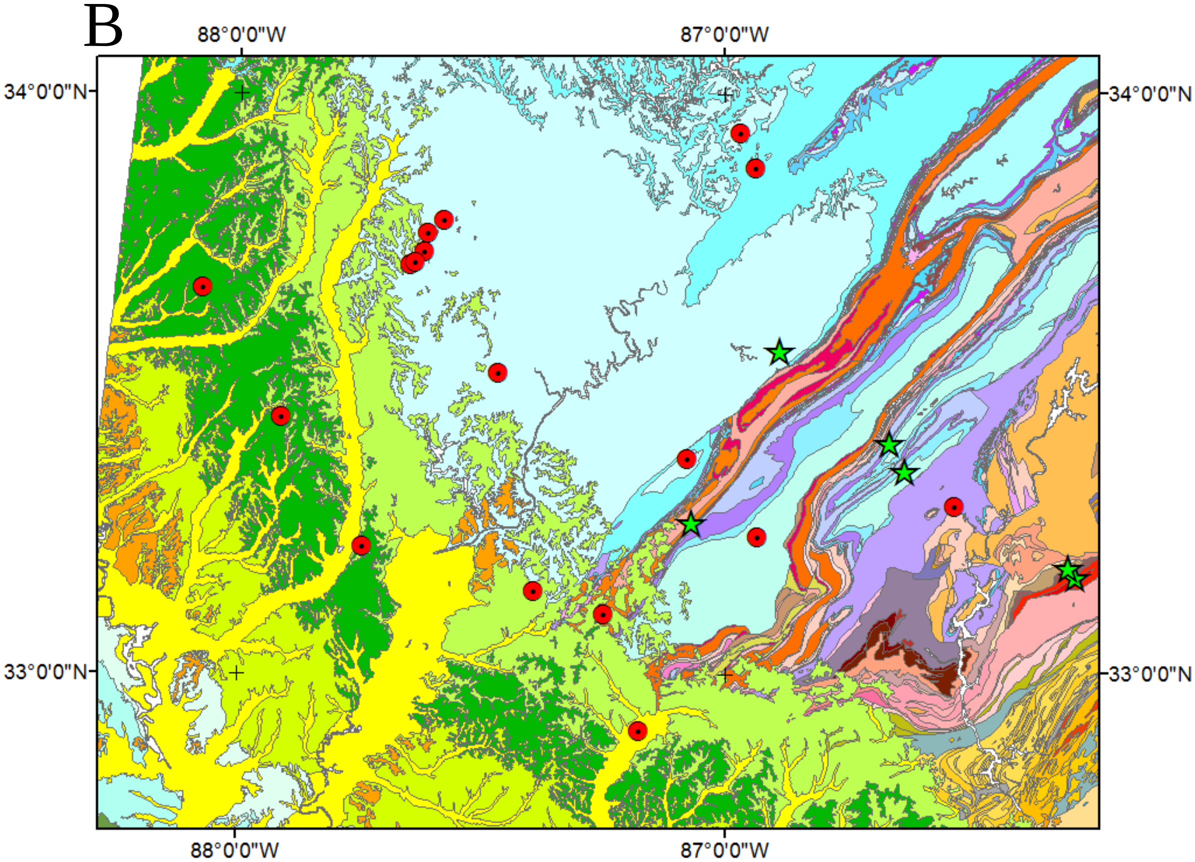


Figure 16. (A) KT-10 magnetic susceptibility/conductivity meter at an outcrop of the Knox Group near Tannehill State Park in McCalla, Alabama. The instrument uses two free-air measurements and a direct measurement on the outcrop to determine susceptibility. (B) Geologic map of central Alabama with locations of wells used in this study (red dots) and outcrops where susceptibility measurements were recorded (green stars). Modified after Geological Survey of Alabama, 2006.

Data Processing

Gravity and magnetic data were digitally processed using Geosoft's Oasis Montaj™ to prepare the data for modeling. This software has many options for gridding and filtering of the gravity and magnetic data. The program provides dynamic linking between multiple open grids, maps, images, graphs, profiles, and databases. GM-SYS®, an interactive gravity and magnetic profile module, was used to create cross-sectional models in the study area. Cross-sections consist of polygons whose attributes, such as depth, density, and magnetic susceptibility, are used to simulate rock bodies.

Gravity Data Processing

Filters and residuals are often used when working with gravity to help enhance features not normally seen due to a regional trend or isostasy. This study applies an upward continuation residual (UCR) to create a wavelength separation. The UCR filter in Oasis Montaj™ allows the program to simulate the measurement surface at a specified height above the actual Earth's surface. This method provides frequency separation in potential field data that is more interpretable than a fixed frequency or band-pass filter (Jacobson, 1987). What is essentially a low-pass filter, the UCR attenuates higher frequencies, including noise, and transfers the anomalies measured on one surface to what would have been measured on a raised parallel surface (Blakely, 1995). For gravity data, this study applied the UCR filter to a height of 20 km to view long wavelength structures associated with isostatic compensation and regional trends. This result was then subtracted from the complete Bouguer anomaly map to produce a residual that highlights the upper crust (Figure 17).

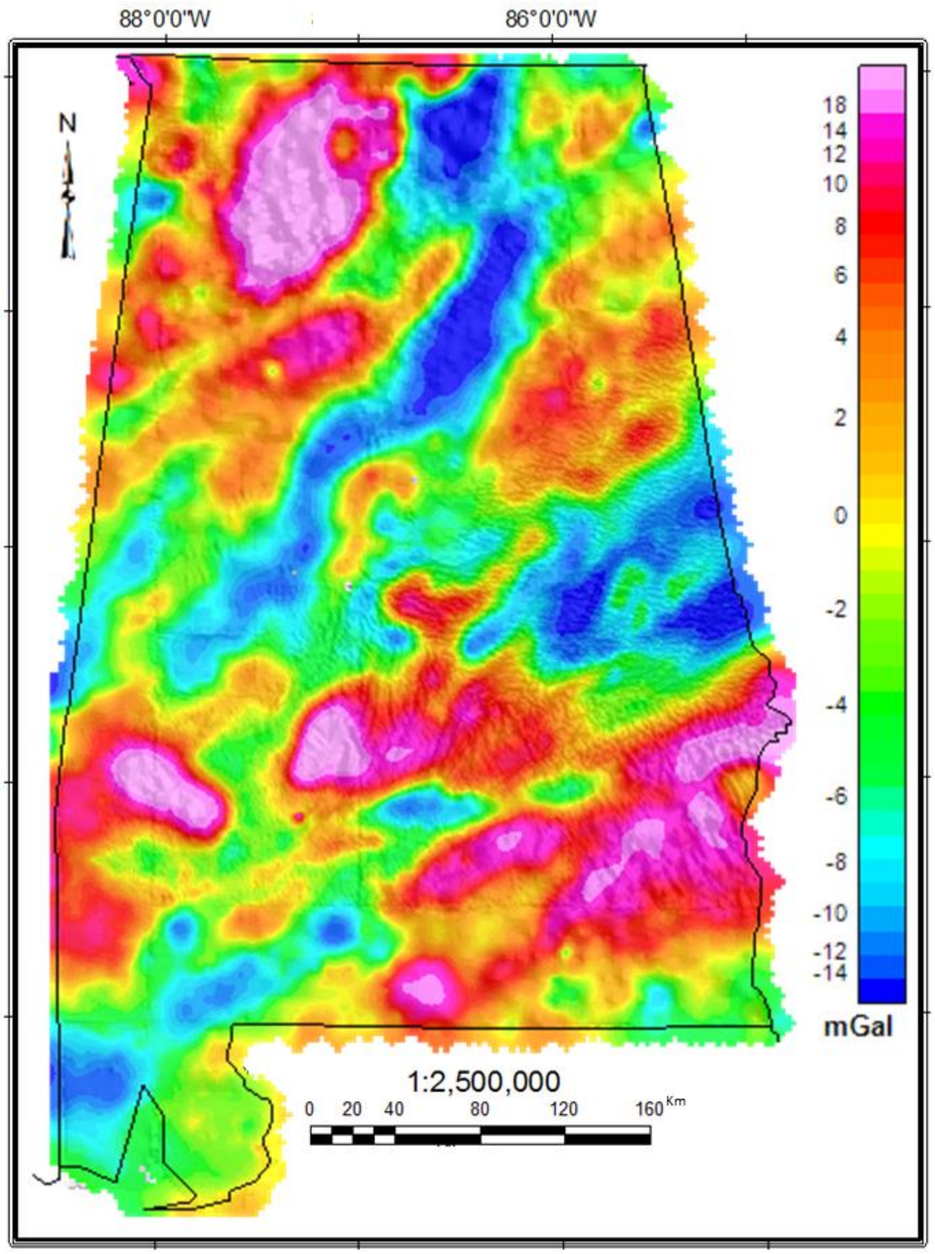


Figure 17. Upward continuation residual of complete Bouguer gravity data to 20 km. Note the short-wavelength features associated with the upper crust are made more visible compared to the total-field gravity map (Figure 14).

Similar to the UCR filter, an isostatic residual (**I_{corr}**) grid was also created by removing the overall regional trend from the complete Bouguer anomaly map, shown in Equation 2 and Figure 18. Long-wavelength, deep crustal anomalies that are a result of isostatic compensation of topographic loads are removed, highlighting features in the upper crust (Burger et al., 2006). Regional topographic data was used to calculate the regional gravity trend. This regional gravity trend is then subtracted from the original grid, and the resultant grid is the isostatic residual anomaly map (Figure 19).

$$\Delta g_b = g_{obs} - g_n + FA_{corr} - B_{corr} + TC \pm I_{corr} \qquad [2]$$

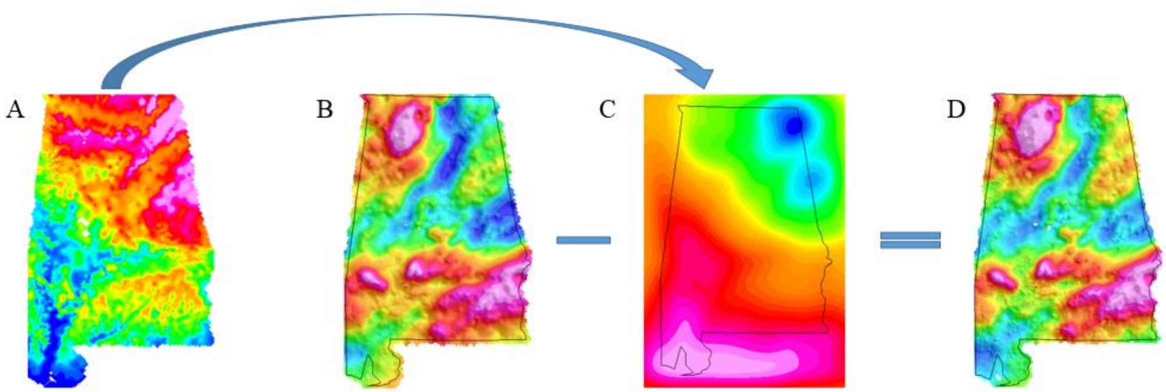


Figure 18. Gravity data processed as an isostatic residual anomaly map. (A) Elevation grid (30 m resolution); (B) complete Bouguer gravity grid; (C) regional gravity trend calculated from the elevation grid; and (D) the final isostatic residual anomaly map calculated by subtracting the regional gravity trend from the complete Bouguer.

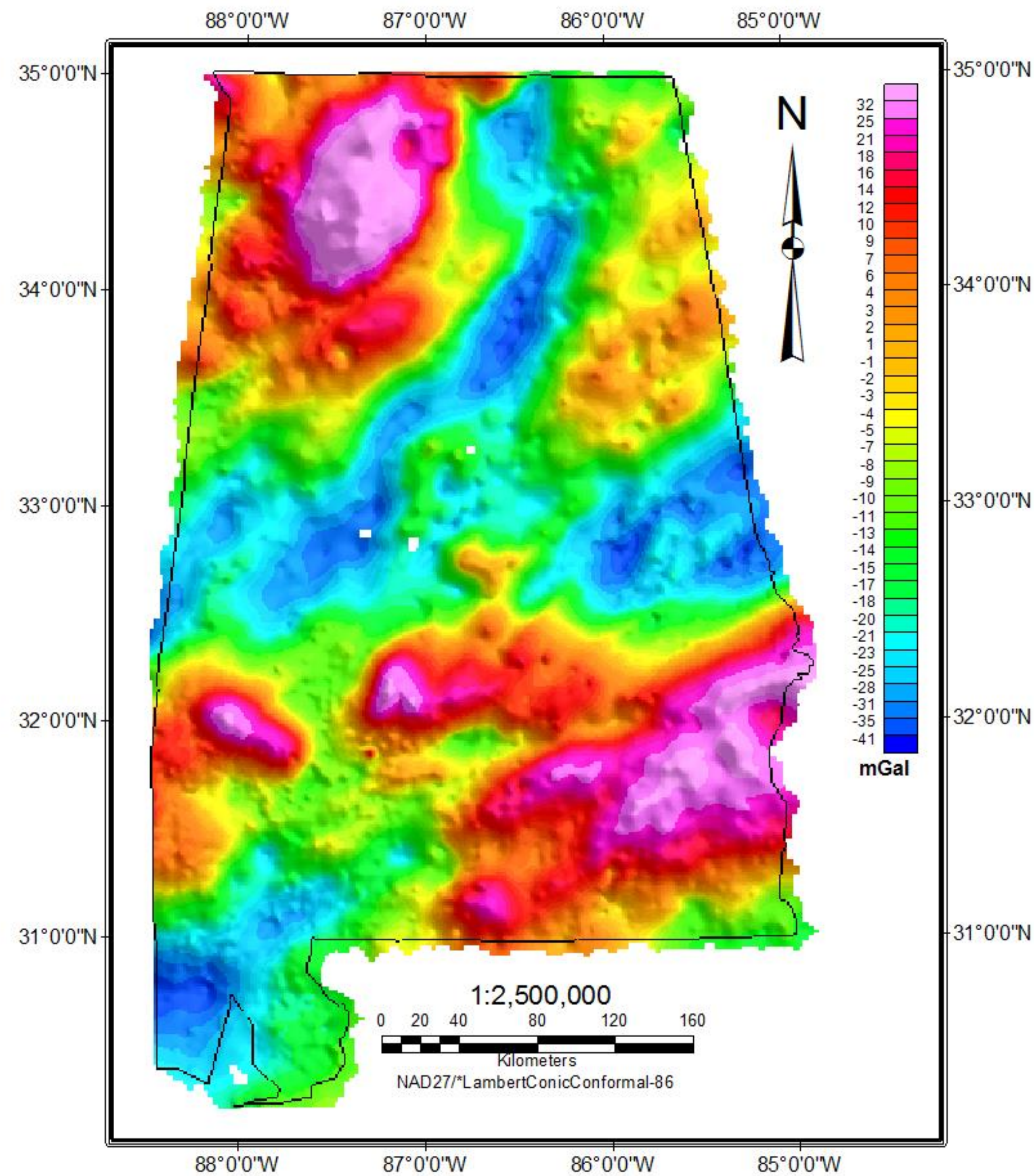


Figure 19. Isostatic residual anomaly map of Alabama.

Magnetic Data Processing

A magnetic anomaly is directly related to the orientation of the ambient field and magnetization. If the orientation of both the magnetization and ambient field are not vertical, which is the case for the current study area, symmetrical magnetic bodies will produce an asymmetrical anomaly, creating an inaccurate representation of the subsurface (Blakely, 1995). A reduction to pole removes the effect caused by inclination by correcting the field to a vertical inclination. After a reduction to pole is preformed, magnetized bodies in the Earth's crust will produce anomalies that are closer representations to the actual shape of the body (Figure 20) (Blakely, 1995). Ambient magnetic field values for the study area were obtained from the National Oceanic and Atmospheric Administration (NOAA) and applied prior to modeling.

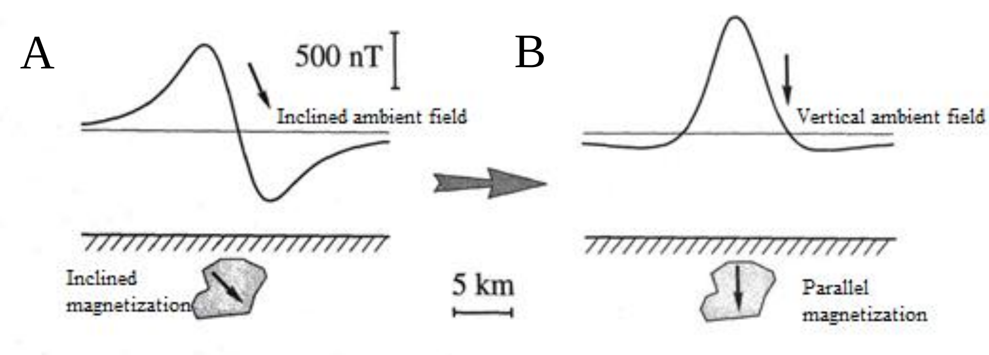


Figure 20. Diagram illustrating how a symmetrical object produces (A) an asymmetric anomaly before preforming a reduction-to-pole filter and (B) a symmetrical anomaly after reduction-to-pole. In (A) the ambient field is inclined and induced magnetization is not vertical. After reduction-to-pole (B), the field is vertical and parallel with the induced magnetization (modified from Blakely, 1995; Bajgain, 2011).

In addition to a reduction-to-pole, a UCR filter was applied to the magnetic data, though processed differently than the gravity data. A height of 50 m was used to separate lower-frequency components from the total field. The resulting grid was subtracted from the total field magnetic data to create a UCR (Figure 21). This UCR highlights short wavelength features that accentuate faults and geologic contacts, important when examining crustal structures like the NY-AL lineament and Amish anomaly.

Ancillary Data

Ancillary data were digitized and georeferenced when necessary. Well-log data included the longitude and latitude, elevation, depths, and lithologic information for most wells (Table 2). These wells were displayed in Oasis Montaj™ and GM-SYS® to help constrain the models. Generalized cross-sections (Thomas and Bayona, 2005), geologic maps, and magnetic susceptibility values recorded in the field were used to construct preliminary gravity and magnetic models. The values of crustal blocks used in previous studies (e.g., Savrda, 2008; Bajgain, 2011) were considered when estimating values for density and susceptibility.

Well-logs and cross-sections (Thomas and Bayona, 2005) provided information only for the very upper portion of the crust (< 8 km). Because detailed crustal models extended no more than a few kilometers in depth, previous research outside the study area was used to help constrain the models. Gravity and seismic models by Harry and Londono (2004) in Mississippi, COCORP seismic reflection models in adjacent states (Nelson et al., 1985a; 1985b; Nelson et al., 1987; McBride and Nelson, 1988; 1991; Culotta et al., 1990; McBride et al. 2005), and gravity and magnetic models by Bajgain (2011) in Alabama were all used to help develop a deep crustal model for Alabama.

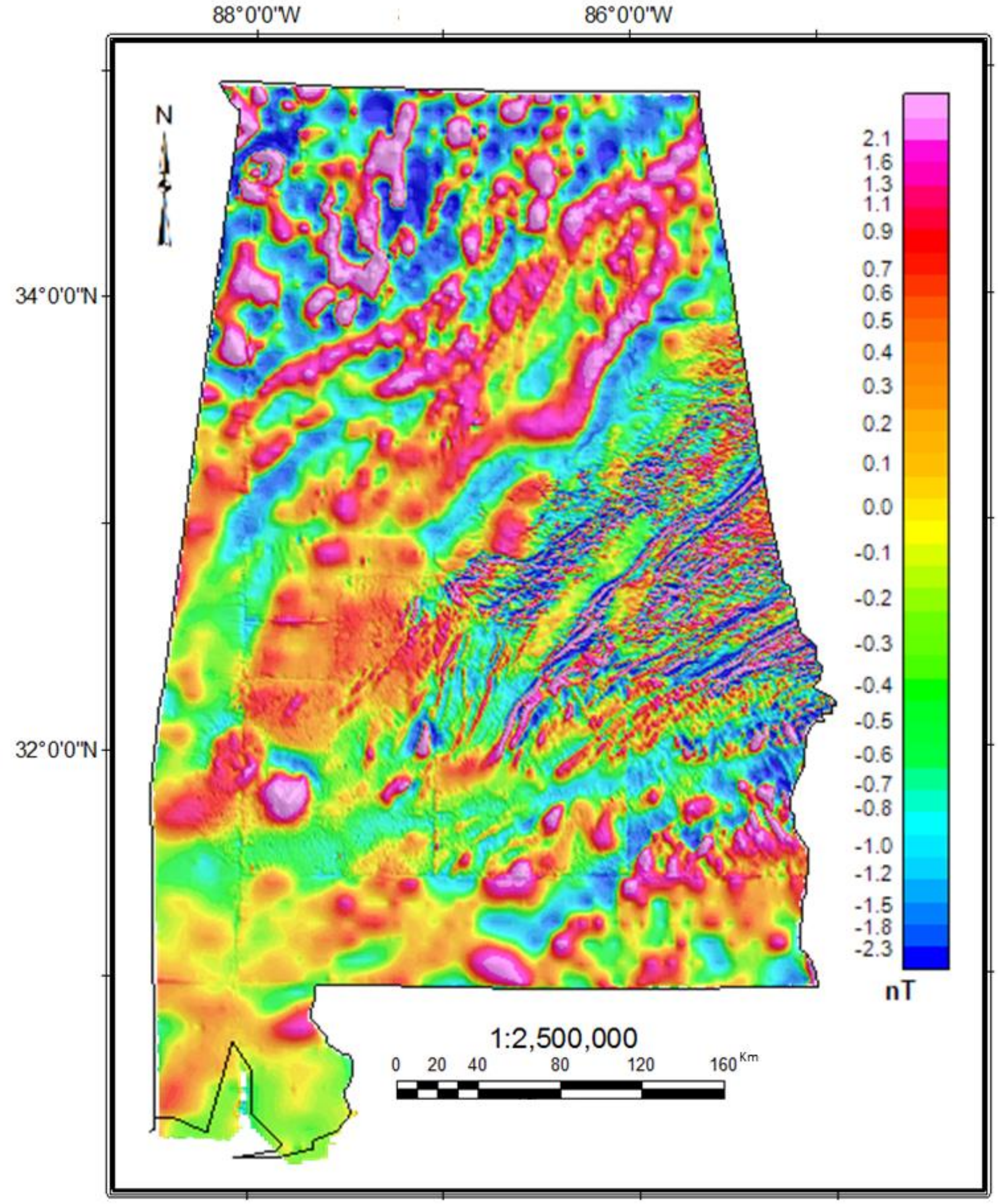


Figure 21. Upward continuation residual of magnetic data (50 m). Note the short-wavelength features compared to the original magnetic map (Figure 15).

Gravity and Magnetic Modeling

Gravity and magnetic modeling was completed in GM-SYS® 2.5D. An iterative process was followed to match the observed data to the model-generated data until an acceptable fit was achieved. Cross-sectional models for this study were constructed along two transects (A-A′ and B-B′) from the original dataset (Figure 22). These locations were chosen to cross key tectonic and geophysical features, including the NY-AL lineament, the Birmingham anticlinorium, and the Black Warrior, Cahaba, and Coosa basins. Transects A-A′ and B-B′ were selected to be parallel to the potential field gradient to minimize three-dimensional effects.

The GM-SYS® software calculates both gravity and the magnetic values for a geologic model. Whereas two-dimensional modeling only considers the gravity effect produced by the bodies directly below the line, GM-SYS® 2.5-dimensional modeling expands the theoretical calculation to include the effects of bodies perpendicular to the line, allowing for a more accurate representation of the subsurface.

Polygons are used to represent individual rock units or layers in the cross-sectional model. Each layer is initially created horizontally and assigned a density and magnetic susceptibility value. The value chosen is based on rock type, known measurements, and previous models (Dobrin and Savit, 1988; Telford et al., 1990; Savrda, 2008; Bajgain, 2011). The ranges of density and magnetic susceptibility used in this study can be found in Table 4. These simple horizontal layers are then adjusted until an acceptable fit is achieved. Density and susceptibility values of individual rock units were assumed to vary due to composition, depth, structure, and geometry of the units.

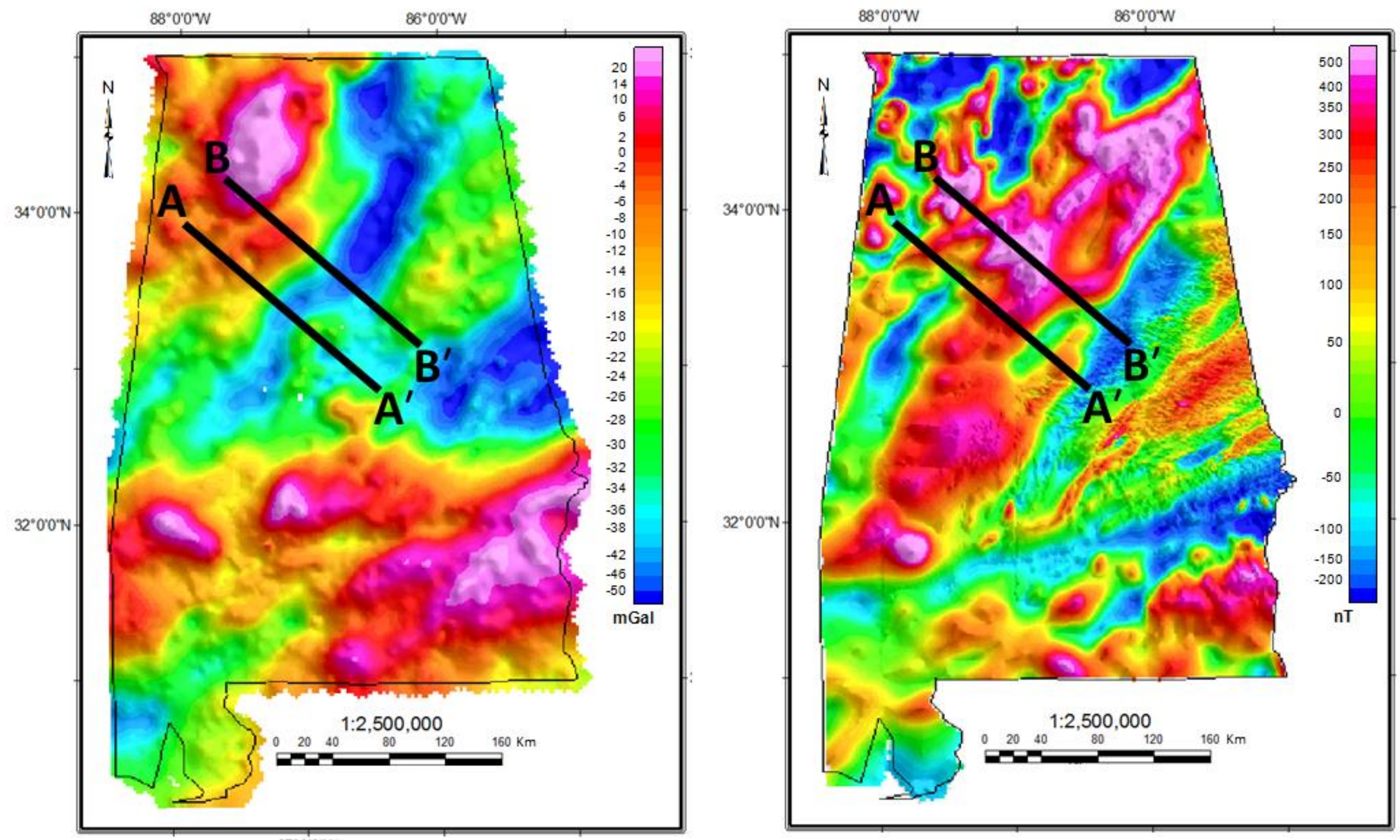


Figure 22. (A) Complete Bouguer gravity map and (B) total-field magnetic map showing transect locations for profiles A-A′ and B-B′.

Table 4. Estimated density and magnetic susceptibility values for different stratigraphic units and crustal blocks (Dobrin and Savit, 1988; Telford et al., 1990; Savrda, 2008; Bajgain, 2011). Values represented in table are the average values used for those units. Values for density and magnetic susceptibility can vary up to 5-10% from the mean due to vertical and lateral changes in the rock.

Rock Unit	**Density (kg/m^3)**	**Susceptibility (SI)**	**General Lithology**
Pottsville	2350-2650	0.00020-0.00025	Sandstone, siltstone, clay, shale, coal
“Stiff/Resistant Units” Ketona Dolomite – Parkwood Formation	2500-2780	0.00020-0.00025	Limestone, Dolostone, Sandstone, Siltstone, Shale
“Weak/Mushwad Units” Rome Formation – Conasauga Formation	2650-2800	0.00020-0.00025	Shale, Limestone, Siltstone
Talladega Block	2780	0.00100-0.00150	Low-grade metamorphic
Mafic Rock	2850	0.00800	Mafic block, likely highly metamorphosed
Metasediments	2770	0.00150-0.00600	Highly metamorphosed sediments
Continental Crust	2720	0.00100	Igneous or Metamorphic Rock
Mantle	3300	0.00300	Igneous Rock

Results

Upward continuation residual (UCR) filters

UCR filters were applied to both the complete Bouguer gravity data (Figure 17) and the total-field magnetic data (Figure 21) to accentuate features such as faults, geologic contacts, and terrane boundaries in the upper crust. In the filtered gravity data (20 km), some features appear to be slightly more pronounced. There is a linear gravity-low matching the location of the NY-AL lineament, and south of the study area, the BMA is highlighted as a gravity low (Figure 23).

The total-field magnetic UCR map accentuated more features compared to the complete Bouguer gravity UCR map. The NY-AL lineament can be seen as a strong linear feature of magnetic high values, and the AA also appears to be significantly enhanced (Figure 24). These short-wavelength features are accentuated because they are upper-crustal features. Very short-wavelength features, such as those circled in Figure 24, are likely faults near or at the surface, while those features with longer wavelengths, such as the NY-AL lineament and AA, are likely crustal-scale features.

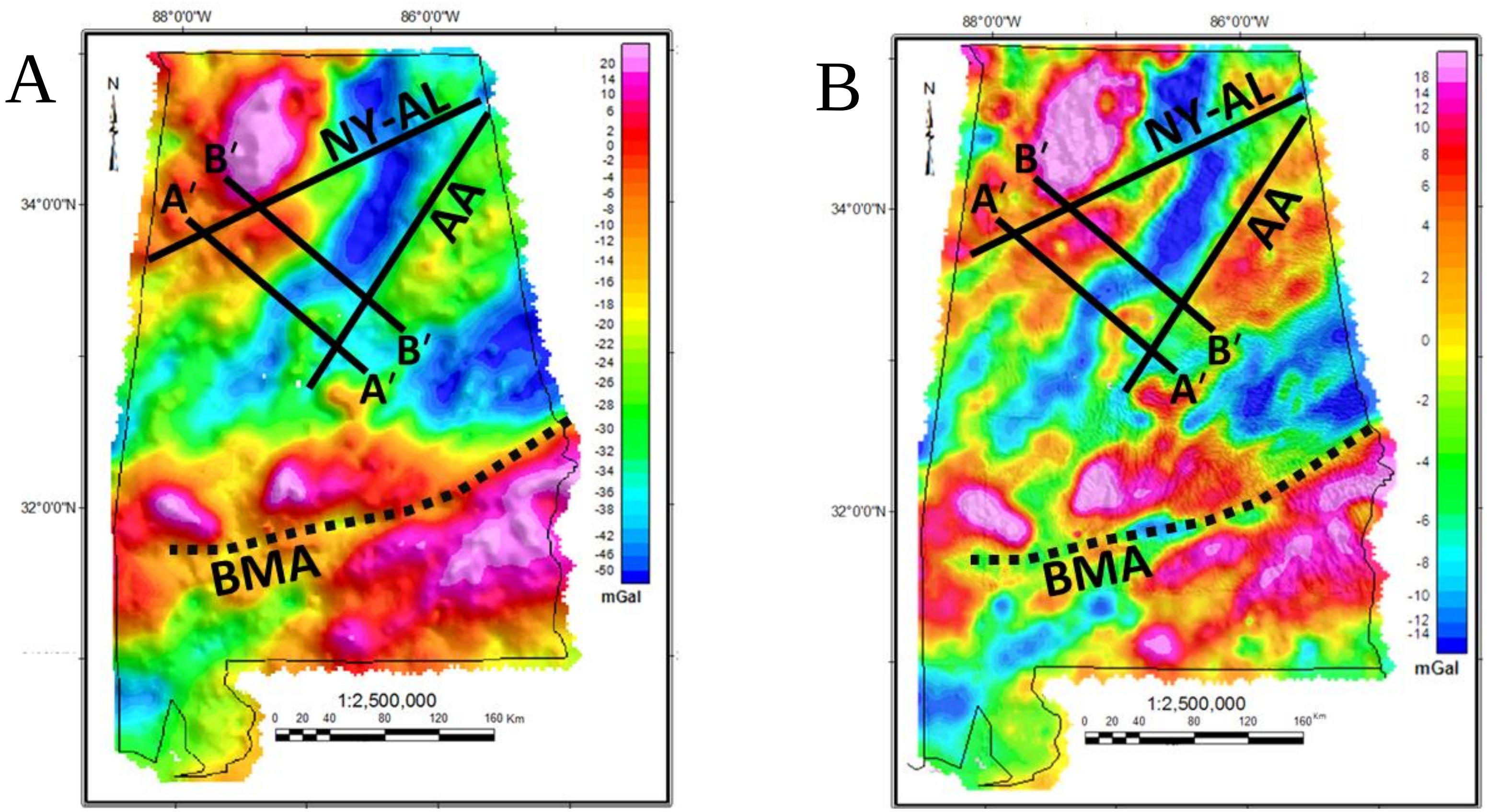


Figure 23. (A) Complete Bouguer gravity map and (B) UCR filtered gravity map. UCR filter was done to a height of 20 km. Transects A-A′ and B-B′ are shown in both (A) and (B). The trace of the BMA (dashed line) has a low-gravity signature and is accentuated by the UCR filter. The NY-AL lineament (NY-AL) also has a low-gravity signature, though less so than the BMA, and the Amish Anomaly (AA) is not emphasized by the UCR.

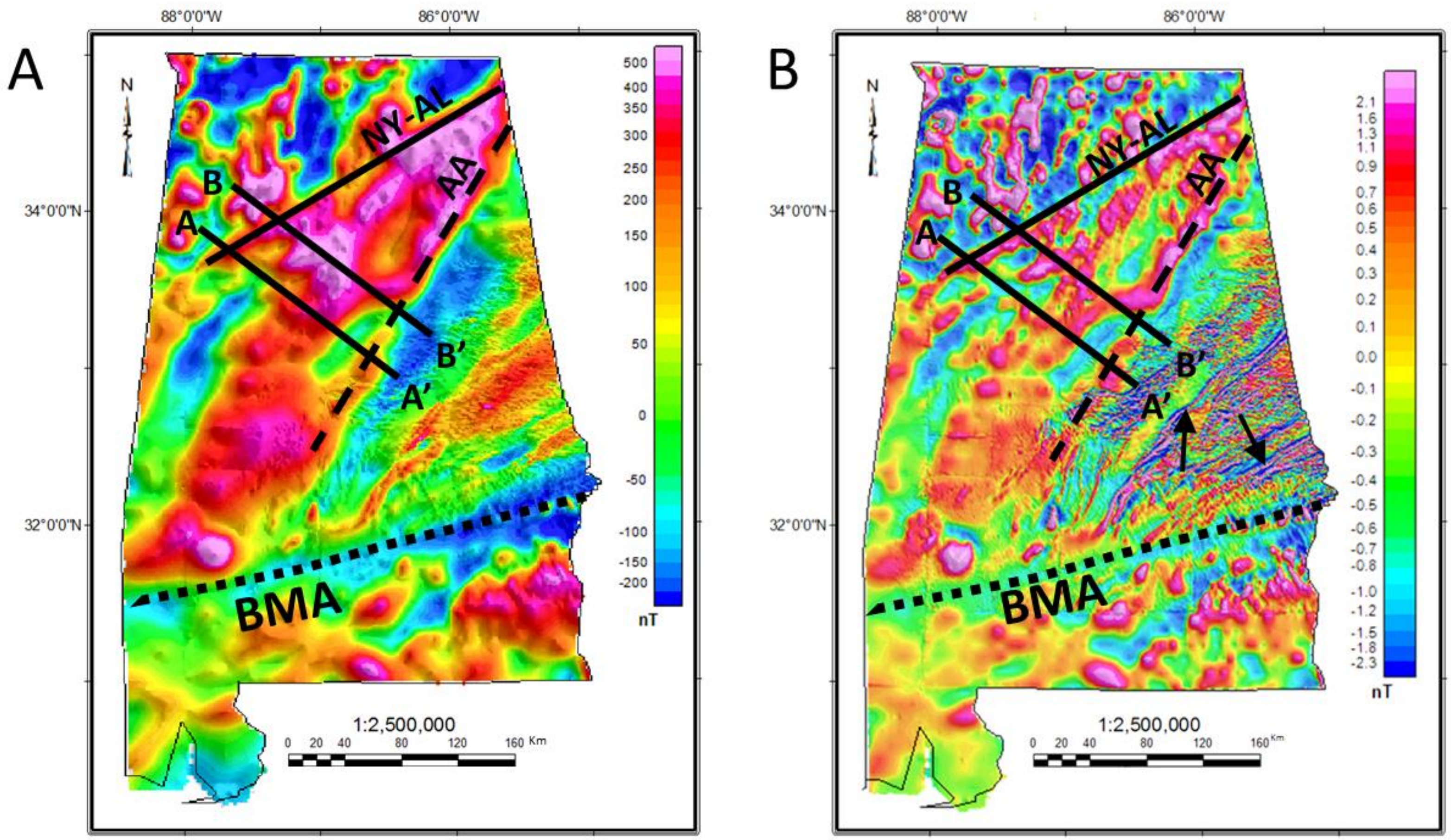


Figure 24. (A) Total-field magnetic anomaly map of the study area, and (B) upward continuation residual map of the study area. Both maps show transects A-A′ and B-B′, as well as the NY-AL lineament (NY-AL) and the Amish Anomaly (AA). BMA is marked by a dashed line, and arrows show short-wavelength signatures of near-surface faults. Modified from Raymond et al., 2005; Steltenpohl et al., 2010; Daniels, pers. communication, 2007; Bajgain, 2011.

Profiles

The gravity and magnetic profiles (A-A′ and B-B′) modeled in this study, were chosen to cross both the NY-AL lineament and the continuation of the AA (Figure 22) (Steltenpohl et al., 2010). Line A-A′ is approximately 200 km in length and is oriented N40°W. Line B-B′ is located 45 km northeast of A-A′ and is parallel to A-A′. Transect B-B′ is also approximately 200 km in length. Combined, the two profiles allow for interpolation along the strike of major geologic structures.

The potential field properties of the rocks are expressed by various polygons embedded in the cross-section, which are described as positive or negative contrasts relative to a magnetically and gravitationally homogeneous crust. All cross-sections extend 55 km below the surface. The contacts between polygons on the surface and a few kilometers (~8 km) below the surface are constrained by the location of geological units and structures as represented in published geologic maps (Szabo et al., 1988; Osborne et al., 1998; Osborne and Irvin, 2002; Rindsberg et al., 2003a; Rindsberg et al., 2003b; Irvin and Osborne, 2006; Osborne et al., 2006; Ward and Osborne, 2006). Results from each model are described below separately.

Profile A-A′

Gravity and magnetic data for A-A′ show an observable regional trend, with a maximum value of ~ -5 mGal in the northwestern portion of the transect, decreasing to a minimum value of ~ -42 mGal in the central portion of the transect (Figure 25). This minimum also coincides with the trough of a long-wavelength feature at approximately ~ 94 km along the profile. Magnetic data ranges from a maximum of ~ 360 nT to a minimum of ~ -200 nT, with three peaks at ~ 25 km, 100 km, and 155 km. Subtle, short-wavelength features occur at ~ 50 km and 85 km.

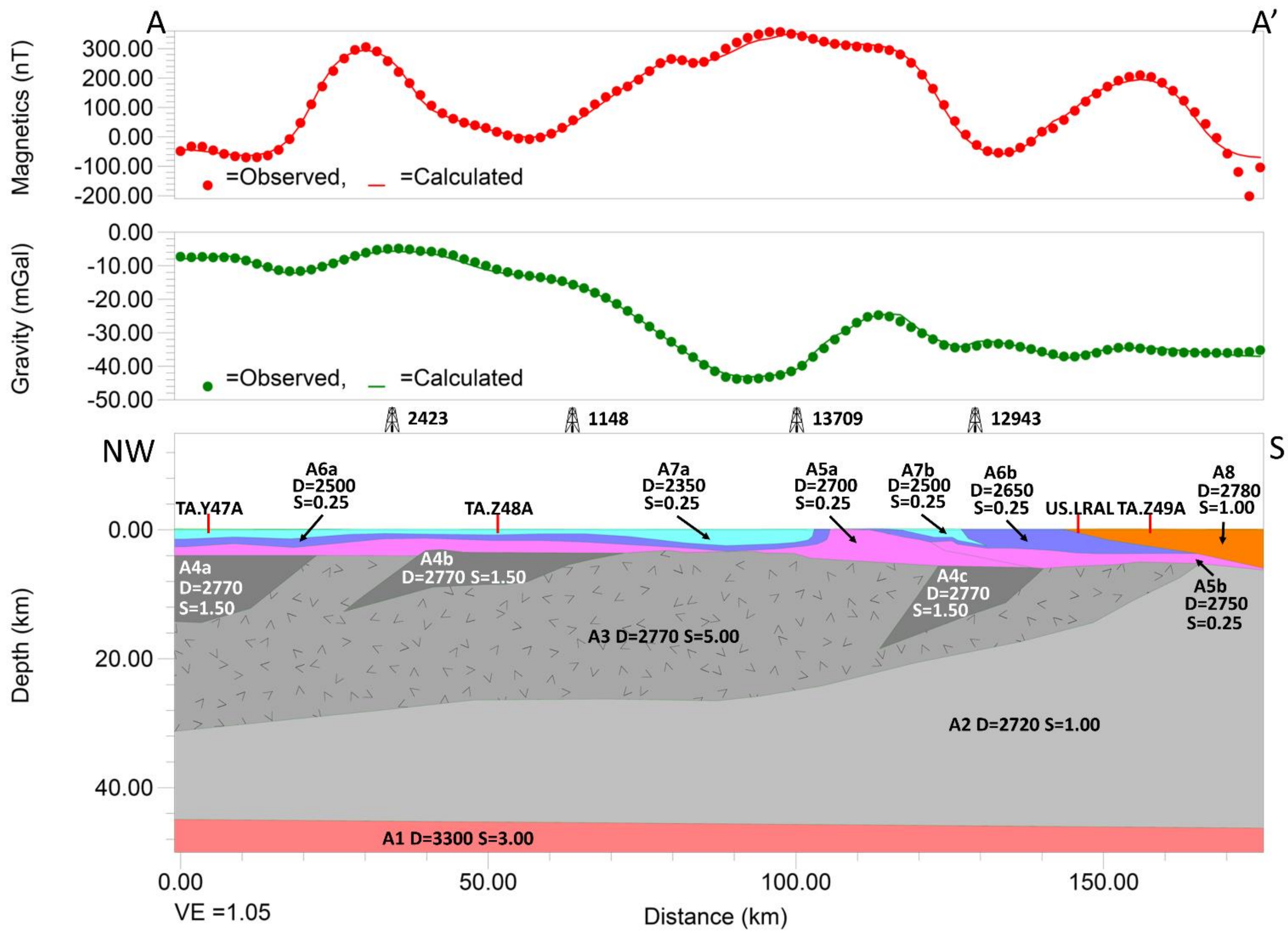


Figure 25. Gravity and magnetic model results for transect A-A′, showing the calculated fit of the model to the observed data. The calculated curves were adjusted by assigning density and magnetic susceptibility values to polygons (seen in the cross section) until a satisfactory fit to the data was achieved. Profile location shown in Figure 24. Magnetic susceptibility values are x 10^{-3}. Well locations shown above profile, EARS stations shown with red lines.

The lowest layer in the model (A1) denotes the upper mantle, whose depth increases slightly from ~ 44 km in the northwest to ~ 46 km in the southeast. Immediately above this is A2, a continental crustal block with a density and susceptibility of 2720 kg/m^3 and 1.00×10^{-3} SI, respectively. The upper crustal block A3 has high magnetic susceptibility (5.00×10^{-3} SI) and density (2770 kg/m^3). The contact between A2 and A3 is a northwestern dipping structure that separates two inherently different rock bodies (see discussion). Included in A3 are blocks labeled A4a-c of lower susceptibility (1.50×10^{-3} SI) with the same density as A3. These accommodate the magnetic high seen at ~ 25 km and ~ 140 km. Blocks A2-A4 make up the basement rock in the model. Gravity values are relatively low (~ -25 to -42 mGal) in the eastern portion of the profile and are higher the western portion (<-5 mGal). This is accommodated by a large wedge-shaped block (A2) that is thicker in the east, and a denser block (A3) that is thicker in the west. Blocks A4a-c (D=2770 kg/m^3, S=1.50×10^{-3} SI) have slightly lower values of magnetic susceptibility than the surrounding block A3, and account for the very significant dips seen the magnetic profile (Figure 25).

Above the basement are sedimentary rocks (A5 to A7), as well as low-grade metamorphic rocks (A8) that have been included based on outcrop data, geologic maps, cross-sections, and well-log data. Densities for A5 to A7 range from 2350 kg/m^3 to 2750 kg/m^3, while susceptibilities are 0.25×10^{-3} SI. Block A8 has a slightly higher density and susceptibility of 2780 kg/m^3 and 1.00×10^{-3} SI than its adjacent blocks. All block values corresponding to the model are listed in Table 5.

Table 5. List of model blocks and their densities, magnetic susceptibilities, and rock types for profile A-A′.

Block	**Density (kg/m^3)**	**Magnetic Susceptibility (SI)**	**Rock Type**
A8	2780	0.00100	Low-grade metamorphic, slate, greenstone
A7a	2350	0.00025	Shale, coal beds, sandstones
A7b	2500	0.00025	Shale, coal beds, sandstone
A6a	2500	0.00025	Sandstone, shale, silt, carbonates
A6b	2650	0.00025	Sandstone, shale, silt, carbonates
A5a	2700	0.00025	Shale, carbonates
A5b	2750	0.00025	Shale, carbonates
A4a-c	2770	0.00150	Metamorphic rock
A3	2770	0.00500	Metamorphic rock
A2	2720	0.00100	Crystalline continental crust
A1	3300	0.00300	Upper mantle

Profile B-B′

Similar to line A-A′, the model for line B-B′ suggests that the deep crust is divided into rocks with varying physical properties (Figure 26). There is a regional trend in the gravity data, decreasing from northeast to southeast. There is one long-wavelength feature whose trough represents the minimum gravity value in the transect (~ 40.0 mGal) at 110 km. The maximum gravity value (~ 20.0 mGal) is located around 12 km in the northwestern portion of the transect. Shorter wavelength features are present with troughs located at approximately 38 km, 86 km, 110 km, 130 km, and 155 km. These features are accommodated by introducing normal faults in blocks B2 and B3. Magnetic anomalies have overall higher values than those observed along profile A-A. Short wavelength anomalies are present at approximately 18 km, 32 km, 52 km, 61 km, 82 km, 105 km. 140 km, and 170 km, and are accommodated by introducing low-susceptibility wedges. There is a slight decrease in magnetic values to the southeast along the profile. The highest value is ~ 680.0 nT at 10 km and the lowest value ~ -200.0 nT at 175 km.

The deepest layer in the model (B1) denotes the upper mantle, whose depth increases slightly to the southeast along the transect, in agreement with profile A-A′. B2 is comparable to A2 with a density and magnetic susceptibility of 2720 kg/m^3 and 1.00 x 10^{-3} SI, respectively. The upper crustal block B3 has high magnetic susceptibility (6.00 X 10^{-3} SI) and density (2770 kg/m^3), similar to the large unit (A3) in profile A-A′. Blocks B4a-b have a density and magnetic susceptibility of 2770 kg/m^3 and 1.50 x 10^{-3} SI, respectively. In profile B-B′ there is a distinct increase in magnetic susceptibility corresponding to the location of the AA, suggesting an abrupt change in crustal structure or composition. This block, B5, has a very high density and magnetic susceptibility of 2850 kg/m^3 and 8.00 x 10^{-3} SI, respectively.

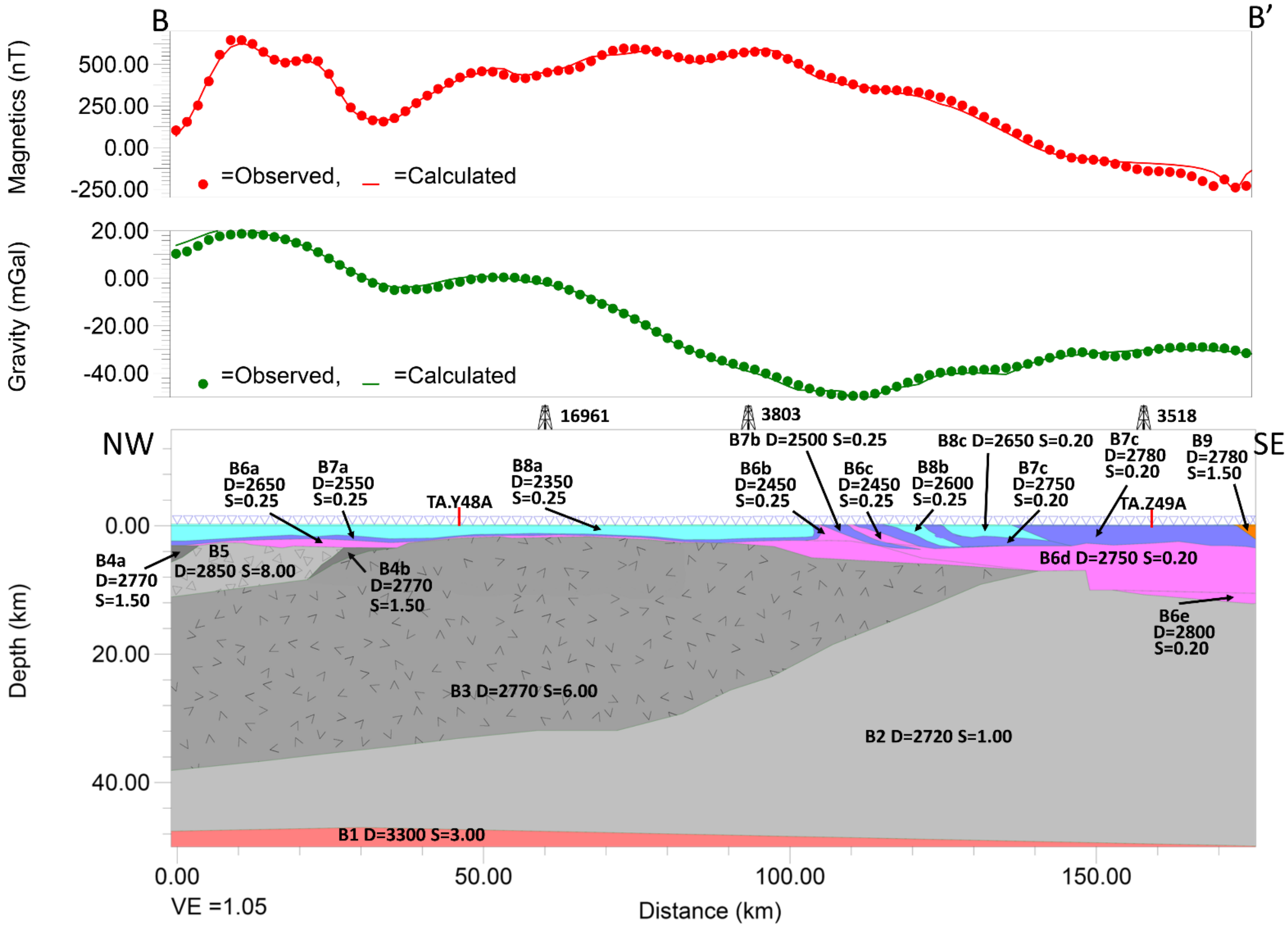


Figure 26. Gravity and magnetic model results for transect B-B′, showing the calculated fit of the model to the observed data. The calculated curves were adjusted by assigning density and magnetic susceptibility values to polygons (seen in the cross section) until a satisfactory fit to the data was achieved. Profile location shown in Figure 23. Magnetic susceptibility values are x 10^{-3}. Well locations shown above profile, EARS stations shown with red lines.

Above the basement units are sedimentary rocks that comprise the Appalachian/Cumberland Plateau and Valley and Ridge rocks. Both provinces contain rocks with similar properties. The main difference between the two terranes is structural (see background). This creates a discrepancy in densities between the two regions despite containing the same units. Units that have undergone more thrusting and deformation likely have been exposed to higher pressures and increased compaction, contributing to higher densities (e.g. Valley and Ridge rocks). Blocks B6a-c have densities of 2450 kg/m^3 to 2650 kg/m^3, while B6d-e have densities of 2750 kg/m^3 to 2800 kg/m^3. Block B7a has a density of 2550 kg/m^3, while B7b-d have densities ranging from 2650 to 2780 kg/m^3. Block B8a has a density of 2350 kg/m^3, while B8b-c have densities of 2600 kg/m^3 to 2650 kg/m^3. These sedimentary rocks have magnetic susceptibilities ranging from 0.20×10^{-3} to 0.25×10^{-3} SI. There is a small portion of the Talladega block, a metamorphic terrane, present in the profile, and is represented by block B9 with a density of 2780 kg/m^3 and a magnetic susceptibility of 1.50×10^{-3} SI. All block values are listed in Table 6.

Table 6. List of blocks, their densities, magnetic susceptibilities, and their rock description for profile B-B′.

Block	**Density (kg/m^3)**	**Magnetic Susceptibility (SI)**	**Rock Type**
B9	2780	0.00150	Low-grade metamorphic, slate, greenstone
B8a	2350	0.00025	Shale, coal beds, sandstones
B8b	2600	0.00025	Shale, coal beds, sandstones
B8c	2650	0.00020	Shale, coal beds, sandstones
B7a	2550	0.00025	Sandstone, shale, silt, carbonates
B7b	2650	0.00025	Sandstone, shale, silt, carbonates
B7c	2750	0.00020	Sandstone, shale, silt, carbonates
B7d	2780	0.00020	Sandstone, shale, silt, carbonates
B6a	2650	0.00025	Shale, carbonates
B6b-c	2450	0.00025	Shale, carbonates
B6d	2750	0.00020	Shale, carbonates
B6e	2800	0.00020	Shale, carbonates
B5	2850	0.00800	Metamorphic rock
B4a-b	2770	0.00150	Metamorphic rock
B3	2770	0.00600	Metamorphic rock
B2	2720	0.00100	Crystalline continental crust
B1	3300	0.00300	Upper mantle

Discussion

Upper mantle depths in the models are consistent with depths calculated from recent seismic studies conducted by the EARS. The basement rocks above the upper mantle are interpreted as having three distinct rock types: low-density and low-susceptibility rock, high-susceptibility and high-density rock, and low-susceptibility and high-density rock, corresponding to blocks A2 and B2, A3 and B3, and A4 and B4, respectively (Figures 27 and 28). A fourth rock type (B5), only present in profile B-B′ north of the NY-AL lineament, is interpreted as a metamorphic rock with increased amounts of magnetic minerals (e.g., magnetite). Earlier interpretations have suggested that these basement rocks are Grenville-aged (~ ca. 1000 Ma) and are a part of the ancient Laurentian margin (Bajgain, 2011). Models presented here suggest that that these basement rocks were likely accreted during the Grenville orogeny (Figure 27).

North of the study area in Tennessee, and even further north in Ohio, the AA has been interpreted as a west-dipping interface between a granulite terrane to the east and a metasedimentary belt to the west (Figure 9) (Culotta et al., 1990). These COCORP reflection profiles show this west-dipping structure terminating at the Moho (Figure 9) (Culotta et al., 1990). The current models are consistent with Culotta et al. (1990), though my models do not show the termination of this structure (Figure 28). The gravity and magnetic curves of profile A-A′ are notably similar to the gravity and magnetic curves of the OH1 profile from the Culotta et al. (1990) study (Figure 9), suggesting that these boundaries are continental-scale features. The matching magnetic and gravity signatures also suggest that the rock types are similar, and that these rocks can be used as an analogue for the basement rocks beneath Alabama.

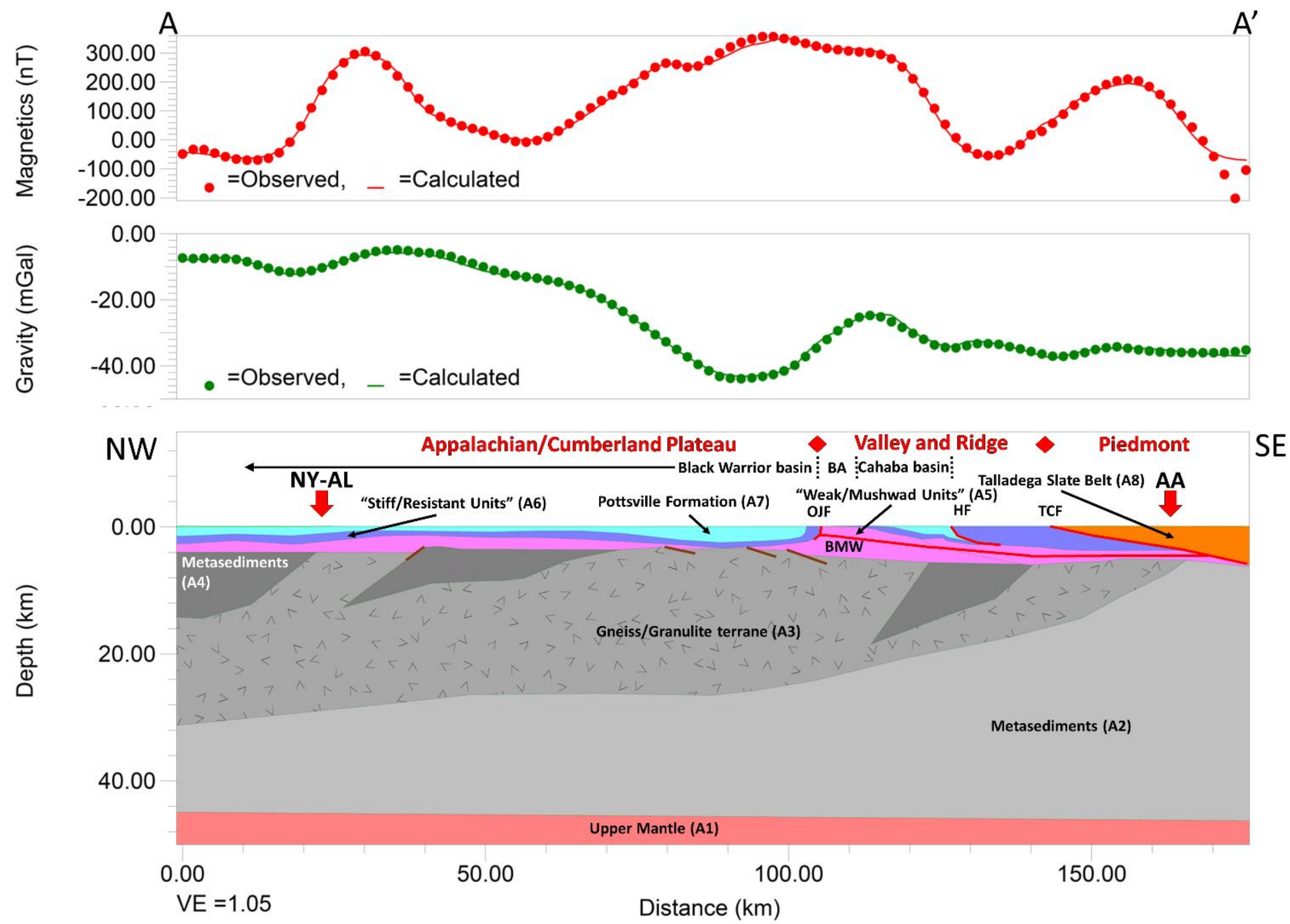


Figure 27. Geologic interpretation of profile A-A′ based on gravity and magnetic modeling. The magnetic and gravity data are shown above the profile. Dots represent the observed data, and the lines through the dots represent the calculated curve (red for magnetics, green for gravity). The interpreted geologic cross-sections shows the range of densities and magnetic susceptibilities ($x10^{-3}$) for each colored unit, as well as general information, such as the location of normal faults (dark orange lines), thrust faults (red lines) tectonic terranes, basins, and structures.

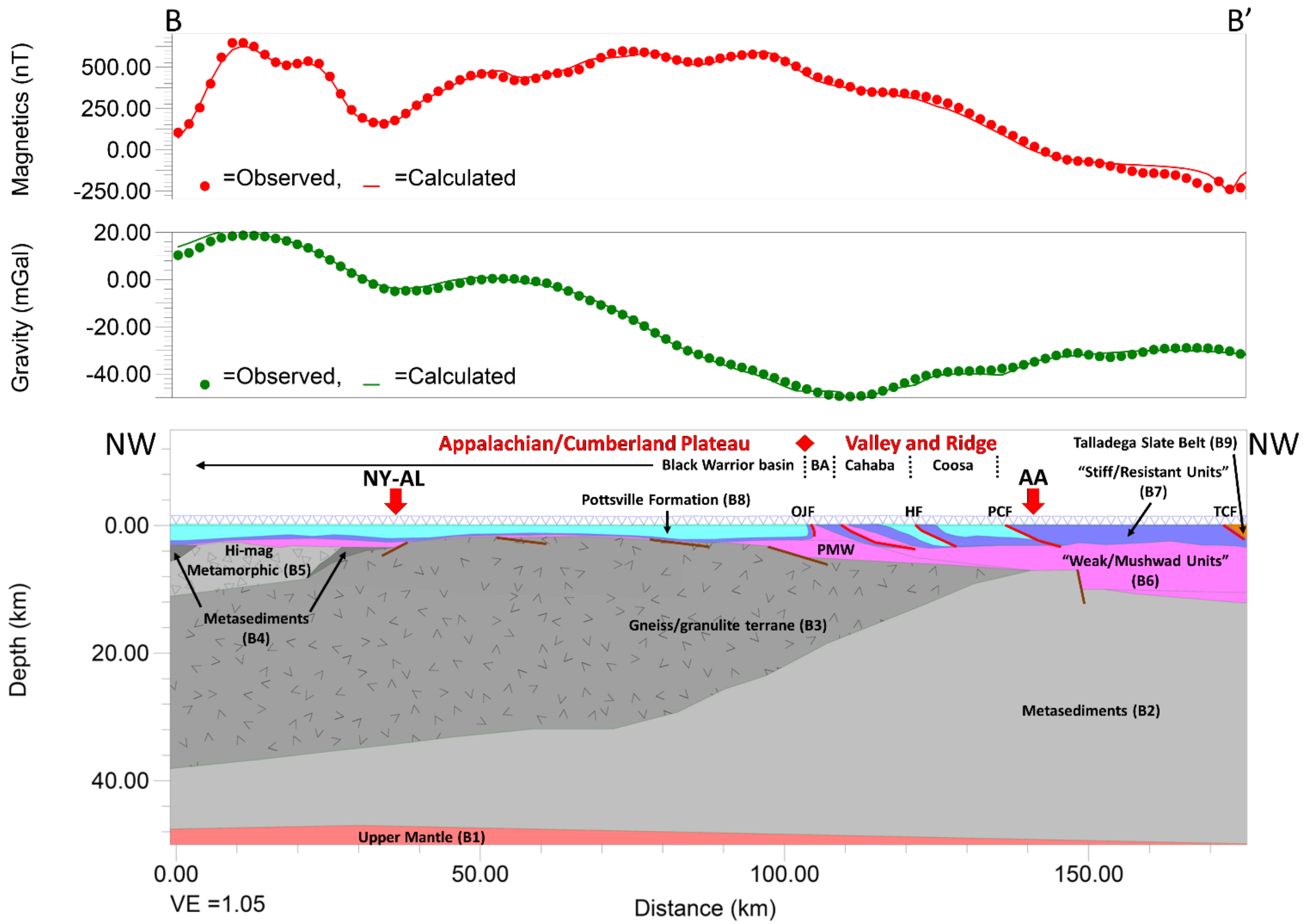


Figure 28. Geologic interpretation of profile B-B′ based on gravity and magnetic modeling. The magnetic and gravity data are shown above the profile. Dots represent the observed data, and the lines through the dots represent the calculated curve (red for magnetics, green for gravity). The interpreted geologic cross-sections shows the range of densities and magnetic susceptibilities (x10^{-3}) for each colored unit, as well as general information, such as the location of normal faults (orange lines), thrust faults (red lines), tectonic terranes, basins, and structures.

In the current study, the NY-AL lineament (~22 km in A-A′; ~35 km in B-B′) is created by a west-dipping interface between two distinct rock types: Blocks A3 and B3, high-density and high-susceptibility rocks, and Blocks A4 and B4, high-density and relatively low-susceptibility rocks. Using known magnetic susceptibility and gravity values (Dobrin and Savit, 1988; Telford et al., 1990) and Culotta et al. (1990) as an analogue, Blocks A3 and B3 are interpreted as a highly magnetized gneisses or granulites, and Blocks A4 and B4 are interpreted to be metamorphosed sediments.

The AA (~ 160 km in A-A′; ~142 km in B-B′) is delineated by Blocks A3 and B3, rocks with high-density and high-susceptibility, and Blocks A2 and B2, rocks with low-density and low-susceptibility. The gravity and magnetic properties of Blocks A2 and B2 are similar to those of nonmagnetic metamorphosed sediments or cratonic continental crust (Dobrin and Savit, 1988; Telford et al., 1990; Bajgain, 2011).

Two possible scenarios exist for the origin of the rocks represented by Blocks A2 and B2, A3 and B3, and A4 and B4. The first is that Blocks A2 and B2 were the leading edge of the Laurentian paleocontinent or an approaching microcontinent prior to the Grenville orogeny (Figures 27-29). Blocks A3 and B3 are interpreted to be a belt of metasedimentary rocks, and in this case the sediments were likely deposited in a foreland basin intercontinental sea or large gulf prior to the Grenville orogeny. As an ancient continental block collided with Laurentia during the Grenville orogeny, these sediments underwent a high degree of metamorphism as Block A2 and B2 was subducted beneath them. The AA marks the interface between these metamorphosed sediments and the east-leading edge of Laurentian crust. Blocks A4 and B4 are interpreted as being metasediments of different composition than the surrounding rocks (e.g. a large

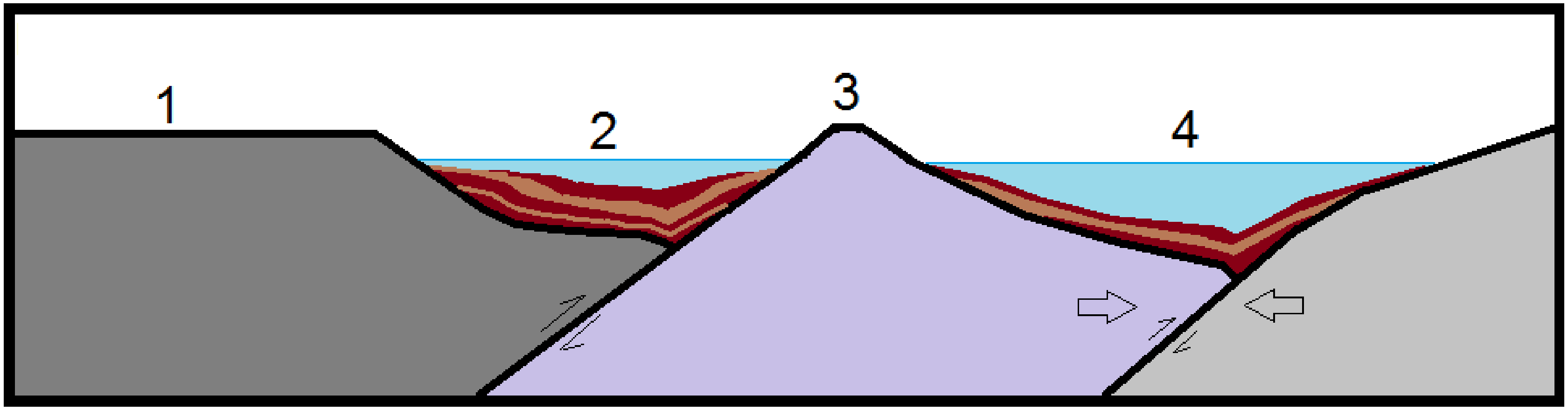


Figure 29. Schematic diagram of tectonic setting just prior to the Grenville orogeny. In the first scenario, an approaching microcontinent or a leading edge of a the Laurentian continent (3) is subducted beneath the main Laurentian continent (1), and a large wedge of sediments (2) is metamorphosed to create the high magnetic, high density rocks (A3 and B3) seen in the models. In the second scenario, an island arc (3) correlates with the high magnetic, high density rocks (A3 and B3), and sediments of a forearc basin (4) and a foreland basin (2) constitute lower magnetic rocks in the basement (A2 and B2, A4, and B4).

metamorphosed carbonate platform surrounded by metamorphosed shale). The NY-AL lineament marks the interface between these high magnetic susceptibility metasediments and metamorphic or igneous rock with a different composition.

The second scenario suggests that Blocks A2 and B2 are the west-leading edge of a microcontinent or island-arc that collided with Laurentia, and that Blocks A3 and B3 are a metamorphosed island-arc terrane or metasediments that comprised a back-arc basin (Figures 27-29). As this proposed microcontinent or island-arc approached, sediments in the back-arc basin would be accreted to the Laurentian craton, followed by the accretion of the island-arc. Blocks A2 and B2 would be composed of either the continental crust of the approaching landmass or metamorphosed sediments from a forearc basin. Blocks A4 and B4 are interpreted similarly as the first case, in that they are likely metasediments of different composition than the surrounding rocks.

Blocks A5 and B6 to A8 and B9 represent rocks underlying the physiographic provinces that were deformed during the Appalachian orogenic episodes. Blocks A5 and B6 are sediments deposited from the Lower Cambrian to Upper Cambrian, and represent the weak, ductile layers that formed the Bessemer and Palmerdale “mushwads” (Thomas, 2007). Most of these rocks are carbonaceous shales (Raymond et al., 1988). Blocks A6 and B7 are stiff, resistant layers, mostly dolostones, limestones, cherty limestones, and sandstones that did not deform in the same fashion as the lower sediments (Raymond et al., 1988). Block A7 and B8 were deposited in the Pennsylvanian and represent the Pottsville Formation, a series of coal seams, shale, and sandstone (Raymond et al., 1988; Pashin, 1999; Gomes, 2012). These rocks were deformed mainly by Alleghanian thrusting. Although they constitute the same formations and were deposited synchronously, rocks in the Valley and Ridge province have slightly higher densities than their counterparts in the Appalachian/Cumberland Plateau. This likely reflects the higher degree of strain in rocks of the Valley and Ridge. Block A8 and B9 is the westernmost edge of the Talladega block, a low-metamorphic grade greenschist-facies terrane accreted during the Acadian orogeny (Thomas and Neathery, 1980; Raymond et al., 1988).

In the models, the Black Warrior basin is deeper (~5-6 km) near the Birmingham anticlinorium (~110 km in profile), and shallows to the west to ~3-4 km. The Birmingham anticlinorium in this profile matches Thomas' (2007) interpretation that ductile deformation of shale and thin-bedded limestones was localized due to the presence of basement faults that constituted the leading edge of the BMW (Figures 27 and 28). The depth to basement beneath the Cahaba basin, the corresponding synclinorium structure to the Birmingham anticlinorium, is greater than that of the Black Warrior basin proximal to the Appalachian thrust belt, lending credence to the interpretation that these basement faults were constitutive structures resulting in the frontal ramp along the regional décollement (Thomas, 2007).

Conclusions

The results of this study suggest two possible origins of rocks in the subsurface of Alabama, although other explanations may be possible. The first is that the AA marks the contact between the leading (western) edge of Laurentia prior to the Grenville orogeny, associated with metamorphosed sediments of an inland sea or gulf. As contraction and deformation ensued during the Grenville orogeny, these sediments were metamorphosed and thrust upon one another, leading to at least four distinctive rock types.

The second, and favored by the author, of these explanations is that the basement blocks represent exotic terranes that were not originally part of Laurentia but a back-arc basin, island arc, and a forearc basin or microcontinent that were accreted to Laurentia during the Grenville orogeny. During the breakup of Rodinia and opening of the Iapetus ocean, these exotic terranes remained orphaned as a part of the Laurentian continent.

Another significant result of the current study is the delineation and geophysical characterization of the AA in Alabama. While this anomaly has been interpreted before as the NY-AL lineament (Raymond et al., 2008), newer research moved the position of the NY-AL lineament further north (Steltenpohl et al., 2010) and determined that this anomaly was an offset portion of the AA. This study supports that there is a continental-scale structure here, and that it likely marks a significant terrane boundary in the crust.

Lastly, the current study is in agreement with previous interpretations for shallow-crustal structures of the Black Warrior basin, Cahaba basin, and Coosa basin (Thomas and Bayona, 2005). It also indicates that basement faults beneath the Birmingham anticlinorium were controlling factors in producing the “mushwads” in the area (Thomas, 2006).

Gravity and magnetic data reveal buried structures that cannot not otherwise be easily recognized or modeled based on surface exposures and rock cores. The structures underlying regional basins in Alabama are significant to unraveling the sequence of events and tectonic history that shaped the geologic landscape of the southeastern United States. Additional models that cross the Grenville front could help explain the NY-AL lineament and test the interpretations put forward in this study.

References

Bajgain, S.K., 2011, Gravity and magnetic modeling of basement beneath Alabama Gulf Coastal Plain, M.S. Graduate Thesis, Auburn University, p. 66-75.

Bankey, V., Cuevas, A., Daniels, D., Finn, C.A., Hernandez, I., Hill, P., Kucks, R., Miles, W., Pilkington, M., Roberts, C., Rystrom, V., Shearer, S., Snyder, S., Sweeney, R., Velez, J., 2002, New digital magnetic anomaly map database of North America – processing, compilation and geologic mapping applications, USGS Mineral News, v.1, n. 2., figure 1.

Burger, H.R., Sheehan, A.F., Jones, C.H., 2006, Introduction to Applied Geophysics, W.W. Norton and Company, Inc., p. 356-369.

Blakely, R.J., 1995, Potential theory in gravity and magnetic applications: New York, Cambridge Univ. Press p. 441.

Carroll, R.E., Pashin, J.C., 2003, Relationship of sorption capacity to coal quality: CO2 sequestration potential of coalbed methane reservoirs in the Black Warrior basin, Proceedings of the International Coal Bed Methane Symposium, paper, v. 317.

Carroll, R.E., Pashin, J.C., Barnett, R.L., Beg, M.A., 1995, Geology and coal resources of the Cahaba coal field, Geological Survey of Alabama, no. 163, p. 59-69.

Carroll, R.E., Pashin, J.C., and Kugler, R.L., 1995, Burial history and source-rock characteristics of Upper Devonian through Pennsylvanian strata, Black Warrior basin, Alabama: Geological Survey of Alabama Circular 187, p. 29.

Cates, L.M., and Groshong, R.H., 1999, Confirmation of regional thin-skinned extension in the eastern Black Warrior Basin, Alabama, 2010 Alabama Geological Society 36th annual field trip guidebook, p. 49-57.

Culotta, R.C., Pratt, T., Oliver, J., 1990, A tale of two sutures: COCORP's deep seismic surveys of the Grenville province in eastern U.S. midcontinent, Geology, v. 18, n. 7, p. 646-649.

Daniels, D.L., 2007, Gridded gravity and magnetic data: Personal communication via Bajgain, S.K., 2011, Gravity and magnetic modeling of basement beneath Alabama Gulf Coastal Plain, M.S. Graduate Thesis, Auburn University.

Dobrin, M.B., and Savit, C.H., 1988, Introduction to geophysical prospecting, McGraw- Hill Book Co., p. 867.

Drake, A., Sinha, A., Laird, J., and Guy, R., 1989, The Taconic orogen: The Geology of North America, The Appalachian-Ouachita Orogen in the United States: Geological Society of America Bulletin, v. F-2, p. 101-178.

EarthScope Automated Receiver Survey online database, Incorporated Research Institutions for Seismology, <http://ears.iris.washington.edu/index.html>.

Geological Survey of Alabama, 2006, Geologic map of Alabama, digital version 1.0, Alabama Geological Survey Special Map 220A, adapted from Szabo, M. W., Osborne, W. E., Copeland, C. W., Jr., and Neathery, T. L., 1988, Geologic map of Alabama (1:250,000): Alabama Geological Survey Special Map 220.

Glover, L., Speer, J., Russell, G., and Farrar, S., 1983, Ages of regional metamorphism and ductile deformation in the central and southern Appalachians: Lithos, v. 16, p. 223-245.

Godson, R.H., 1986, Description of magnetic tape containing Conterminous United States magnetic data in a gridded format, National Technical Information Service Report PB86-197423, p. 5.

Gomes, S., 2012, A sequence stratigraphic synthesis of the Lower Pennsylvanian Pottsville Formation encountered in two drill cores in the Cahaba synclorium, Alabama, M.S. Graduate Thesis, Auburn University, p. 17-57.

Guthrie, G.M., and Raymond, D.E., 1992, Pre-Middle Jurassic rocks beneath the Alabama Gulf coastal plain, Geological Survey of Alabama Bulletin p. 150, 155.

Hall, D.R., and Bolin, D.E., 2009, The Petroleum Industry in Alabama, 1999-2007, Alabama State Oil and Gas Board, Oil and Gas Report 3U, plate 2-3.

Harry, D.L., and Londono, J., 2004, Structure and evolution of the central Gulf of Mexico continental margin and coastal plain, southeast United States: Geological Society of America Bulletin, v. 116, p. 188-199.

Harry, D.L., Londono, J., and Huerta, A., 2003, Early Paleozoic transform-margin structure beneath the Mississippi coastal plain, southeast United States: Geology, v. 31, p. 969-972.

Hatch, J.R. and Pawlewicz, M.J., 2007, Introduction to the assessment of undiscovered oil and gas resources of the Black Warrior Basin Province of Alabama and Mississippi, in Hatch, Joseph R., and Pawlewicz, Mark J., compilers, Geologic assessment of undiscovered oil and gas resources of the Black Warrior Basin Province, Alabama and Mississippi: U.S. Geological Survey Digital Data Series DDS–69–I, chap. 2, p. 6.

Hatcher Jr., R.D., 1978, Tectonics of the western Piedmont and Blue Ridge, Southern Appalachians; review and speculation: American Journal of Science, v. 278, p. 276-304.

—, 1987, Tectonics of the southern and central Appalachian internides: Annual Review of Earth and Planetary Sciences, v. 15, p. 337-362.

—, 1989, Tectonic synthesis of the U.S. Appalachians, in Hatcher, R.D., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita Orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2, p. 511-535.

—, 2005, North America: Southern and Central Appalachians, in Selley, R.C., Cocks, L.R., and Plimer, I.R., eds., Encyclopedia of Geology: Oxford, Elsevier, p. 72-81.

—, 2010, The Appalachian orogen: A brief summary, in Tollo, R. P., Bartholomew, M. J., Hibbard, J. P., and Karabinos, P. M., eds., From Rodinia to Pangaea: the lithotectonic record of the Appalachian Region: Geological Society of America memoirs 206, p. 1-19.

Horton, J.W., Jr., Drake, A.A., and Rankin, D.W., 1989, Tectonostratigraphic terranes and their boundaries in the central and southern Appalachians: Geological Society of America Special Paper 230, p. 213-245.

Irvin, G.D., Osborne, W.E., 2006, Geologic map of the Birmingham North 7.5-minute quadrangle, Jefferson County, Alabama, vector digital data, e. 1, i. QSM-45-2006.

Jacobsen, B.H., 1987, A case for upward continuation as a standard separation filter for potential-field maps: Geophysics, v. 52, p. 1138-1148.

King, E.R., Daniels, D.L., Hanna, W.F., and Snyder, S.L., 1998, Magnetic and gravity anomaly maps of West Virginia: U.S. Geological Survey Miscellaneous Investigations Series Map I-2364-H, 2 sheets, scale 1:1,000,000.

King, E.R., and Zietz, I., 1978, The New York-Alabama lineament: Geophysical evidence for a major crustal break in the basement beneath the Appalachian basin, Geology, v 6 no 5, p 312-318.

Mack, G.H., Thomas, W.A., and Horsey, C.A., 1983, Composition of carboniferous sandstones and tectonic framework of southern Appalachian-Ouachita Orogen, Journal of Sedimentary Petrology, v 53 no 3, p 0931-0946.

McBride, J.H., Nelson, K.D., and Brown, L.D., 1989, Evidence and implications of an extensive Early Mesozoic rift basin and basalt/diabase sequence beneath the southeast Coastal Plain: Geological Society of America Bulletin, v. 101, p. 512-520.

McBride, J.H., and Nelson, K.D., 1988, Integration of COCORP deep reflection and magnetic anomaly analysis in the southeastern United States: Implications for origin of the Brunswick and East Coast magnetic anomalies: Geological Society of America Bulletin, v. 100, p. 436-445.

—, 1991, Deep seismic reflection constraints on Paleozoic crustal structure and definition of the Moho in the buried southern Appalachian orogen, *in* Meissner, R., Brown, L. , Dürbaum, H., -J. , Franke, W., Fuchs, K., and Seifert, F., Eds., Continental Lithosphere: Deep Seismic Reflections American Geophysical Union, Geodynamics Series 22, p. 9–20.

National Geophysical Data Center, 2007, gridded magnetic and gravity data, https://www.ngdc.noaa.gov/ngdcinfo/onlineaccess.html.

Nelson, K.D., Arnow, J.A., McBride, J.H., Willemin, J.H., Huang, J., Zheng, L., Oliver, J.E., Brown, L.D., and Kaufman, S., 1985a, New COCORP profiling in the southeastern United States. Part I: Late Paleozoic suture and Mesozoic rift basin: Geology, v. 13, p. 714-718.

Nelson, K.D., McBride, J.H., Arnow, J.A., Oliver, J.E., Brown, L.D., and Kaufman, S., 1985b, New COCORP profiling in the southeastern United States. Part II: Brunswick and east coast magnetic anomalies, opening of the north-central Atlantic Ocean: Geology, v. 13, p. 718-721.

Osborne, W.E., Brewer, M.C., Ward, W.E., 1998, Geologic map of the McCalla 7.5-minute quadrangle, Jefferson and Tuscaloosa Counties, Alabama, vector digital data, e. 1, i. QSM-43-2006.

Osborne, W.E., Irvin, G.D., 2002, Geologic map of the Montevallo 7.5-minute quadrangle, Chilton and Shelby Counties, Alabama, vector digital data, e. 1, i. QSM-21-2002.

Osborne, W.E., Raymond, D.E., 1992, The Knox Group in the Appalachian Fold-thrust Belt and Black Warrior Basin of Alabama: Stratigraphy and Petroleum Exploration, Geological

Survey of Alabama, Stratigraphy and Paleontology Division.

Osborne, W.E., Ward, W.E., Irvin, G.D., 1998, Geologic map of the Alabaster 7.5-minute quadrangle, Shelby County, Alabama, vector digital data, e. 1, i. QSM-16-1998.

Parker, E.H. 2014, Crustal magnetism, tectonic inheritance, and continental rifting in the southeastern United States, GSA Today v 24 no 4-5, p 4-9.

Pashin, J.C., 1999, Stratigraphy and Structure of the Pottsville Formation in the Cahaba Coalfield, 2010 Alabama Geological Society 36th Annual Field Trip Guidebook, p. 1-15.

—, 2005, Coalbed methane exploration in the thrust belts: Experience from the southern Appalachians, USA, International Coalbed Methane Symposium, Tuscaloosa, AL, p. 18-19.

Pashin, J.C., Kopaska-Merkel, D.C., Arnold, A.C., McIntyre, M.R., & Thomas, W.A., 2012, Gigantic, gaseous mushwads in Cambrian shale: Conasauga Formation, southern Appalachians, USA, International Journal of Coal Geology, 103, p. 70-91.

Phillips, J.D., Duval, J.S., and Ambroziak, R.A., 1993, National geophysical data grids; gamma ray, gravity, magnetic, and topographic data for the conterminous United States: US Geological Survey Digital Data Series DDS-09, 1 CD-ROM.

Pindell, J., and Dewey, J.F., 1982, Permo-Triassic reconstruction of western Pangaea and the evolution of the Gulf of Mexico/Caribbean region: Tectonics, v. 1, p. 179-211.

Powell, C.A., Bollinger, G.A., Chapman, M.C., Sibol, M.S., Johnston, A.C., and Wheeler, R.L., 1994, A seismotectonic model for the 300-kilometer-long Eastern Tennessee Seismic Zone: Science, v. 264, p. 686–688.

Powell, C. A., Withers, M.M., R. T. Cox, G. Vlahovic, and P. Arroucau, 2014, Crustal velocity structure associated with the eastern Tennessee seismic zone: Vp and Vs images based upon local earthquake tomography, J. Geophys. Res. Solid Earth, 119, 464–489, doi:10.1002/2013JB010433.

Raymond, D.E, Ebersole, S.M., Irvin, G.D., 2008, Basement Fault Map of Alabama, Geological Survey of Alabama, Open-File Report 0810, Plate 1.

Raymond, D.E., Osborne, W.E., Copeland, C.W., and Neathery, T.L., 1988, Alabama Stratigraphy, Circular 140, Geological Survey of Alabama, p. 1-13.

Rindsberg, A.K., Ward, W.E., Osborne, W.E., Irvin, G.D., 2003a, Geologic map of the Irondale 7.5-minute quadrangle, Jefferson County, Alabama, vector digital data, e. 1, i. QSM-26-2003.

Rindsberg, A.K., Ward, W.E., Osborne, W.E., Irvin, G.D., 2003b, Geologic map of the Vandiver 7.5-minute quadrangle, Jefferson and Shelby Counties, Alabama, vector digital data, e. 1, i. QSM-24-2003.

Rutter, R.S., 2012, A geophysical characterization of stratigraphy in the eastern Black Warrior Basin underlying Gorgas Power Generation Plant, Walker County, Alabama: M.A. Thesis, Department of Geological Sciences, University of Alabama, p. 1-92.

Salvador, A., 1991, Origin and development of the Gulf of Mexico basin: The Gulf of Mexico Basin: Geological Society of America, Decade of North American Geology, v. J, p. 389-444.

Sapp, C.D., and Emplaincourt, J., 1975, Physiographic regions of Alabama: Geological Survey of Alabama Special Map 168.

Savrda, A.M., 2008, Establishing tighter constraints on the structural configuration of basement rocks beneath the Alabama Gulf Coastal Plain through computer modeling and petrologic studies: B. S. Thesis, Auburn University Honors College, Auburn University, p.32.

Steltenpohl, M.G., 2005, Southernmost Appalachian terranes, Alabama and Georgia: Southeastern Section of the Geological Society of America Field Trip Guidebook, Alabama Geological Society, Tuscaloosa, p. 162.

Steltenpohl, M.G., Horton, J.W., Hatcher, R.D., Zietz, I., Daniels, D.L., and Higgins, M.W., 2013, Upper crustal structure of Alabama from regional magnetic and gravity data: Using geology to interpret geophysics, and vice versa, Geosphere; August 2013, v9 no 4, online publication, GSA.

Steltenpohl, M.G., Zietz, I., Horton, J.W., and Daniels, D.L., 2010, New York–Alabama lineament: A buried right-slip fault bordering the Appalachians and mid-continent North America: Geology, v. 38, p. 571-574.

Szabo, M. W., Osborne, E. W., Copeland, C. W. Jr., Neathery; T. L., 1988, Geologic Map of Alabama, Geological Survey of Alabama Special Map 220, scale 1:250,000.

Telford, W.M., Geldart, L.P., and Sheriff, R.E., 1990, Applied geophysics, 2nd ed., Cambridge University Press, p. 63-74.

Thomas, W.A., and Bayona, G., 2005, Monograph 16, Geological Survey of Alabama, plates 1-2.

Thomas, W.A., 1989, The Appalachian-Ouachita orogen beneath the Gulf Coastal plain between the outcrops in the Appalachian and Ouachita mountains, *in* Hatcher, R. D., Thomas, W. A., and Viele, G. W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado: Geological Society of America, Geology of North America, v. F-2, p. 537-553.

—, 1995, Diachronous Thrust Loading and Fault Partitioning of the Black Warrior Foreland Basin within the Alabama Recess of the Late Paleozoic Appalachian-Ouachita Thrust Belt, Society for Sedimentary Geology, Special Publication, 52, p. 111-126.

—, 2001, Mushwad: Ductile duplex in the Appalachian thrust belt in Alabama, AAPG Bulletin, v. 85, n. 10, p. 1847-1869.

—, 2004, Genetic relationship of rift-stage crustal structure, terrane accretion, and foreland tectonics along the southern Appalachian-Ouachita orogen: Journal of Geodynamics, v. 37, p. 549-563.

—, 2006, Tectonic inheritance at a continental margin: GSA Today, v. 16, p. 4–11.

—, 2007, Role of the Birmingham basement fault in thin-skinned thrusting of the Birmingham anticlinorium, Appalachian thrust belt in Alabama, American Journal of Science, v. 307, p. 46-62.

Thomas, W.A., and Neathery, T.L., 1980, Tectonic framework of the Appalachian orogen in Alabama: Excursions in southeastern geology, v. 2, p. 465-526.

Tull, J.F., 1980, Overview of the sequence of timing of deformational events in the Southern Appalachians; evidence from the crystalline rocks, North Carolina to Alabama, in Wones, D.R., ed.: The Caledonides in the USA Memoir, Virginia Polytechnic Institute, Department of Geological Sciences, v. 2, p. 167-177.

Ward, W.E., Osborne, W.E., 2006, Geologic map of the Greenwood 7.5-minute quadrangle, Jefferson and Shelby Counties, Alabama, vector digital data, e. 1, i. QSM-44-2006.

Wilson, J.T., 1966, Did the Atlantic close and then reopen?, Nature, v. 211, p. 676-681.

Zietz, I., 1982, Composite magnetic anomaly map of the United States; Part A – Conterminous United States: U.S. Geological Survey Geophysical Investigations Map GP-954-A, 2 sheets, scale 1;2,500,000.