Rare earth mineral potential in the southeastern U.S. Coastal Plain from integrated geophysical, geochemical, and geological approaches

By Anjana K. Shah, Carleton R. Bern, Bradley S. Van Gosen, David L. Daniels, William M. Benzel, James R. Budahn, Karl J. Ellefsen, Adam Karst, and Richard Davis

Published in: GSA Bulletin, vol. 129, issue 9-10, May 2017, p. 1140-1157

Rare-earth mineral potential in the southeastern U.S. Coastal Plain from integrated geophysical, geochemical, and geological approaches

A.K. Shah[1]*, C.R. Bern[1], B.S. Van Gosen[2], D.L. Daniels[3], W.M. Benzel[2], J.R. Budahn[2], K.J. Ellefsen[1], A. Karst[4], and R. Davis[5]

[1]*U.S. Geological Survey, DFC MS 964, Box 25046, Denver, CO 80225*

[2]*U.S. Geological Survey, DFC MS 973, Box 25046, Denver, CO 80225*

[3]*U.S. Geological Survey, 12201 Sunrise Valley Drive, Reston, VA 20192*

[4]*Iluka Resources, LLC, 12472 St. John Church Rd., Stony Creek, VA 23882*

[5]*Southern Ionics, Inc., 13291 Vantage Way, Ste. 103, Jacksonville, FL 32218*

*Corresponding author. Email: ashah@usgs.gov, Phone: 303-236-1218.

ABSTRACT

We combine geophysical, geochemical, mineralogical and geological data to evaluate the regional presence of rare earth element (REE)-bearing minerals in heavy mineral sand deposits of the southeastern U.S. Coastal Plain. We also analyze regional differences in these data to determine probable sedimentary provenance. Analyses of heavy mineral separates covering the region show strong correlations among Th, monazite, and xenotime, suggesting that radiometric equivalent Th (eTh) can be used as a geophysical proxy for those REE-bearing minerals. Airborne radiometric data collected during the National Uranium Resource Evaluation (NURE) program cover the southeastern U.S. with line spacing varying from ~2 to 10 km. These data show eTh highs over Cretaceous and Tertiary Coastal Plain sediments from the Cape Fear arch in North Carolina to eastern Alabama; these highs decrease with distance from the Piedmont. Quaternary sediments along the modern coasts show weaker eTh anomalies except near coast-parallel ridges from South Carolina to northern Florida. Prominent eTh anomalies are also observed over large riverbeds and their floodplains, even north of the Cape Fear arch where surrounding areas are relatively low. These variations were verified using ground geophysical measurements and sample analyses, indicating that radiometric methods are a useful exploration tool at varying scales. Further analyses of heavy mineral separates showed regional differences not only in concentrations of monazite but also of rutile and staurolite, and in magnetic susceptibility. The combined properties suggest the presence of sub-regions where heavy mineral sediments are primarily sourced from either high-grade metamorphic, low-grade metamorphic, or igneous terrains, or represent a mixing of these sources. Comparisons between interpreted sources of heavy mineral sands near the Fall Line and nearby igneous and metamorphic Piedmont and Blue Ridge units showed a strong correspondence with rocks closest to the Fall

Line, and poor correspondences with rocks farther inland. This strongly suggests that the primary source of those heavy minerals, especially monazite, is the rocks that formed the rocky coast that was present during Atlantic opening, which in turn indicates the importance of coastal processes in forming heavy mineral sand concentrations. Furthermore, narrow radiometric eTh and K anomalies are associated with major rivers, indicating limited spatial influence of fluvial processes. Later coastal plain sediment deposition appears to have involved reworking of sediments, providing an “inheritance” of the rocky coast composition that persists for some distance from the Fall Line. However, this inheritance is reduced with distance, and sediments within ~100 km of the coast in Georgia and Florida exhibit properties indicative of mixing from multiple sources.

INTRODUCTION

Rare earth element (REE)-bearing minerals have become increasingly important resources worldwide due to the use of REEs in advanced technology such as cell phones, rechargeable batteries, solar panels, super-magnets, and defense systems. Although REE deposits occur worldwide, more than 95% of global production during the last decade has come from a single country, China (Long et al., 2010; Tse, 2011; Hatch, 2012). In an effort to diversify sources of REE, there is increased interest in evaluating occurrences of REE-mineral concentrations elsewhere. Sediment-hosted deposits are of particular interest because minerals are typically easier to extract than from their igneous and metamorphic counterparts. REE-bearing minerals have been recovered from heavy mineral sand (placer) deposits, typically as monazite [$(REEs,Th)PO_4$] and xenotime [$(REE,Y,U,Th)PO_4$], as these minerals are particularly resistant to chemical and mechanical weathering. Monazite has been recovered from placers and stockpiled in Australia, Brazil, India, Malaysia, Sri Lanka, and Thailand (Long et al., 2010; Hoatson et al., 2011; Van Gosen et al., 2014), and is actively being processed for Th and REE's in India (Mohanty, 2015). The development of REE exploration methods and gaining a better understanding of their formation are of high interest.

Heavy mineral sand deposits are formed as rivers, streams and coastal processes erode rock and transport sediment to coastal areas where sediments are subsequently deposited and reworked by wind, waves and currents. Sediments become sorted according to density, size, roughness, and shape. Minerals of similar density that are resistant to chemical weathering such as ilmenite, staurolite, rutile, zircon, hematite, and monazite tend to become concentrated together in sands, forming heavy mineral deposits that can be economic. These concentrations typically occur in the form of lenses or layers which, when combined, can be anywhere from a few meters to several kilometers in length and width (Force, 1991; Garnett and Bassett, 2005). Heavy mineral sand deposits are relatively easy to mine where sands are poorly consolidated (usually Cretaceous age or younger) and may provide multiple salable products, such as ilmenite ($FeTiO_3$), leucoxene (altered ilmenite), rutile (TiO_2), and zircon ($ZrSiO_4$). Separation methods are typically mechanical, using gravity, magnetic, and less commonly, electrical methods to isolate minerals of interest. Chemical agents are not used in the separation process, and therefore mined areas are relatively easy to remediate (Van Gosen et al., 2014).

Economic deposits of heavy mineral sand deposits have been recognized in the southeastern U.S. since the beginning of the 20th century (e.g., Watson and Hess, 1913), and probably earlier (Berquist et al., 2015). The majority of mined deposits are located in Cretaceous and Tertiary sediments near the boundary between the Piedmont and Atlantic Coastal Plain physiographic provinces, commonly referred to as the “Fall Line.” Quaternary sands have also been mined, including the Pleistocene Trail Ridge deposit (Figure 1), and Holocene areas such as at Cove Point, Maryland, and in parts of northeastern Florida (Staatz et al., 1980; Staff, Bureau of Mines, 1987; Berquist et al., 2015). At present, such deposits are typically mined for ilmenite, rutile and zircon. Monazite and xenotime have been recognized as co-minerals (Overstreet, 1967; Staatz et al., 1979; Staatz et al., 1980; Grosz and Schruben, 1994), but concentrations of 1-2% of the heavy mineral assemblage are not currently sufficient for economic recovery. Recent research, however, suggests that monazite concentrations reach up to 12% of the heavy mineral assemblage in some areas, and xenotime concentrations commonly co-vary with monazite, with concentrations up to 1-2% (Bern et al., 2016).

Little is understood regarding the provenance of monazite and xenotime in the Atlantic Coastal Plain. The heavy mineral sands have their ultimate sources in the neighboring metamorphic and igneous rocks of the Piedmont and Blue Ridge provinces, but deposit formation is complicated by a >200 m.y. history of erosion and mixing. Early studies (Dryden, 1958; Overstreet, 1967) assumed that Coastal Plain monazite was derived from one of several Piedmont monazite "belts" described by Mertie (1953), but neither the delivery mechanism nor the actual source location was determined. More recent provenance studies have focused on fluvial inputs at the local scale (e.g., Darby, 1984; Naeser et al., 2006) and reveal little about monazite or xenotime. Literature describing studies of detrital zircon and detrital monazite from Atlantic Coastal Plain sediments is currently very sparse.

Radiometric methods provide an approach for exploration and characterization of heavy mineral sand deposits, particularly those containing REE-bearing minerals (e.g. Meleik et al., 1978; Mudge and Teakle, 2003; Singh et al., 2007). Natural gamma photons emitted during radioactive decay series of potassium (K-40), thorium (Th-232), and uranium (U-238 and U-235) isotopes (e.g., Force et al., 1982) are measured; spectral properties may be used to estimate relative amounts of K, U and Th. Many early airborne radiometric surveys in the southeastern U.S. measured only gamma total count because they were conducted before spectral methods were fully developed. Total count highs over Atlantic Coastal Plain sediments have been associated with both U in phosphates and Th in heavy mineral sands (Force et al., 1982; Grosz, 1983; Grosz et al., 1989). Some of these observations were later verified with ground or airborne spectral data showing relative contributions of K, U, and Th (Grosz et al., 1989; Grosz et al., 1992). In the Piedmont, total count highs have been observed over high-grade metamorphic rocks, presumably due to monazite, but also over felsic igneous rocks containing potassium feldspars (Pitkin, 1968; Neathery et al., 1976).

Magnetic methods have also been used to explore for placer deposits. The success of these methods depends on the presence of magnetic minerals (e.g. magnetite, maghemite, hematite and to a lesser degree ilmenite) within the heavy mineral assemblage, and percentage of these minerals within the bulk sand being high enough so that a detectable anomaly is generated. Early efforts to use aeromagnetic surveys were typically not successful (Wynn et al., 1985), although more recent low-altitude (<50 m) airborne surveys have shown anomalies associated with heavy mineral concentrations in South Australia (Mudge and Teakle, 2003). Greater success has been attained using ground and shipboard surveys, attributable to the reduced distance between source and sensor (Siddiquie et al., 1984, Peterson et al., 1986; Shah et al., 2012; Shah and Harris, 2012). The use of magnetic methods in placer deposit exploration is described in further detail by Van Gosen et al. (2014).

We have combined airborne and ground geophysical data with geochemical and mineralogical studies of sand samples to delineate concentrations of the REE-bearing minerals monazite and xenotime at the regional scale across the southeastern U.S. Coastal Plain. These data reveal broad, regional variations in the heavy mineral assemblages that have implications for source rock type. Further analyses show how heavy mineral concentrations may be broadly traced to their sources in the Piedmont and Blue Ridge provinces, providing insights into the dominant processes forming these deposits. These variations also show a regional dependence for the sensitivity of geophysical methods from which we suggest corresponding exploration strategies.

GEOLOGIC SETTING

The Atlantic Coastal Plain, consisting of sediments and sedimentary rocks of Jurassic to Holocene age, first formed with the opening of the Atlantic Ocean. With opening, erosion of the ancient metamorphic and igneous coastline by coastal processes and fluvial transport from inland areas brought sediments to the new coast. Once delivered and deposited, those sediments continued to be reworked by waves, currents, and winds until buried by subsequent deposition. The original rocky coastline is visible today as steep topographic gradients along the boundary between the Coastal Plain and Piedmont provinces. This boundary is commonly referred to as the “Fall Line,” partly for associated waterfalls such as Great Falls, Va., and Roanoke Rapids, N.C. As the Atlantic Coastal Plain grew, sediments continued to be reworked and mixed by both coastal and fluvial processes. Relics of changes in sea level and deposition can be observed in various features such as topographic ridges and barrier islands parallel to the coast.

The system of rises and embayments in bedrock along the coastline of the eastern U.S. has likely influenced transport of coastal plain sediments at the regional scale and the resulting shape of the modern shoreline (Owens and Gohn, 1985). Prominent rises include the Cape Fear arch in North Carolina and the Peninsular arch in Florida (Figure 1). The rises would have blocked longshore transport and thus potential mixing from different areas. They also locally inhibited deposition of marine and terrigenous sediments. For example, surface sediments over the Cape Fear arch are Cretaceous in age, while surrounding sediments are Paleogene or younger (Figure 1).

The metamorphic and igneous Piedmont and Blue Ridge provinces serve as the primary source for heavy mineral sands within the Atlantic Coastal Plain (Force, 1991). The Piedmont and Blue Ridge have experienced multiple episodes of compression and extension and display a diverse array of rock types of varying age. However, even though these provinces are very complex, various workers have recognized regions commonly referred to as “belts” that reflect different episodes of metamorphism and intrusive emplacement (e.g., Hatcher and Odum, 1980).

These include the Carolina and Eastern slate belts, which are marked by slate and other low-grade metamorphic rocks as well as intrusive rocks; the Raleigh/Goochland belt, the Kiokee and Uchee belts, and the Inner Piedmont, which are marked by high-grade metamorphism; and the Charlotte belt, which contains numerous granitoid intrusions (Figure 2).

The presence of monazite in the Piedmont is well documented. Through analyses of stream sediments, Mertie (1953, 1979) proposed the existence of three monazite belts that extended much of the length of the Piedmont and Blue Ridge (Figures 1-2). Comparisons to surrounding geologic units demonstrated that large sections of the monazite belts overlap areas of high-grade metamorphism, leading Overstreet (1967) to propose a metamorphic source for Piedmont monazite. However, monazite has also been observed within granitoid intrusions such as the Liberty Hill pluton in South Carolina, and in some cases, the monazite belts include both intrusive and metamorphic rocks.

METHODS AND MATERIALS

Airborne geophysical data

During the 1970s, as part of the National Uranium Resources Evaluation (NURE) program, airborne radiometric and magnetic surveys were conducted over most of the conterminous U.S. In order to cover such a large area, the line spacing of these surveys typically varied from 5-8 km. The resolution of these data is thus very coarse, but they remain one of the few datasets covering most of the southeastern U.S. The spectral properties of measured gamma emissions were processed in order to estimate relative values of K, U, and Th; surveys were leveled relative to each other in order to provide continuous data at a national scale (Duval et al., 2005). Because multiple gamma emission events are associated with both the U and Th decay series, each with different corresponding energy spectra, estimates are usually referred to as equivalent U and Th (eU and eTh, respectively). We note that gamma emissions generally reflect rock and sediment within about 0-100 cm of the surface because gamma photons from the decay of deeper sources tend to be scattered (through Compton scattering) before reaching the atmosphere and thus the sensor. However, in many cases the gamma particles are emitted from residual soils derived from deeper underlying rock or sediments. Areas covered with water usually produce no gamma emissions due to impenetrability.

During the 1960s and 1970s, a number of aeromagnetic surveys with 1.6-3.2-km line spacing and 120-150 m height above ground were flown in the southeastern U.S. Total count scintillometer sensors were added to many of these surveys although the technology was still emerging and standards had not been established. In South Carolina, a combination of six such surveys produced total count data for about 90% of the state with 1.6 km (1-mile) line spacing. Using total count data from two NURE 4.8-km (3-mile) surveys to fill the remaining 10%, we leveled the survey data relative to each other to create a statewide map. The total count data do not distinguish among K, U and Th sources, but the closer flight line spacing provides intensity information at a much more detailed scale than the NURE surveys.

Airborne magnetic data are available at the national scale through the Magnetic Anomaly Map of North America (North American Magnetic Anomaly Group, 2002). These data were later corrected for long wavelength variations (Ravat et al., 2009). In the Piedmont and Blue Ridge provinces, numerous workers have explored correspondences between magnetic anomalies and surface or subsurface rocks (e.g., Hatcher and Zietz, 1980); these maps thus complement radiometric survey data. In the Atlantic Coastal Plain, magnetic survey anomalies generally reflect buried basement rock. The distance between sensor and source combined with relatively coarse sampling along flight lines makes detecting sedimentary sources very challenging (e.g., Shah et al., 2012).

Regional sample measurements

Geophysical measurements of heavy mineral sands reflect the combined effect of the concentration of heavy minerals within the sands and the composition of the heavy mineral assemblage. This creates ambiguity in interpretation: for example, a Th anomaly may represent a minor concentration of heavy minerals that is rich in monazite, or it may represent a rich concentration of heavy minerals with only a small component of monazite. Analyses of heavy mineral separates, i.e., samples that include sands of a minimum density (typically 3.3 g/cm^3), allow distinction between the two scenarios. In particular, regional differences in heavy mineral separate mineralogy can allow "calibration" of geophysical anomalies by indicating whether heavy mineral concentrates are likely to be rich in Th-bearing minerals, magnetic minerals, or both. Mineralogy may also provide information regarding source rock if linkages to igneous and/or metamorphic mineralogy can be made. It is important to note that sorting of sands as they are reworked will also create local variations that can make such linkages less clear.

We conducted laboratory measurements of magnetic susceptibility and radioactivity of heavy mineral separates derived from sand samples collected at field sites (Figure 1). Concentrations of 55 elements were measured on heavy mineral separates by SGS Mineral Services using inductively coupled plasma atomic emission spectroscopy and mass-spectrometry (ICP-AES-MS) after decomposition of the sample by a sodium peroxide sinter. X-ray diffraction (XRD) was used to estimate mineral content of the separates. In order to increase regional coverage, geophysical and geochemical properties of a subset of archived stream sediment samples collected during the NURE program (Smith, 1997) were also measured. The NURE samples were chosen with a slight bias, where those samples showing greater concentrations of La were favored to assist studies of REE minerals. Samples were also collected from ground survey sites where a significant fraction of heavy mineral sands could be extracted, as is discussed below. The geochemical and XRD data are described in detail by Bern et al. (2016).

Ground geophysical surveys

The NURE and total count airborne surveys provide coverage over large areas, but they reveal little information regarding the distribution of source materials at a local scale. Furthermore, radiometric and magnetic anomalies can arise from a number of different types of geological sources. In order to ground-truth the airborne data, we conducted ground surveys using a portable gamma spectrometer (a Radiation Solutions RS-125 and a GF Instruments Gamma Surveyor) and handheld cesium magnetometer (a Geometrics G-858 gradiometer system). The surveys took place between February 2013 and March 2015.

The survey sites, shown in Figure 1, were chosen based on (1) the presence of airborne NURE Th and/or total count anomalies, (2) whether the local surface geology suggested heavy mineral sand potential (3) coverage of diverse ages, (4) a wide geographic distribution, (5) accessibility of sites, and (6) in some cases, availability of drill hole data. The sites included Cretaceous sands (Cheraw State Park, South Carolina and Aurelian Springs, North Carolina; the latter represent terrace deposits), Pleistocene sand bars (near the Folkston deposit in southeastern Georgia), Holocene fluvial floodplains in eastern South Carolina and southern Virginia (Frances Marion State Forest and the James River), and modern coastal sites from North Carolina to Florida (the Outer Banks, Folly Beach, Cumberland Island and Little Talbot Island).

Where feasible, surveys were conducted along profiles spaced 50-200 m apart, usually in a “mow-the-lawn” configuration. At some sites, accessible areas were narrow due to dense forest or sand dunes, so data in these instances were collected along a single profile. Some areas were relatively small so only a few assay measurements were taken. For continuous measurement recordings along profiles, the RS-125 calculates a running average of total count readings while the Gamma Surveyor averages spectral readings over a fixed time period (for this study, 30 seconds). To verify contributions to RS-125 total count data, specific sites were also occupied for 1 minute or more, allowing for a spectral calculation. During the surveys, either the RS-125 or the Gamma Surveyor was available, but not both. A subset of sites was thus reoccupied using both instruments to estimate consistency between the different meters. For sites that were re-occupied within 4 m of each other, the difference in eTh measurements was less than 5% of the larger value, while for sites within 10 m of each other the differences were less than 35%. The difference in radiometric K and eU varied more widely, probably because both of these values were very low and close to the detection limits of the instrument. A summary of these data is provided in the GSA Data Repository.

Where the width of the survey area allowed, tie-line profiles were used to level magnetic survey data. At sites where tie lines could not be obtained, survey data were leveled relative to regional airborne magnetic grids (Ravat et al., 2009). In order to highlight shallow magnetic sources (within a few dozen meters from the surface), profiles were upward continued a distance of 50 m, and the upward continued profile was subtracted from the observed profile. All survey data were corrected for diurnal variations through the use of a magnetic base station set up near the survey site.

Samples were collected at field sites. In beach areas, grab samples were obtained with spacing 50-500 m, depending on the size of the survey area. In soil-covered areas, samples were collected by hand auger. For these samples, either a Niton XL3t GOLDD+ portable X-ray fluorescence (XRF) analyzer or ICP-AES-MS was used to estimate chemical concentrations. A ZH Instruments SM-30 was used to estimate magnetic susceptibility. Two of the ground survey sites, near Aurelian Springs, North Carolina, and north of Folkston, Georgia (the “Mission” mine) are actively being explored for ilmenite, zircon, and other heavy minerals by Iluka Resources, Inc. and Southern Ionics, Inc., respectively. In Aurelian Springs, Iluka drilled various sites and obtained measurements of heavy mineral content and major element geochemistry. Southern Ionics, Inc. acquired similar data for the Mission mine.

RESULTS

Regional airborne geophysical data

Correlations between sample Th and La (Grosz, 1993) and among Th, monazite, and xenotime (Bern et al., 2016) have been observed throughout the southeastern U.S., indicating a direct link between Th and REE-bearing minerals. Radiometric equivalent Th (eTh) is thus of primary interest. Radiometric K is also of interest because it tends to reflect the presence of K-bearing minerals such as feldspars. Radiometric equivalent U (eU) anomalies are commonly co-located with eTh anomalies; however, because U is associated with multiple isotopes that each have their own decay series, eU anomalies tend to be noisy compared to eTh and radiometric K. This study is thus focused on eTh anomalies, and to a lesser degree, radiometric K anomalies.

Within coastal plain sediments along the eastern seaboard from Virginia to Georgia, NURE aeroradiometric eTh (Figure 3) and eU generally show higher values closer to the Piedmont and decreasing values with distance from the Fall Line (see also Ellefsen et al., 2015). In Virginia and North Carolina, eTh anomalies are very low over Quaternary sediments. However, this trend is reversed from South Carolina to northern Florida, where coast-parallel bands of eTh and K highs are observed over Pleistocene and Holocene sediments. In Georgia and

Florida, these bands are located close to the Trail Ridge placer deposit. Farther west, in Mississippi, Alabama and Tennessee, a band of eTh highs (as well as increased eU) is observed along Cretaceous carbonates of the Demopolis Chalk, and in Georgia, a similar band is observed over the Ocala Limestone. These latter observations are consistent with absorption of Th in carbonate rocks.

Sinuous eTh and K highs are observed along major rivers from Virginia to Georgia, corresponding to their floodplains, with K anomalies being more prominent and persisting for a somewhat greater distance along those rivers than eTh anomalies. We note that K-feldspars are less dense than monazite, and therefore may be carried greater distances from their sources. In South Carolina and Georgia, eTh highs associated with the floodplains of the Santee, Altamaha and Savannah Rivers are particularly wide. The rivers themselves, other large bodies of water, and water-saturated ground, such as the Okefenokee Swamp (Ga.), Lakes Marion and Moultrie (S.C.), and the Great Dismal Swamp (Va. and N.C.), show prominent eTh and K lows.

Anomalies within the Atlantic Coastal Plain also show regional variations, with generally higher eTh in an area covering southern North Carolina, South Carolina, Georgia and eastern Alabama relative to Virginia and northern North Carolina. In particular, large (> 100 km wide) areas with eTh highs are present near the Fall Line from the Cape Fear arch through eastern Alabama. In contrast, K anomalies are generally higher in Virginia and northern North Carolina than in Coastal Plain areas farther south. The K anomalies in Alabama, Tennessee and Mississippi are also elevated. Together, these data suggest a marked difference in composition north and south of the Cape Fear arch. A second transition is observed near the Georgia-Alabama border, where eTh highs occur mostly near the Fall Line over sands east of the state boundary line and mostly in carbonate rocks to the west.

Over the Piedmont, eTh anomalies correspond well to geologic belts described by Hatcher and Odum (1980), Secor et al. (1986), and Hibbard et al. (2002) (Figure 4). High values are observed over high-grade metamorphic terranes, including the Kiokee and Raleigh/Goochland belts, parts of the Pine Mountain belt and sillimanite schist areas of the Inner Piedmont and Blue Ridge. Highs are also observed over certain granites such as the chains of smaller granitic plutons within the Charlotte belt and Carolina slate belts. A notably broad high is observed over the Petersburg Granite in Virginia. Parts of the Inner Piedmont also show local highs over igneous rocks, especially in eastern Alabama and western Georgia.

The monazite belts described by Mertie (1953, 1979) correspond to eTh highs in numerous places, but they do not correspond to a single rock type. The two western belts mostly coincide with high-grade metamorphic rocks of the Inner Piedmont and Blue Ridge, as proposed by Overstreet (1967). However, in central Virginia, a slight modification of the central belt so that it is oriented more northerly is suggested by the radiometric data (Figure 4); we note that Mertie (1979) did not have samples from this area. Additionally, the eastern belt continues from metamorphic rocks of the Raleigh/Goochland belt to monazite-rich plutons of the Carolina slate belt.

Magnetic data often show either positive or negative correlations with eTh anomalies depending on rock type. Within the Charlotte belt, several plutons are associated with both eTh highs and magnetic anomaly highs, particularly near the border between North and South Carolina (Figure 4). In contrast, in areas with eTh highs attributable to sillimanite schist or other high-grade metamorphic rock, such as the Kiokee belt or Raleigh/Goochland belt, the magnetic anomalies tend to be lower. This may be associated with the destruction of magnetite in areas that have undergone high-grade metamorphism (e.g., Hatcher and Zietz, 1980). We note, however, that some high-grade metamorphic areas displaying eTh highs also show magnetic anomaly highs (such as parts of the Inner Piedmont), perhaps due to secondary magnetite.

Regional sample data

Sample geochemical and geophysical data show distinct regional variations, with higher concentrations of Th and La corresponding well with radiometric eTh anomalies (Figure 5; GSA Data Repository). Th concentrations are greatest near the Fall Line in South Carolina amidst prominent eTh highs. Intermediate Th concentrations are present in neighboring areas in North Carolina and Georgia, and within a smaller area of high eTh values in eastern Alabama. Near the Atlantic coast in both southeastern Georgia and northern Florida, Th concentrations are more variable, with some samples showing medium concentrations and others showing lower concentrations. In Virginia, where aeroradiometric eTh is relatively low, La and Th also show decreased concentrations in heavy mineral separates. These variations are also reflected in field site data (Table 1). Together, these data provide further evidence that the composition of the heavy mineral assemblage contributes significantly to the magnitude of eTh anomalies.

The magnetic susceptibility map also shows regional variations, but with more local variability. Near the Fall Line, higher susceptibility values are observed in eastern Alabama and in some locations north of the Cape Fear arch (Figure 5). In areas closer to the coast, these values are more mixed. Correspondences with minerals are more difficult to ascertain because trace amounts of highly magnetic minerals, such as magnetite, can strongly impact magnetic susceptibility. However, for most samples, magnetic susceptibility is correlated with Fe content (see GSA data repository). Regional magnetic anomalies do not show correspondences with magnetic susceptibility values of heavy mineral separates, probably because they are dominated by sources in the crystalline basement. These regional variations in magnetic susceptibility are examined in more detail using ground surveys, discussed below.

Rutile concentrations, which were estimated using X-ray diffraction, show broad, distinct regional variation, with highest concentrations near the Fall Line from south of the Cape Fear arch through Georgia (Figure 5). The rutile concentrations show little to no correlation with Ti concentrations, which are high over most of the southeastern U.S., probably because Ti appears in other minerals such as ilmenite. The rutile concentrations show a nearly inverse correlation with magnetic susceptibility (with exception of Tennessee, which is low in both). We note that rutile is sourced predominantly from high-grade metamorphic rocks (Force, 1980), and that high-grade metamorphism typically has a destructive effect on magnetite. We also note that many areas with increased rutile show increased Th and monazite, suggesting that monazite in those areas may also have been formed under higher grade metamorphic conditions. Staurolite, which is primarily found in low- to mid-grade metamorphic rocks, is more variable. Areas near the Fall Line in South Carolina are notably low in staurolite while areas in Virginia and northern North Carolina generally have greater staurolite content.

The distributions of Th and monazite concentrations, rutile concentrations and magnetic susceptibility suggest that the study area can be divided into sub-regions with the following properties (see also Table 2):

1. Virginia and northern North Carolina (except near major rivers): characterized by low monazite and Th concentrations except near major rivers, higher magnetic susceptibility and mostly low rutile content.
2. Southern North Carolina (near the Cape Fear arch): characterized by mixed magnetic susceptibility and concentrations of monazite and rutile.

3. Near the Fall Line from South Carolina through Georgia: characterized by high Th and monazite, low magnetic susceptibility and mostly high rutile.
4. Eastern Alabama near the Fall Line: characterized by high Th and monazite, high magnetic susceptibilities and low rutile.
5. Coastal South Carolina, Georgia, and northern Florida: characterized by highly variable from sample to sample.
6. Western Tennessee: characterized by low Th, low magnetic susceptibility, and low rutile.

Detailed surveys

High-resolution surveys provide a key component of interpretation of widely spaced airborne gamma spectrometry data by providing detailed views of local variation that cannot otherwise be resolved. This includes the airborne total count data collected over South Carolina and ground surveys at various locales.

Airborne total count data over South Carolina

The high-resolution airborne total count data over South Carolina (Figure 6) provide a detailed picture of radiometric anomalies. These anomalies correspond well with the NURE eTh maps, suggesting that in South Carolina the total count signature is dominated by Th and perhaps U, because the two are commonly associated in certain minerals.

Within the Piedmont, the total count data show distinct circular highs over various plutons. Broad total count highs are also observed in the presence of sillimanite schist, reflecting high-grade metamorphism that produced monazite. This includes a wedge-shaped high that exists where the Kiokee belt crops out near the Fall Line. Near the Santee/Broad/Congaree River system, 1-2 km wide striations parallel to the river system are observed, especially near the Winnsboro pluton and the Santuck granite, suggesting the transport and deposition of Th-rich sediments within the associated riverbed. Such striations are not observed, however, near smaller rivers, even near the Th-rich sillimanite schist of the Inner Piedmont.

Coastal Plain sediments adjacent to the Kiokee belt show particularly high total count values for a distance of about 75 km downslope, toward the southeast. They also extend for about 75 km eastward from the edge of the Kiokee belt outcrop, reaching past the Santee River and downslope of areas near the Fall Line. At distances more than 75-100 km from the Fall Line, total count values are low (Figure 6) until Quaternary sediments are reached (see Figure 1). Highs are also observed along the floodplains of the Santee and PeeDee Rivers. Between these rivers, in the Cretaceous Peedee Formation, numerous 25-50-km long striations oriented similarly to the northwest-southeast floodplains are observable. While total count lows likely correspond to smaller fluvial systems, other highs may reflect differences in sand composition. These striations are not present in the Piedmont. Near the coast, the total count map exhibits anomalies alongside northeast-southwest coast-parallel Pleistocene ridges.

Modern Beaches from Florida to North Carolina

Several modern beaches in different parts of the southeastern U.S. were surveyed (Figure 1). The beaches provide easy access to samples and, in most cases, visual confirmation of heavy mineral sand presence. At both Folly Beach, South Carolina, and Little Talbot Island, Florida, data grids were obtained by surveying troughs in rows of linear sand dunes at Little Talbot Island and by utilizing a wide beach area at Folly Beach (Figure 7). At two other sites, the Outer Banks, North Carolina, and Cumberland Island, Georgia, single profiles along the shore were obtained (Figure 8).

The highest eTh values were observed at Folly Beach and Little Talbot Island. Significant (up to ~5 nT) magnetic anomalies in locations near eTh anomalies were observed at Folly Beach

(Figure 7), whereas smaller 1-2 nT anomalies were observed at Little Talbot Island. This is consistent with slightly increased magnetic susceptibilities of heavy mineral separates for Folly versus Little Talbot Island. At Cumberland Island, both eTh and XRF measurements of Th were generally lower (Figure 8). A clear magnetic anomaly is not apparent, but there is suggestion of slightly greater variation of magnetic anomalies in areas where eTh is higher (the variations may represent noise, however). Magnetic susceptibility and Th content of heavy mineral separates are similar for both Cumberland and Little Talbot Islands, so we infer that heavy mineral concentrations are lower in the Cumberland Island survey area than the Little Talbot Island survey area.

XRF analyses of surface-grab samples from these three sites show strong correlations between Th content and eTh anomalies. Ti, Fe and Zr concentrations correlate well with both Th concentrations and eTh, indicating that the eTh anomalies not only represent Th content, but that they also reflect enriched concentrations of heavy minerals. There are some exceptions, mostly at Cumberland Island, presumably due to layering of heavy minerals that can cause differences between surface sands and those just a few inches below.

The Outer Banks survey data showed notably different characteristics from those of the more southern beaches. The eTh measurements generally fell within sensitivity and precision levels of the instrument and sample XRF Th concentrations were all below 35 ppm. However, magnetic anomalies show much more variation (10-15 nT). The wavelength of these anomalies is too short to represent rocks in the crystalline basement, which are several kilometers deep. These results are consistent with heavy mineral concentrate measurements that show higher magnetic susceptibilities (5.5 x 10^{-3} SI) than those from beaches farther south, but also much lower Th content. Although the magnetic anomalies don't directly correspond with grab-sample measurements of Th, Ti or Fe, there is generally greater short-wavelength (10-50 m length scale) variation in areas where Th concentrations are higher, indicating shallower magnetic sources and further suggesting that the anomalies represent heavy mineral sand layers.

Aurelian Springs, North Carolina

The Aurelian Springs deposit is located within Tertiary terrace deposits of northern North Carolina, close to the Fall Line (Figure 9). This area has been evaluated for a future mineral sands mining operation that would produce ilmenite and zircon by Iluka Resources, Inc. We conducted a single-line profile magnetic and radiometric survey along a dirt path where drill samples had been obtained by Iluka Resources, Inc., with a spacing of roughly 60 m (Figure 9). The drill data show highest heavy mineral concentrations toward the western part of the profile. Total count anomalies were collected in "continuous" mode using the RS-125, and were very similar to eTh measurements from 1-minute assays. Radiometric eTh values are not very high, but they do show elevated values where heavy mineral concentrations are higher.

Magnetic data also showed higher values where heavy mineral concentrations are present, but the magnetic highs are somewhat offset from the eTh highs. This may partly be due to the fact that magnetic data can image deeper sources than radiometric data. There may also be a contribution from basement rock, which is less than 200 m deep in this area. The latter possibility is supported by the magnitude of the highs, exceeding 200 nT, which is very high for sedimentary sources.

We also obtained two depth profiles of samples along the survey, one within the deposit, and one farther east outside of the deposit. Magnetic susceptibility and geochemistry of bulk sands as a function of depth were estimated using a SM-30 field susceptibility meter and ICP-AES-MS, respectively. At the site within the deposit, heavy mineral concentrations range from 3 to 4%. Ti was elevated near the surface (Figure 10), corresponding to increased heavy mineral concentrations there. Th was also slightly elevated mainly in the upper 1 m, with a maximum value near 35 ppm near a depth of 50 cm. Magnetic susceptibility values were notably high in the upper 30 cm of the hole but decreased abruptly with depth; they did not show a correspondence with heavy mineral content. This may be an effect of leaching or alteration of magnetite through the soil column. Nonetheless, magnetic susceptibility laboratory measurements of heavy mineral separates from Aurelian Springs were ~14.34 x 10^{-3} SI, which is comparable to igneous rocks. It is thus difficult to determine which part of the magnetic signal might be due to heavy minerals and which part is due to basement rock. Outside of the deposit area, eTh and magnetic anomalies were lower, along with heavy mineral concentrations, Ti, Th, and magnetic susceptibility. To further explore the utility of these methods, an additional grid survey was conducted over a wide area on a nearby farm. Results were similar (GSA Online Repository).

Other sites in South Carolina

Cheraw State Park is located within the band of eTh highs along the Fall Line in South Carolina and is underlain by the Cretaceous Peedee Formation. Ground radiometric surveys exhibit intermediate eTh values in that area (Table 2, GSA Online Repository). Two hand-auger holes of ~80 cm depth were obtained, one within the eTh highs (CH A1) and one within an eTh low (CH A2). Heavy mineral concentrations within these sites were low (<1 %), however, bulk sands within CH A1 showed significant Th (Figure 10) and La concentrations (up to 150 ppm). These are higher than those observed at Aurelian Springs (up to 35 and 50 ppm for Th and La, respectively) even though heavy mineral concentrations there were 3-4%.

The Francis Marion National Forest survey site (Figure 1) is located within radiometric highs associated with the Santee River and is part of the Pleistocene Socaste Formation. Ground radiometric eTh surveys show intermediate values there as well, but not as high as those at Cheraw (Table 2). A hand-auger hole obtained within local radiometric eTh highs also showed very small amounts (< 1%) of heavy mineral sands, but bulk sand Th and La values were 20-23 ppm and 60-67 ppm, respectively, on par with Aurelian Springs (Figure 10) in spite of much lower heavy mineral concentrations.

Magnetic anomalies show little relation to eTh anomalies at these sites and magnetic susceptibilities of auger samples were very low ($<0.05 \times 10^{-3}$ SI). Within Cheraw, magnetic anomalies over the area vary up to 400-500 nT, whereas within Francis Marion they vary 15-20 nT over the respective survey areas. The magnetic anomalies at both sites likely reflect basement rock, noting that the crystalline basement is shallower at Cheraw, reducing the distance to the magnetic source.

North of Folkston, Georgia

The Trail Ridge and Folkston deposits are located along a >200-km long Pleistocene ridge extending from northern Florida to southern Georgia, oriented parallel to the Atlantic Coast. This ridge was likely once a barrier island (Force and Rich, 1989). Parts of these deposits are actively being mined for ilmenite, rutile and zircon. We conducted ground radiometric and magnetic surveys over an area north of Folkston, corresponding with Southern Ionics drill holes spaced ~100-200 m along several profiles (Figure 11). Continuous measurements using the Gamma Surveyor showed a direct correspondence between eTh and estimated heavy mineral concentrations, although eTh values were low compared to other field sites. Total count data showed similar patterns. The magnetic data, on the other hand, exhibited a rather different pattern. Magnetic anomalies were lowest in areas where the deposit is thickest (determined by models based on drill hole data). The base of the heavy mineral sands is marked by hard, consolidated Fe-rich sedimentary rock referred to as "hardpan." Measured magnetic susceptibilities of samples of this rock were very high (>20 x 10^{-3} SI), suggesting that the magnetic anomalies reflect the shape of the hardpan surface. The magnetic susceptibility of the heavy mineral separates was lower, ~0.98 x 10^{-3} SI.

James River, Virginia

Along the James River east of the Fall Line, small crescent-shaped beaches commonly contain visible heavy mineral concentrations (see Berquist et al., 2015). These areas were too small for geophysical surveys, but spot radiometric assays at two sites showed the highest eTh readings of all surveys. Concentrations of heavy minerals were very high at both sites, and the second site was almost 100% heavy minerals; a grab sample of bulk sands had a density of 2.9 g/cm^3. The high eTh readings are then likely due to the enriched concentration of heavy minerals. Magnetic susceptibilities were also remarkably high at these sites. Samples showed low to negligible amounts of rutile and staurolite.

Relations to local geologic features

Geophysical data provide much denser coverage of an area than is possible with sampling or drilling. They thus have the potential to highlight relations to geologic features and can provide insights into processes that lead to heavy mineral concentrations. The ground radiometric surveys show anomalies that correspond to several geologic features. For example, at Little Talbot Island, the highest eTh values were observed along a stretch of beach that is bounded by an eroding cliff wall and thus only accessible during low tides (Figure 7). The sand dunes at Little Talbot Island had much lower eTh values, except at their northern end where they approach the modern shore. In contrast, on Cumberland Island, higher eTh values were observed mainly in overwash areas and in a bend of the shoreline where the beach was very narrow. At

Cheraw State Park, eTh values were high along topographic gradients that likely represent ancient riverbeds, and peaked near the apparent confluence of two riverbeds (GSA Online Repository). While an in-depth analysis of sedimentary processes in these three areas is beyond the scope of this work, together the geophysical data suggest the importance of erosional processes at Little Talbot Island (e.g., through entrainment sorting and the formation of lag deposits), fluvial transport and deposition at Cheraw State Park, and both at Cumberland Island.

DISCUSSION

Regional distribution of Th and REE-bearing minerals

Regional variations in Th, monazite and associated xenotime are evident in radiometric, geochemical, and mineralogical datasets. Within southeastern U.S. Coastal Plain sediments, NURE eTh anomalies are generally higher in areas near the Fall Line from southern North Carolina through eastern Alabama and in Quaternary sediments near the Atlantic Coast from South Carolina through northern Florida. Such anomalies are also observed along most major alluvial plains, but they generally cover wider areas in South Carolina and Georgia.

Sections of the Coastal Plain with high eTh values that lie near the Fall Line (Figure 12) form an area greater than 33,000 km^2. Pleistocene ridges and fluvial flood plains, as well as modern beaches from South Carolina to Georgia also exhibit high eTh and add an additional 2,600 km^2. The possible total resource of monazite and xenotime in these areas is significant. For example, an area south of Folkston near Boulonge, Fla., covering ~4 km^2 (~1,000 acres) was mined from 1974-1978 to about 5 m depth. This area contained about 4% heavy minerals of which monazite composed 0.3-0.4% (Staatz et al., 1980), suggesting ~40,000 metric tons of monazite for the area. Coastal sand-silt deposits of northeastern Florida were estimated to contain 330,000 metric tons of monazite, of which 198,000 metric tons represent REE oxides

(Staatz et al., 1980). Together, these represent a very small percentage of the region covered with radiometric eTh highs that likely correspond to heavy mineral sand deposits.

Regional variations in source rock type

Regional variations in monazite and xenotime are correlated with regional variations in co-minerals and magnetic susceptibility (Tables 1-2, Figure 5), which in turn are associated with different source rock types. This suggests that it is possible to gain information regarding the sources of the heavy mineral sands. Monazite is usually observed in both high-grade metamorphic rocks and many types of igneous rocks, rutile is primarily observed in high-grade metamorphic rocks and staurolite is usually observed in low- to mid-grade metamorphic rocks (e.g., Force, 1980; Force, 1981).

Elevated magnetic susceptibilities are observed in igneous, low-grade metamorphic, and high-grade metamorphic rocks. However, in igneous and low-grade metamorphic rocks they are typically associated with magnetite, hematite and maghemite while in high-grade metamorphic rocks hematite and/or maghemite are rarer, and elevated susceptibilities are usually attributable to magnetite (Grant, 1984). Once magnetite is eroded into sediments, it is typically altered over time through oxidation and/or other weathering processes. Elevated magnetic susceptibilities in older sediments are thus commonly attributable to hematite, maghemite, and to a lesser degree, ilmenite. Sediments with higher magnetic susceptibilities are thus usually associated with igneous and/or lower-grade metamorphic source rocks, unless they were recently eroded.

Regional variations in the heavy mineral assemblage suggest the following distribution of dominant source rocks (summarized in Table 1 and Figure 12):

- Heavy mineral sands in Virginia and northern North Carolina away from major river systems appear to be derived mainly from low- to medium- grade metamorphic rocks based on lower rutile, increased staurolite, lower monazite and high magnetic susceptibilities. This appears to be the case for sediments both near to and distal from the Fall Line.

- In southern North Carolina near the Fall Line, a combination of intermediate rutile, variable staurolite, mostly high magnetic susceptibility, and mostly high monazite concentrations suggests a combination of high-grade metamorphic rocks and igneous rocks as a source of monazite.
- In South Carolina and eastern Georgia near the Fall Line, high rutile, lower staurolite, high monazite, and low magnetic susceptibilities suggest that the heavy minerals are derived from high-grade metamorphic rocks.
- In western Georgia and eastern Alabama near the Fall Line, decreased rutile, mixed staurolite, and high magnetic susceptibilities combined with high monazite concentrations suggest a primarily igneous source for monazite, but perhaps with mixing from nearby areas.
- In eastern Tennessee and Mississippi, lower concentrations of denser minerals suggest that these heavy mineral sands were transported a long distance; variable rutile, magnetic susceptibility, and other properties also suggest significant mixing and/or differentiation during transport.
- In areas within ~100 km from the coast between northern Florida and South Carolina, the local variability of geophysical and geochemical properties of samples from these areas is high, suggesting mixing from multiple sources and differentiation of minerals during transport.

- Coastal plain sediments sampled from near the James River, Virginia, are low in rutile and staurolite, highly magnetic, and high in monazite, as inferred from Th content. This combination is consistent with an igneous source such as the Petersburg Granite, which the James River traverses farther inland. These sediments also showed fewer signs of alteration, suggesting they were more recently eroded.

Implications for sedimentary provenance and deposit formation

The regional variation in inferred source rock type allows us to consider the likely provenance of the heavy mineral sands. This is most feasible at the scale of the Piedmont and Blue Ridge belts since they are defined by different degrees of metamorphism and variable presence of igneous rocks. We find that the Atlantic Coastal Plain sub-regions near the Fall Line correspond best to proximal Piedmont/Blue Ridge belts that border those sediments (Figure 12). For example:

- In Virginia and northern North Carolina, Atlantic Coastal Plain sediments border the Piedmont's 10-20-km wide Eastern slate belt; properties of both are consistent with low grade metamorphism. These sediments show little resemblance to the 20-60-km wide high-grade metamorphic Raleigh/Goochland belt farther inland.
- In South Carolina and Eastern Georgia near the Fall Line, heavy mineral sand properties suggest high-grade metamorphism; these sediments border the 5-20-km wide high-grade metamorphic Kiokee and Uchee belts. Areas farther inland comprise mostly low-grade metamorphic and igneous rocks.
- In southern North Carolina near the Fall Line, the coastal plain sediments border the Lilesville pluton, which is associated with an eTh high (Figure 6) and thus likely to have higher concentrations of monazite and xenotime. Mixing of sediments derived from both

igneous and high-grade metamorphic rocks is suggested for this area. Heavy mineral sands from areas near the Kiokee belt may contribute to this area via northeasterly transport.

- In eastern Alabama near the Fall Line, coastal sediments border a complex series of Piedmont/Blue Ridge units that include granodiorite and monzonite, granite, gneisses, amphibolite, and schist, consistent with both igneous and mixed sources. Most areas farther inland are characterized by high-grade metamorphism although there are also intrusions present.

The belts further inland appear to contribute little to heavy mineral assemblages near the Fall Line, even though they crop out over a much wider area than those near the Fall Line. The dominant source of heavy mineral sands near the Fall Line thus appears to be those units that formed the ancient rocky coast during opening of the Atlantic Ocean. This in turn suggests that coastal processes contributed much more to heavy mineral sand deposit formation than alluvial processes since the latter would have delivered more sediment eroded from rocks farther inland. This scenario is similar to heavy mineral sand deposits in the Eucla and Murray Basins in Australia and along the coast of Brazil near the Atlantides belt, where strong correlations between beach placer composition and hinterland rocks have been observed (Keeling et al., 2015; Leonardos, 1974; Reid et al., 2013). In contrast however, there are Quaternary beach deposits within the Perth Basin and on the east coast of Australia where an extensive history of sediment reworking, longshore transport, and possibly tectonic uplift results in distinct differences between placer deposits and neighboring crystalline rock (Roy, 1999; Sircombe and Freeman, 1999).

While coastal processes appear to have dominated hard rock erosion and formation of heavy mineral sand deposits, the influence of alluvial processes can be observed at a more local scale within ancient and modern riverbeds. The narrow width of radiometric K and eTh highs along major river beds (Figure 3) strongly suggest that the influence of alluvial processes is spatially limited, as might be expected within river valleys. This has been observed in studies of modern costal sediments in the mid-Atlantic (Prusak and Mazzullo, 1987) and in part of the Old Hickory deposit in southern Virginia (Newton and Romeo, 2006). We note that intermediate eTh anomalies associated with major rivers in Virginia and North Carolina may be due to small amounts of monazite and xenotime derived from the Raleigh/Goochland belt (inland of the Eastern slate belt). Higher and wider eTh anomalies are associated with rivers further south, such as the Santee River in South Carolina. The latter traverses both the Kiokee belt and monazite-rich intrusions of the Charlotte belt and may contribute to sediment deposition at Folly Beach. Additional contribution might be derived from the high-Th rocks of the southern Inner Piedmont.

Heavy mineral concentrates in areas distal from the Piedmont, including coastal areas, Mississippi, and Tennessee suggest mixed sources. This is likely due to repeated reworking of sands and coast-parallel transport by longshore currents over time. We note, however, that Quaternary sediments in South Carolina, Georgia and Florida are generally richer in monazite and xenotime than their counterparts in northern North Carolina and Virginia. More generally, radiometric eTh anomalies are generally higher over Cenozoic sands south of the Cape Fear arch, and Bern et al. (2016) noted gradual decreases in monazite and xenotime of bulk sands with distance from the Fall Line. Together, these data suggest in areas south of the Cape Fear arch, elevated monazite and xenotime are maintained with distance from the Fall Line, albeit as smaller percentages of bulk sands. We hypothesize that repeated reworking, transport, and deposition of sands as the shoreline gradually moved from the ancient rocky coast resulted in an "inheritance" of composition. This inheritance becomes diluted, however, with mixing by longshore currents. Remarkably, if such inheritance is indeed present, it suggests that a very small portion of the Piedmont and Blue Ridge provinces, i.e., that which formed the rocky coast during Mesozoic opening, may be the dominant source of heavy minerals in the Atlantic Coastal Plain. Future work such as dating of detrital zircons and monazite may provide further insight into this possibility.

Implications for geophysical survey sensitivity

Geophysical methods can be used as exploration tools, but broad, regional differences in heavy mineral composition suggest how these tools might be "calibrated" when surveying in different areas for heavy mineral concentrates. For example, radiometric eTh anomalies in areas south of the Cape Fear arch such as those at Cheraw, S.C. typically reflect a heavy mineral composition with elevated monazite and xenotime, but the overall heavy mineral percentage is likely to be small compared to the same anomaly farther north in Aurelian Springs, N.C. In contrast, magnetic ground surveys south of the Cape Fear arch are generally lower in magnitude, and a magnetic anomaly observed in say Folly Beach, S.C. will be associated with a much higher heavy mineral sand percentage than the same anomaly in the Outer Banks, N.C. However, magnetic survey data can be complicated by weathering, alteration and leaching of magnetic minerals. Furthermore, care must be taken to distinguish sources from within the sediments and sources within the underlying crystalline basement. In general, beach or offshore environments may provide greater consistency when using magnetic data to image heavy mineral concentrations.

CONCLUSIONS

1. Combined geochemical, mineralogical and ground geophysical survey data support an interpretation of broad eTh highs in NURE aeroradiometric data indicating the occurrence of monazite- and xenotime-bearing heavy mineral sands across the coastal plain of the southeastern United States.
2. Regional radiometric data support previous studies at local scales which show that geophysical surveys can help identify and delineate heavy mineral concentrations.
3. The sensitivity of each geophysical method varies according to broad regional differences in the heavy mineral assemblage, with magnetic methods showing greater response to heavy minerals north of the Cape Fear arch in North Carolina and radiometric methods showing greater response farther south.
4. Characterization of heavy mineral assemblages is aided by analyses of geophysical, geochemical, and mineralogical properties of heavy mineral separates. These variations show a strong correlation between the composition of coastal plain heavy mineral sands near the Fall Line and neighboring crystalline rock types, similar to placer deposits observed in several Australian basins and along Brazil's coastline near metamorphic rocks. In contrast, coastal areas of the southeastern U.S. farther from the Fall Line show heavy mineral concentrations that are more mixed and more fractionated, resembling coastal Quaternary placer deposits in Australia.
5. The correlation between heavy mineral sands and units of the ancient rocky coast suggests that coastal processes dominate heavy mineral sand deposition and accumulation in those areas. This is supported by relatively narrow radiometric anomalies associated with major rivers, indicating limited spatial influence of alluvial processes.

6. A dominance of coastal processes in turn suggests that smaller areas of the Piedmont and Blue Ridge provinces contribute more to heavy mineral sands in the adjacent coastal plain than previously assumed. With increasing distance from the Piedmont, compositions become more mixed, especially within 100 km of the Atlantic coastline. However, a small degree of compositional “inheritance” appears to be maintained.

ACKNOWLEDGEMENTS

We thank C. Ailes, B. Burton and J. Reitman for their help with collecting the ground geophysical survey data. H. Lowers assisted with sample preparation and analysis. We thank Iluka resources, Inc., and Southern Ionics, Inc., for providing access to private lands and for sharing drill data in areas surveyed. We thank the Florida Department of Agriculture, the Florida Park Service, the Georgia Department of Natural Resources, the National Park Service, South Carolina State Parks, and the U.S. Forest Service for providing access to various survey areas. We especially appreciate logistical assistance received from the National Park Service at Cumberland Island and the Florida Park Service at Little Talbot Island. Thoughtful discussions with Andrew Grosz, J. Wright Horton, Jr., and C. Saunders contributed to this manuscript. We thank Jeff Mauk, Mike Thomas and an anonymous reviewer for detailed and thoughtful reviews that helped the manuscript. This effort was supported by the U.S. Geological Survey Mineral Resources Program. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES

Bern, C.R., Shah, A.K., Benzel, W.M., and Lowers, H.A., 2016, The distribution and composition of REE-bearing minerals in placers of the Atlantic and Gulf coastal plains, USA: Journal of Geochemical Exploration, v. 162, p. 50-61.

Berquist, C.R., Shah, A.K., and Karst, A., 2015, Placer deposits of the Atlantic Coastal Plain: Stratigraphy, sedimentology, mineral resources, mining and reclamation: Guidebook Series of the Society of Economic Geologists, Inc., Guidebook 50, 48 p., ISSN 2374-6955 online.

Darby, D.A., 1984, Trace elements in ilmenite: A way to discriminate provenance or age in coastal sands: Geological Society of America Bulletin, v. 95, p. 1208-1218.

Dryden, L., 1958, Monazite in part of the southern Atlantic Coastal Plain: U.S. Geological Survey Bulletin 1042-L, p. 393-429.

Duval, J.S., Carson, J.M., Holman, P.B., and Darnley, A.G., 2005, Terrestrial radioactivity and gamma-ray exposure in the United States and Canada: U.S. Geological Survey Open-File Report 2005-1413. Available online only at http://pubs.usgs.gov/of/2005/1413/.

Ellefsen, K., Van Gosen, B.S., Fey, D., Budahn, J. Smith, S., and Shah, A.K., 2015, First steps of integrated spatial modeling of titanium, zirconium, and rare earth element resources within the Coastal Plain sediments of the southeastern United States: U.S. Geological Survey Open-file report 2015-1111, 40 p.

Force, E.R., 1980. The provenance of rutile: Journal of Sedimentary Petrology, v. 50, p. 485-488.

Force, E.R., 1991, Geology of titanium-mineral deposits: Geological Society of America Special Paper 259, 112 p.

Force, E.R., and Rich, F.J., 1989, Geologic evolution of Trail Ridge eolian heavy-mineral sand and underlying peat, northern Florida: U.S. Geological Survey Professional Paper 1499, 16 p.

Force, E.R., Grosz, A.E., Loferski, P.J., and Maybin, A.H., 1982, Aeroradioactivity maps in heavy-mineral exploration—Charleston, South Carolina, area: U.S. Geological Survey Professional Paper 1218, 19 p., 2 plates.

Garnett, R. H. T., and Bassett, N. C., 2005, Placer deposits, in Hedenquist, J. W., Thompson, J. F. H., Goldfarb, R. J., and Richards, J. P., eds., Economic Geology one hundredth anniversary volume 1905-2005: Littleton, Colorado, Society of Economic Geologists, p. 813-843.

Grant, F.S., 1984, Aeromagnetics, geology and ore environments, 1. Magnetite in igneous, sedimentary and metamorphic rocks: An overview: Geoexploration, v. 23, p. 303-333.

Grosz, A.E., 1983, Application of total-count aeroradiometric maps to the exploration for heavy-mineral deposits in the Coastal Plain of Virginia: U.S. Geological Survey Professional Paper 1263, 20 p., 5 plates.

Grosz, A.E., 1993, Use of geochemical surveys in Ti-Hf-REE-Th-U placer exploration—A mid-Atlantic-States example (Chapter R), in Scott, R.W., Jr., Detra, P.S., and Berger, B.R., eds., Advances related to United States and international mineral resources—Developing frameworks and exploration technologies: U.S. Geological Survey Bulletin 2039, p. 181–188.

Grosz, A.E., Cathcart, J.B., Macke, D.L., Knapp, M.S., Schmidt, Walter, and Scott, T.M., 1989, Geologic interpretation of the gamma-ray aeroradiometric maps of central and northern Florida: U.S. Geological Survey Professional Paper 1461, 48 p., 5 plates.

Grosz, A.E., Francisco, C.S.J., Jr., and Reid, J.C., 1992, Heavy-mineral concentrations associated with some gamma-ray aeroradiometric anomalies over cretaceous sediments in North Carolina: implications for locating placer mineral deposits near the fall zone: USGS Open-File Report 92-396, 27 p.

Grosz, A.E., and Schruben, P.G., 1994, NURE Geochemical and Geophysical Surveys – Defining prospective terranes for United States Placer Exploration: U.S. Geological Survey Bulletin 2097, 9 p., 2 plates.

Hatch, G.P., 2012, Dynamics in the global market for rare earths: Elements, v. 8, no. 5, p. 341–346.

Hatcher, R.D. and Odum, A.L., 1980, Timing of thrusting in the southern Appalachians, USA: model for orogeny?: Journal of the Geological Society of London, v. 137, p. 321-327.

Hatcher, R.D. and Zietz, I. 1980, Tectonic implications of regional aeromagnetic and gravity data from the southern Appalachians: *in* Wones, D.R., ed., The Caledonides in the USA.: IGCP Project 27: Caledonide Orogen: Virginia Tech Department of Geological Sciences, Memoir, v. 2, p. 235-244.

Hibbard, J.P., Stoddard, E.F., Secor, D.T., and Dennis, A.J., 2002, The Carolina Zone: overview of Neoproterozoic to Early Paleozoic peri-Gondwanan terranes along the eastern Flank of the southern Appalachians: Earth-Science Reviews, v. 57, p. 299-339.

Hoatson, D.M., Jaireth, S., and Miezitis, Y., 2011, The major rare-earth-element deposits of Australia— Geological setting, exploration, and resources: Geoscience Australia, 204 p.

Horton, J.W. and Dicken, C.L., 2001, Preliminary Geologic Map of the Appalachian Piedmont and Blue Ridge, South Carolina Segment: U.S. Geological Survey, Open-File Report 01-298, CD-ROM.

Keeling, J.L., Reid, A.J., Hou, B., Pobjoy, R., 2015. Provenance of zircon in heavy mineral sand deposits, western Murray Basin: Department of State Development, South Australia, Report Book, 2015/00031, 62 p.

Leonardos Jr., O.H., 1974, Origin and provenance of fossil and recent monazite deposits in Brazil: Economic Geology, v. 69, p. 1126-1128.

Long, K.R., Van Gosen, B.S., Foley, N.K., and Cordier, D., 2010, The principal rare earth elements deposits of the United States—A summary of domestic deposits and a global perspective: U.S. Geological Survey Scientific Investigations Report 2010–5220, 96 p., http://pubs.usgs.gov/sir/2010/5220/.

Meleik, M.L., Fouad, K.M., Wassef, S.N., Ammar, A.A. and Dabbour, G.A., 1978, Aerial and ground radiometry in relation to the sedimentation of radioactive minerals in the Damietta beach sands, Egypt: Economic Geology, v. 73, p. 1738-1748.

Mertie, Jr., J.B., 1953, Monazite deposits of the Southeastern Atlantic States: U.S. Geological Survey Circular 237, 31 p.

Mertie, Jr., J.B., 1979, Monazite in the granitic rocks of the southeastern Atlantic states – an example of the use of heavy minerals in geologic exploration: U.S. Geological Survey Professional Paper 1094, 86 p., 1 plate.

Mohanty, H., 2015, Country's only monazite processing plant goes on stream: Business Standard, October 9, 2015, available online at http://www.business-standard.com/article/companies/countrys-only-monazite-processing-plant-goes-on-stream-115100900778_1.html, accessed Dec. 21, 2015.

Mudge, S., and Teakle, M., 2003, Geophysical exploration for heavy-mineral sands near Mindarie, South Australia: Australian Society of Exploration Geophysicists (ASEG) Extended Abstracts 2003, no. 3, p. 249–255.

Naeser, N.D, Naeser, C.W., Newell, W.L., Southworth, S., Weems, R., and Edwards, L., 2006, Provenance studies in the Atlantic coastal plain: What fission-track ages of detrital zircons can tell us about the erosion history of the Appalachians: Geological Society of America Abstracts with Programs, Vol. 38, No. 7, p. 503.

Neathery, T. L., Bentley, R. D., Higgins, M. W., and Zietz, I., 1976. Preliminary interpretation of aeromagnetic and aeroradioactivity maps of the Alabama Piedmont: Geology, v. 4, p. 375-381.

Newton, M.C., III, and Romeo, A.J., 2006, Geology of the Old Hickory heavy mineral sand deposit, Dinwiddie and Sussex counties, Virginia, in Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: North Carolina Geological Survey Information Circular 34, p. 464-481.

North American Magnetic Anomaly Group, 2002, Magnetic Anomaly Map of North America: U.S. Geological Survey Special Map, http://pubs.usgs.gov/sm/mag_map/

Overstreet, W.C., 1967, The geologic occurrence of monazite: U.S. Geological Survey Professional Paper 530, 327 p., 2 plates

Owens, J.P. and Gohn, G., 1985. Depositional history of the Cretaceous Series in the U.S. Atlantic coastal plain: stratigraphy, paleoenvironments and tectonic controls of sedimentation: *in* Poag, C.W. (Ed.), Geologic Evolution of the United States Atlantic Margin. Van Nostrand Reinhold Company, New York, p. 25–86.

Peterson, C.D., Komar, P.D., and Scheidegger, K.F., 1986, Distribution, geometry, and origin of heavy mineral placer deposits on Oregon beaches: Journal of Sedimentary Petrology, v. 56, p. 67-77.

Pitkin, J.A. 1968. Airborne measurements of terrestrial radioactivity as an aid to geologic mapping: U.S. Geological Survey Professional Paper 516-F, v. 1-29, 42 p.

Prusak, D. and Mazzullo, J., 1987, Sources and provinces of late Pleistocene and Holocene sand and silt on the mid-Atlantic continental shelf, Journal of Sedimentary Petrology, v. 57, no. 2, p. 278-287

Ravat, D., Finn, C., Hill, P., Kucks, R., Phillips, J., Blakely, R., Bouligand, C., Sabaka, T., Elshayat, A., Aref, A., and Elawadi, E., 2009, A preliminary, full spectrum, magnetic anomaly grid of the United States with improved long wavelengths for studying continental dynamics--A website for distribution of data: U.S. Geological Survey Open-File Report 2009–1258, 2 p.

Reid, A., Keeling, J., Boyd, D., Belousova, E., Hou, B., 2013. Source of zircon in world-class heavy mineral placer deposits of the Cenozoic Eucla Basin, southern Australia from LA-ICPMS U-Pb geochronology: Sedimentary Geology, v. 286-287, p. 1–19.

Roy, P.S., 1999, Heavy mineral beach placers in southeastern Australia: Their nature and genesis: Economic Geology, V. 94, p. 567-588.

Secor, Jr., D.T., Snoke, A.W., and Dallmeyer, R.D., 1986, Character of the Alleghanian orogeny in the southern Appalachians: Part III. Regional tectonic relations: Geological Society of America Bulletin, v. 97, p. 1345-1353.

Shah, A.K. and Harris, M.S., 2012, Shipboard magnetic field data trace magnetic sources in marine sediments: Geophysical studies of the Stono and North Edisto Inlets near Charleston, South Carolina: U.S. Geological Survey Open-File Report 2012-1112.

Shah, A.K., Vogt, P., Rosenbaum, J., Newell, W., Cronin T., Willard, D., Hagen, R., Brozena, J., and Hofstra, A., 2012, Shipboard magnetic field "noise" reveals shallow heavy mineral sediment concentrations in Chesapeake Bay: Marine Geology, v. 303-306, p. 26-41.

Siddiquie, H.N., Gujar, A.R., Hashimi, N.H., and Valsangkar, A.B., 1984, Superficial mineral resources of the Indian Ocean, Deep Sea Research Part A: Oceanographic Research Papers, v. 31, p. 763-812.

Singh, H.N., Shanker, V.N., Neelakandan, V.N., and Singh, V.P., 2007, Distribution patterns of natural radioactivity and delineation of anomalous radioactive zones using in situ radiation observations in Southern Tamil Nadu, India, Journal of Hazardous Materials, v. 141, p. 264-272.

Sircombe, K.N., and Freeman, M.J., 1999, Provenance of detrital zircons on the Western Australia coastline—Implications for the geologic history of the Perth basin and denudation of the Yilgarn craton: Geology, v. 27., no. 10, p. 879-882.

Smith, S.M., 1997. National Geochemical Database: reformatted data from the National Uranium Resource Evaluation (NURE) Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) Program, Version 1.40 (2006): U.S. Geological Survey Open-File Report 97–492. WWW release only, URL: http://pubs.usgs.gov/of/1997/ofr-97- 0492/index.html.

Staatz, M.H., Armbrustmacher, T.J., Olson, J.C., Brownfield, I.K., Brock, M.R., Lemons, J.F., and Clingan, B.V., 1979, Principal thorium resources in the United States: U.S. Geological Survey Circular 805, 42 p.

Staatz, M.H., Hall, R.B., Macke, D.L., Armbrustmacher, T.J., and Brownfield, I.K., 1980, Thorium resources of selected regions in the United States: U.S. Geological Survey Circular 824, 32 p.

Staff, Bureau of Mines, 1987, An economic reconnaissance of selected heavy mineral placer deposits in the U.S. Exclusive Economic Zone: Bureau of Mines Open File Report 4-87, 130 p.

Tse, P.-K., 2011, China's rare-earth industry: U.S. Geological Survey Open-File Report 2011–1042, 11 p.

Van Gosen, B.S., Fey, D.L., Shah, A.K., Verplanck, P.L., and Hoefen, T.M., 2014, Deposit model for heavy-mineral sands in coastal environments: U.S. Geological Survey Scientific Investigations Report 2010–5070–L, 51 p., http://dx.doi.org/10.3133/sir20105070L.

Watson, T.L. and Hess, F.L., 1913, Zirconiferous sandstone near Ashland, Virginia: *in* Watson, T.L., Hess, F.L. and Stose, G.W., eds., Biennial Report on the Mineral Production of Virginia During the Calendar Years 1911 and 1912: With Chapters on Zirconiferous Sandstone Near Ashland, Virginia: Charlottesville, Virginia, University of Virginia, Report No. 8, 76 p.

Wynn, J.C., Grosz, A.E., and Foscz, V.M., 1985, Induced polarization and magnetic response of titanium placer deposits in the southeastern United States: U.S. Geological Survey Open-File Report 85-756, 42 p.

Table 1. Summary of field site survey and heavy mineral separate properties

Site	Location (latitude, longitude degrees)	Max field eTh (ppm)	Laboratory sample eTh (ppm)	Magnetic Susceptibility (x 10^{-3} SI)	Monazite present?	Th (ppm)	La (ppm)	Lu (ppm)
Scientists Cliffs, Md.	38.51450, -76.51039	24.6	12.59	4.07	N	42.5	84.9	7.44
James River, Va.*	37.24243, -76.86176	1305.9		26		751	3002	
Aurelian Springs, N.C.	36.377, -77.745	27.7	40.09	14.34	N	200	408	6.98
Outer Banks, N.C.	35.68847, -75.48327	10.7	33.29	5.51	N	143	319	5.24
Cheraw, S.C.	34.63135, -79.92900	43.6		<0.1	Y			
Francis Marion, S.C.	33.22483, -79.48665	25.1		<0.1	Y			
Folly, S.C.	32.64340, -79.96450	826.8	154.14	2.9	Y	700	1640	13.1
Folkston, Ga.	31.041, -81.996	25.1	59.2	0.98		146	332	7.98
Cumberland Island, Ga.	30.84653, -81.42642	191.6	105.78	1.95	Y	269	686	9.37
Little Talbot Island, Fla.	30..44942, -81.40998	578.5	105.86	2.2	Y	312	801	11.4

*Heavy mineral separates were not available for this sample so measurements were conducted on bulk sands. The heavy mineral concentration was very high, however, with a sample density of 2.9 g/cm^3.

Table 2. Regional variations in sample heavy mineral separate properties

	Thorium content	Magnetic Susceptibility	Monazite content	Rutile content	Inferred dominant source type
VA and northern NC, away from major rivers	Low	Medium-high	Low	Low (with exceptions)	Low-medium grade metamorphic
Southern NC near the Fall Line	High	Medium, mixed	High	Medium, mixed	Mixed igneous and high-grade metamorphic
SC to GA near the Fall Line	High	Low (with exceptions)	High	High	High-grade metamorphic
Eastern AL near the Fall Line	High, mixed	High	High/mixed	Low	Mostly igneous, some mixed
Coastal SC, southeast GA, and northern FL	Mixed	Mixed	Mixed	Mixed	Mixed
TN and MS near the Fall Line	Low	Low	Low	Low	Ambiguous or mixed

FIGURE CAPTIONS

Figure 1. Geologic provinces of the southeastern U.S. Placer deposits containing ilmenite, rutile and zircon are present throughout Coastal Plain sediments. REE-bearing monazite and xenotime have also been observed in smaller amounts in various locales. Triangles represent ground survey areas. Elongate, lightly shaded areas spanning the Piedmont and Blue Ridge provinces represent “monazite belts” of Mertie (1979). Ages of Coastal Plain sediments were obtained from combined state geologic maps available online from the U.S. Geological Survey Mineral Resources On-Line Spatial Data website, http://mrdata.usgs.gov.

Figure 2. Left: Geologic belts of the Piedmont province (combined from Hatcher and Odum, 1980; Secor et al., 1986; Hibbard et al., 2002). Striped areas delineate “monazite belts” by Mertie (1979). The Raleigh/Goochland, Kiokee, Inner Piedmont, and Pine Mountain belts as well as the Blue Ridge province are associated with high-grade metamorphism, whereas the Charlotte, Carolina slate belt and Eastern slate belt are characterized by lower-grade metamorphism. The Charlotte and Carolina slate belts are marked by numerous intrusions.

Figure 3. Top: NURE radiometric equivalent thorium (eTh; ppm) superimposed over shaded relief topography. Bottom: NURE radiometric K (%) over shaded relief topography. Radiometric data were gridded from processed flight line data by Duval et al. (2005). Dashed line represents the inland boundary of Coastal Plain sediments, also referred to as the “Fall Line” where it is adjacent to the Piedmont and Blue Ridge provinces. Elevation data are from the Shuttle Radar Topography Mission (SRTM).

Figure 4. NURE radiometric equivalent thorium (eTh; left) and aeromagnetic anomaly (right) (Ravat et al., 2009) over the Piedmont and Blue Ridge provinces. Belts with high-grade metamorphic rocks are associated with eTh highs; broad magnetic highs in these areas are

commonly associated with secondary magnetite. Certain intrusive bodies in lower-grade metamorphic belts also exhibit local eTh highs and magnetic anomalies, especially in the Charlotte and Carolina slate belts. Gray lines delineate monazite belts by Mertie (1979).

Figure 5. Thorium (upper left) and monazite (lower left) concentrations, magnetic susceptibility (upper right) and rutile concentrations (lower right) measured from heavy mineral separates of sand samples are indicated with colored circles. Monazite and rutile were estimated using X-ray diffraction (XRD). Background image shows NURE aeroradiometric equivalent thorium (eTh). Polygons show geologic belts (see Figure 2). Additional sample characteristics are shown in the GSA Data Repository.

Figure 6. South Carolina airborne total count survey data (top) and NURE radiometric equivalent thorium (eTh; bottom) draped over shaded relief topography. The total count data were collected with a flight line spacing of 1.8 km, whereas the NURE data were spaced 3-6 km. Triangles represent ground survey sites labeled in Figure 1. Piedmont features from Horton and Dicken (2001).

Figure 7. Geophysical survey and grab sample measurements for Little Talbot Island, FL (A-C) and Folly Beach, SC (D-E). A: Satellite image, survey path (orange lines), and grab-sample thorium determined via XRF. B: Radiometric equivalent thorium (eTh) obtained via continuous surveys. C. Magnetic residual anomaly. D. Radiometric eTh obtained via 120-second assays (white x's) and grab-sample thorium estimated via XRF (boxes). E. Magnetic anomaly and grab-sample magnetic susceptibility (boxes).

Figure 8. Radiometric and magnetic anomaly data collected along single profiles on the eastern shores of Cumberland Island, GA (top profiles) and the Outer Banks, NC (bottom profiles). XRF measurements were also conducted on grab samples; gray symbols show sample Th. For the

Cumberland Island magnetic anomaly, the gray line shows the residual anomaly, and the black line shows the same anomaly with a linear trend removed. Note differences in y-axis scales.

Figure 9. Geophysical drill hole data in Aurelian Springs, NC. White circles show drill collars, colored squares show heavy mineral concentrations for 5-meter intervals. Pink circles show USGS auger holes AS-A1 (west) and AS-A2 (east). Background image shows elevation. Top: Radiometric eTh from 2-minute assays (colored swath). Drill hole data courtesy of Iluka, Inc. (colored boxes). Bottom: magnetic anomaly (colored swath). Inset shows location, colors as in Figure 1; triangle marks the survey site location.

Figure 10. Downhole measurements made on bulk sands derived from auger holes in Aurelian Springs, NC (AS; see Figure 7 for locations) and Cheraw, SC (CH; see also GSA data repository). “A1” auger holes are located within radiometric eTh highs; “A2” auger holes were in radiometric eTh lows. Th and Ti were measured by inductively coupled plasma–atomic emission spectrometry–mass spectrometry (ICP-AES-MS); magnetic susceptibility measured using a ZH Instruments SM-30.

Figure 11. Geophysical data and drill hole data near Folkston, Georgia. Circles show drill collars, colored squares show heavy mineral concentrations for 2.5-foot intervals. Yellow dashed line shows an approximate boundary of the heavy mineral resource. Background image shows satellite imagery. Top: Radiometric equivalent thorium (eTh; colored swath) and heavy mineral concentrations (HM; colored boxes). Middle: magnetic anomaly (colored swath) and heavy mineral concentrations (HM; colored boxes). Bottom: Location within a series of Pleistocene ridges. Triangle marks the survey site. Drill hole data provided courtesy of Southern Ionics, Inc.

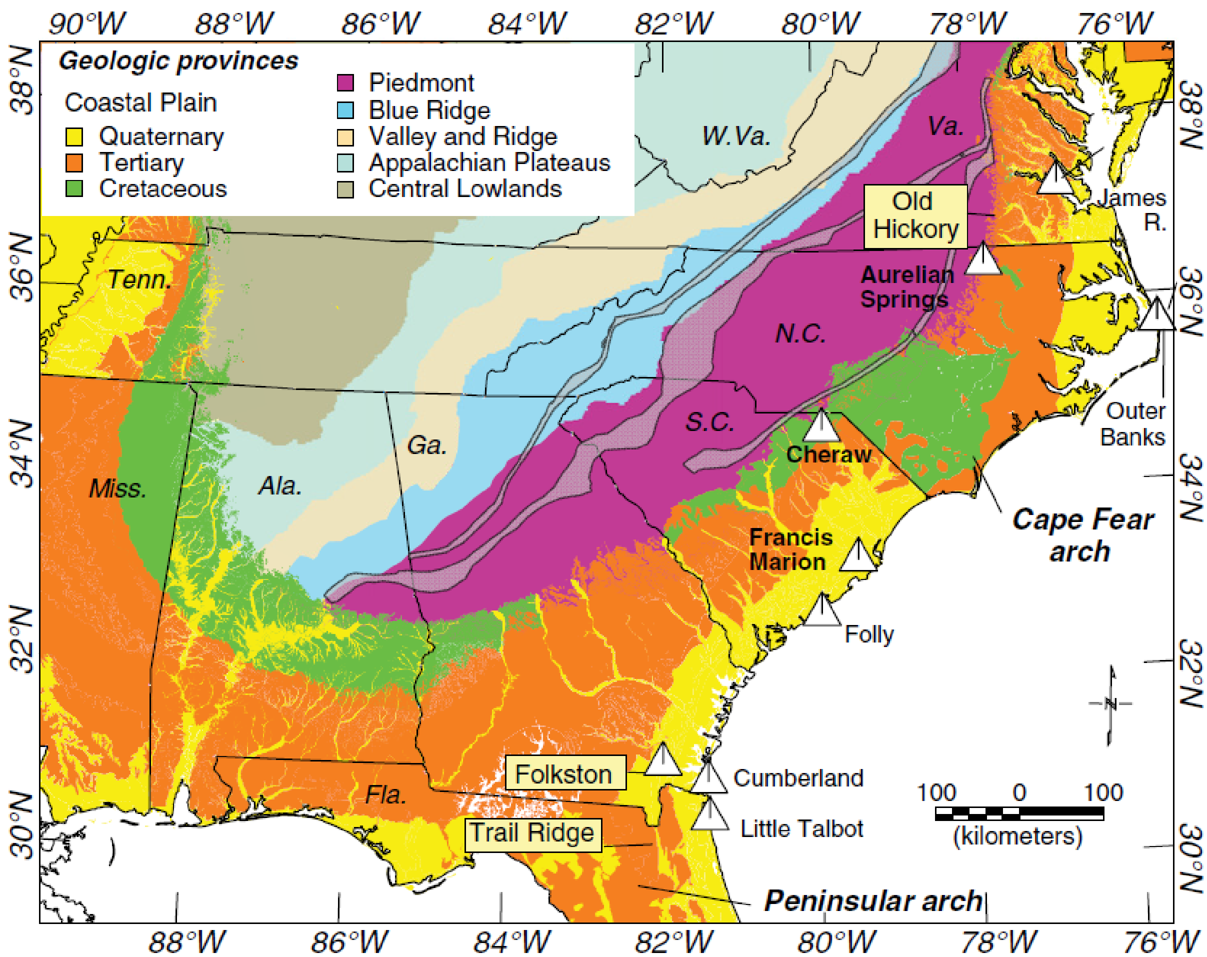
Figure 12. Top: Radiometric equivalent thorium (eTh; background) shows high values in parts of the Atlantic Coastal Plain inferred to contain elevated monazite and xenotime (red outlines);

grayed areas represent carbonate rocks (also associated with eTh highs). Black lines delineate belts of the Piedmont and Blue Ridge provinces. Bottom: Belts of the Piedmont and Blue Ridge have been colored according to rock type. Heavy mineral sands in the Atlantic Coastal Plain show regional compositional variations that suggest they were derived from specific rock types. These rock types correspond to Piedmont or Blue Ridge units adjacent to Atlantic Coastal Plain sediments. Dashed shapes delineate areas believed to contain elevated monazite and xenotime concentrations.

[1]GSA Data Repository item 201Xxxx, Comparison of the RS-125 to the Gamma Surveyor, is available online at www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

[2]GSA Data Repository item 201Xxxx, Additional sample properties, is available online at www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

[3]GSA Data Repository item 201Xxxx, Additional grid surveys for Aurelian Springs, N.C. and Cheraw, S.C., is available online at www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.



90°W
88°W
86°W
84°W
82°W
80°W
78°W
76°W
38°N
36°N
34°N
32°N
30°N
Geologic provinces
Coastal Plain
Quaternary
Tertiary
Cretaceous
Piedmont
Blue Ridge
Valley and Ridge
Appalachian Plateaus
Central Lowlands
W.Va.
Va.
Old Hickory
James R.
Tenn.
Aurelian Springs
N.C.
S.C.
Ga.
Miss.
Ala.
Cheraw
Outer Banks
Cape Fear arch
Francis Marion
Folly
Folkston
Cumberland
Fla.
Trail Ridge
Little Talbot
100
0
100
(kilometers)
Peninsular arch

Figure 1

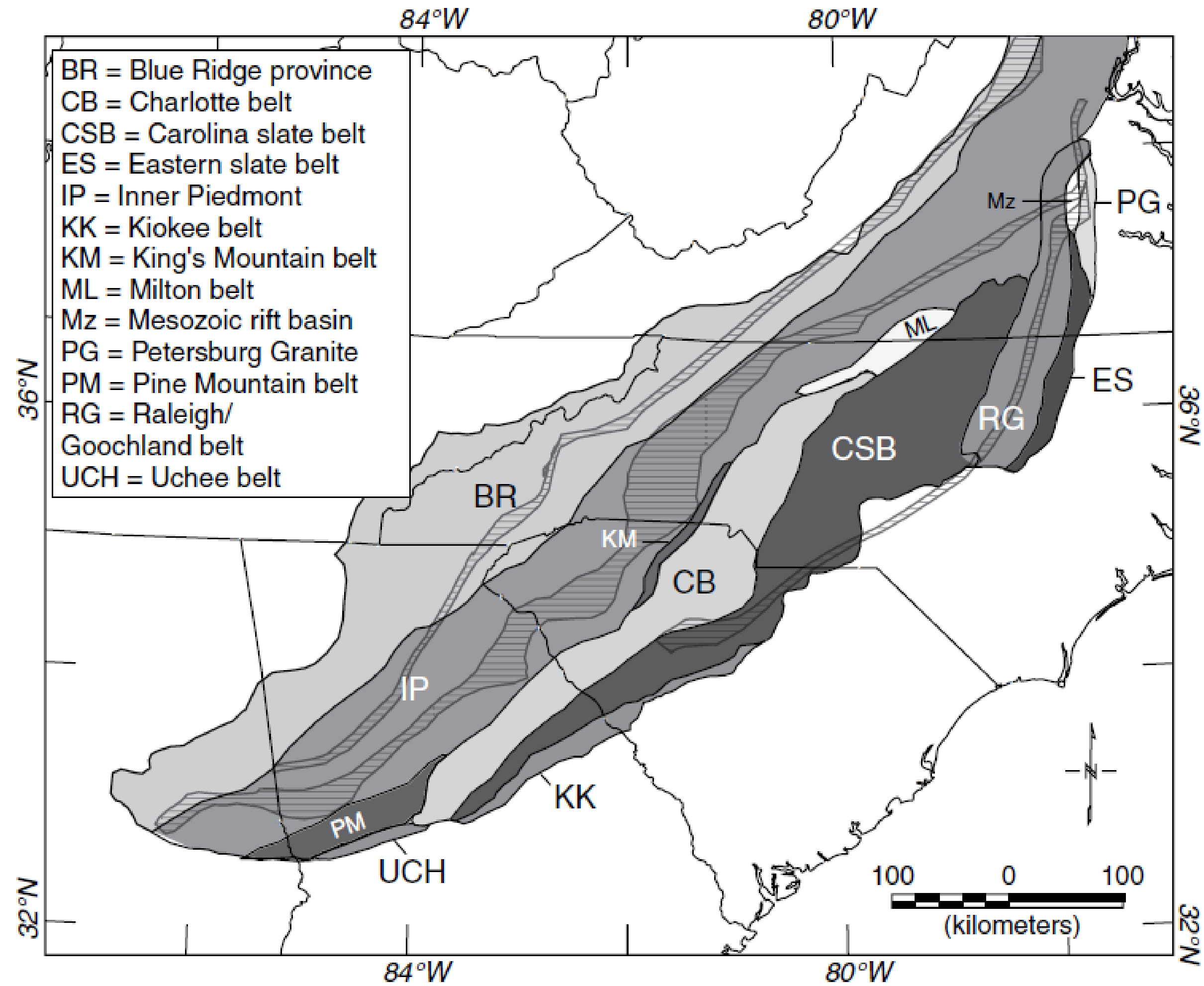
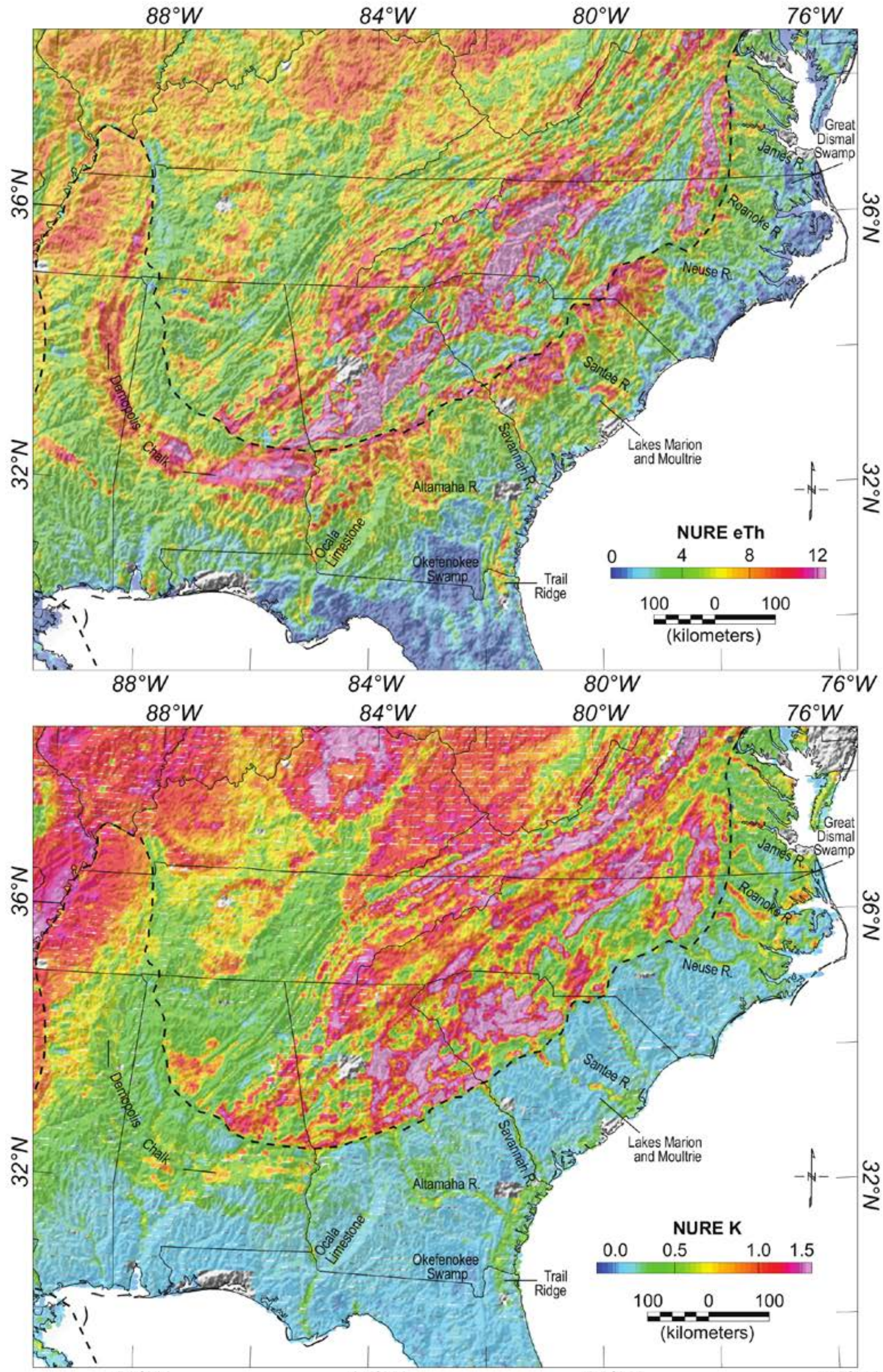
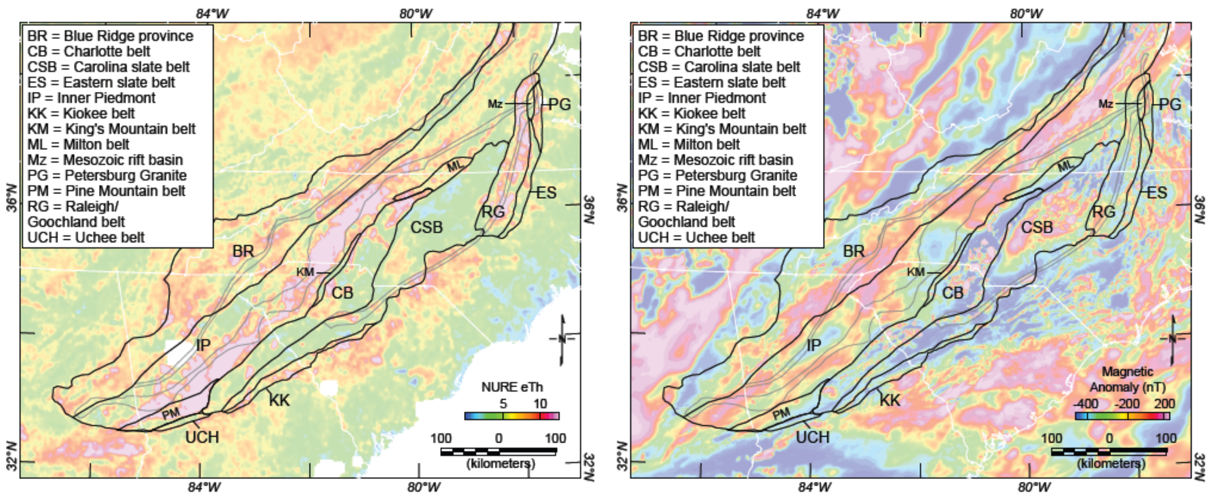

84°W
80°W
BR = Blue Ridge province
CB = Charlotte belt
CSB = Carolina slate belt
ES = Eastern slate belt
IP = Inner Piedmont
KK = Kiokee belt
KM = King's Mountain belt
ML = Milton belt
Mz = Mesozoic rift basin
PG = Petersburg Granite
PM = Pine Mountain belt
RG = Raleigh/
Goochland belt
UCH = Uchee belt
BR
KM
CB
CSB
RG
ES
ML
Mz
PG
IP
PM
UCH
KK
36°N
32°N
100
0
100
(kilometers)

Figure 2



1026

1027 Figure 3.



BR = Blue Ridge province
CB = Charlotte belt
CSB = Carolina slate belt
ES = Eastern slate belt
IP = Inner Piedmont
KK = Kiokee belt
KM = King's Mountain belt
ML = Milton belt
Mz = Mesozoic rift basin
PG = Petersburg Granite
PM = Pine Mountain belt
RG = Raleigh/
Goochland belt
UCH = Uchee belt
84°W
80°W
36°N
32°N
BR
CSB
CB
KM
IP
KK
PM
UCH
RG
ES
ML
Mz
PG
NURE eTh
5 10
100 0 100
(kilometers)
Magnetic
Anomaly (nT)
-400 -200 200

Figure 4

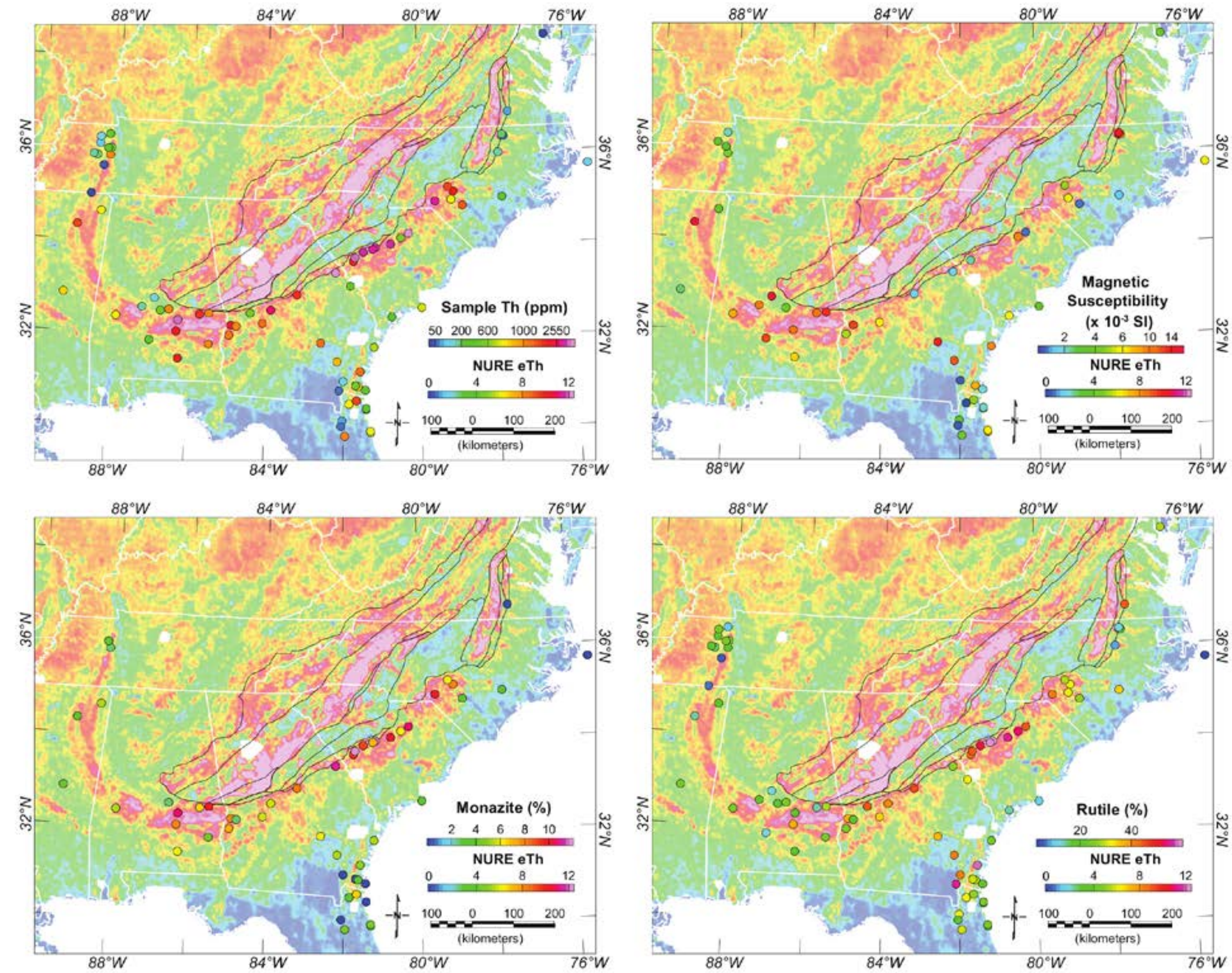

88°W
84°W
80°W
76°W
36°N
32°N
Sample Th (ppm)
50 200 600 1000 2550
NURE eTh
0 4 8 12
100 0 100 200
(kilometers)
Magnetic Susceptibility (x 10⁻³ SI)
2 4 6 10 14
Monazite (%)
2 4 6 8 10
Rutile (%)
20 40

Figure 5

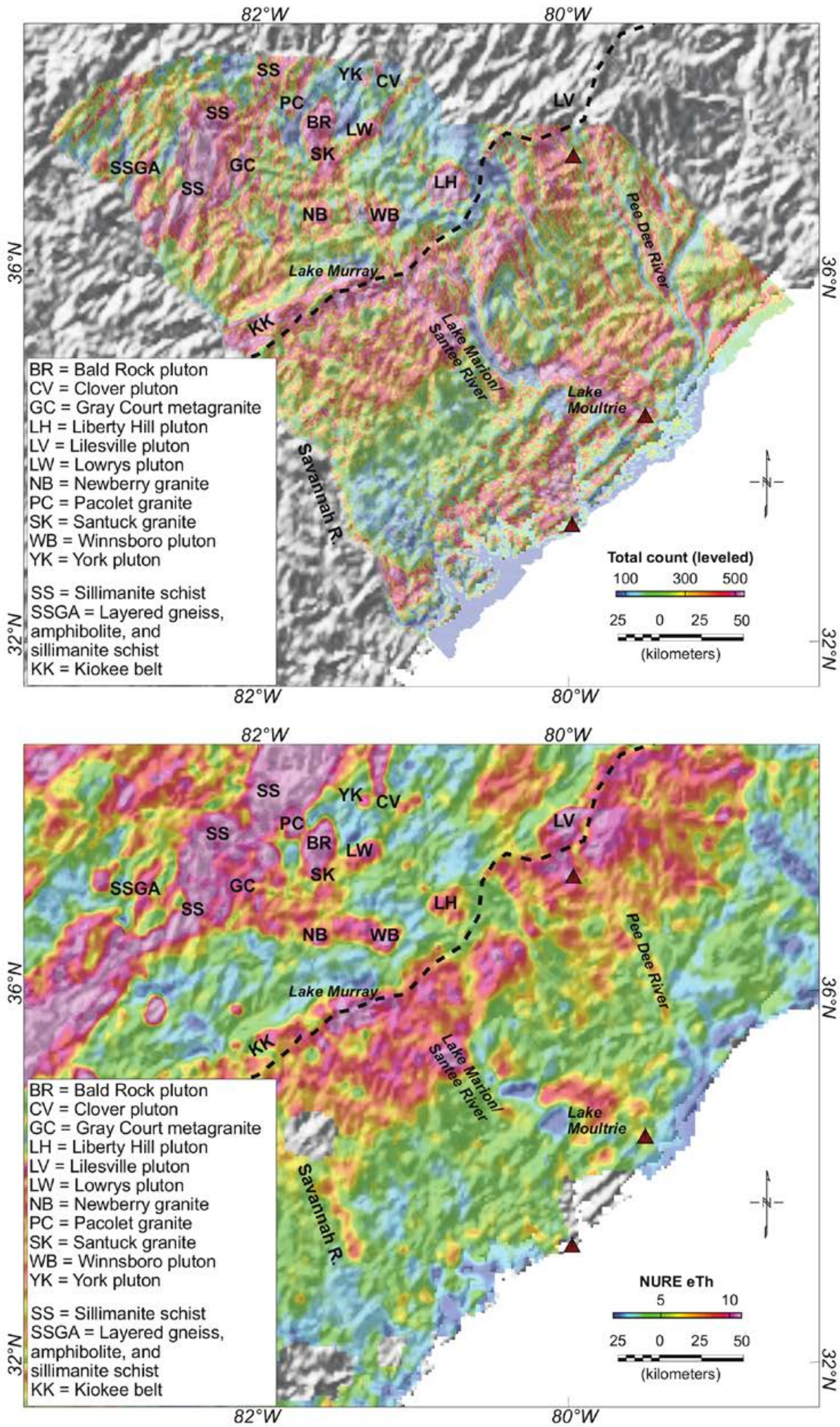

82°W
80°W
36°N
32°N
SS
YK
CV
PC
BR
LW
SK
SSGA
GC
LH
NB
WB
LV
KK
Lake Murray
Pee Dee River
Lake Marion/ Santee River
Lake Moultrie
Savannah R.
BR = Bald Rock pluton
CV = Clover pluton
GC = Gray Court metagranite
LH = Liberty Hill pluton
LV = Lilesville pluton
LW = Lowrys pluton
NB = Newberry granite
PC = Pacolet granite
SK = Santuck granite
WB = Winnsboro pluton
YK = York pluton
SS = Sillimanite schist
SSGA = Layered gneiss, amphibolite, and sillimanite schist
KK = Kiokee belt
Total count (leveled)
100 300 500
25 0 25 50
(kilometers)
NURE eTh
5 10

Figure 6

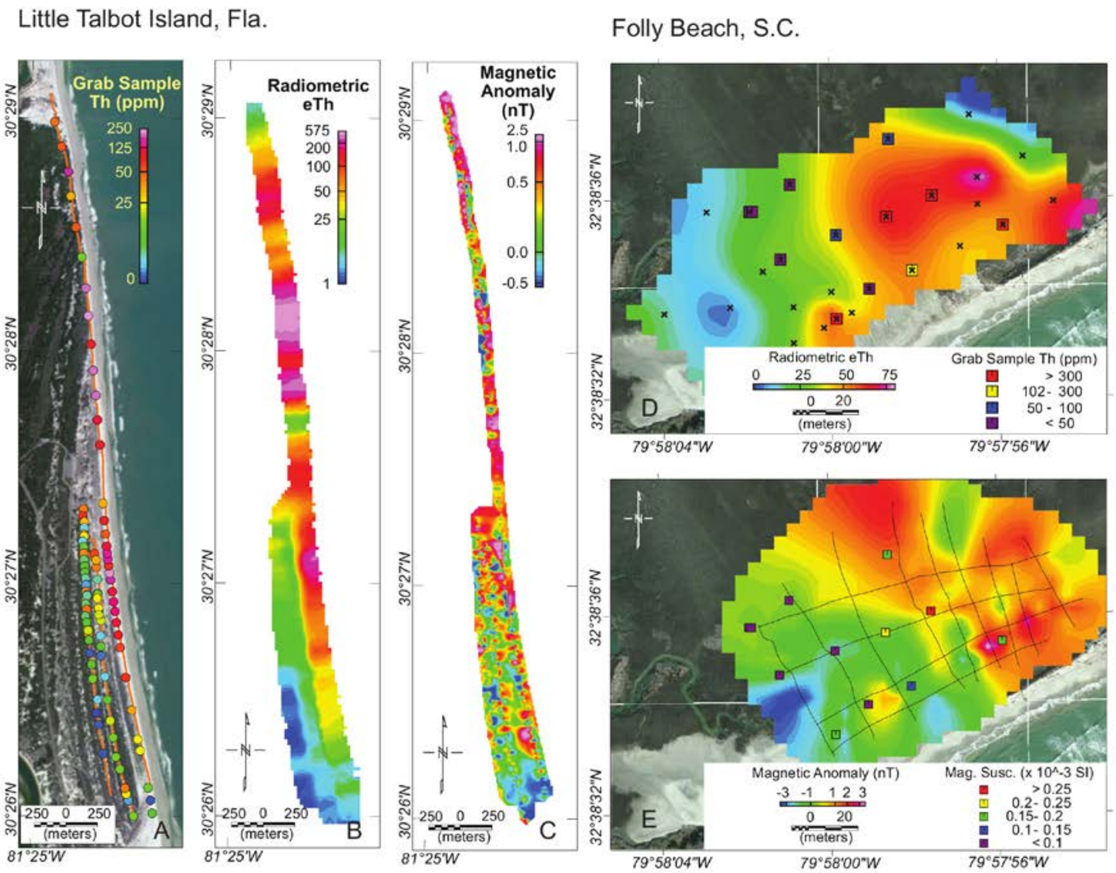
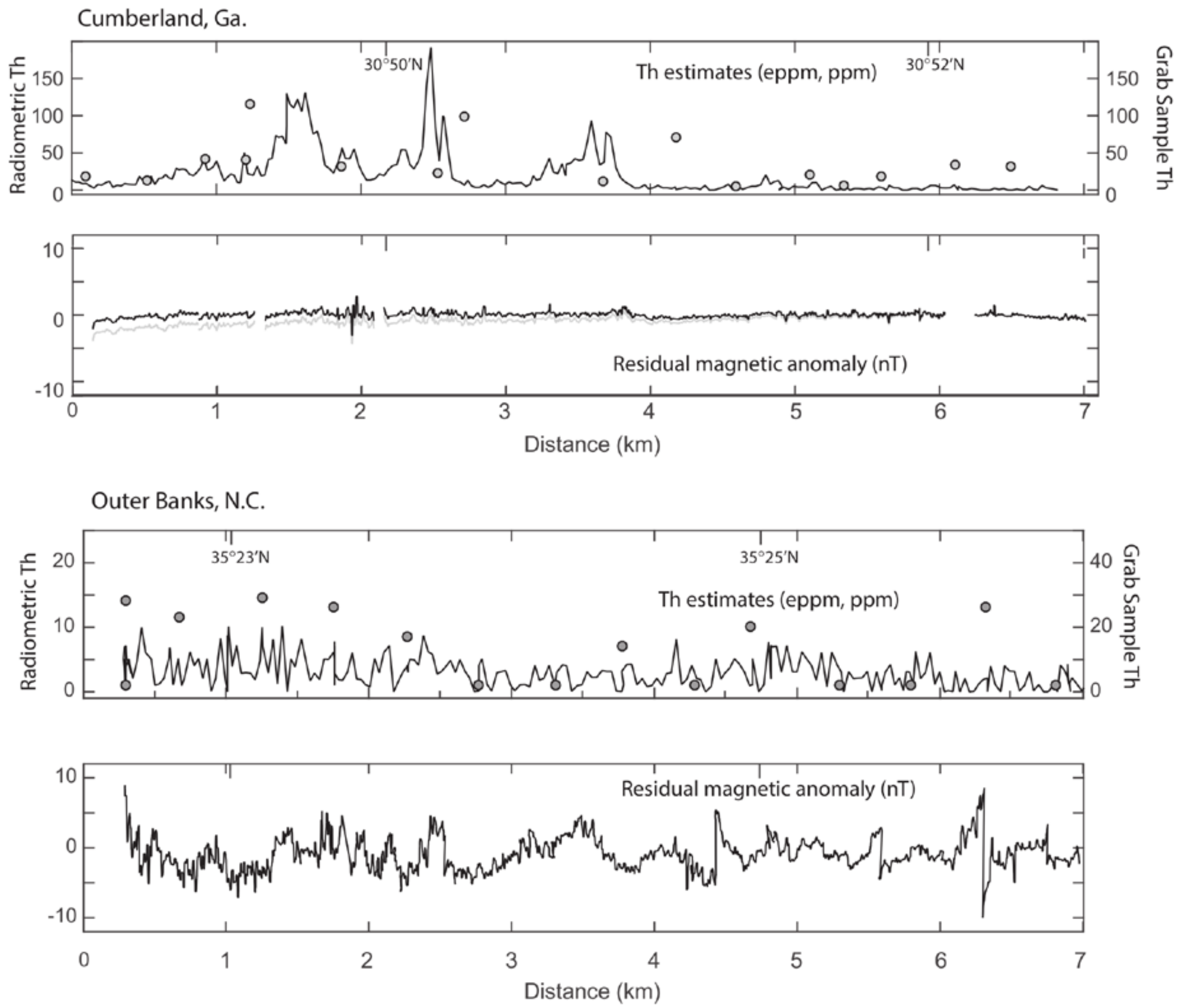
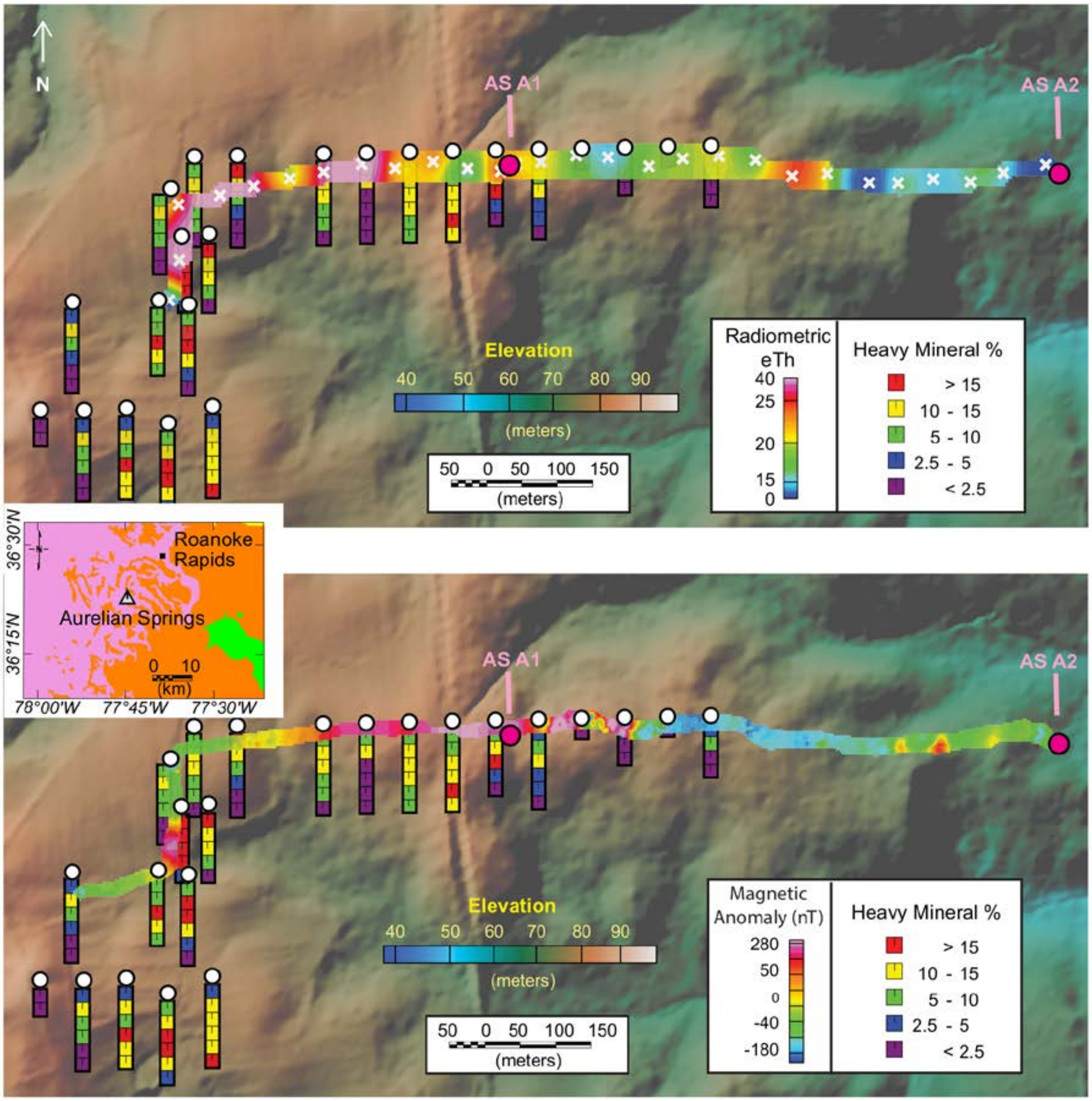

Little Talbot Island, Fla.
Folly Beach, S.C.
Grab Sample Th (ppm)
250
125
50
25
0
Radiometric eTh
575
200
100
50
25
1
Magnetic Anomaly (nT)
2.5
1.0
0.5
0.0
-0.5
30°29'N
30°28'N
30°27'N
30°26'N
81°25'W
250 0 250
(meters)
A
B
C
32°38'36"N
32°38'32"N
79°58'04"W
79°58'00"W
79°57'56"W
Radiometric eTh
0 25 50 75
Grab Sample Th (ppm)
> 300
102- 300
50 - 100
< 50
0 20
(meters)
D
Magnetic Anomaly (nT)
-3 -1 1 2 3
Mag. Susc. (x 10^-3 SI)
> 0.25
0.2- 0.25
0.15- 0.2
0.1- 0.15
< 0.1
E

Figure 7



Cumberland, Ga.
Radiometric Th
Grab Sample Th
30°50'N
30°52'N
Th estimates (eppm, ppm)
Residual magnetic anomaly (nT)
Distance (km)
Outer Banks, N.C.
35°23'N
35°25'N
Th estimates (eppm, ppm)
Radiometric Th
Grab Sample Th
Residual magnetic anomaly (nT)
Distance (km)

Figure 8



1042

1043 Figure 9

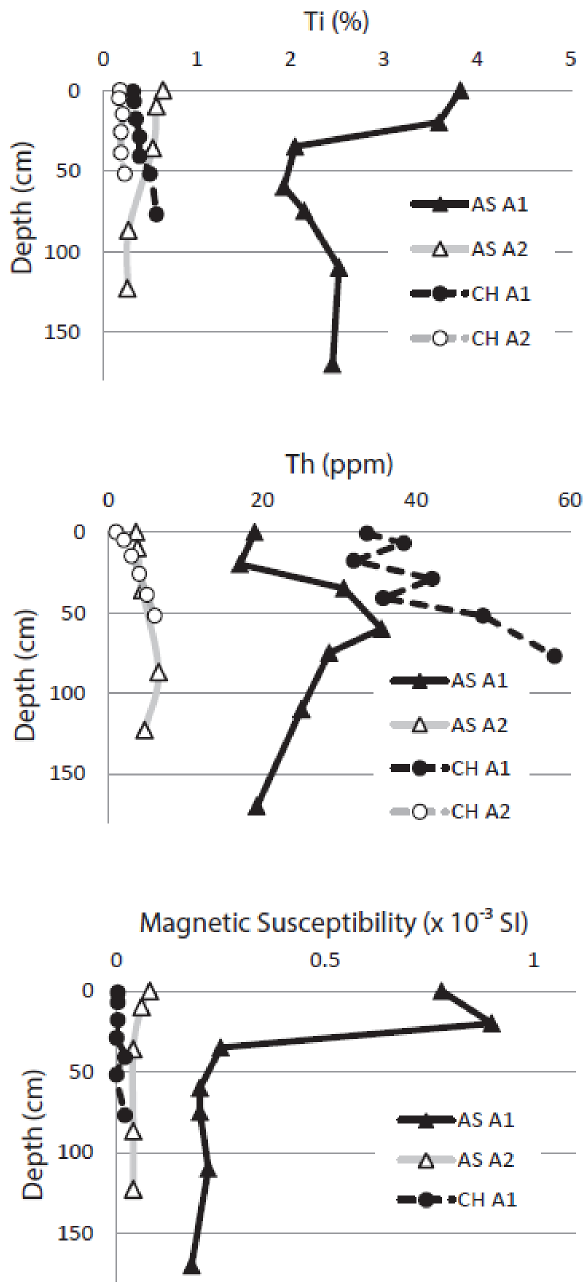

Ti (%)
0
1
2
3
4
5
0
50
100
150
Depth (cm)
AS A1
AS A2
CH A1
CH A2
Th (ppm)
0
20
40
60
0
50
100
150
Depth (cm)
AS A1
AS A2
CH A1
CH A2
Magnetic Susceptibility (x 10-3 SI)
0
0.5
1
0
50
100
150
Depth (cm)
AS A1
AS A2
CH A1

Figure 10

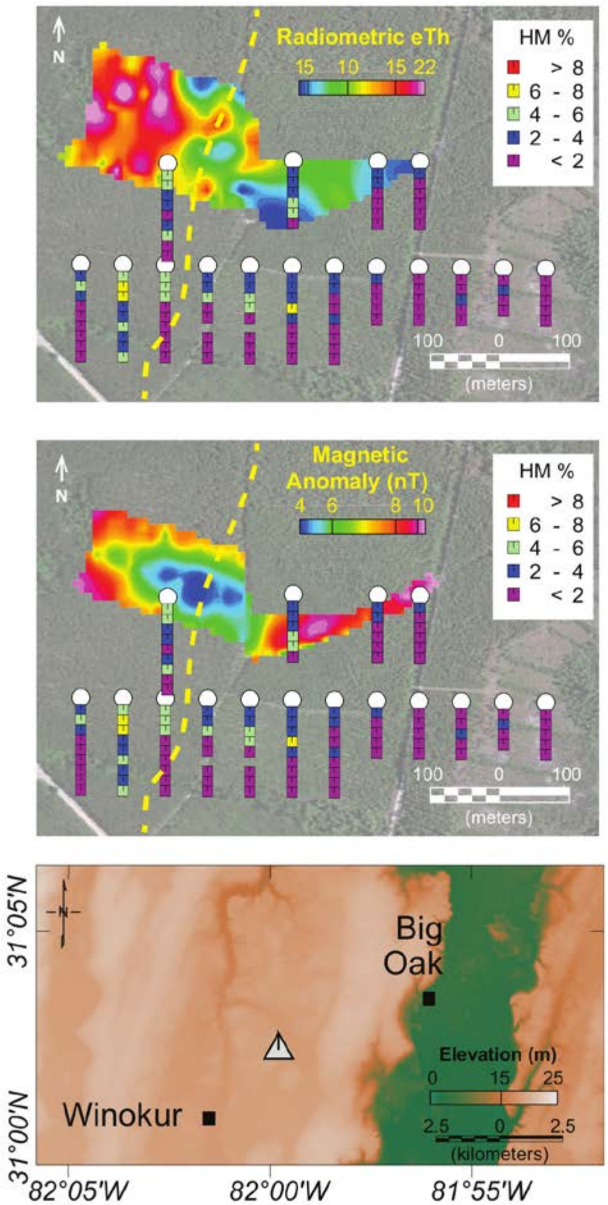

N
Radiometric eTh
15 10 15 22
HM %
> 8
6 - 8
4 - 6
2 - 4
< 2
100 0 100
(meters)
N
Magnetic
Anomaly (nT)
4 6 8 10
HM %
> 8
6 - 8
4 - 6
2 - 4
< 2
100 0 100
(meters)
N
31°05'N
31°00'N
Big
Oak
Winokur
Elevation (m)
0 15 25
2.5 0 2.5
(kilometers)
82°05'W
82°00'W
81°55'W

Figure 11

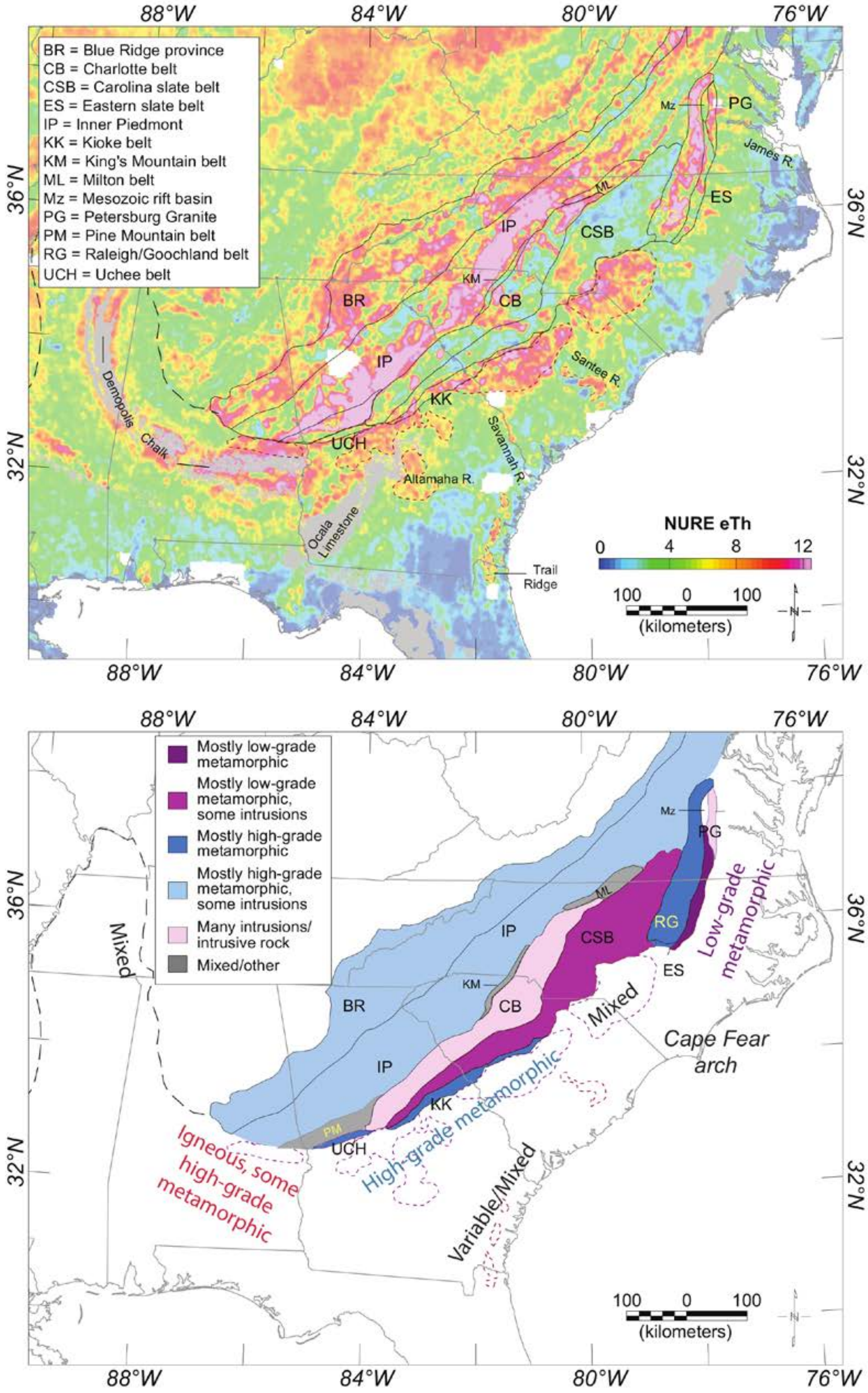

88°W
84°W
80°W
76°W
36°N
32°N
BR = Blue Ridge province
CB = Charlotte belt
CSB = Carolina slate belt
ES = Eastern slate belt
IP = Inner Piedmont
KK = Kioke belt
KM = King's Mountain belt
ML = Milton belt
Mz = Mesozoic rift basin
PG = Petersburg Granite
PM = Pine Mountain belt
RG = Raleigh/Goochland belt
UCH = Uchee belt
Mz
PG
James R.
ES
ML
IP
CSB
KM
BR
CB
IP
Santee R.
KK
Demopolis Chalk
UCH
Savannah R.
Altamaha R.
Ocala Limestone
Trail Ridge
NURE eTh
0
4
8
12
100
0
100
(kilometers)
Mostly low-grade metamorphic
Mostly low-grade metamorphic, some intrusions
Mostly high-grade metamorphic
Mostly high-grade metamorphic, some intrusions
Many intrusions/ intrusive rock
Mixed/other
Mz
PG
ML
RG
CSB
IP
Low-grade metamorphic
Mixed
ES
KM
BR
CB
Mixed
Cape Fear arch
IP
High-grade metamorphic
KK
PM
UCH
Igneous, some high-grade metamorphic
Variable/Mixed
100
0
100
(kilometers)

Figure 12