Upper crustal structure of Alabama from regional magnetic and gravity data: Using geology to interpret geophysics, and vice versa

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We dedicate this paper to the memory of coauthor Isidore (Izzy) Zietz, who died at age 93 while this paper was in review. After contributing to the early theoretical foundation for analysis of airborne magnetic surveys, Izzy became a leading advocate for aeromagnetic survey acquisition and interpretation throughout the U.S., combining surveys into regional, state, and national maps, and working with regional geologists in interpreting geophysical anomalies. Like many geologists, we have been energized by Izzy’s contagious enthusiasm for using magnetic and gravity anomalies to delineate and characterize major tectonic features. Lessons from working with him on data from Alabama and elsewhere over the years will continue to influence our appreciation and understanding of aeromagnetic and gravity anomalies for interpreting the Earth’s upper crust.

“Magnetics is never good, and gravity is even worse!”
“…all of it can just be dashed.” –Isidore Zietz

ABSTRACT

Aeromagnetic and gravity data sets obtained for Alabama (United States) have been digitally merged and filtered to enhance upper-crustal anomalies. Beneath the Appalachian Basin in northwestern Alabama, broad deep-crustal anomalies of the continental interior include the Grenville front and New York–Alabama lineament (dextral fault). Toward the east and south, high-angle discordance between the northeast-trending Appalachians and the east-west-trending wedge of overlapping Mesozoic and Cenozoic Gulf Coastal Plain sediments reveals how bedrock geophysical signatures progressively change with deeper burial. High-frequency magnetic anomalies in the Appalachian deformed domain (ADD) correspond to amphibolites and mylonites outlining terranes, while broader, lower-amplitude domains include Paleozoic intrusive bodies and Grenville basement gneiss. Fundamental ADD structures (e.g., the Alexander City, Towaliga, and Goat Rock–Bartletts Ferry faults) can be traced southward beneath the Gulf Coastal Plain to the suture with the Gondwanan crust of the Suwannee terrane. Within the ADD, there is clear magnetic distinction between Laurentian crust and the strongly linear, high-frequency magnetic highs of peri-Gondwanan (Carolina-Uchee) arc terranes. The contact (Central Piedmont suture) corresponds to surface exposures of the Bartletts Ferry fault. ADD magnetic and gravity signatures are truncated by the east-west-trending Altamaha magnetic low associated with the Suwannee suture. Arcuate northeast-trending magnetic lines of the Suwannee terrane reflect internal structure and Mesozoic failed-rift trends. Geophysical data can be used to make inferences on surface and subsurface geology and vice versa, which has applicability anywhere that bedrock is exposed or concealed beneath essentially non-magnetic sedimentary cover.

INTRODUCTION

Alabama (United States) contains several major crustal-lithospheric boundaries that played an important role in J. Tuzo Wilson’s (1966) formulation of what later would become known as the Wilson cycle. The Appalachians and all other crustal blocks in the subsurface of Alabama are truncated along the boundary with the Suwannee terrane, a huge mass of Gondwanan crust sutured to the Laurentian margin and left orphaned here as the modern Gulf of Mexico (Early Jurassic) and Atlantic oceans (Early Triassic) began to form (Applin, 1951; Barnett, 1975; Neathery and Thomas, 1975; Pojeta et al., 1976; Chowns and Williams, 1983; Horton et al., 1984, 1989, 1991; Guthrie and Raymond, 1992). The discovery in the late 1950s of Lower Ordovician through Devonian sedimentary rocks containing Gondwanan faunal assemblages from exploration wells penetrating the pre-Jurassic basement (here meaning either or both Gondwanan and crystalline Appalachian basement) beneath Gulf Coastal Plain sedimentary rocks in south Alabama (Applin, 1951) was a critical piece of the puzzle that Wilson needed to help solidify his thoughts on cycles of ocean basins opening and closing and continents colliding.

Thick accumulations of younger sedimentary rock coupled with deep, sub-tropical weathering and saprolitization of crystalline Appalachian rocks in Alabama leave us, however, with a fragmented understanding of parts of this geo-
logical history. Eighty percent of the crystalline rocks in the state are concealed beneath Paleozoic and younger sedimentary cover, with 60% of that cover comprising Mesozoic and younger sediments of the Gulf Coastal Plain. The high-angle discordance between strike of the north-east-trending Appalachians and the generally east-west–trending Coastal Plain onlap is one of the more prominent features on the geological map of North America (Reed et al., 2005), and nowhere is this difference more pronounced than in Alabama (Fig. 1). This southward-thickening wedge of Coastal Plain sediments provides the opportunity to evaluate how remotely sensed geophysical signatures from surface exposures progressively change with deeper burial.

The objectives of this paper are to use digital maps of aeromagnetic and gravity data to better understand the upper-crustal surface and subsurface structure of Alabama with the goal of incorporating its broader significance for the tectonic evolution of southeastern North America. Aeromagnetic and gravity data that have been obtained for parts of Alabama over several decades have been merged and digitally filtered to enhance anomalies. Aeromagnetic anomalies record upper-crustal structure down to the Curie isotherm (25–30 km) for induced magnetization of the buried rocks. Temperatures beneath these depths exceed the blocking temperatures of magnetic minerals such that remanent magnetization is absent. Gravity data reveal upper-crustal and deeper structures. New digital map images combine contours, shaded relief, and color to accentuate regional patterns of highs and lows, gradients, and lineaments simultaneously. Combined aeromagnetic and gravity data, and to a lesser extent limited radioactivity data, provide much more useful information on this crust than does their separate analysis. Interpretation of the crustal-lithospheric structure of Alabama cannot be made without consideration of adjacent regions (Fig. 1), although the geologic interpretation is based largely on geophysical maps of Alabama. In addition, owing to the hydrocarbon wealth of the Gulf Coast, wells have been drilled that sporadically penetrate the pre-Mesozoic basement beneath the Coastal Plain sedimentary rocks (Neathery and Thomas, 1975; Guthrie and Raymond, 1992), helping to define the nature of the crust in the subsurface.

Our analysis paints a much clearer picture of key tectonic elements, such as the Grenville “front,” the New York–Alabama (NY–AL) lineament, the Suwannee terrane, and the Suwannee suture, that are cryptic because they are not exposed due to their burial beneath younger sediments and/or Appalachian thrust sheets. More importantly, these and Appalachian deformed domain (ADD) elements now are imaged to display their interactions with one another, providing new insights into the tectonic evolution of southeastern North America.

**GEOLOGIC SETTING**

Two complete Wilson cycles and the beginning of a third are recorded in the lithosphere of southeastern North America (Hatcher, 1978, 1987, 2004, 2010; Thomas, 2006) (Fig. 1). The final phase of assembly of the supercontinent Rodinia was the closing of ocean basins and collision of eastern Laurentia with pre-Gondwanan continents during the ca. 1 Ga Grenville event (Hoffman, 1991). Breakup of Rodinia involved separation of Laurentia from West Gondwana and opening of the Iapetus ocean at roughly 570–535 Ma (Odom and Fullagar, 1984; Aleinikoff et al., 1995). Subduction in Iapetus, 470–455 Ma, accreted the Taconian volcanic arc system to southeast Laurentia (Hatcher and Odom, 1980). An ocean remained off eastern Laurentia that closed obliquely in the middle to late Paleozoic with zipped collision of a collage of peri-Gondwanan arcs with Laurentia (West, 1998; Wortman et al., 1998; Hatcher et al., 1999; Bream et al., 2000, 2004; Hibbard et al., 2002, 2007; Merschat et al., 2005; Hatcher and Merschat, 2006; Steltenpohl et al., 2006, 2008). At ca. 330 Ma, thermal activity marked the beginning of the Alleghanian orogeny and construction of Pangaean (see Secor et al., 1986, and Hatcher, 1987). Alleghanian collision was oblique north-to-south, producing dextral strike-slip blocks, followed by late Pennsylvanian–Permian collision producing the Blue Ridge–Piedmont megathrust sheet and foreland fold-thrust belt (Clarke, 1952; Bentley and Neathery, 1970; Cook et al., 1979). Finally, Mesozoic breakup of Pangaean led to the opening of the Atlantic Ocean (Thomas, 2006; Huerta and Harry, 2012).

Key elements that help to define these Wilson cycles are found in the surface and subsurface geology of Alabama, which consists of components of the Interior Low Plateaus (otherwise known as the Highland Rim, along the southernmost flank of the Nashville dome) and the Appalachian Plateaus, Valley and Ridge, and Piedmont physiographic provinces (Sapp and Emplaincourt, 1975) (Fig. 2). Each of these geologic provinces is truncated at the surface in western and south-central Alabama by the Creatacesous to Holocene sedimentary rocks of the Gulf Coastal Plain. Surface rocks in north-ermost Alabama consist of Ordovician to Mississippian and Pennsylvanian carbonate and siliciclastic rocks of the Appalachian foreland. The southwestern segment of the Appalachian basin (i.e., the Black Warrior basin; Fig. 2) is also the Ouachita foreland basin, and perhaps is best characterized as a foreland basin that formed adjacent to the syntaxis of both orogenic belts. Regional dip of this part of the continental platform is southwest toward the Ouachitas and subparallel to Appalachian strike. Interrupting the continuity within the foreland are several anticlines (Sequatchie and Birmingham; Fig. 2) cored by Ordovician and younger rocks that constitute the western limits of thin-skinned Alleghanian deformation in Alabama (Rodgers, 1950). The Appalachian foreland fold-thrust belt consists of a series of major folds and large imbricate thrust sheets that have a northeast-southwest trend and become continuous with other structures to the northeast in Georgia. These areas are underlain by platform Cambrian to Ordovician carbonate and siliciclastic rocks unconformably beneath Middle Ordovician and Silurian carbonate and siliciclastic rocks, which are themselves unconformably overlain by Devonian and Mississippian carbonate and siliciclastic rocks, and finally by the Pennsylvanian clastic sedimentary rocks of the Alleghanian clastic wedge (Thomas, 1988, 1991, 1995; Pashin, 1994, 2004).

Southeast of the Appalachian foreland are the remnants of the Blue Ridge geologic province extending southwestward from Pennsylvania to Alabama. The Talladega fault (Fig. 2) separates the Appalachian foreland from the Blue Ridge. Blue Ridge rocks of the Talladega slate belt consist of Cambrian to early Mississippian clastic and carbonate rocks, which are overthrusted from the southeast by the Hollins line fault (Butts, 1926; Tull, 1982; Tull et al., 1988; Gastaldo et al., 1993). The Hillabee and Hollins line faults thrust the Ordovician Hillabee Greenstone (dominantly mafic but containing some felsic volcanic rocks) and overlying distal Laurentian clastic metasedimentary and metavolcanic rocks of the eastern Blue Ridge over all of the tectonic units to the west (Tull, 1978, 1980, 1982, 1984, 1995; Tull et al., 2007; McClellan et al., 2005, 2007). These faults may be a suture equivalent to the Allatoona–Haysville–Soque River fault system farther northeast. The Goodwater–Enitachopco fault (Neathery and Reynolds, 1973; Tull, 1978; McConnell and Costello, 1980; Raymond et al., 1988; Tull and Holm, 2005) has cut the frontal edge of the eastern Blue Ridge thrust sheet, leaving two “marooned” structural salients that are partitioned by the Millerville reentrant and contain correlative sequences of migmatic Ashland Supergroup (i.e., northern salient is Mad Indian above Poe Bridge Mountain Groups, and southern salient is Hatchet Creek above Higgins Ferry Groups; Fig. 2). Directly southeast of the Goodwater–Enitachopco fault, Paleozoic granitic plutons, such as
Figure 1. (A) Tectonic map illustrating Alabama’s position within the southern Appalachians with section line A–A’ (modified from Hatcher, 2004; Horton et al., 1984, 1989; Hibbard et al., 2002, 2006; Steltenpohl, 2005); Alabama is partially outlined in red. (B) Simplified cross section A–A’ (modified from W.A. Thomas and coworkers as depicted in Thomas [1989], Thomas et al. [1989], Hatcher et al. [1990], and Steltenpohl [2005]). Abbreviations: CR—Cartersville reentrant; CST—Cat Square terrane; DRW—Dog River window; EBR—eastern Blue Ridge; GMW—Grandfather Mountain Window; PMW—Pine Mountain window; SMW—Sauratown Mountains Window; SRA—Smith River allochthon; TS—Tallassee synform; WBR—western Blue Ridge. Cross Section: A—Away; T—toward; no vertical exaggeration.
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Figure 2. Geologic map of surface exposures in Alabama (simplified from Szabo et al., 1988) illustrating rock units, rock packages, and faults discussed in the text. Inset map of physiographic provinces is from Sapp and Emplaincourt (1975) and Raymond et al. (1988). A digital geological map of Alabama can be found at http://www.ogb.state.al.us/gsa/gis_data.aspx (Geological Survey of Alabama and State Oil and Gas Board, 2012).
the major Elkahatchee Quartz Diorite batholith and smaller bodies of Rockford, Bluff Springs, and Almond granites, occur in the eastern Blue Ridge (Russell, 1978; Drummond et al., 1997; Tull et al., 2009; Schwartz et al., 2011). Timing of pluton emplacement in the Alabama eastern Blue Ridge is only beginning to be understood (Russell, 1978; Stowell et al., 1996; Steltenpohl et al., 2005b; Tull et al., 2009; Schwartz et al., 2011). The Elkahatchee Quartz Diorite, a pre-metamorphic batholith (Fig. 2; Tull, 1978; Allison, 1992; Drummond et al., 1994, 1997), was previously reported to be ca. 490 Ma based on U-Pb isotopic dating of multi-grain aliquots of zircons (Russell, 1978). Recent reconnaissance SHRIMP-RG U-Pb dating of zircons from two samples assigned to the Elkahatchee, however, suggest igneous crystallization ages between ca. 388 and 370 Ma (Tull et al., 2009; P.M. Mueller, 2010, personal commun.). Other eastern Blue Ridge intrusions northwest of the Brevard zone in Alabama are lumped broadly into the Rockford, Bluff Springs, and Almond suites of granite (Deininger et al., 1973; Deininger, 1975; Russell, 1978; Defant, 1980; Defant and Ragland, 1981; Defant et al., 1987; Drummond, 1986; Osborne et al., 1988; Drummond et al., 1997), from which Schwartz et al. (2011) recently reported U-Pb zircon dates of ca. 365 Ma, ca. 377 Ma, and ca. 350–330 Ma, respectively.

The Alexander City fault separates the Wedowee Group from the Emuckfaw Group (Muangnoichoaroen, 1975; Neathery and Reynolds, 1975). The Emuckfaw Group comprises mostly metagraywacke and schist that is intruded by Paleozoic granitoid plutons assigned to the Kowaliga batholith or the suite of sill-like Zana granites (Fig. 2; Russell, 1978; Stoddard, 1983; Bieler and Deininger, 1987; Grimes et al., 1997; Drummond et al., 1997; Steltenpohl, 2005). Russell (1978) reported whole-rock Rh-Sr “errorchron” ages for the Kowaliga and Zana granites within the Silurian and Devonian Periods, respectively, whereas U-Pb analysis of zircons (multi-grain aliquots) gave Middle Ordovician ages. Most workers interpret the eastern Blue Ridge of Alabama to be part of the Neoproterozoic slope-rise facies of the distal Laurentian margin (Drummond et al., 1994, 1997; Steltenpohl, 2005; McClellan et al., 2007; Tull et al., 2007).

Separating the eastern Blue Ridge from the Inner Piedmont is the Brevard fault zone (Jonas, 1932; King, 1955; Hatcher, 1978, 2001; Higgins et al., 1988). The Brevard fault zone changes character at Jacksons Gap, Alabama (Fig. 2), from a fault zone dominated by medium-grade phyllonite and mylonite derived from fine-grained siliciclastic rocks and orthogneisses, to mylonitic rocks derived from coarse siliciclastic, quartz arenites, and conglomerate (Jacksons Gap Group) (Bentley and Neathery, 1970; Steltenpohl et al., 2005a). The Inner Piedmont of Alabama has been subdivided into the Dadeville and Opelika Complexes (Bentley and Neathery, 1970; Neathery and Tull, 1975; Osborne et al., 1988). The Dadeville Complex is predominantly a meta-igneous and metavolcanic complex whereas the underlying Opelika Complex mainly comprises metasedimentary rocks intruded by Ordovician plutons (i.e., Bottle Granite–Furnville Metagranite; Bentley and Neathery, 1970; Neathery and Tull, 1975; Raymond et al., 1988; Osborne et al., 1988; Steltenpohl et al., 1990, 2005a; Grimes et al., 1997). The contact between these two complexes is the synmetamorphic Stonewall line fault (Bentley and Neathery, 1970; Grimes, 1993; Steltenpohl et al., 1990).

The Pine Mountain window occurs in some of the more southern exposures of the Piedmont in Alabama, and is an east-plunging antiform exposing Grenvillian basement and platformal metasedimentary cover rocks (Galpin, 1915; Adams, 1933; Crickmay, 1933, 1952; Clarke, 1952; Bentley and Neathery, 1970; Sears et al., 1981; McBride et al., 2005; Steltenpohl et al., 2010a). It is framed by the Tonaliga fault that separates the window from the Inner Piedmont to the northwest, the Box Ankle fault that closes the east end of the window and is truncated by the Tonaliga fault, and the Dean Creek and Bartletts Ferry–Goat Rock faults that separate the Pine Mountain window from the Uchee terrane (peri-Gondwanan: Steltenpohl et al., 2008) to the southeast (Bentley and Neathery, 1970; Sears et al., 1981; Hooper et al., 1997). The Pine Mountain basement-cover units are considered to be an outboard remnant of the ancient, subducted Laurentian margin (Clarke, 1952; Odom et al., 1973; Schamel et al., 1980; Sears et al., 1981; Higgins et al., 1988; Hooper and Hatcher, 1988; Mueller et al., 2005; Steltenpohl et al., 2005b, 2010a).

The Uchee terrane is the most outboard Appalachian terrane exposed in Alabama and comprises dioritic gneiss, amphibolite, and various metasedimentary and metavolcanic rocks (Bentley and Neathery, 1970; Hanley, 1983, 1987; Steltenpohl, 2005). Because the Uchee is sandwiched between Laurentian continental basement of the Pine Mountain terrane beneath and Gondwanan crust of the Suwannee terrane above, it occupies a critical tectonic position. U-Pb isotopic dating has demonstrated that the Uchee contains 640–620 Ma zircons, indicating an exotic peri-Gondwanan (Hibbard et al., 2002, 2007) or Gondwanaland origin (Steltenpohl et al., 2006, 2008; Mueller et al., 2010), and the Bartletts Ferry–Goat Rock fault zone here is the Central Piedmont suture (Hatcher and Zietz, 1980; Steltenpohl et al., 2008, 2010a).

The Gulf Coastal Plain occupies ~60% of the exposed surface geology in Alabama. Coastal Plain sediments consist of Cretaceous, Tertiary, and Holocene sediments overlain by Quaternary stream deposits (as shown or described in Osborne et al., 1988; Raymond et al., 1988; Mancini et al., 1989). Coastal Plain sediments include semi-consolidated sand, marl, limestone, and clay units traceable across Alabama. Trends of Coastal Plain units are east-west along the Alabama-Georgia border, but become more northwest in the Mississippi embayment segment in western Alabama (Szabo et al., 1988).

The subsurface geology beneath the south Alabama Gulf Coastal Plain contains well-consolidated Triassic, Jurassic, and Cretaceous rock units that consist of sandstone, shale, evaporite, and carbonate of the rift-to-drift sequence that accompanied the opening of the Gulf of Mexico. These include the Eagle Mills continental rift-facies clastics (Triassic) and the eastern extent of the Louann Salt, the Buckner Anhydrite, and the Smackover Limestone (Jurassic) overlain by Lower Cretaceous and younger sequences (Mancini et al., 1989; Salvador, 1991).

Drill cores penetrating the pre-Mesozoic basement reveal the distinctly Gondwanan rocks of the Suwannee terrane (Applin, 1951; King, 1961). In Alabama, the Suwannee terrane contains felsic volcanic rocks intruded by granodiorite that are overlain by Lower Ordovician through Devonian sedimentary rocks containing Gondwanan faunal assemblages (Applin, 1951; Barnett, 1975; Neathery and Thomas, 1975; Pojeta et al., 1976; Chown and Williams, 1983; Guthrie and Raymond, 1992; Mueller et al., 1994, 1996).

**DATA SOURCES AND PROCESSING METHODOLOGY**

The Geologic Map of Alabama (Szabo et al., 1988) is a product of many decades of geologic mapping (Fig. 2 is a small-scale derivative). The aeromagnetic anomaly map of Alabama (Fig. 3) is a composite of aeromagnetic surveys (see the Supplemental File) flown at different altitudes, flight-line separations, and flight-line directions between 1972 and 1981, and compiled digitally. An aeromagnetic map of the exposed crystalline Appalachians in central-eastern Alabama was made to aid geologists attempting to map in the highly saprolitized units (Neathery et al., 1976, 1987).
Figure 3. Major crustal features annotated on a composite magnetic anomaly map of Alabama. Thicker black lines, and dashed ones, are our geologic interpretations of regional aeromagnetic and gravity anomaly gradients (see text). Red lines are surface faults from the Alabama state geologic map (Szabo et al., 1988) and are dashed where we interpret their projection beneath the Coastal Plain sedimentary rocks. Numbers and lines are described in the text; data sources are in the Supplemental File (see footnote 1). White line is the Gulf Coastal Plain onlap.
DELINEATION AND GEOLOGIC INTERPRETATION OF MAGNETIC AND GRAVITY ANOMALIES

Figures 3 and 4 show the aeromagnetic and gravity maps of Alabama, respectively, with our geologic interpretations of regional anomaly gradients. Our interpretations were developed first using the original individual magnetic surveys because some features were smoothed when digitized at 1:500,000 scale; these data sources are provided in the Supplemental File (see footnote 1). For this reason, some boundaries may not appear to lie precisely upon the steepest gradients in Figure 3. Figure 5 illustrates how features exposed at the surface relate to our interpretations of the aeromagnetic features. Where geophysics provides the primary evidence for a buried feature, the interpreted line (black) depicted in Figure 3 is generally sketched along the steepest gradient taken from the data source maps in the Supplemental File (see footnote 1); black lines are dashed where the gradients are relatively shallow and also where they separate geophysical domains. The position of a magnetic gradient can be affected by factors such as varying depths to the contact of a source body, dip of the contact, magnetic-mineral distributions, and data quality. The evaluation of such factors and modeling of subsurface features, however, are beyond the scope of this regional study. Interpretations of aeromagnetic anomaly gradients that are associated spatially with shallow geologic features are constrained by knowledge of the local surface geology. In a given geologic formation, group, sequence, belt, or terrane, only a small fraction of the lithologic components may be sufficiently magnetic to produce anomalies on the aeromagnetic maps, and these anomalies represent an average of a volume of rock. Thus, while interpreted boundaries may differ from observed geologic contacts, the trends are commonly similar. The following numbers are keyed to numbers identifying geophysical anomalies and patterns attributed to crustal features in Figures 3, 4, and 5. The list below constitutes an attempt to describe each feature, indicating what characteristics separate it from adjacent crustal features. Table 1 provides an abbreviated guide to aid in relating these features to Figures 3, 4, and 5 and an interpretation of each feature.

1. Domains characterized by correlative magnetic highs and gravity highs, interpreted to be buried basement mafic-rock bodies.

2. Crustal block having north-northeast magnetic grain, constituting country rock to mafic bodies of domain 1.

3. Southern extension of the NY-AL lineament based on the originally defined features using composite aeromagnetic anomaly maps of the eastern U.S. (King and Zietz, 1978; Steltenpohl et al., 2010b). It is a magnetic gradient bounding crustal blocks 2 and 4, and thus separates two different types of crust with the southeastern block characterized by relatively smoother and higher magnetic and lower gravity signatures.

4. Large crustal block characterized by indistinct magnetic and gravity character and northeast-trending structural grain, bordered to the northwest by feature 3 and southeast by features 5, 6, and 8. It is generally characterized by northeast-trending magnetic highs with 1200–1520 nT relief and gravity lows ranging from 0 to ~50 mGal. This block may also include the area of circular feature 6, described below.

4A. Northeastern part of domain 4, having relatively high, 880–1600 nT relief. The Sequatchie anticline and other Appalachian foreland structures and rocks overlie the area of feature 4.

4B. Southwestern part of domain 4, distinguished by magnetic lows (as much as 300 nT).

4C. Distinct N15°E-trending magnetic low within domain 4.

5. Magnetic gradient bounding crustal domains 4 (relatively high) and 9 (relatively low). Near the triple point between the Talladega–St. Clair–Calhoun County lines (Figs. 2 and 4), this lineament loses definition as indicated by the dashed line. Magnetic gradient 5 loosely follows the southeast boundary of Carboniferous-cored synclines and the Coosa deformed belt (Fig. 2; Thomas and Drahozal, 1974; Thomas, 2007), suggesting a relationship with upper-level detachments in the thrust belt.

6. Broad circular feature defined by a magnetic high anomaly and coincident with a gravity low. Magnetic gradients are relatively flat in the center (1400–1520 nT) and steeper on the margins (1400–1000 nT, ~25 mGal). This feature corresponds to part of a regional Appalachian gravity low, and it is one of the most prominent features on the map. It appears to truncate short-wavelength anomalies and thus is attributed to a shallow-crustal feature, possibly a large bulbo us pluton of unknown age. The northwestern margin of this feature is not clearly defined and is dashed.

7. Magnetic gradient bounding crustal domains 6 (relatively high) and 9 (relatively low).

8. Localized short-wavelength magnetic high interpreted as a possible mafic enclave within the pluton of domain 6, or perhaps a segment of the same thrust sheet containing mafic rock of nearby domain 17, described below.

9. Crustal domain characterized by relative magnetic (up to 1700 nT) and gravity highs.
Figure 4. Major crustal features from Figure 3 superposed on a Bouguer gravity anomaly map of Alabama.
Figure 5. Annotated features from Figure 3 layered on the simplified geologic map of Alabama presented in Figure 2. Figure also serves to illustrate county locations relative to the aeromagnetic interpretations to aid in our discussion.
TABLE 1. GEOPHYSICAL FEATURES AND PATTERNS ATTRIBUTED TO UPPER CRUSTAL SOURCES AS NUMBERED IN FIGURES 3, 4, AND 5

<table>
<thead>
<tr>
<th>Feature (type)*</th>
<th>Geophysical feature and distinguishing characteristics based on combined magnetic and gravity anomalies</th>
<th>Upper-crustal source interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (A)</td>
<td>Domains characterized by correlative magnetic highs and gravity highs.</td>
<td>Buried basement mafic-rock bodies.</td>
</tr>
<tr>
<td>2 (A)</td>
<td>Domain distinguished by north-northwest magnetic gradient.</td>
<td>Country rock to mafic bodies of domain 1.</td>
</tr>
<tr>
<td>3 (L)</td>
<td>Magnetic gradient bounding domains 2 (northwest) and 4 (southeast). Domain 4 has relatively smoother and higher magnetic signatures and lower gravity signatures; it thus separates two different types of crust.</td>
<td>Southern extension of the New York–Alabama lineament, based on that originally defined using composite magnetic anomaly maps of the eastern U.S. (King and Zietz, 1978; Stetenhof et al., 2010b).</td>
</tr>
<tr>
<td>4 (A)</td>
<td>Area of indistinct magnetic and gravity character and NE-trending grain, bordered on the northwest by feature 3 and on the southeast by features 5, 6, and 8. Generally characterized by NE-trending magnetic highs with 1200–1520 nT relief and gravity lows ranging from 0 to -50 mGal. May also include the area of circular feature 6, described below. 4A. Northeastern part of domain 4 having relatively high, 880–1600 nT relief. 4B. Southwestern part of domain 4, distinguished by magnetic lows (as much as 300 nT). 4C. Distinct N15°E-trending magnetic low within domain 4.</td>
<td>Large crustal block characterized by indistinct magnetic and gravity character and NE-trending structural grain. The Sequatchie anticline and other Appalachian foreland structures and rocks overlie the area of feature 4.</td>
</tr>
<tr>
<td>5 (L)</td>
<td>Magnetic gradient bounding crustal domains 4 (relatively high) and 9 (relatively low). Near the triple point between the Talladega–St. Clair–Calhoun County lines (Figs. 2 and 4), this lineament loses definition as indicated by the dashed line.</td>
<td>Possibly a large bulbous pluton of unknown age.</td>
</tr>
<tr>
<td>6 (A)</td>
<td>Broad circular feature defined by a magnetic-high anomaly and coincident gravity low. Magnetic gradients are relatively flat in the center (1400–1520 nT) and steeper on the margins (1400–1000 nT; ~25 mGal). This feature corresponds to part of regional Appalachian gravity low, and it is one of the most prominent features on the map. It appears to truncate short-wavelength anomalies and thus is attributed to a shallow-crustal feature. The northwestern margin of this feature is not clearly defined and is dashed.</td>
<td>Possibly a large bulbous pluton of unknown age.</td>
</tr>
<tr>
<td>7 (L)</td>
<td>Magnetic gradient bounding crustal domains 6 (relatively high) and 9 (relatively low).</td>
<td>Possible mafic enclave within the pluton of domain 6, or perhaps a segment of the same thrust sheet containing mafic rock of nearby domain 17, described below.</td>
</tr>
<tr>
<td>8 (A)</td>
<td>Localized short-wavelength magnetic high.</td>
<td>Possible mafic enclave within the pluton of domain 6, or perhaps a segment of the same thrust sheet containing mafic rock of nearby domain 17, described below.</td>
</tr>
<tr>
<td>9 (A)</td>
<td>Crustal domain characterized by relative magnetic (up to 1700 nT) and gravity highs.</td>
<td>Interpreted to be mafic plutons.</td>
</tr>
<tr>
<td>9A (A)</td>
<td>9A. Circular magnetic and gravity highs (up to 1600 nT relief) mostly within crustal block 9.</td>
<td>Interpreted to be mafic plutons.</td>
</tr>
<tr>
<td>9B (L)</td>
<td>Northwest-trending lineament that appears to offset domains 9 and 17.</td>
<td>Left-slip shear zone that offsets domains 9 and 17.</td>
</tr>
<tr>
<td>10 (A)</td>
<td>Domains with small, short-wavelength, relatively high magnetic anomalies (up to 900 nT relief) within domain 9 that, although muted in Figure 3, were clearly defined on the more detailed 1:500,000-scale aeromagnetic map of Alabama (Wilson and Zietz, 2002).</td>
<td>Corresponds to ferruginous sandstones of the Kahatchee Mountain Group (Talladega slate belt) and Weiser Formation (Appalachian foreland), both of which correlate with the Chilhowee Group in Tennessee, Georgia, and North Carolina. The Kahatchee Mountain Group produces a stronger anomaly than the Weiser Formation likely because the former is the low-grade (chlorite zone) metamorphosed equivalent of the latter and magnetite is a product of chlore-grade metamorphism. The Talladega thrust marks the boundary between the Appalachian foreland and Talladega slate belt in Alabama but does not have much expression in the aeromagnetic data.</td>
</tr>
<tr>
<td>11 (L)</td>
<td>Regional gravity gradient (dashed line to emphasize the lack of an associated magnetic signature), generally low to the north and high to the south with an easterly trend distinct from the normal Appalachian gravity gradient trend.</td>
<td>Interpreted as the northern boundary of the Suwannee-Wiggins suture zone (Neathery and Thomas, 1975; Neathery et al., 1977a; Horton et al., 1984).</td>
</tr>
<tr>
<td>12 (L)</td>
<td>E-W–trending linear truncation of all NE-trending magnetic and gravity anomalies to the north that correspond to Appalachian and older structures.</td>
<td>The suture zone is overprinted by Mesozoic extensional faults, and the Altamaha magnetic-low anomaly may or may not correspond to a deep part of the early Mesozoic South Georgia Basin. Early Mesozoic sediments of the South Georgia Basin are crudely delineated by drilling and produce a muted, flat magnetic signature. Mesozoic basalt and diabase coincide with local magnetic highs that interrupt the magnetic-low anomaly.</td>
</tr>
<tr>
<td>13 (A)</td>
<td>Prominent magnetic-low (13B) domain and gradient (13A) on its north side as distinguished on a more detailed, 1,250,000-scale magnetic map (Neathery et al., 1977a). 13A. Magnetic gradient on the north side of the Altamaha magnetic-low anomaly (Higgins and Zietz, 1983). 13B. Altamaha magnetic-low anomaly (Higgins and Zietz, 1983).</td>
<td>The suture zone is overprinted by Mesozoic extensional faults, and the Altamaha magnetic-low anomaly may or may not correspond to a deep part of the early Mesozoic South Georgia Basin. Early Mesozoic sediments of the South Georgia Basin are crudely delineated by drilling and produce a muted, flat magnetic signature. Mesozoic basalt and diabase coincide with local magnetic highs that interrupt the magnetic-low anomaly.</td>
</tr>
<tr>
<td>14 (L)</td>
<td>Southern boundary of the Altamaha magnetic low.</td>
<td>Possible southern boundary of a rift basin (early Mesozoic?) formed across the earlier suture zone.</td>
</tr>
<tr>
<td>15 (A)</td>
<td>Large domain including parallel arcuate, ~N45°E trends on the magnetic anomaly map of southern Alabama. Contains circular magnetic-high anomalies coincident with circular gravity highs.</td>
<td>Suwannee terrane (undivided). Circular magnetic-high anomalies coincident with circular gravity highs are here interpreted as mafic plutons within the Suwannee terrane.</td>
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(continued)
### TABLE 1. GEOPHYSICAL FEATURES AND PATTERNS ATTRIBUTED TO UPPER CRUSTAL SOURCES AS NUMBERED IN FIGURES 3, 4, AND 5 (continued)

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<tr>
<td>16 (L)</td>
<td>Northwestern limit of short-wavelength magnetic highs (up to 1300 nT).</td>
<td>Hollins line fault and the northwestern limit of eastern Blue Ridge amphibolites that coincide with short-wavelength magnetic highs (up to 1300 nT). The Hillabee Greenstone, mostly a massive greenstone, appears to be non-magnetic. The Hollins line fault is aeromagnetically distinct where it truncates amphibolites of the eastern Blue Ridge but has little expression elsewhere.</td>
</tr>
<tr>
<td>16A (L)</td>
<td>Right-slip offset of feature 16 and magnetic linear anomalies in domain 17.</td>
<td>Transcurrent right-slip shear zone that offsets both the Hollins line fault and magnetic linear anomalies of domain 17; here it is interpreted as a transcurrent shear zone because it appears to cut the overlying thrust sheet.</td>
</tr>
<tr>
<td>17 (A)</td>
<td>Domain of short-wavelength, high-magnetic (up to 1600 nT) signatures. 17A, 17B. Sub-areas lacking high-frequency magnetic-high anomalies. 17C Sub-area generally having higher-frequency magnetic anomalies. 17D. Sub-area characterized by weakly elliptical, N-NE–trending, low- to moderate-wavelength magnetic highs (-200 to -260 nT). The magnetic signature of this domain is different from the much-broader-wavelength character of domain 21 to the east and the less-elliptical and lower-magnitude magnetic contours of domain 17B to the west.</td>
<td>Zone of amphibolite-rich Hatchet Creek (Mitchell Dam Amphibolite) and Poe Bridge Mountain (Ketchapedrakee Amphibolite) Group metasedimentary and metavolcanic rocks (eastern Blue Ridge). 17A. Corresponds to amphibolite-poor Wedowee and Higgins Ferry Group metasedimentary and metavolcanic rocks. 17B. Corresponds to amphibolite-poor Mad Indian Group metasedimentary and metavolcanic rocks. 17C. Wedowee Group metasedimentary and metavolcanic rocks (mostly undifferentiated phyllite, schist, and gneiss), containing intermittent amphibolite (Beaver Dam Amphibolite) generally having higher-frequency anomalies, injected by Devonian to Carboniferous granitoid bodies (Almond Trondhjemite and Bluff Springs Granite) with lower-frequency anomalies. 17D. Crustal domain (not exposed) interpreted as possible non-magnetic Wedowee Group metasedimentary rocks.</td>
</tr>
<tr>
<td>18 (L)</td>
<td>Boundary between domains 17 and 17A and between domains 17 and 17B distinguished by contrasting magnetic signatures.</td>
<td>Goodwater-Entitachopco fault, where previously mapped (Osborne et al., 1988), has essentially no magnetic expression and juxtaposes metasedimentary rocks that cannot be distinguished by magnetic signatures. 19A. Questionable segment of the Goodwater-Entitachopco fault as previously mapped (Osborne et al., 1988) crosses apparent structural grain suggested by numerous small short-wavelength anomalies on both the magnetic map and radioactivity map. 19B. Relatively sharp, linear magnetic anomaly that may be a shear zone or fault, perhaps an alternate extension of the Goodwater-Entitachopco fault (needs to be field checked).</td>
</tr>
<tr>
<td>20 (A)</td>
<td>Long-wavelength (low frequency) magnetic pattern resembles that of the nearby Elkahatchee pluton (domain 21) directly to the east.</td>
<td>Wedowee Group metamorphic rocks and Rockford Granite; the latter is suggested to be a Devonian to early Mississippian intrusion.</td>
</tr>
<tr>
<td>21 (A)</td>
<td>Long-wavelength (low frequency) magnetic pattern; one of the most distinctive large domains on the magnetic-anomaly map.</td>
<td>Elkahatchee pluton: Paleozoic quartz diorite batholith. Extension of the Elkahatchee pluton beneath the Coastal Plain is clearly delineated by its characteristic magnetic pattern, which shows it to be one of the largest and most extensive bodies of plutonic rock in the southeastern United States.</td>
</tr>
<tr>
<td>22 (L)</td>
<td>Linear zone of NE-trending, short-wavelength, magnetic anomalies along distinctive SE border of domain 21.</td>
<td>Alexander City fault zone. Magnetic character varies along strike and includes SE margin of Elkahatchee pluton, and local NE-trending lineament strands. The characteristic magnetic signature of the Elkahatchee pluton combines with the linear set of distinct, short-wavelength strands associated with the Alexander City fault zone to make the latter the most distinct and continuous anomaly on the map, appearing to continue southwestward to the suture zone where it is truncated.</td>
</tr>
<tr>
<td>23 (A)</td>
<td>Relatively featureless magnetic domain of broad, flat, long-wavelength anomalies (similar to domain 21). Sub-domain 23A has an indistinct magnetic pattern except in areas marginal to major faults (e.g., Brevard and Towaliga faults), where linear, moderate-frequency anomalies occur. Sub-domain 23B has a magnetic signature similar to that of sub-domain 23A, although with generally even lower magnitudes and lacking the moderate-frequency anomalies.</td>
<td>Magnetically featureless terrane between major faults, comprising domains 23A and 23B. 23A. Corresponds mostly to Emuckaw Formation (eastern Blue Ridge) and Auburn Gneiss and Loachapoka Schist (Opelika Complex, Inner Piedmont) metasedimentary rocks. A relatively thin package of metasedimentary rocks, the Jacksons Gap Group, crops out along the structurally upper parts (i.e., east) of this domain. 23B. Corresponds to Paleozoic granitic plutons of the eastern Blue Ridge (Kowaliga Gneiss and Zara Granite) and Opelika Complex of the Inner Piedmont (Bottle Granite and Farmville Metagranite).</td>
</tr>
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### TABLE 1. GEOPHYSICAL FEATURES AND PATTERNS ATTRIBUTED TO UPPER CRUSTAL SOURCES AS NUMBERED IN FIGURES 3, 4, AND 5 (continued)

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<td>24 (L)</td>
<td>Linear zone of high-frequency, N55°E-trending, linear magnetic anomalies, which changes character just northeast of Jacksons Gap (see Fig. 2 for location) and to the south is marked by truncation of ENE-trending magnetic anomalies.</td>
<td>The Brevard fault zone; this N55°E-trending mylonite zone changes character south of Jacksons Gap (see Fig. 2 for location) corresponding to an apparent lack of the late brittle Alleghanian overprint. From there southwestward, the older ductile Brevard fault zone swings around the Inner Piedmont due to late folding related to the formation of the Tallassee synform (Fig. 2).</td>
</tr>
<tr>
<td>24A, 24B (A)</td>
<td>24A and 24B: Arcuate-shaped “islands” of higher-frequency anomalies.</td>
<td>24A and 24B. May be faults involving imbrication of the Emuckfaw Formation.</td>
</tr>
<tr>
<td>25 (A)</td>
<td>Domain containing both high-frequency, curved and linear magnetic highs and broad low-frequency anomalies.</td>
<td>Inner Piedmont (Dadeville Complex). High-frequency, curved and linear magnetic highs represent amphibolites of Dadeville Complex (Ropes Creek Amphibolite) as well as local ultramafic bodies. Broad low-frequency anomalies are felsic metaplutonic and metavolcanic units (Camp Hill Gneiss, Rock Mills Granite Gneiss, Chattasofka Creek Gneiss, and Waverly Gneiss). Overall pattern is consistent with the Dadeville Complex as a gently northeast-plunging, recumbent sheath fold, similar to those mapped in the Inner Piedmont of the Carolinas (Merschat et al., 2005; Hatcher and Merschat, 2006).</td>
</tr>
<tr>
<td>25A and 25B (L)</td>
<td>25A. No correlation with magnetic anomaly map. 25B. Magnetic lineament.</td>
<td>25A. Stonewall line fault zone, which separates mainly meta-igneous rocks of the Dadeville Complex from mainly metasedimentary units of the Opelika Complex (Inner Piedmont). Although there is no correlation of the Stonewall line with the magnetic anomaly map, the fault trace is distinct from linear trends on the radioactivity map (not shown; Neathery et al., 1977b). 25B. Magnetic lineament internal to Opelika Complex that may separate Farmville Metagranite plutonic bodies from Auburn Gneiss metasedimentary rocks.</td>
</tr>
<tr>
<td>26 (A)</td>
<td>Domain of high-frequency magnetic anomalies (similar to domain 25) with a substantial area of broader, low-frequency positive magnetic anomalies.</td>
<td>Emuckfaw Formation metasedimentary rocks and Zana Granite. The magnetic character is similar to that of domain 25 (Inner Piedmont, Dadeville Complex). Area of broader, low-frequency positive magnetic anomalies may represent metasedimentary rocks or metaplutons as in domain 25; high-frequency parts resemble amphibolite-rich areas of Dadeville Complex in domain 25. Although the Emuckfaw Formation is known to locally contain minor, thin amphibolite layers (Bentley and Neathery, 1970; Raymond et al., 1988), the aeromagnetic signature of domain 26 suggests that this area may contain more-substantial mafic and perhaps even ultramafic material that is not depicted on the state geologic map (Osborne et al., 1988). The northernmost parts of domain 26 are exposed north of the Coastal Plain onlap, and field checking in that area is needed to examine the source of this distinctive magnetic character.</td>
</tr>
<tr>
<td>27 (L)</td>
<td>E-NE–trending linear anomalies.</td>
<td>Interpreted to mark an unnamed splay of the Towaliga fault.</td>
</tr>
<tr>
<td>28 (A)</td>
<td>Magnetic signature is similar to domain 26.</td>
<td>Block (beneath coastal plain) between two splays of the Towaliga fault (i.e., features 27 and 29).</td>
</tr>
<tr>
<td>30 (A)</td>
<td>Domain having similar magnetic and gravity signature as domain 32A.</td>
<td>Crustal block between the main strand of the Towaliga fault (feature 31) and splay 29 that has a similar magnetic and gravity signature as domain 32A.</td>
</tr>
<tr>
<td>31 (L)</td>
<td>Main Towaliga fault, which is younger than and has excised plastic mylonites and ultramylonites of the Towaliga fault zone. The main Towaliga fault marks the boundary between the Opelika Complex (Inner Piedmont) and the Pine Mountain basement-cover massif.</td>
<td></td>
</tr>
<tr>
<td>31A (L)</td>
<td>Another splay of the Towaliga fault.</td>
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| 32 (A)          | 32A. Area of moderate-frequency, elliptical magnetic highs.  
|                 | 32B. Area of low-frequency, broad, flat, only weakly elongate magnetic lows.  
|                 | 32C. Magnetically high area of high-frequency anomalies.  
|                 | 32D. Area of broad, flat magnetic anomalies. |
| 33 (L)          | Linear zone characterized by contrasting broad flat magnetic lows to the northwest and the strong, high-frequency magnetic highs to the southeast (domain 35 below). |
| 34 (L)          | Sharp, linear magnetic gradients. |
| 34A (L)         | Strands of mylonite and ultramylonite within the Bartletts Ferry–Goat Rock fault zones that interlace the Uchee terrane. The numerous fault strands south of the Bartletts Ferry fault zone define patterns typical of a strike-slip duplex (Steltenpohl, 1988). |
| 35 (A)          | Uchee terrane (peri-Gondwanan) rocks serving as country rock protoliths sheared by the Bartletts Ferry–Goat Rock system of fault zones. |
| 36 (A)          | E-NE–trending domain of magnetic and gravity highs (amplitudes up to 1400 nT and ~+30 mGal, respectively) lying south of domain 35 (Uchee terrane) and south of domains 12 and 13. |

*Type: L—linear feature or gradient; A—area.

9A. Circular magnetic and gravity highs interpreted to be mafic plutons (up to 1600 nT relief) mostly within crustal block 9.

9B. Northeast-trending lineament that resembles a left-slip shear zone that offsets domains 9 and 17.

10. Domains with small, short-wavelength, relatively high-magnetic anomalies (up to 900 nT relief) within domain 9 that, although muted in Figure 3, were clearly defined on the more detailed 1:500,000-scale aeromagnetic map of Alabama (Wilson and Zietz, 2002). These correspond to fenninogen sandstones of the Kahatchee Mountain Group (Talladega slate belt) and Weisner Formation (Appalachian foreland), both of which correlate with the Chilhowee Group in Tennessee, Georgia, and North Carolina (Tull, 1982; Tull and Guthrie, 1985). The Kahatchee Mountain Group produces a stronger anomaly than the Weisner Formation likely because the former is the low-grade (chlorite zone) metamorphosed equivalent of the latter and magnetite is a product of chlorite-grade metamorphism. The Talladega fault marks the boundary between the Appalachian foreland and Talladega slate belt in Alabama but does not have much expression in the aeromagnetic or gravity data.

11. Regional gravity gradient (dashed line to emphasize the lack of an associated magnetic signature), generally low to the north and high to the south with an easterly trend distinct from the normal Appalachian gravity gradient trend.

12. East–west–trending linear truncation of all northeast-trending magnetic and gravity anomalies to the north that correspond to Appalachian and older structures, interpreted as the northern boundary of the Suwannee–Wiggins suture zone (Neathery and Thomas, 1975; Neathery et al., 1977a; Horton et al., 1984).

13. Suture zone overprinted by Mesozoic extensional faults. The distinction between 13A and 13B is based on a more detailed 1:250,000-scale magnetic map (Neathery et al., 1977a).

13A. Magnetic gradient on the north side of the Altamaha magnetic low (Higgins and Zietz, 1983).

13B. Altamaha magnetic low, which may or may not correspond to a deep part of the early
Mesozoic South Georgia Basin. Early Mesozoic sediments of the South Georgia Basin are crudely delineated by drilling and produce a muted, flat magnetic signature. Mesozoic basalt and diabase coincide with local magnetic highs that interrupt the magnetic low anomaly (Guthrie and Raymond, 1992).

14. Southern boundary of the Altamaha magnetic low. This is possibly the southern boundary of a rift basin (early Mesozoic?) formed across the earlier suture zone.

15. Suwannee terrane (undivided), which includes parallel arcuate, ~N45°E trends on the magnetic anomaly map of southern Alabama. Circular magnetic high anomalies coincident with circular gravity highs are here interpreted as mafic plutons within the Suwannee terrane and/or basaltic lavas within the South Georgia Basin. The circular magnetic high in Covington and Escambia Counties (see Fig. 2 for county locations) corresponds with several wells penetrating amygdaloidal basalt and interbedded mudstones below the Jurassic Smackover section (Guthrie and Raymond, 1992). Whereas relief on the basement could be the cause of some magnetic anomalies, no rationale was found to identify such anomalies. Euler magnetic source analysis of the magnetic map gives highly variable depths depending on the structural index used. Such analysis is beyond the scope of this study.

16. Hollins line fault (Neathery and Reynolds, 1975; Tull, 1978) and the northwestern limit of eastern Blue Ridge amphibolites (short-wavelength magnetic highs up to 1300 nT). The Hillabee Greenstone, mostly a massive greenstone, appears to be non-magnetic. The Hollins line is aeromagnetically distinct where it truncates amphibolites of the eastern Blue Ridge but has little expression elsewhere.

16A. Transcurrent right-slip shear zone that offsets magnetic linear anomalies of domain 17 and, apparently, merges with or cuts the Hollins line fault beneath the Coastal Plain cover; here it is interpreted as a transcurrent shear zone because it appears to cut the overlying thrust sheet.

17. Zone of amphibolite-rich Hatchet Creek (Mitchell Dam Amphibolite) and Poe Bridge Mountain (Ketchapadeek Amphibolite) Group metasedimentary and metavolcanic rocks (eastern Blue Ridge) with short-wavelength, high-magnetic (short-wavelength magnetic highs up to 1600 nT) signatures.

17A. Sub-area lacking high-frequency magnetic-high anomalies corresponding to amphibolite-poor Wedowee and Higgins Ferry Group metasedimentary and metavolcanic rocks.

17B. Sub-area lacking high-frequency magnetic-high anomalies corresponding to amphibolite-poor Mad Indian Group metasedimentary and metavolcanic rocks.

17C. Wedowee Group metasedimentary and metavolcanic rocks (mostly undifferentiated phylilitic, schist, and gneiss; Bentley and Neathery, 1970; Osborne et al., 1988), containing intermittent amphibolite (Beaver Dam Amphibolite, generally having higher-frequency anomalies), injected by Devonian (Russell, 1978; Schwartz et al., 2011) granitoid bodies (Almond Trondhjemite and Bluff Springs Granite with lower-frequency anomalies; Bentley and Neathery, 1970; Osborne et al., 1988).

17D. Domain that is not exposed but characterized by weakly elliptical, north-northeast-trending, low- to moderate-wavelength magnetic highs (~200 to ~260 nT). The magnetic signature of this domain is different from the much-broader-wavelength character of domain 21 to the east and the less-elliptical and lower-magnitude magnetic contours of domain 17B to the west. This domain is interpreted as possible non-magnetic Wedowee Group metasedimentary rocks.

18. Boundary between domains 17 and 17A and between domains 17 and 17B, distinguished by contrasting magnetic signatures.

19. Goodwater-Enitachopco fault, which has essentially no magnetic expression and juxtaposes metasedimentary rocks that cannot be distinguished by magnetic signatures.

19A. Questionable segment of the Goodwater-Enitachopco fault as previously mapped (Osborne et al., 1988). It crosses apparent structural grain suggested by numerous small short-wavelength anomalies on both the magnetic map and radioactivity map.

19B. Relatively sharp linear magnetic anomaly that may be a shear zone or fault, perhaps an alternate extension of the Goodwater-Enitachopco fault (this needs to be field checked).

20. Wedowee Group metamorphic rocks and Rockford Granite; the latter is suggested to be a Devonian to early Mississippian intrusion based on scattered Rb-Sr and U-Pb zircon results and field relations (Russell, 1978; Drummond, 1986; Drummond et al., 1997). The long-wavelength (low-frequency) magnetic pattern resembles that of the nearby older Elkahatchee pluton (feature 21) directly to the east.

21. Elkahatchee pluton. This Paleozoic quartz diorite batholith (Gault, 1945; Bentley and Neathery, 1970; Russell, 1978; Drummond et al., 1994, 1997) is characterized by a long-wavelength (low-frequency) magnetic pattern that makes it one of the most distinctive units on the magnetic anomaly map. Extension of the Elkahatchee pluton beneath the Coastal Plain is clearly delineated by its characteristic magnetic pattern, which shows it to be one of the largest and most extensive bodies of plutonic rock in the southeastern United States.

22. Alexander City fault zone. Its magnetic character varies along strike and includes the southeast margin of Elkahatchee pluton, and local northeast-trending lineament strands. The characteristic magnetic signature of the Elkahatchee pluton combines with the line set of distinct, short-wavelength strands associated with the Alexander City fault zone to make the latter the most distinct and continuous anomaly on the map, appearing to continue southwestward to the suture zone where it is truncated.

23. Magnetically featureless (broad, flat, long-wavelength, like feature 21) terrane between major faults, comprising domains 23A and 23B.

23A. Mostly indistinct magnetic domain except in areas marginal to major faults (e.g., Brevard and Towaliga faults) where linear, moderate-frequency anomalies occur; this domain corresponds mostly to Emuckfaw Group (eastern Blue Ridge) and Auburn Gneiss and Loachapoka Schist (Opelika Complex, Inner Piedmont) metasedimentary rocks. A relatively thin package of metasedimentary rocks, the Jacksons Gap Group (Bentley and Neathery, 1970; Neathery and Tull, 1975; Raymond et al., 1988; Osborne et al., 1988), crops out along the structurally upper parts (i.e., east) of this domain.

23B. Magnetic signature like domain 23A although with generally even lower magnitudes and lacking the moderate-frequency anomalies. This domain corresponds to Paleozoic granitic plutons of the eastern Blue Ridge (Kowaliga Gneiss and Zana Granite) and the Opelika Complex (Bottle Granite and Farmville Metagranite; Bentley and Neathery, 1970; Neathery and Tull, 1975; Osborne et al., 1988; Steltenpohl et al., 1990, 2005a, 2005b).

24. Brevard fault zone, characterized by high-frequency, linear, N55°E-trending magnetic anomalies; the magnetic signature changes character just northeast of Jacksons Gap (see Fig. 2 for location), where to the south it is marked by truncation of east-northeast-trending magnetic anomalies within the Inner Piedmont (Dadeville Complex, feature 25, below; see Fig. 2 for location). This change in character corresponds to an apparent loss of the late brittle Alleghanian overprint at Horseshoe Bend. From there southwestward, the older ductile Brevard fault zone swings around the Inner Piedmont due to late folding related to the formation of the Tallassee synform (Fig. 2; Bentley and Neathery, 1970; Steltenpohl et al., 2005a).

24A and 24B. Arcuate-shaped “islands” of higher-frequency anomalies that may indicate imbricate faults involving imbrication of the Emuckfaw Group.
25. Inner Piedmont (Dadeville Complex). High-frequency, curved and linear magnetic highs represent amphibolites of Dadeville Complex (Ropes Creek Amphibolite; Bentley and Neathery, 1970; Osborne et al., 1988) as well as local ultramafic bodies; broad low-frequency anomalies are felsic metatupetonic and metavolcanic units (Camp Hill Gneiss, Rock Mills Granite Gneiss, Chattasofka Creek Gneiss, and Waverly Gneiss; Bentley and Neathery, 1970; Osborne et al., 1988; Raymond et al., 1988; Neilsen and Bittner, 1990; Neilsen et al., 1997; Steltenpohl et al., 1990; Drummond et al., 1997). The overall pattern is consistent with the Dadeville Complex as a gently north-east-plunging, recumbent shear fold, similar to those mapped in the Inner Piedmont of the Carolinas (Merschat et al., 2005; Hatchet and Merschat, 2006).

25A. Stonewall line fault zone (red line traced from Alabama state geologic map). This fault zone separates mainly meta-igneous rocks of the Dadeville Complex from mainly metasedimentary units of the Opelika Complex (Inner Piedmont; Steltenpohl et al., 1990). Although there is no correlation of the Stonewall line with the magnetic anomaly map, the fault trace is distinct from linear trends on the radiotactivity map (not shown; Neathery et al., 1977b).

25B. Magnetic lineament internal to Opelika Complex that may separate Farmville Metagranite plutonic bodies from Auburn Gneiss metasedimentary rocks.

26. Domain of high-frequency magnetic anomalies corresponding to Emuickaw Formation metasedimentary rocks and Zana Granite. The magnetic character is similar to that of domain 25 (Inner Piedmont, Dadeville Complex). There is a substantial area of broader, low-frequency positive magnetic anomalies that may represent metasedimentary rocks or metaplutons as in domain 25; high-frequency parts resemble amphibolite-rich areas of the Dadeville Complex in domain 25. Although the Emuickaw Formation is known to locally contain minor, thin amphibolite layers (Bentley and Neathery, 1970; Raymond et al., 1988), the aeromagnetic signature of domain 26 suggests that this area contains more-substantial mafic and perhaps even ultramafic material that is not depicted on the state geologic map (Osborne et al., 1988). The northernmost parts of domain 26 are exposed north of the Coastal Plain onlap, and field checking in that area is needed to examine the source of this distinctive magnetic character.


28. Block (beneath coastal plain) between two splays of the Towaliga fault (i.e., features 27 and 29). The magnetic signature is similar to domain 26.


30. Block of rock between the main strand of the Towaliga fault (feature 31) and splay 29 that has a similar magnetic and gravity signature as feature 32A.

31. Main Towaliga fault, which is younger than and has excited plastic mylonites and ultramylonites of the Towaliga fault zone (Sears et al., 1981; Steltenpohl, 1992). The main Towaliga fault marks the boundary between the Opelika Complex (Inner Piedmont) and the Pine Mountain basement-cover massif (Sears et al., 1981; Steltenpohl, 1988).

31A. Another splay of the Towaliga fault.

31B. Pine Mountain window.

32A. Pine Mountain Group cover sequence, Halawaka Schist, and mylonites and ultramylonites, characterized by moderate-frequency, elliptical magnetic highs.

32B. Mesoproterozoic granitic gneiss basement rocks of Pine Mountain window, characterized by low-frequency, broad, flat, only weakly elongate magnetic lows (a magnetic signature grossly similar to that of the Paleozoic granitoids of the eastern Blue Ridge, domains 21 and 23B). Some Halawaka Schist occurs within this domain.

32C. High-frequency magnetic-high domain beneath the Coastal Plain that is similar to Pine Mountain Group cover of domain 32A.

32D. Broad flat anomalies buried deeply beneath the Coastal Plain that are similar to domain 32B, but with domain 32C in between them, interpreted as possible Mesoproterozoic basement of the Pine Mountain window.

33. Bartletts Ferry fault zone (Bentley and Neathery, 1970). This feature is delineated on the magnetic map by contrasting broad flat magnetic lows of the Pine Mountain basement granites to the northwest and the strong, high-frequency magnetic highs of mylonites and mylonitized amphibolites and dioritic gneisses of the Uchee terrane to the southeast (domain 35, below). The Uchee terrane has a peri-Gondwanan or Gondwanan origin, requiring that the northwest limit of Bartletts Ferry fault zone must also be the Central Piedmont suture or a later structure that has overprinted the suture (Steltenpohl et al., 2008).

34. Sharp magnetic gradients that are strands of mylonite and ultramylonite within the Bartletts Ferry–Goat Rock fault zones that interlace the Uchee terrane. The numerous fault strands south of the Bartletts Ferry fault zone define patterns typical of a strike-slip duplex (Steltenpohl, 1988).

34A. Goat Rock fault zone based on the geologic map. Note that the magnetic signature is not remarkably different from the strands of mylonite that otherwise lace the Uchee terrane.

35. Uchee terrane (peri-Gondwanan) rocks serving as country rock protoliths sheared by the Bartletts Ferry–Goat Rock system of fault zones.

36. East-northeast–trending terrane of magnetic and gravity highs (amplitudes up to 1400 nT and +430 mGal, respectively) lying south of domain 35 (Uchee terrane) and south of the suture (domains 12 and 13). These anomalies likely correspond to mafic and ultramafic complexes. They appear in and adjacent to the suture zone and thus could reflect remnant oceanic lithosphere from between the peri-Gondwanan arcs (Uchee terrane) and Gondwanan crust of the Suwannee terrane. Alternatively, they may represent substantial accumulations of basaltic lava associated with the Mesozoic South Georgia Basin.

DISCUSSION AND DIRECTIONS FOR FUTURE STUDIES

Based on decades of surface geological studies, correlations of buried rocks with otherwise known features outside of Alabama, and drill-core data, the crust underlying Alabama is recognized as belonging to three fundamental types: 1) Laurentian, 2) peri-Gondwanan, and 3) Gondwanan (Neathery and Thomas, 1975; Hatcher, 1978, 1987, 2010; Tull, 1982; Chowns and Williams, 1983; Horton et al., 1984; Tull, 1978, 1980, 1982, 1984; Thomas, 1989; Thomas et al., 1989; Guthrie and Raymond, 1992; Drummond et al., 1994, 1997; Steltenpohl, 2005; McClellan et al., 2005, 2007; Steltenpohl et al., 2008, 2010a). Our results from comparing regional geophysical data with the surface and subsurface geology indicate clear demarcation of Laurentian crust in roughly the northwestern half of Alabama, and peri-Gondwanan or Gondwanan crust underlying the southeastern quarter. The remaining east-central, triangle-shaped area underlain by Piedmont rocks is distinct and contains the Appalachian rocks and structures responsible for the collision and suturing of these fundamental crustal blocks, which we refer to as the Appalachian deformed domain (ADD).

The Grenville front (Ciesielski, 1991), as defined on the regional magnetic or gravity anomaly maps and by samples recovered from drilling outside of Alabama (Society of Exploration Geophysicists, 1982), and how, or if, it is expressed in the subsurface of Alabama have been the subject of debate (see Steltenpohl et al., 2010b, and references therein). It is inferred to connect northward with the Grenville front of Ontario, Canada, and the adjacent northern U.S.
Traversing toward the southeast, the first, weak but fine-scale Appalachian magnetic signatures appear with the Hollins line fault (feature 16 in Figs. 3, 4, and 5). The macro-scale ductile right-slip offset (i.e., feature 16A) of linear aeromagnetic signatures of domains 8 and 17 apparently merges with or cuts the Hollins Line fault beneath the Coastal Plain cover (Figs. 3, 4, and 5). This could explain the macro-scale ductile thinning of the Hillabee Greenstone depicted in this general area on the Alabama state geologic map (Osborne et al., 1988). Other faults depicted as thrusts in the foreland on the state geologic map, as well as lithologic contacts within both the Talladega slate belt and eastern Blue Ridge, similarly swing from northeast strike to northwest strike mimicking the strike of this hypothetical transient shear zone (Figs. 2 and 5). The Shady Grove fault within the Millerville reentrant, as depicted in Neathery and Reynolds (1975, their plate 5), has a similar orientation, geometry, and sense of offset as linear feature 16A. Further, the position of lineament 16A fits within the somewhat regular, ~70–80 km wavelength spacing of major orogenic reentrants in the southernmost Appalachian Blue Ridge, that is, from southwest to northeast, at feature 16A, Millerville, Hightower, and Cartersville (Figs. 1, 2, and 5). The origin of these reentrants remains unresolved.

The Goodwater-Enitachopco fault (Fig. 2; Neathery and Reynolds, 1975) is an unusual and somewhat perplexing structure and our interpretation of the aeromagnetic data in this area provides more questions than answers. In surface exposures, it is an important post–peak-metamorphic shear zone that has excised the Hollins line thrust to form isolated structural salients of the Higgins Ferry and Mad Indian Groups in the eastern Blue Ridge (Tull et al., 1985; Mies, 1991; Tull, 1995). Further northeast into Georgia most geologic maps depict the fault to be the Allatoona fault (Hurst, 1973; Tull, 1978; Hatcher et al., 1990; Tull and Holm, 2005). The Goodwater-Enitachopco/Allatoona fault has been interpreted as a southeast-dipping reverse (thrust) fault (Neathery and Tull, 1975; Pickering, 1976; Tull, 1978, 1984; McConnell and Costello, 1980, 1982; Crawford and Cressler, 1982; McConnell and Abrams, 1984; Osborne et al., 1988; McClellan et al., 2005; Tull and Holm, 2005). Tull et al. (1985), on the other hand, interpreted the Goodwater-Enitachopco to be a normal fault, reasoning that a thrust fault cutting the basal eastern Blue Ridge thrust (i.e., the Hollins line) should emplace Talladega slate belt rocks in the hanging wall. Steltenpohl (2005) reported oblique normal-and-right-slip movement indicators in several exposures of the Goodwater-Enitachopco fault and noted that a systematic analysis of the geometry, kinematics, and rheologies of the fault rocks was needed. Our alternative extension of the Goodwater-Enitachopco fault in the area of the Hightower reentrant suggested in Figure 3 (feature 19B) does not follow any geological contact shown on the state geologic map. The segment of the Goodwater-Enitachopco fault shown on the state geologic map in this area (i.e., the most northeastern segment of feature 16 in Fig. 3) is questionable because it crosses multiple short-wavelength magnetic and radiometric lineaments. Mies (1991) reported detailed map observations from the Hightower area that appear most compatible with the geophysics. Field investigations are needed to resolve inconsistencies between the geophysical anomalies and existing geologic maps showing the fault, as well as possible extensions of the fault.

The aeromagnetic character of the Elkahatchee Quartz Diorite (Fig. 2) and its immediate country rocks (feature 21 in Figs. 3 and 4) can be confidently traced to the Suwannee-Wiggins suture, together with the Alexander City fault zone that borders it to the southeast (feature 22, Figs. 3 and 4). The Alexander City fault zone presents the most intense and continuous high-amplitude/short-wavelength shear zone anomaly on the entire map (Fig. 3). This is surprising because the Alexander City fault zone is restricted to the eastern Blue Ridge, and it is generally not considered a "fundamental" southern Appalachian fault zone. The geometry and kinematics of the Alexander City fault zone has not been examined in detail and movement sense has been suggested as reverse slip (Bentley and Neathery, 1970; Neathery and Reynolds, 1973; Osborne et al., 1988), right slip (Guthrie, 1995), and normal slip (Drummmond, 1986; Drummmond et al. 1994, 1997). Our observations are that it dips steeply to the southeast and exhibits oblique-normal but predominantly dextral shear, and it is cut by later (Mesozoic?) normal-slip faults. Perhaps the steep attitude of the zone contributes to the sharp aeromagnetic lineament but more work needs to be done on this potentially important feature.

One of the more prominent aeromagnetic features of the ADD is the anomalous, curving "hook" shape of domain 23B (Fig. 3), which has important implications for delimiting the geometry of the most southern surface exposures of the Appalachians. Domain 23B corresponds to partially exposed units that frame the closure of the regional, gently northeast-plunging Talasssee synform (Fig. 2; Bentley and Neathery, 1970; Keefer, 1992; Sterling, 2006; White, 2007). Major Appalachian fault zones, the Brevard fault zone and the Towliga fault, mark the west and east limbs, respectively, and traditionally, units in the core have been assigned...
There is a clear aeromagnetic distinction between the broad, flat magnetic lows of the Laurentian crust in the Pine Mountain basement (domains 32A–32D) and the strongly linear, high-frequency magnetic highs of mylonitized amphibolites and dioritic gneisses of the peri-Gondwanan Uchee terrane to the southeast (domain 35; Figs. 1–5). Surface exposures of the Bartletts Ferry fault zone correspond to this geophysical break (domains 33–34A) that is interpreted as the southern continuation of the Central Piedmont suture (Fig. 1) between the ancient Laurentian margin and the peri-Gondwanan arc terranes (Hibbard et al., 2002, 2007; Steltenpohl et al., 2006, 2008). The high-frequency magnetic highs corresponding to the peri-Gondwanan rocks appear to continue southward to the Suwannee-Wiggins terrane suture (Steltenpohl et al., 2010a).

The aeromagnetic and gravity signatures for crust of the Laurentian margin and the ADD are sharply truncated by lineament 12 along the northern margin of the east-west–trending Altamaha magnetic low that is associated with the Suwannee-Wiggins suture (Higgins and Zietz, 1983). Aeromagnetic anomalies of the Gondwanan Suwannee terrane show distinct, parallel, arcuate, ~N45°E trends on Figure 3. These trends may reflect either lithologic structure within the Suwannee terrane or trends resulting from failed rifting and extension of the terrane during early Mesozoic time. Along the southern boundary of the ADD, there is a gradual, though distinct, west-to-east decrease in the angle of discordance such that south of domain 35 (Fig. 3) the high-frequency magnetic highs of the peri-Gondwanan rocks parallel the Altamaha anomaly. Given the high concentration of major mylonite zones exposed directly along the Coastal Plain onlap in this area, and their correspondence to these high-frequency magnetic highs, we interpret this asymptotic approach of linear magnetic anomalies to the Suwannee-Wiggins suture to reflect progressive mylonitization and rotation into the suture zone. This interpretation is supported by aeromagnetic maps of the southeastern U.S. (Zietz and Gilbert, 1980; Steltenpohl et al., 2010b) that indicate an intense, interlaced system of magnetic highs (mylonite zones?) beneath Atlantic Coastal Plain deposits that projects into this part of Alabama. Aeromagnetic lineaments tracing this anastomosing network of mylonite zones clearly end at the Suwannee-Wiggins suture where lineament 33 (i.e., our projected trace for the Bartletts Ferry fault zone) is truncated by lineament 12 roughly 80 km south of the onlap boundary (Fig. 3). The aggregate width of peri-Gondwanan terranes narrows drastically from ~450 km along the South Carolina–North Carolina state line to ~80 km along the Alabama-Georgia state line, and all Appalachian components appear to be completely excised only 100 km farther southwest along the Suwannee-Wiggins suture. We interpret the 285 Ma age established for the Goat Rock–Bartletts Ferry fault zone (Steltenpohl et al., 1992) to, therefore, place a maximum age of the suture.

CONCLUSIONS

The map of digitally processed aeromagnetic data from Alabama (Fig. 3) paints a clearer picture of the anomalies caused by rocks exposed at the surface and those buried beneath younger sedimentary cover and Appalachian thrust sheets. Combining the aeromagnetic map with gravity data (Fig. 4) and, to a lesser extent, limited radioactivity data (not shown) provides more comprehensive information on the crust underlying Alabama than does their separate analysis.

In terms of Wilson cycles recorded in the crust and lithosphere of Alabama, this work has elucidated several buried tectonic elements that are not exposed. The Grenville front records the final phase of assembly of the supercontinent Rodinia, and we interpret it to be related to the N15°E-trending magnetic low in northwest Alabama (feature 4C in Fig. 3) that is coupled with another low to the east (feature 9 and associated lows) considered to be the southern continuation of the Amish anomaly, an intra-Grenville suture zone. The NY-AL lineament is clearly expressed with its characteristic sharply demarcated between molten aeromagnetic textures of the Mid-Continent granite-rhyolite province to the northwest and the distinct N15°E-trending lineaments to the southeast. As described in Steltenpohl et al. (2010b), the NY-AL lineament appears to be a right-slip fault that has displaced the Grenville “front” and the Amish anomalies, which explains the earlier difficulty with recognizing Grenville structures south of Tennessee. Right-slip movement along the NY-AL lineament likely initiated during the final stages of assembly of Rodinia, and it might have been reactivated during the rifting of Rodinia, during Appalachian dextral shearing, and/or under the active stress field of the eastern U.S. (Steltenpohl et al., 2010b).

With regard to Appalachian consolidation of Pangaea, aeromagnetic lineaments defined by exposed Piedmont units and their structures can be traced with remarkable clarity for large distances (>145 km) and depths (>6000 m) beneath the Coastal Plain cover, to their truncation by the Suwannee-Wiggins suture, as if the Coastal Plain sediments were transparent. Despite the correlations of geology with our magnetic map, there is little correlation between...
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