

# Titanium Mineral Resources in Heavy-Mineral Sands in the Atlantic Coastal Plain of the Southeastern United States



Scientific Investigations Report 2018–5045

**Cover.** Upper left: Layered deposits of heavy-mineral sands exposed by an open-pit mine within the Trail Ridge complex, near the town of Starke in northeastern Florida. Lower right: A concentrate of heavy minerals created from the first-stage processing of a heavy-mineral sands deposit. The mineral concentrate is primarily ilmenite, an important source of titanium oxide and zircon, used in refractory products such as ceramics and tiles. Lower left: Modern deposits of heavy minerals (dark sediments) on a beach of Little Talbot Island near Jacksonville, Florida. Photographs by B.S. Van Gosen, August, 2017.

# **Titanium Mineral Resources in Heavy-Mineral Sands in the Atlantic Coastal Plain of the Southeastern United States**

By Bradley S. Van Gosen and Karl J. Ellefsen

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**U.S. Department of the Interior  
U.S. Geological Survey**

**U.S. Department of the Interior**

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**U.S. Geological Survey**

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U.S. Geological Survey, Reston, Virginia: 2018

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Suggested citation:

Van Gosen, B.S, and Ellefsen, K.J., 2018, Titanium mineral resources in heavy-mineral sands in the Atlantic Coastal Plain of the southeastern United States: U.S. Geological Survey Scientific Investigations Report 2018–5045, 32 p., <https://doi.org/10.3133/sir20185045>.

ScienceBase data release files that support this report are available at <https://doi.org/10.5066/F7J38R16>.

ISSN 2328-0328 (online)

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## Conversion Factors

U.S. customary units to International System of Units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km <sup>2</sup> )

International System of Units to U.S. customary units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
	Length	
meter (m)	3.281	foot (ft)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
metric ton (t)	1.102	ton, short (2,000 lb)
metric ton (t)	0.9842	ton, long (2,240 lb)

## Abbreviations

GIS	Geographic Information System
HMS	heavy-mineral sands
ICP-AES	inductively coupled plasma-atomic emission spectrometry
IP	induced polarization
NGS	National Geochemical Survey ( <a href="https://mrdata.usgs.gov/geochem/">https://mrdata.usgs.gov/geochem/</a> )
REE	rare earth element
U.S.	United States
USGS	U.S. Geological Survey



# Titanium Mineral Resources in Heavy-Mineral Sands in the Atlantic Coastal Plain of the Southeastern United States

By Bradley S. Van Gosen and Karl J. Ellefsen

## Abstract

This study examined titanium distribution in the Atlantic Coastal Plain of the southeastern United States; the titanium is found in heavy-mineral sands that include the minerals ilmenite ( $\text{Fe}^{2+}\text{TiO}_3$ ), rutile ( $\text{TiO}_2$ ), or leucoxene (an alteration product of ilmenite). Deposits of heavy-mineral sands in ancient and modern coastal plains are a significant feedstock source for the titanium-dioxide pigments industry. Currently, two heavy-mineral sands mining and processing operations are active in the southeast United States producing concentrates of ilmenite-leucoxene, rutile, and zircon. The results of this study indicate the potential for similar deposits in many areas of the Atlantic Coastal Plain.

This study used the titanium analyses of 3,457 stream sediment samples that were analyzed as part of the U.S. Geological Survey's National Geochemical Survey program. This dataset was analyzed by an integrated spatial modeling technique known as Bayesian hierarchical modeling to map the regional-scale, spatial distribution of titanium concentrations. In particular, clusters of anomalous concentrations of titanium occur (1) along the Fall Zone, from Virginia to Alabama, where metamorphic and igneous rocks of the Piedmont region contact younger sediments of the Coastal Plain; (2) a paleovalley near the South Carolina and North Carolina border; (3) the upper and middle Atlantic Coastal Plain of North Carolina; (4) the majority of the Atlantic Coastal Plain of Virginia; and (5) barrier islands and stretches of the modern shoreline from South Carolina to northeast Florida. The areas mapped by this study could help mining companies delimit areas for exploration.

## Keywords

Titanium resources, Atlantic Coastal Plain, heavy-mineral sands, stream sediments.

## Introduction

This study examined the distribution of titanium (Ti) in deposits of ancient and recent sediments within the Atlantic Coastal Plain of the southeastern United States (U.S.), a broad flat plain along part of the eastern seaboard of the U.S. bordered on the east by the Atlantic Ocean. Large areas of the Atlantic Coastal Plain contain clastic sediments enriched in heavy minerals, "heavy-mineral sands," representing sources of titanium, in the form of the minerals ilmenite ( $\text{Fe}^{2+}\text{TiO}_3$ ), rutile ( $\text{TiO}_2$ ), and leucoxene (an alteration product of ilmenite). We used the titanium concentrations of 3,457 preexisting stream sediment samples that were analyzed as part of the U.S. Geological Survey's (USGS) National Geochemical Survey (NGS) program (USGS, 2004). The samples selected for this study were those collected from stream channels associated with the coastal plain. Titanium concentrations in the stream sediments were used as a proxy for mapping the distribution of potential titanium resources within the coastal plain. The stream-sediment sample sites were well distributed across the study area. This dataset was analyzed by an integrated spatial modeling technique known as Bayesian hierarchical modeling to map the regional-scale, spatial distribution of titanium concentrations, which are related to ilmenite, leucoxene, and rutile abundances in heavy-mineral sands across the vast surface of the Atlantic Coastal Plain. Our study area for this report includes the region of the Atlantic Coastal Plain that extends from eastern Alabama and northern Florida to Virginia (fig. 1).

This study builds upon an earlier geospatial study of the Atlantic Coastal Plain by Ellefsen and others (2015). That study was designed to map areas in the Atlantic Coastal Plain that appear most favorable for exploration and development of titanium minerals, zircon ( $\text{ZrSiO}_4$ ), and rare earth element (REE) resources (hosted in the minerals monazite and xenotime). Ellefsen and others (2015) integrated concentrations of titanium, zirconium (Zr), and REEs in the stream sediments (as proxies for titanium minerals, zircon, monazite and xenotime, respectively) with geological, geophysical, hydrological, and geographical data, as well a large set of airborne measurements of equivalent thorium concentrations (as a proxy for

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**Figure 1.** Map showing the extent of Upper Cretaceous and Cenozoic sediments of sand, gravel, silt, clays, and peat (yellow area) that form the Atlantic Coastal Plain of the southeastern United States (modified from Gohn, 1988). Red dots indicate recent heavy-mineral-sands operations: (1) the Concord and (2) Brink mines of Iluka Resources in southeastern Virginia; (3) the Mission mine of Southern Ionics Inc. in southeastern Georgia; and the (4) Trail Ridge operations (Trail Ridge, Maxville, and Highlands deposits) of the Chemours Company in northeastern Florida. The “Fall Zone” (or “Fall Line”) is a regional term used to describe the contact zone between the lithified basement rocks of the Piedmont region on the west and much younger sediments of the Atlantic Coastal Plain on the east.

monazite and xenotime) (Hill and others, 2009). The study by Ellefsen and others (2015) established the foundation for this current investigation. Bayesian hierarchical modeling as used in the current study is a robust way to map both the titanium concentrations and their variability.

This study has identified several areas where clusters of titanium-rich sediments occur within the Atlantic Coastal Plain. These clusters, described in this report, indicate areas that could be investigated for exploration of undeveloped titanium resources. An accompanying data release (Ellefsen, 2017) provides the raw data used in the analyses. This USGS data release can be accessed through ScienceBase at <https://www.sciencebase.gov/catalog/item/59245249e4b0b7ff9fb2723b> or <https://doi.org/10.5066/F7J38R16>.

## Heavy-Mineral Sands

Ancient and modern coastal deposits of heavy-mineral sands (HMS) are sources of several “heavy” industrial minerals with mining and processing operations on many coastal regions worldwide (Van Gosen and others, 2014). For example, HMS deposits are a significant source of titanium feedstock for the titanium dioxide (TiO<sub>2</sub>) pigments industry. The titanium feedstock is extracted from the minerals ilmenite (Fe<sup>2+</sup>TiO<sub>3</sub>), rutile (TiO<sub>2</sub>), and leucoxene (an alteration product of ilmenite). HMS deposits are also the principal source of zircon (ZrSiO<sub>4</sub>), which is used mostly in refractory products. Sometimes monazite [(Ce,La,Nd,Th)PO<sub>4</sub>] is recovered as a byproduct mineral and is sought for the rare earth elements and thorium that it contains (Ault and others, 2016; Sengupta and Van Gosen, 2016; Van Gosen and Tulsidas, 2016).

HMS are sediments containing dense (heavy) minerals that accumulate with sand, silt, and clay in coastal environments locally forming economic concentrations of heavy minerals. Economic (mined) HMS deposits include Holocene (Recent) sediments on modern coasts (such as examples in India and Brazil) (Van Gosen and others, 2014), as well as coastal deposits formed by transgressions and regressions of the seas during intervals in the Quaternary, Tertiary (Paleogene and Neogene), and Cretaceous (such as in Australia and the southeastern U.S.) (Gohn, 1988; Van Gosen and others, 2014; Hou and Keeling, 2017). Economic deposits typically contain heavy-mineral concentrations of at least 2 percent.

Individual “heavy minerals” are commonly defined as minerals with a specific gravity greater than about 2.85 (table 1). These minerals are generally resistant to chemical weathering and physical degradation and thus survive well in fluvial and coastal environments. Heavy minerals in coastal HMS deposits may include, in order of general abundance: ilmenite, leucoxene, rutile, magnetite, zircon, staurolite, kyanite, sillimanite, tourmaline, garnet, epidote, hornblende, spinel, iron oxides (hematite, goethite, and limonite), sulfides (such as pyrite), anatase, monazite, cassiterite, and xenotime. Of these, ilmenite, leucoxene, rutile, and zircon are the primary economic minerals; garnet, staurolite, monazite, cassiterite, and

xenotime are occasionally recovered as byproducts. The heavy minerals as a suite usually make up no more than 15 weight percent of a deposit, and most often much less; quartz grains and clay minerals generally form the bulk of the sediment. Typically, approximately 80 percent of a heavy-mineral suite is ilmenite, rutile, iron-oxide minerals, and zircon, with lesser amounts of leucoxene, monazite, garnets, sillimanite, and staurolite. The geology of HMS deposits and examples of significant districts are summarized in Van Gosen and others (2014).

To form HMS deposits, heavy minerals are disaggregated from inland source rocks by weathering and erosion, and the detritus is transported by streams and rivers to coastal areas. Here, the sediments are deposited, reworked by the actions of waves, tides, longshore drift, and wind. These physical processes sort the light and heavy minerals based primarily on their density, thereby concentrating the heaviest minerals as layered sediments in a variety of coastal depositional environments. The principal zone of mineral separation is the upper part of the beach face, also known as the foreshore or swash zone (fig. 2). The heaviest grains, which have the highest settling velocities, are deposited at the bottom of the swash zone. Coarse low-density detritus is carried by backwash to the wave zone, whereas heavy minerals tend to settle out and accumulate on the upper beach face (Komar and Wang, 1984). HMS can accumulate in deltas, the beach face, sand dunes landward of the shore, the offshore (seaward of the beach), in barrier islands, and in tidal lagoons, as well as the channels and floodplains of rivers, streams, and estuarine channels; see Hou and Keeling (2017) for a discussion on various HMS depositional environments. Economic deposits of heavy-mineral sands represent innumerable thin layers of heavy-mineral accumulations separated by very small unconformities (fig. 3).

Processes that one can observe now provide modern analogues to the processes that are assumed to have formed the ancient deposits (figs. 3 and 4). That is, the natural processes that act upon coastal areas today, such as effects of waves, storm surges, tides, longshore drift, and a sediment supply from inland sources are assumed to be similar processes to those that formed HMS over thousands to millions of years ago along ancient shores across the world.

Dozens of coastal deposits of HMS are serving as internationally important sources of some industrial minerals with active mining and processing operations on every continent except Antarctica (Van Gosen and others, 2014). Since about 2010, about 96 percent of the zircon, 90 percent of the rutile, 30 percent of the ilmenite, and 80 percent of the monazite produced by the global minerals industry was mined from coastal placer deposits of HMS (Australian Atlas of Mineral Resources, Mines, and Processing Centres, 2013). Ilmenite and rutile are the principal economic minerals derived from HMS, and zircon is typically recovered as a profitable coproduct. Australia and China are the major global producers of HMS (Australian Atlas of Mineral Resources, Mines, and Processing Centres, 2013). Recent exploration for HMS deposits has occurred in Australia, India, Kenya, Madagascar, South Africa, Sri Lanka, the U.S., and other countries (Van Gosen and others, 2014).

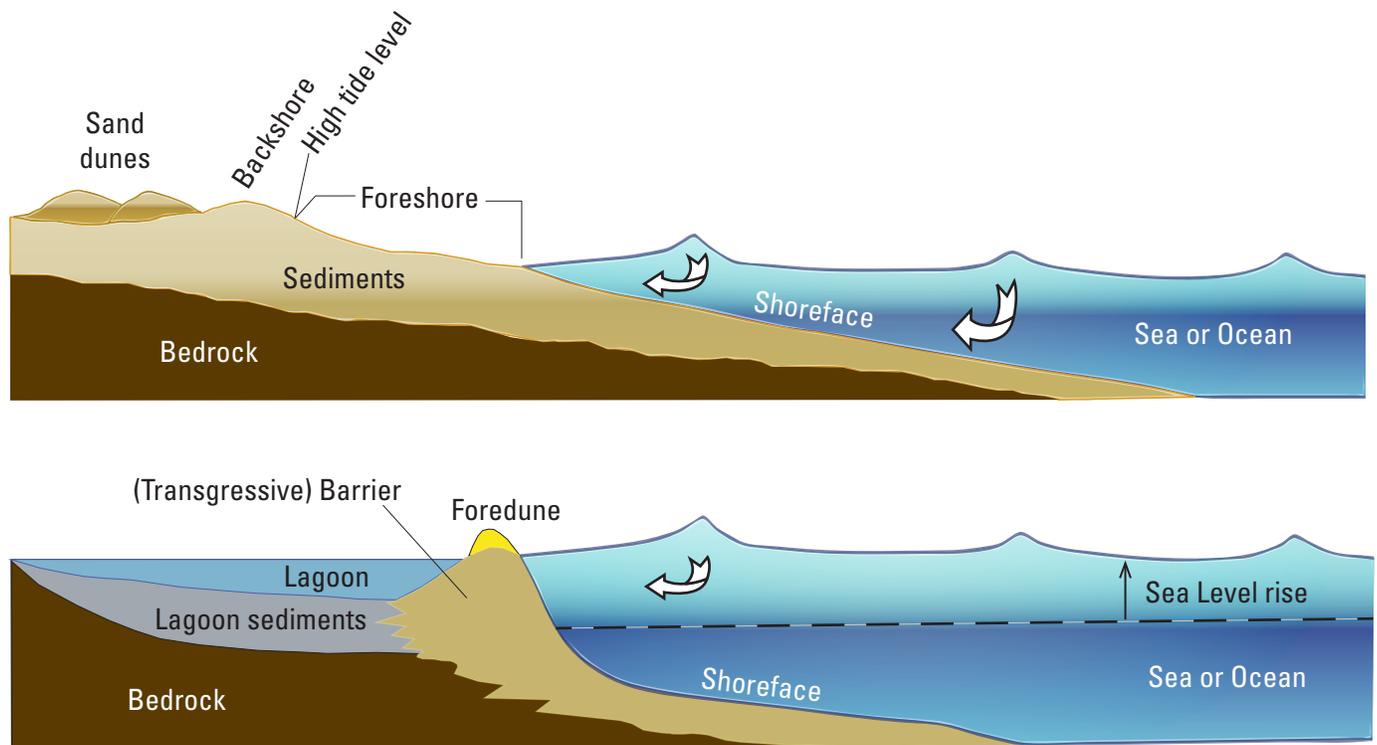
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**Table 1.** Common minerals in heavy-mineral sand deposits, listed in order of average specific gravity. “Heavy minerals” are generally defined as minerals that have a specific gravity greater than 2.85; leucoxene is an informal name for altered ilmenite. In nature, the specific gravity of a mineral varies from the mineral’s pure form due to impurities and alterations. The principal minerals of this study are shown in bold. For comparison, the common gangue minerals section lists other minerals most commonly mixed with the heavies in this deposit type, in particular, quartz. Hardness defined using Mohs hardness scale.

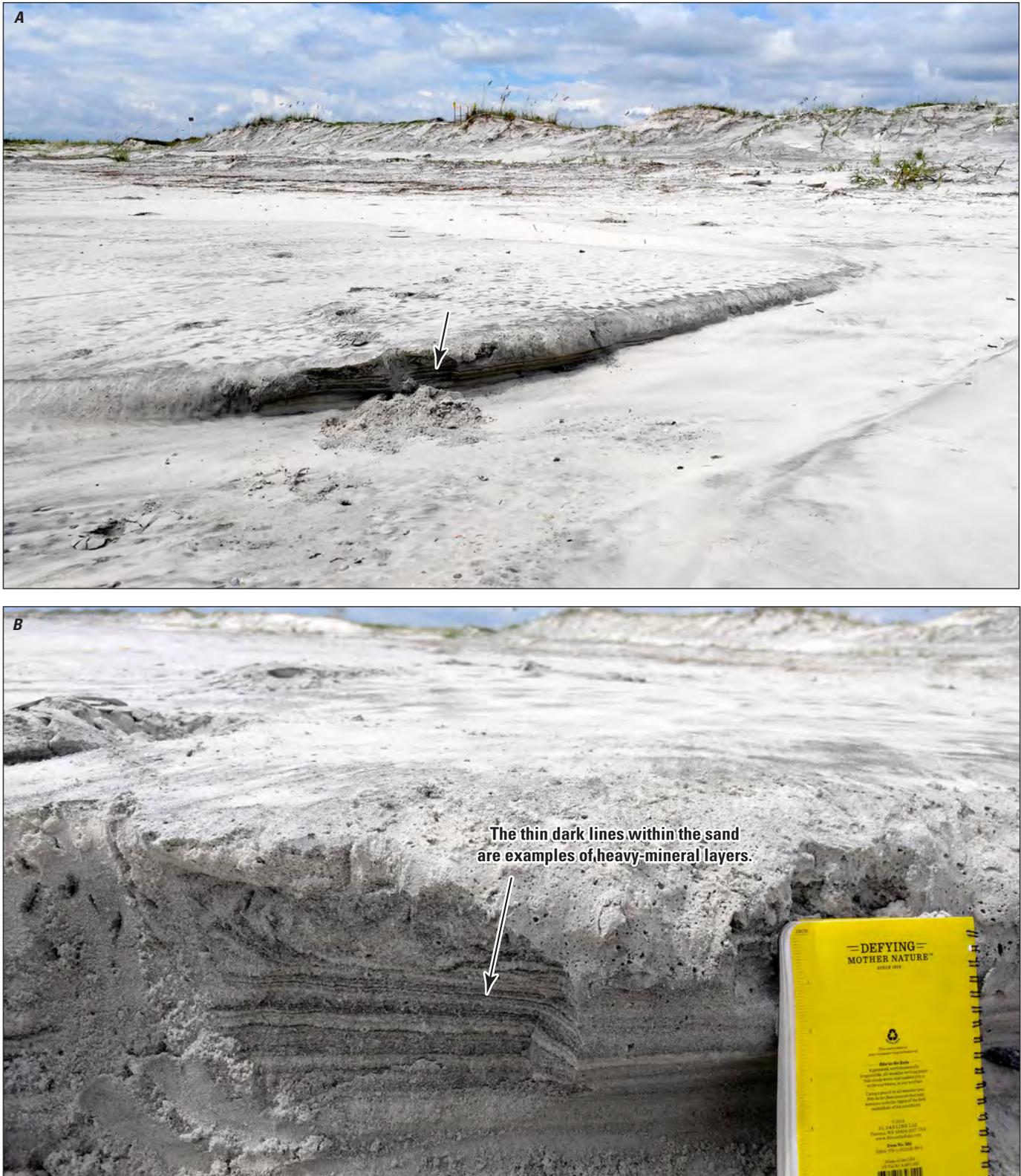
Heavy minerals	Ideal composition	Specific gravity	Hardness	Color	Stability in weathering	Provenance
Cassiterite	SnO <sub>2</sub>	7	6–7	reddish, brown, yellow	high	Igneous rocks, pegmatites, hydrothermal veins
Hematite	Fe <sub>2</sub> O <sub>3</sub>	5.3	5–6	steel-gray, black	low-moderate	Igneous, sedimentary and metamorphic rocks
Magnetite	Fe <sub>3</sub> O <sub>4</sub>	5.2	5.5–6.5	black, dark gray	moderate	Igneous and metamorphic rocks, hydrothermal veins
Pyrite	FeS <sub>2</sub>	5.0	6–6.5	yellow	low	Igneous, sedimentary and metamorphic rocks, hydrothermal veins
Monazite	(Ce,La,Y,Th)PO <sub>4</sub>	4.9–5.5	5–5.5	brownish red	high	Igneous and metamorphic rocks
Pyrolusite	MnO <sub>2</sub>	5.0	2–6.5	black, dark gray	low	Sedimentary, hydrothermal, and secondary
<b>Ilmenite</b>	FeTiO <sub>3</sub>	4.7	5–6	black	moderate-high	Igneous and metamorphic rocks
<b>Zircon</b>	(Zr,Hf,U)SiO <sub>4</sub>	4.2	7.5–8	many	high	Igneous and metamorphic rocks
Barite	BaSO <sub>4</sub>	4.5	3–3.5	shades of white, yellow	low	Pegmatites, hydrothermal veins
Xenotime	YPO <sub>4</sub>	4.4–5.1	4–5	brown, yellow	high	Igneous and metamorphic rocks
Goethite	αFeO·OH	4.3	5–5.5	brown, yellow	low	Sedimentary and hydrothermal, weathering product
<b>Rutile</b>	TiO <sub>2</sub>	4.2–4.3	6–6.5	brownish red	high	Igneous and metamorphic rocks
Corundum	Al <sub>2</sub> O <sub>3</sub>	4.0	9	colorless, blue, red	low-moderate	Igneous and metamorphic rocks
Uranothorite	(Th,U)SiO <sub>4</sub>	~3.9	4.5–5	reddish	moderate	Pegmatites, hydrothermal veins
<b>Leucoxene</b>	FeTiO <sub>3</sub> to mostly TiO <sub>2</sub>	3.5–4.5	4–4.5	white to yellow-brown	high	Igneous and metamorphic rocks
Anatase	TiO <sub>2</sub>	3.8–4	5.5–6	many colors	high	Metamorphic rocks
Staurolite	Fe <sub>2</sub> Al <sub>9</sub> O <sub>6</sub> (SiO <sub>4</sub> ) <sub>4</sub> (OH) <sub>2</sub>	3.7–3.8	7–7.5	brown	high	Metamorphic rocks
Limonite	FeO(OH)·nH <sub>2</sub> O	2.7–4.3	4–5.5	light brown	low	Oxidized zones of iron-bearing deposits
Spinel	MgAl <sub>2</sub> O <sub>4</sub>	3.6–4.1	7.5–8	black, blue, red	low-moderate	Igneous and metamorphic rocks
Sphene/Titanite	CaTiO(SiO <sub>4</sub> )	3.4–3.6	5–5.5	yellowish-green, brown	moderate	Igneous and metamorphic rocks
Epidote	Ca <sub>2</sub> (Al <sub>2</sub> Fe)(Si <sub>2</sub> O <sub>7</sub> )(SiO <sub>4</sub> )O(OH)	3.4–3.5	6	yellowish-green, green	low	Mostly metamorphic rocks, less in igneous rocks
Clinozoisite	Ca <sub>2</sub> Al <sub>3</sub> (Si <sub>2</sub> O <sub>7</sub> )(SiO <sub>4</sub> )O(OH)	3.3–3.4	7	green, gray, pink	high	Igneous and metamorphic rocks
Garnets	(Mg,Fe,Mn,Ca)Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub> (general formula)	3.1–4.3	7–7.5	colorless, all colors	moderate	Mostly metamorphic but igneous also
Kyanite	Al <sub>2</sub> SiO <sub>5</sub>	3.5–3.7	5.5–7	blue, white, gray, green, black	high	Metamorphic rocks, rarely in igneous rocks
Sillimanite	Al <sub>2</sub> SiO <sub>5</sub>	3.2	6.5–7.5	colorless, white, various colors	high	Metamorphic rocks, sometimes granite
Andalusite	Al <sub>2</sub> SiO <sub>5</sub>	3.1–3.2	6.5–7.5	pink to red brown	high	Metamorphic rocks
Tourmaline	(Ca,K,Na) <sub>3</sub> (Al,Fe,Li,Mg,Mn) <sub>3</sub> (Al,Cr,Fe,V) <sub>6</sub> (BO <sub>3</sub> ) <sub>3</sub> (Si,Al,B) <sub>6</sub> O <sub>18</sub> (OH,F) <sub>4</sub>	3.0–3.3	7	black, various colors	high	Granitic pegmatites, some metamorphic rocks
Apatite	Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> (F,Cl,OH)	3.1–3.2	5	white, yellow, brown	high	Igneous and metamorphic rocks, and pegmatite
Hornblende	Ca <sub>2</sub> (Mg,Fe,Al) <sub>5</sub> (Al,Si) <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	2.9–3.4	5–6	black, dark green	moderate	Igneous and metamorphic rocks

**Table 1.** Common minerals in heavy-mineral sand deposits, listed in order of average specific gravity. “Heavy minerals” are generally defined as minerals that have a specific gravity greater than 2.85; leucoxene is an informal name for altered ilmenite. In nature, the specific gravity of a mineral varies from the mineral’s pure form due to impurities and alterations. The principal minerals of this study are shown in bold. For comparison, the common gangue minerals section lists other minerals most commonly mixed with the heavies in this deposit type, in particular, quartz. Hardness defined using Mohs hardness scale.—Continued

Common gangue minerals	Ideal composition	Specific gravity	Hardness	Color	Stability in weathering	Provenance
Amphibole	$W_{0-1}X_2Y_5Z_8O_{22}(OH,F)_2$ (general formula)	2.85–3.6	5–6	dark green, dark brown, black	low	Igneous and metamorphic rocks
Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$	2.8–3.2	2.5–3	blackish brown	low	Igneous and metamorphic rocks
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$	2.8–2.9	2–2.9	white, gray	low	Igneous and metamorphic rocks
Quartz	$SiO_2$	2.65	7	colorless	high	Igneous and metamorphic rocks
Kaolinite	$Al_2Si_2O_5(OH)_4$	2.6	1.5–2	white	low	Igneous and metamorphic rocks
Feldspars	$(K,Na,Ca)AlSi_3O_8$	2.54–2.76	6–6.5	pink, white, gray, brown	low-moderate	Igneous and metamorphic rocks



**Figure 2.** Schematic cross sections showing the features commonly used to describe shoreline depositional environments associated with heavy-mineral sands. Upper cross section: mainland beach depositional environment; the foreshore (the beach) is sometimes referred to as the “swash zone.” Lower cross section: barrier-tidal lagoon shoreline depositional environment (modified from Roy and others, 1994).



**Figure 3.** Example of recently deposited heavy-mineral sands on a modern beach on Little Talbot Island, northeast Florida. *A*, Photograph of a layered deposit of heavy minerals on the shoreface; *B*, Photograph of a close-up view of heavy mineral layers in the area indicated by the arrow in 3A. The notebook is 7 inches tall for scale. Photographs by B.S. Van Gosen, 2017.



**Figure 4.** A, Photograph of heavy minerals deposits (black sands, indicated by arrows) that were brought from offshore sediments up to the beach by a strong storm surge along a shoreline of the Atlantic Ocean at Vero Beach, Florida (location: lat 27.6708°N., long -80.3570°W.). Hurricane Frances, a Category 4 hurricane (The Saffir–Simpson hurricane wind scale, SSHSW), hit this area on September 5, 2004, and deposited these concentrations of heavy minerals. Storms can bring heavy minerals from the shallow shoreface to the foreshore (most commonly referred to as “the beach,” fig. 2), where the actions of waves, tidal currents, and wind can mechanically sort the heavy minerals into layered deposits. Modern processes observed today on a wide variety of coastal environments provide direct analogues to the processes that formed the ancient heavy-mineral sands deposits. This view was photographed on September 8, 2004, by the U.S. Geological Survey St. Petersburg Coastal and Marine Science Center (accessed February 7, 2018, at [https://coastal.er.usgs.gov/hurricanes/jeanne/site.php?storm\\_id=10&site\\_id=23&location\\_number=13](https://coastal.er.usgs.gov/hurricanes/jeanne/site.php?storm_id=10&site_id=23&location_number=13)). B, Heavy minerals (black sands) deposited in the foreshore of a modern beach on Little Talbot Island, northeastern Florida (see figs. 2 and 6). Yellow notebook is 7 inches in length for scale. Photograph by B.S. Van Gosen, September 2017.

## Industrial Uses and Significance of Titanium and Zircon

### Production of Titanium Mineral Concentrates and Industrial Applications

Deposits of heavy-mineral sands are usually mined by surface operations involving dredging or dry surface mining techniques (fig. 5). Onsite gravity separation operations carry out the initial heavy-mineral separation utilizing the density contrasts between the light and heavy minerals by settling out the “heavies” from slurries of sediment-water mixtures. Further processing and separation of the heavy-mineral suite are accomplished at specialized separation plants, usually offsite, using magnetic, electric, and electrostatic techniques. Ilmenite and rutile are the two principal mineral concentrates for titanium, with ilmenite accounting for about 92 percent of the world’s consumption of titanium minerals (Bedinger, 2016a).

Ilmenite is typically the most abundant titanium mineral in HMS deposits. It has a stoichiometric  $\text{TiO}_2$  content of 53 percent, but intercalation and weathering causes the  $\text{TiO}_2$  content to vary significantly. After deposition in sediments, weathering enhances the  $\text{TiO}_2$  content of some titanium-oxide minerals. In particular, iron is leached from ilmenite by weathering, which thereby naturally upgrades the  $\text{TiO}_2$  content of the ilmenite (Force, 1991). Ideal rutile contains about 95 percent  $\text{TiO}_2$ , but rutile is usually less abundant than ilmenite in HMS deposits.

Ilmenite is often further processed to produce a titanium concentrate, either as synthetic rutile or titaniferous slag. Natural ilmenite usually contains about 55 to 65 percent  $\text{TiO}_2$  with the remaining content being iron oxide. Heating of ilmenite in a rotary kiln with air converts the iron to iron (III) oxide, while leaving a residue with at least 90 percent  $\text{TiO}_2$ , known as synthetic rutile (Australian Atlas of Mineral Resources, Mines, and Processing Centres, 2007). Although numerous technologies are used to produce synthetic rutile, nearly all are based on either selective leaching or thermal reduction of iron and other impurities in ilmenite (Bedinger, 2013).

Most titanium derived from the processing of ilmenite, rutile, and leucoxene is not consumed in its metal form but as titanium dioxide ( $\text{TiO}_2$ ). In powder form,  $\text{TiO}_2$  is a white pigment used in paints, paper, and plastics because it provides even whiteness, brightness, very high refractive index, and opacity (Woodruff and Bedinger, 2013). In 2015, on a gross weight basis, 95 percent of the U.S. domestic consumption of titanium mineral concentrates was used to produce  $\text{TiO}_2$  pigment (Bedinger, 2016a). The remaining 5 percent, mainly from rutile, was used in welding-rod coatings and for manufacturing carbides, chemicals, and metal. For example, some rutile and leucoxene are blended to produce HiTi (High-grade titanium

with a  $\text{TiO}_2$  content of 70 percent to 95 percent), which is used as a feedstock to produce titanium dioxide to make titanium metals for the aerospace industry and to manufacture welding rods (Woodruff and Bedinger, 2013; Bedinger, 2016a). Titanium metal, derived from processing rutile, ilmenite, and (or) leucoxene is also used in spacecraft, guided missiles, jewelry, artificial joints, and heart pacemakers to name a few. The estimated value of titanium mineral concentrates consumed in the U.S. in 2015 was \$670 million (Bedinger, 2016a). Thus, titanium mineral concentrates obtained from HMS deposits are a significant contributor to the industrial minerals industry, and hence the U.S. economy.

### Industrial Applications of Zircon Derived from Heavy-Mineral Sands

As noted earlier, more than 90 percent of the zircon ( $\text{ZrSiO}_4$ ) produced globally is obtained as a coproduct along with the separation of the titanium minerals from HMS deposits. Micronized zircon (zircon “flour”) offers high light reflectivity and thermal stability, and thus is used mostly in refractory products as an opacifier for glazes on ceramics such as tiles, and as foundry sands (Bedinger, 2016c; Zircon Industry Association, 2017). In 2015, the dominant end-use market for zircon was the ceramics industry, which accounted for about 50 percent of the total zircon market (Bedinger, 2016b, 2016c). Zircon flour is used in abrasives, chemicals, pharmaceuticals and medicine, nuclear fuel cladding, chemical piping in corrosive environments, heat exchangers, and also in various specialty metal alloys, food, welding rod coatings, cosmetics, lightweight warm and protective clothing, ballpoint pens, and wear-resistant knives (Bedinger, 2016c; Zircon Industry Association, 2017).

### Zircon Distribution in the Atlantic Coastal Plain

Zircon is ubiquitous in the sediments of the Atlantic Coastal Plain. The study by Ellefsen and others (2015) found no obvious relationship between zirconium and titanium concentrations in stream sediments. Their study suggested that the geologic processes governing the distribution of zirconium in the Atlantic Coastal Plain (as a proxy for zircon) differ from those governing the distribution of titanium minerals.

Our current study did not pursue an explanation for the complex distribution of zirconium (as a proxy for zircon) in the study area, nor did we notice an obvious spatial pattern. It is assumed that titanium minerals will be the principal minerals of economic interest in the coastal plain, and that zircon exists in sufficient quantities to be a coproduct commodity if titanium minerals are mined.



**Figure 5.** Recent mining at the Trail Ridge deposits (Maxville mines) of the Chemours Company, located in northeastern Florida (fig. 1). Photographs courtesy of Chemours Company. *A*, open-pit (dry) mining; *B*, dredge mining. Photographs taken in 2016. Used with permission.

## Outlook for Heavy-Mineral Sands Production

We believe heavy-mineral sands will continue to serve as a major source of titanium oxide pigment, zircon sand for foundries, and zircon powder for ceramics because:

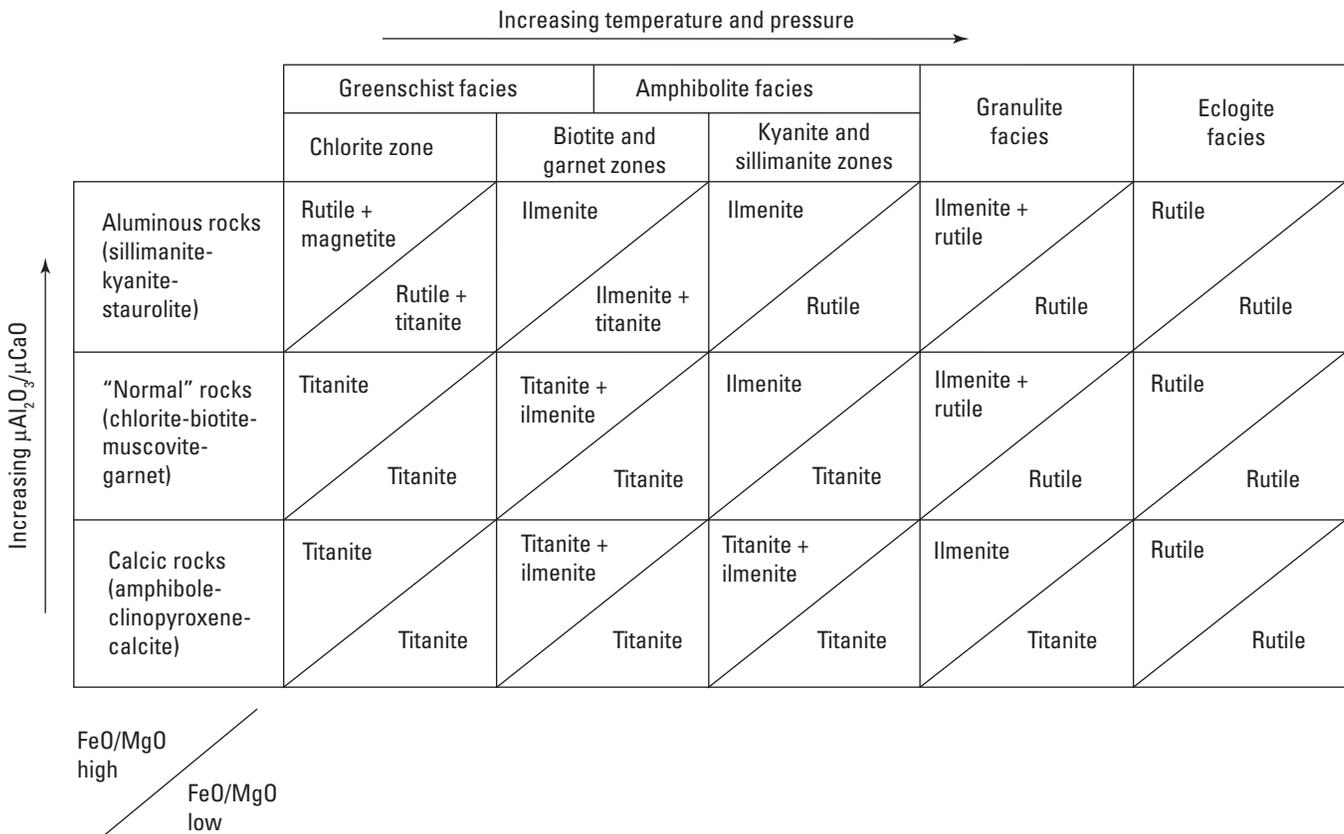
- Economic deposits are typically located at shallow depth or near the surface, buried by thin sedimentary/regolith covers.
- The deposits currently mined are voluminous, typically comprising >10 million metric tons (t) of ore (the total size of the individual sand-silt body) and containing >2 or 3 percent heavy-mineral content.
- The deposits are easy to excavate with most being mined today varying in coherence from unconsolidated to poorly consolidated, such that they are generally easily excavated and worked with heavy equipment.
- Well established, highly mechanized mineral-separation techniques are used at onsite plants that can process a continuous feed of high volumes of ore materials and efficiently perform the initial separation processes.

- The deposits can potentially supply several salable minerals as coproducts to the titanium minerals and zircon, such as staurolite, garnets, or monazite.

## The Bedrock Provenance of Titanium Minerals

### Lithologic Sources of Ilmenite and Rutile

While many types of igneous rocks can contain accessory ilmenite, studies indicate that metamorphic rocks of upper amphibolite facies to granulite facies are the principal source of ilmenite and rutile grains in placers (Force, 1991). Titanium-bearing silicate phases of titanite (sphene), biotite, and hornblende are the most stable titanium minerals in lower grade metamorphic rocks, while titanium minerals in oxide forms are those that are stable in higher grade metamorphic facies (fig. 6). Titanium in the rock becomes bound to titanium oxide phases, ilmenite and rutile, as metamorphism progresses to higher temperature and pressure facies, specifically to sillimanite and higher metamorphic grades (Ramberg, 1948, 1952). Subsequent studies by Force (1976, 1991) and



**Figure 6.** Relationships of rutile, ilmenite, and titanite (sphene) to the composition of metamorphic rocks and grade of metamorphism. Modified from Force (1991, his figure 2, p. 12).  $\mu$ , chemical potential.

Goldsmith and Force (1978) confirmed this relationship. They describe the transformation of titanite ( $\text{CaTiSiO}_5$ ) to ilmenite ( $\text{Fe}^{2+}\text{TiO}_3$ ) or rutile ( $\text{TiO}_2$ ), which involves the transfer of calcium from titanite to plagioclases and amphiboles during progressive metamorphism. As a result, in granulite-facies metamorphic rocks, ilmenite and rutile are by far the most common titanium minerals, while titanium-rich silicates (titanite, biotite, and hornblende) disappear (Force, 1976, 1991). As noted earlier, rutile can remain stable in metamorphic rocks of eclogite facies, while ilmenite disappears (fig. 6).

In addition to a range of high-grade metamorphic rocks, ilmenite can occur in a broad variety of igneous rocks. Igneous rocks with the highest ilmenite content include anorthosite-ferrodiorite massifs and alkaline plutonic complexes (Force, 1991; Woodruff and others, 2013). In alkalic complexes, significant enrichments of ilmenite can occur in pyroxenites (Force, 1991; Woodruff and others, 2013). Lesser concentrations of ilmenite, yet significant in total volume, can occur in some granitoids, basaltic rocks, and layered mafic intrusions. Woodruff and others (2013) describe economic and subeconomic examples of magmatic ilmenite deposits in detail.

According to Force (1980, p. 485), "...high-grade regional metamorphic terranes are the most important bedrock source of rutile..." and these rock types are the primary source of "...rutile [that is] sufficiently coarse to contribute sand-size grains to sediments." For example, a study of metamorphic units in the Great Smoky Mountains of North Carolina Blue Ridge by Goldsmith and Force (1978) found that: (1) pelitic metamorphic rocks contain rutile grains only in zones of upper amphibolite facies (kyanite and sillimanite zones) and higher-grade metamorphism; and (2) a variety of metamorphic rocks of granulite and eclogite facies also contain rutile (fig. 6).

While metamorphic rocks are substantial bedrock sources of rutile, studies by Force (1980, 1991) concluded that igneous rocks are *not* a significant source of rutile. Exceptions are: (1) some hydrothermally altered igneous rocks in which rutile forms as an alteration phase; (2) alkalic igneous rocks, including alkalic anorthosites; and (3) kimberlites. Force (1980, p. 486) stated that "...in fresh granitic rocks, rutile is extremely sparse."

In summary, the ilmenite grains in most HMS deposits were predominantly sourced by metamorphic rocks of sillimanite and granulite facies, with lesser contributions from a variety of igneous rocks. The bedrock sources of rutile are primarily metamorphic rocks of granulite and eclogite facies. Rutile is limited in occurrence in most igneous rocks, with the notable exception of alkalic igneous intrusions. These relationships are detailed by Force (1991) and summarized graphically in figure 6.

## Bedrock Sources of Ilmenite and Rutile in the Southeastern United States

The western boundary of the Atlantic Coastal Plain abuts the Piedmont region of the southeastern U.S. (fig. 1). The Piedmont region is mountainous and hilly terrain that is between the Atlantic Coastal Plain and the Appalachian

Mountains and extends approximately from southern New Jersey to central Alabama. Bedrock in this region, with contributions from the Appalachian Mountains farther west, have served for millennia as sources of detrital ilmenite, rutile, zircon, and other heavy minerals to the coastal plain. Extensive areas of the Piedmont region and the Appalachians contain rock types that are permissive as sources of ilmenite and rutile, including moderate- to high-grade metamorphic rocks (Espenshade and Potter, 1960), as well as several varieties of igneous intrusions (fig. 7).

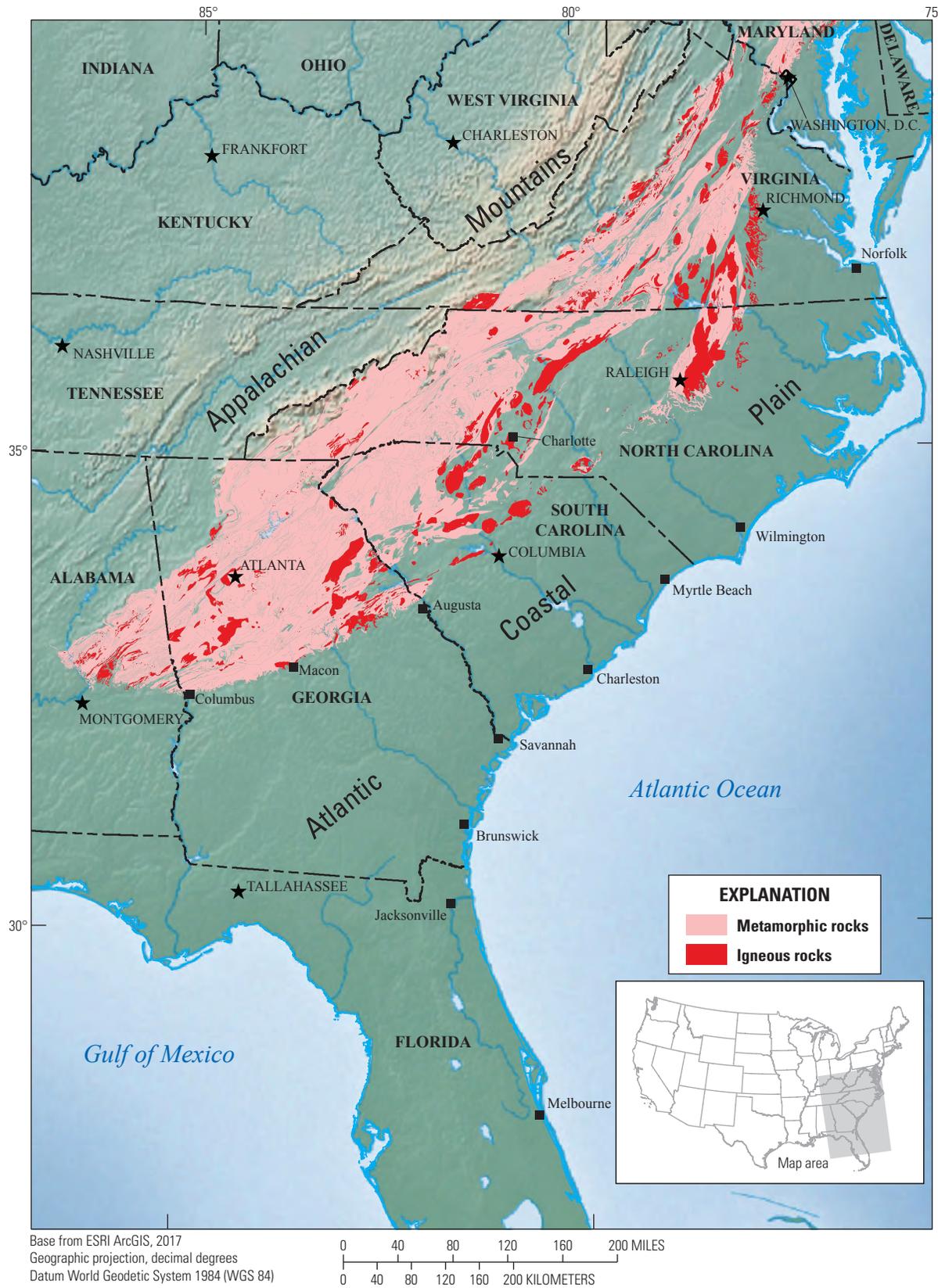
Metamorphic rocks in the Piedmont region and Appalachians Mountains that could contribute ilmenite and rutile grains to the Atlantic Coastal Plain include amphibolite and a variety of schists, gneisses, and metamorphosed igneous rocks (as described on the State geologic maps compiled in Horton and others, 2017); specifically amphibole-schist, biotite-gneiss, meta-igneous (unspecific), biotite-schist, gneiss (unspecific), metatonalite, granulite, hornblende-gneiss, mica-schist, muscovite-gneiss, muscovite-schist, orthogneiss, pelitic schist, paragneiss, quartz-feldspar-schist, and schist (non-specific).

To a lesser extent, igneous rocks of the Piedmont region and the Appalachians that are potential sources of ilmenite and rutile include alaskite, hornblendite, quartz diorite, alkali feldspar-syenite, leucocratic-granitic quartz monzonite, anorthosite, monzogranite, syenite, charnockite, monzonite, tonalite, diorite, norite, trondhjemite, granite (unspecific), pegmatite, ultramafic rocks, granodiorite, and pyroxenite.

## The Atlantic Coastal Plain of the Southeastern United States

The Atlantic Coastal Plain of the U.S. (fig. 1) is composed predominantly of thinly layered sequences of weakly consolidated clastic and carbonate sediments that are the products of numerous sea level transgressions and regressions during the Cretaceous (Owens and Gohn, 1985; Coffey and Sunde, 2014), the Tertiary (Paleogene and Neogene) (Segall and others, 1997), and the Quaternary (Pirkle and others, 1970; Toscano and York, 1992; Kulpecz, 2008; Parham and others, 2013; Pirkle and others, 2013), as well as coastal and shoreline processes still active today (Roberts and others, 2013). The Atlantic Coastal Plain is a complex, diverse mosaic of sand, gravel, silt, clay, soils, and carbonate sediments in peneplains, stream and river channels, wetlands, tidal lagoons, offshore barrier islands, and many other coastal plain features (Whittecar and others, 2016). Deposits of HMS can occur in any of these depositional environments in a coastal plain.

Clusters of titanium-rich HMS, regardless of depositional setting, were identified and mapped on a regional scale where they occur within the Atlantic Coastal Plain. Based on the mining history of HMS deposits in this region and the results of our study, we believe there may be substantial titanium mineral resources that remain in clastic sediments within the Atlantic Coastal Plain.



**Figure 7.** Map showing the metamorphic and igneous rocks within the Piedmont Region and the Appalachian Mountains that are permissive bedrock sources for the ilmenite and rutile found in sediments of the Atlantic Coastal Plain. Geologic map units obtained from Horton and others (2017).

## The Fall Zone

“The Fall Zone” (or “Fall Line”) is a regional term used to describe the contact zone between the lithified basement rocks of the Piedmont region on the west and much younger sediments of the Atlantic Coastal Plain on the east (fig. 1). The age of the Atlantic Coastal Plain sediments along the Fall Zone range from Cretaceous to Tertiary in age; these Atlantic Coastal Plain sediments are derived predominantly from the erosion of bedrock of the Piedmont region and subsequent fluvial transport of the eroded sediment to the ancient coasts. Some of the sediments originated from bedrock sources farther to the west in the Appalachian Mountains (Darby and Tsang, 1987; Naeser and others, 2016). The package of sediments that overlie the basement rocks in the Atlantic Coastal Plain range in thickness from thin wedges along the Fall Zone to as much as 3,000 meters (m) near Cape Hatteras, North Carolina (Trapp and Meisler, 1992).

## Heavy-Mineral Sands Mining Districts in the Atlantic Coastal Plain

Many deposits of HMS have been identified in the Atlantic Coastal Plain, including more than a dozen deposits that have been mined. Three Atlantic Coastal Plain districts have seen the bulk of the HMS production and these districts are (1) the Jacksonville district in northeastern Florida and southeastern Georgia, (2) a sequence of deposits along the Fall Zone in southeastern Virginia, and (3) the Lakehurst district in southern New Jersey.

### The Jacksonville District

The Jacksonville district encompasses a large region of Atlantic Coastal Plain environments around Jacksonville, Florida (fig. 8). Several known HMS deposits occur in this region; they range in age from Pleistocene to modern sediments (Force, 1991; Pirkle, Pirkle, and Reynolds, 1991). The evolution, geology, character, and mining history of the HMS deposits of the Jacksonville district are well described by Neihsel (1962), Staatz and others (1980), Pirkle and others (1991), and Elsner (1997).

The first commercial production of ilmenite concentrate from this district occurred in 1916, from a modern beach near Mineral City (now named Ponte Vedra) (Staatz and others, 1980; Elsner, 1997). HMS production in the district was active at many sites during the 1940s to 1960s. Larger production occurred during the 1970s, derived mainly from the Folkston, Boulogne, Trail Ridge, Highland, and Green Cove Springs deposits (Pirkle, Pirkle, and Reynolds, 1991). HMS production continued until 2005 at Green Cove Springs (Iluka Resources Ltd., 2017). Currently (as of 2017), HMS production continues along the Trail Ridge complex (including the Highland and Maxville deposits), which is considered to be the largest HMS deposit of the southeastern U.S. HMS production is also currently active at the Mission mine in southeastern Georgia (fig. 8).

For the last few decades, HMS in the U.S. have been principally produced by the Chemours Company operations (a spin-off from DuPont) located along “Trail Ridge” in northeastern Florida (figs. 1, 5, and 8). Their operations dredge mine and dry mine HMS deposits of the Trail Ridge complex to recover ilmenite, leucoxene, zircon, and staurolite; rutile is minor in amount. DuPont geologists discovered these deposits in 1947 and mining began in 1949 (Carpenter and others, 1953). DuPont began their open-pit mining and heavy-mineral processing facilities on the southern end of Trail Ridge, 7 kilometers (km) east of the town of Starke, Fla. (fig. 8). Subsequent mining along Trail Ridge has accelerated in recent years by the Chemours Company, progressing along the ridge at several sites, terminating against the south side of U.S. Interstate Highway 10; about 4 km east of Macclenny, Fla. Mining operations along Trail Ridge are open-pit mines using dredge and dry-mining techniques.

The Trail Ridge complex is composed of medium-grained eolian sands interbedded with fine sands, silt, and layers of peat. Although the deposits vary in grade along strike and laterally, the Trail Ridge deposits have an average heavy-mineral content of about 4 percent (Force and Rich, 1989). The Trail Ridge complex is 1 to 2 km wide and about 11 m thick on average. The entire geomorphologic feature of Trail Ridge extends from south to north for more than 200 km, extending from near Starke, Florida, to near Jesup in southeastern Georgia (Neihsel, 1962; Force and Rich, 1989; Pirkle, Pirkle, and Reynolds, 1991) (fig. 8). According to the analyses of Elsner (1997), the northern parts of Trail Ridge began as barrier islands and the southern part of the ridge formed as inland dunes. Elsner (1997) concluded that the Trail Ridge complex correlated with a global sea-level high  $1.9 \pm 1$  million years ago (Ma). Studies and descriptions of the Trail Ridge deposits include Creitz and McVay (1948), Spencer (1948), Pirkle and Yoho (1970), Pirkle and others (1971, 1977), Pirkle (1975), Force and Garnar (1985), Force and Rich (1989), Force (1991), and Elsner (1997).

Descriptions of other HMS deposits of the Jacksonville district (fig. 8) include those for the Yulee (Pirkle and others, 1984); Altama (Pirkle and others, 1989); Cabin Bluff (Pirkle and others, 1991; Neihsel, 1962); Cumberland Island (Smith and others, 1967); and Folkston and Amelia Island (Pirkle and others, 1993). Mining of HMS deposits also occurred near the modern eastern coastline of Florida to the south of the Jacksonville district (250 to 325 km to the south) near Melbourne (mined from 1939 to 1955), Winter Beach (1954 to 1965), and Vero Beach (1943 to 1963) (Pirkle, Pirkle, and Reynolds, 1991; Elsner, 1997; Staatz and others, 1980).

In May 2015, Southern Ionics Inc. completed construction of its mineral sands processing plant near Offerman in Charlton County, Georgia, and began to process heavy-mineral concentrates from its Mission mine, which is also in Charlton County. In February 2016, Southern Ionics announced a curtailment of operations owing to a decreased demand for titanium concentrates (Bedinger, 2016b). The mine resumed operations at the Mission mine in 2017, conducting dry



**Figure 8.** Map showing the location of notable deposits of heavy-mineral sands in the Jacksonville district of northeastern Florida and southeastern Georgia. The location symbols (red diamonds) do not reflect the size and shape of each deposit.

mining to produce high-purity individual concentrates of ilmenite, leucoxene, rutile, and zircon for sale (staurolite is also recovered for possible future sale). This HMS deposit is thought to be a barrier island complex (Pirkle and others, 1993), about 1.2 to 1.5 km wide, which is located to the east of (and not part of) the Trail Ridge complex.

### Deposits of Heavy-Mineral Sands along the Fall Zone in Virginia and North Carolina

Berquist (1987) was the first to recognize and report heavy-mineral-rich sand deposits in southern Virginia. His report prompted exploration for this deposit type in southeastern Virginia, leading to the discovery of the Old Hickory deposit (Newton and Romeo, 2006), which was subsequently mined by Iluka Resources until 1998 (Iluka Resources Ltd., 2013).

The HMS deposits of this belt formed in the upper Atlantic Coastal Plain, just east of the Fall Zone in the contact zone between the basement rocks of the Piedmont region on the west and much younger sediments of the Atlantic Coastal Plain on the east (Berquist and others, 2015). Heavy-mineral sands in the western parts of the coastal plain of Virginia and northern North Carolina are interpreted to be Pliocene sedimentary deposits that formed during worldwide transgression-regression events between 3.5 and 3.0 Ma (Carpenter and Carpenter, 1991).

At the end of 2015, Iluka Resources ended production of heavy-mineral concentrate at its two remaining operations in southeastern Virginia, the Concord mine in Sussex County and the Brink mine in Greensville County (figs. 1 and 9), and started remediating the mine sites in 2017 (Bedinger, 2016b; Iluka Resources Ltd., 2017). These HMS deposits are of Pliocene and possibly Miocene age, lying just east of the Fall Zone. Iluka Resources produced final products of chloride ilmenite, zircon,



**Figure 9.** Photograph of the Concord mine of Iluka Resources during dry-mining operation in November 2012; mining ended here in late 2015. Located near the Fall Zone in south-central Virginia (see fig. 1), the mine excavated weakly consolidated Pliocene-age sand-silt deposits containing about 4 percent heavy minerals. The sediments were processed at nearby separation plants, extracting ilmenite, leucoxene, rutile, and zircon for sale. Photograph by B.S. Van Gosen, 2012.

and staurolite from the Virginia operations. They reported that the HMS deposits contained an average HMS content of 4.4 percent, in which ilmenite composed about 64 percent of the heavy minerals and zircon composed about 16 percent. Along this same Pliocene-Miocene strandline within Virginia, Iluka Resources selected another proposed mine site called the Hickory deposit that did not reach production, located between the city of Richmond and the Concord mine to the south.

Carpenter and Carpenter (1991) described this 160-km-long northeast-trending zone of HMS deposits along the Fall Zone as the “North Carolina-Virginia heavy mineral belt.” The northern end of this belt includes the previously mentioned Old Hickory deposit, located 60 km south of Richmond, Virginia, and the belt’s southern end includes deposits located west of Wilson, N.C. (fig. 1) (Carpenter and Carpenter, 1991). On the basis of heavy-mineral estimates for 19 deposits within this belt, Carpenter and Carpenter (1991) calculated a total (semi-quantitative) regional resource of 22.7 million metric tons of heavy minerals in 377.8 million metric tons of sand, with an average heavy-mineral content of 6 percent. Average mineral distribution within the heavy-mineral suite was estimated to be 60 percent ilmenite, 2.5 percent rutile, 12.5 percent zircon, 8.5 percent staurolite, 0.7 percent tourmaline, 3.0 percent kyanite, 1.3 percent sillimanite, and 11.5 percent other heavy minerals (mostly limonite) (Carpenter and Carpenter, 1991).

## **HMS Deposits of the Lakehurst District, New Jersey**

From 1962 to 1982, the Lakehurst district near the city of Lakehurst, southern New Jersey (outside of this study area), was a principal supplier of altered ilmenite, which was produced by two companies that mined from open pits in the Neogene Cohansey Sand. Its highest-grade intervals are about 5-m thick and contain 5–25 percent heavy minerals (Puffer and Cousminer, 1982; Force, 1991). Carter (1978) determined that the Cohansey Sand is most enriched in heavy minerals near the top of the swash zone along the Tertiary beach. Puffer and Cousminer (1982) suggested that the sands were deposited during a period of erosion between the Miocene and Pliocene resulting in a unit dominated by altered ilmenite (85 percent), as well as containing zircon (7 percent), sillimanite (3 percent), staurolite (1 percent), and tourmaline (1 percent) (Puffer and Cousminer, 1982).

## **Previous Mineral Resource Assessments in the Atlantic Coastal Plain**

Several earlier studies have evaluated the potential for HMS deposits in the Atlantic Coastal Plain. Most of these studies analyzed data from geophysical surveys or geochemical surveys, or both. Initial screening for prospective areas of HMS principally utilized regional-scale data collected as (1) total count and spectral gamma-ray aeroradiometric data; and (2) reconnaissance stream sediment geochemical data.

Measurements of radioactivity, whether collected by airborne or by on-the-ground methods, are often used in HMS exploration to detect the presence of monazite, the rare earth elements (REE)-thorium-phosphate mineral [(REE,Th)PO<sub>4</sub>]. Monazite is usually the heaviest of the heavy-mineral suite in coastal sands and thus an indicator of the presence of HMS deposits. Although monazite typically occurs in modest amounts in the coastal sediments (usually no more than 4.4 to 5.5 weight percent (Grosz and others, 1992; Bern and others, 2016), its concentrations are usually adequate to be detected and mapped by airborne radiometric surveys when they are within a few centimeters of the surface (Grosz and Schruben, 1994; Shah and others, 2017). Monazite accumulations in the Atlantic Coastal Plain represent potential sources of the light rare earth elements (Bern and others, 2016; Shah and others, 2017) and thorium (Ault and others, 2016).

Geochemical surveys, such as analyses of stream sediments, have been used to identify areas of shallow HMS deposits, as described by Grosz (1993) and Grosz and Schruben (1994). The potentially commercial heavy minerals, which include ilmenite (FeTiO<sub>3</sub>), rutile (TiO<sub>2</sub>), zircon [(Zr,Hf,U)SiO<sub>2</sub>], monazite [(La,Ce,Th)PO<sub>4</sub>], and xenotime (YPO<sub>4</sub>) can be identified in stream sediments by concentrations of titanium, zirconium, hafnium (Hf), and REEs (Lanthanum [La], Cerium [Ce], Neodymium [Nd], Samarium [Sm], Dysprosium [Dy], Ytterbium [Yb], and Yttrium [Y]).

Examples of reconnaissance HMS studies in the Atlantic Coastal Plain include the following:

To explore for HMS deposits in the vicinity of Charleston, S.C., Force and others (1982) created contoured maps of aeroradioactivity data using data that were recently (the early 1980s) collected by airborne surveys financed by the Coastal Plains Regional Commission and contracted by the USGS. Their study tested this method for mapping this type of data for exploration. The study identified 14 HMS accumulations in the Charleston area in “sands of old beach complexes,” which were confirmed by field checking sites where total-count anomalies were found in the airborne-collected radioactivity data.

A study of the HMS deposits of the coastal plain in Virginia by Grosz (1983) applied total-count aeroradiometric maps as a technique to explore for HMS. His study found that when surveyed on the ground, HMS accumulations produce radiometric spectra of intermediate to low intensity with thorium producing the strongest radiation component and with lesser contributions from uranium and potassium.

Wynn and Grosz (1985) carried out a study of the induced polarization (IP) response of fossil beach HMS deposits in northeastern Florida (Green Cove Springs and Trail Ridge). They found that IP response over these deposits “is unusually strong,” suggesting that the IP method could be used as a field evaluation tool. Their field and laboratory studies on sediment and stockpile samples indicated that altered ilmenite has a strong IP response while that of rutile is weak.

In the northern peninsular and panhandle of Florida, Grosz and others (1989) used total count and spectral

gamma-ray aeroradiometric maps followed by field investigations of radiation anomalies to locate and evaluate HMS deposits. Radiation anomalies, whether associated with fluvial or marine HMS, showed that radiometric spectra are dominantly due to thorium radiation.

Along the inner coastal plain in North Carolina, adjacent to the Fall Zone, Grosz and others (1992) sampled sediments in areas that were identified as high gamma-ray anomalies by aeroradiometric surveys. Auger samples from these sites revealed relatively high concentrations of ilmenite, rutile, zircon, monazite, and minor gold in Cretaceous sediments, with much lower concentrations of heavy minerals in post-Cretaceous sediments.

Two recent studies by Bern and others (2016) and Shah and others (2017) focused on assessing the potential REE resources in the Atlantic Coastal Plain by integrating aeroradiometric data, mineralogical data, geology, and stream sediment geochemistry. The REE resources occur in the form of the minerals monazite and xenotime. Radiometric equivalent thorium (eTh) was shown to be useful as a proxy for locating monazite and xenotime. These two studies demonstrated how incorporating large digital datasets in tandem, such as geophysical, geochemical, and geologic information could be used to locate prospective HMS deposits. Using Geographic Information System (GIS), statistical, and geospatial tools can greatly assist exploration by allowing the display, query, and integrated analysis of multiple, geologically associated factors.

The potential for heavy minerals resources deposited offshore of the Atlantic Coast of the U.S. was examined by Grosz (1987). He reported that “studies based on surficial grab samples suggest an average of [approximately 2 weight-percent heavy minerals] in Atlantic continental shelf sediments” (Grosz, 1987, p. 339). Sediments offshore of the East Coast of the U.S. remain (as of 2017) an undeveloped potential source of heavy minerals.

Similarly, many inlets, bays, and estuaries along the Atlantic Coast of the U.S. have been demonstrated to host sediments rich in heavy minerals. Examples include inlets and deltaic areas near Charleston, South Carolina (Shah and Harris, 2012), the Savannah River, South Carolina (Neiheisel, 1976), and the Chesapeake Bay of Maryland (Shah and others, 2012).

## Study Techniques

### Geochemical Dataset

The titanium concentrations were obtained from the USGS National Geochemical Survey database (U.S. Geological Survey, 2004). Titanium concentrations were measured in stream sediment samples collected within the Atlantic Coastal Plain of the southeastern U.S.; this area includes parts of Virginia, North Carolina, South Carolina, Georgia, Florida, and Alabama. The number of samples, and hence the number of concentrations, is 3,457. Ellefsen (2017) compiled the dataset that was used in this study.

### Geochemical Analyses

Inductively coupled plasma-atomic emission spectrometry (ICP-AES) was used to measure concentrations in milligrams/kilogram (mg/kg, which is equivalent to parts per million [ppm]) for 40 different elements, including titanium, in the 3,457 stream sediment samples in our dataset. Prior to ICP-AES analyses, each sample was dissolved in a mixture of hydrochloric, nitric, perchloric, and hydrofluoric acids. Additional information about the ICP-AES method is found in Briggs (2002) and U.S. Geological Survey (2004).

None of the titanium concentrations in our dataset had values below the reporting limits for the ICP-AES technique, which is 50 mg/kg. Thus, our dataset (Ellefsen, 2017) contains no censored data. The titanium concentrations range from a low value of 100 mg/kg to a high value of 20,920 mg/kg. The concentrations are relative to the bulk stream sediment sample, *not* just the heavy-mineral fraction of it.

### Data Processing

The titanium concentrations are a type of compositional data, which have special properties making it difficult to directly analyze them (Pawlowsky-Glahn and others, 2015). Consequently, the titanium concentrations are transformed to a real-valued, linear vector space (that is, Cartesian coordinates) using the isometric log-ratio transform. Preliminary analysis of the transformed concentrations shows that both the mean and the variance change across the study area. In statistical terminology, the transformed concentrations are non-stationary.

A statistical model of these transformed concentrations must account for the spatial properties of the data, its non-stationarity, and the moderately large number of measurements. We are unaware of any existing model that accounts for these three characteristics, so we built a new model, which uses basis functions to account for these three characteristics. The model is formulated as a Bayesian hierarchical model.

The parameters in the model are estimated using Hamiltonian Monte Carlo sampling. The sampling is checked using various numerical and graphical measurements to ensure that the sampling is done properly. In addition, the parameters are used to generate maps of the mean and the variance across the survey. These maps are then checked to ensure that they are geologically plausible.

Although the mean and variance are estimated from the transformed concentrations, they are back-transformed to the equivalent statistics for concentrations, namely compositional center and compositional total variance (Pawlowsky-Glahn and others, 2015, p. 108–112). In the remainder of this report, the compositional center will be called the “mean titanium concentration” or just “mean,” and may be interpreted as an average. The square root of the compositional total variance will be called the “standard deviation of the titanium concentration,” and may be interpreted as the spread of the concentrations around the mean.

## Study Results

Along the Fall Zone from Virginia to Alabama, anomalous concentrations of titanium exist in sediments (fig. 10), which is a reflection of enrichments in detrital ilmenite, leucoxene, and rutile. This relationship concurs with the results of recent studies by Bern and others (2016) and Shah and others (2017), which found that the highest concentrations of monazite and xenotime (potential sources of REEs) occur primarily along the Fall Zone.

Our study outlined several other areas in the Atlantic Coastal Plain where the mean titanium concentrations are anomalously high. For discussion purposes, these areas are designated as anomalous areas A to E (labeled on figs. 10 and 11). We suggest that these areas A to E with the highest (most anomalous) titanium concentrations are regions where exploration for ilmenite-, leucoxene-, and rutile-bearing HMS deposits could be focused. These areas are described separately in the sections that follow.

The standard deviation in the titanium concentrations is mapped in figure 11. Standard deviation is highest in the southern areas of the study area, including southern Georgia, southeastern Alabama, and northern Florida, as well as the northern part of the study area in northern Virginia (fig. 11). Areas with high standard deviations have relatively high uncertainty in the titanium concentrations, which increases risk when exploring for ilmenite-, leucoxene- and rutile-bearing HMS deposits.

There are limitations to the maps shown in figures 10 and 11. The samples are derived from stream sediments, which are composites of soils and sediments that were eroded from the land surface within the respective watershed. Consequently, the properties of the stream sediments do not necessarily reflect the properties of the sediments that are below the land surface. This limitation is one reason that the HMS deposits in northeastern Florida and southeastern Georgia (fig. 8) do not appear as anomalies in the map of the mean titanium concentration (fig. 10). Specifically, the map does not show anomalous titanium concentrations at the areas of economic HMS deposits in the Trail Ridge complex (Trail Ridge, Highland, and Maxville mines), nor areas near other Pleistocene ridge systems represented by the Green Cove Springs deposit and the Mission mine deposit. However, the mean titanium concentrations are high along the coastline near Jacksonville, Fla. (fig. 10). These anomalies are associated with Quaternary sediments, such as the HMS deposits of Cumberland Island, Amelia Island, and Little Talbot Island (fig. 8). In this case, the stream sediments probably include high concentrations of ilmenite, leucoxene and rutile, which are even visible on the beaches (figs. 3 and 4).

The second limitation is spatial resolution. That is, the maps (figs. 10 and 11) are spatially smooth representations of the actual titanium concentrations. Consequently, features with small spatial scale (that is, less than about 10 km) may not be discernible in the maps. This limitation is another reason that Trail Ridge, which is 1 to 2 km wide, does not appear as an anomaly on the map of mean titanium concentration (fig. 10).

## Anomalous Area A

Coastal plains sediments that border the Fall Zone in Georgia, from the Columbus area to the Augusta area (fig. 12), contain anomalous concentrations of titanium in Cretaceous and Tertiary sediments of the coastal plain. The standard deviation in the titanium concentrations is generally low across this region of the Atlantic Coastal Plain (fig. 11), indicating low variation around the mean concentrations. The Piedmont region along the Fall Zone in Georgia is dominated by gneiss and granite (fig. 12), which are likely sources of detrital grains of ilmenite and rutile in this area of the coastal plain. Areas with a high probability of HMS in the Augusta area of Georgia and South Carolina were also recognized by Grosz (1993) and Grosz and Schruben (1994).

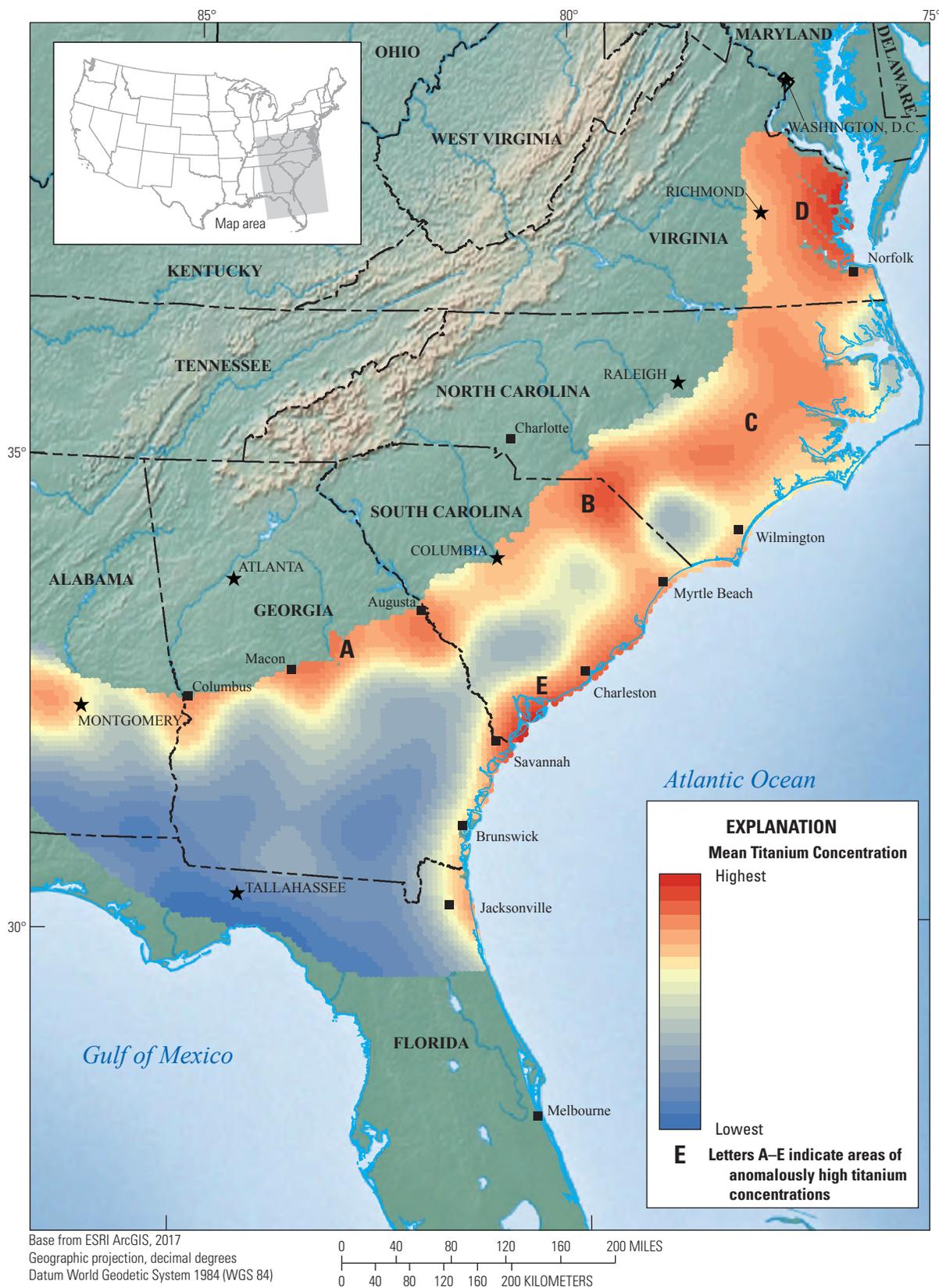
## Anomalous Area B

Anomalous area B, near the border between South Carolina and North Carolina (fig. 13), contains a zone of anomalous concentrations of titanium in Cretaceous and Tertiary sediments, as well as along a paleovalley that carried titanium minerals from the Piedmont to a Pleistocene-age paleo-shoreline in South Carolina. The standard deviation in the titanium concentrations is generally low across this region of the Atlantic Coastal Plain (fig. 11), indicating low variation around the mean concentrations.

It must be noted that the geologic mapping of the Cretaceous and Tertiary sedimentary deposits of the Atlantic Coastal Plain in this region is not consistent (thereby not definitive), as shown in figure 13. Interpretations of the Atlantic Coastal Plain map units, in particular differences in the interpreted age of the lithologies, differ considerably between the State geologic maps of South Carolina and North Carolina (see Horton and others, 2017). For example, lithologic units that cross the state border in South Carolina are Pliocene in age, but are mapped as Cretaceous in age in adjacent North Carolina. Resolving these age differences is beyond the scope of this study. We can say that anomalous titanium concentrations were found in coastal sediments in this region that have been mapped variously as Cretaceous and as Tertiary in age.

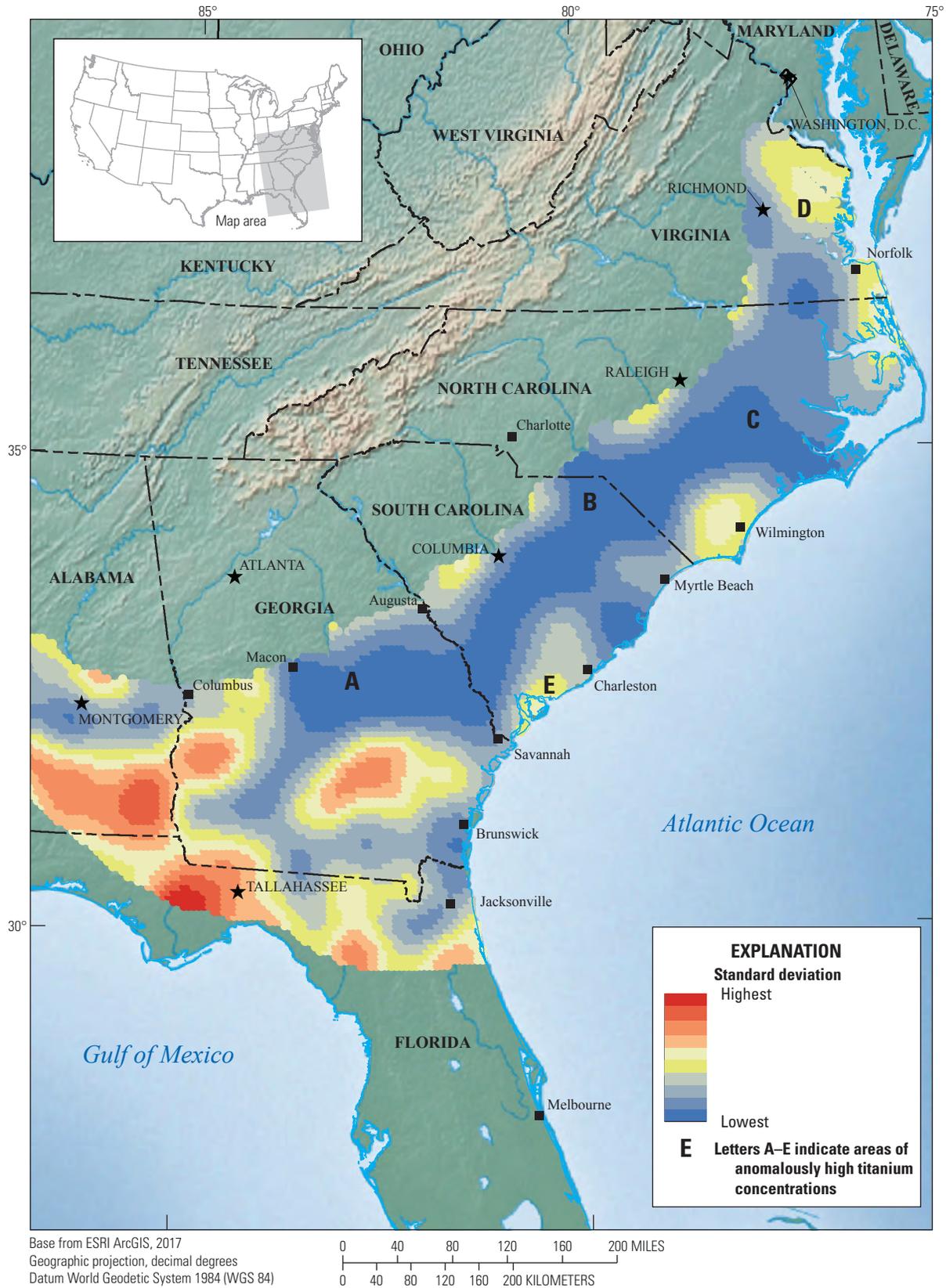
This anomalous region extends as much as 100 km to the east of the Fall Zone in North Carolina. The Piedmont region bedrock units adjacent to anomalous area B contain a relative paucity of high-grade metamorphic rocks. Two granitic plutons lie along the Fall Zone (fig. 13), which could have supplied some of the ilmenite and (or) rutile to the upper coastal plain. More likely, most of the detrital titanium minerals were transported to the Fall Zone from metamorphic complexes in the distant Appalachian Mountains (fig. 7) during the Cretaceous. The studies of Grosz and others (1992), Grosz (1993), and Grosz and Schruben (1994) also recognized areas with a high probability of HMS deposits along the Fall Zone in the region of the South Carolina-North Carolina boundary.

A drainage basin now occupied by the Pee Dee River and its tributaries (fig. 13) carried and deposited titanium-bearing

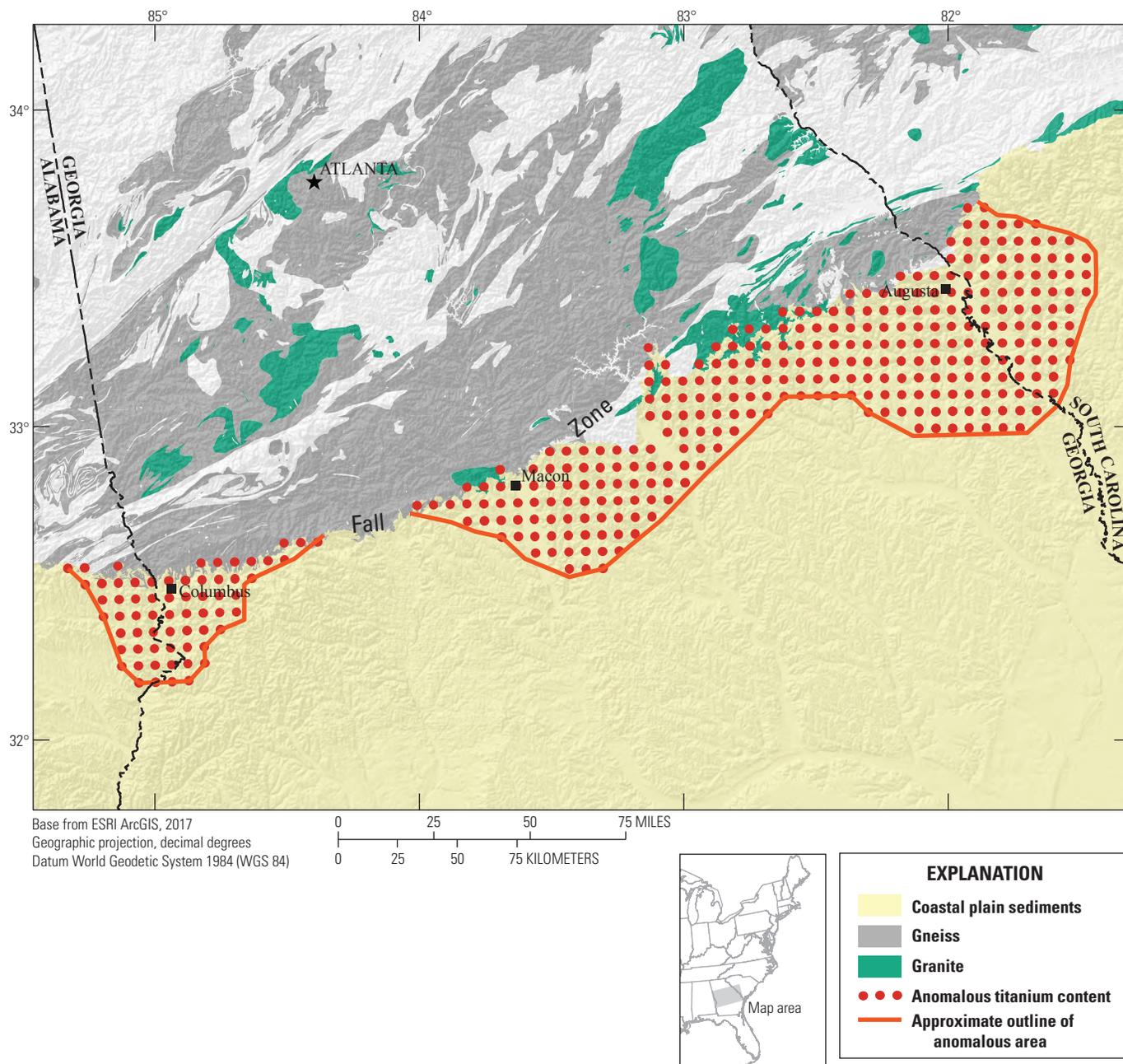


Base from ESRI ArcGIS, 2017  
 Geographic projection, decimal degrees  
 Datum World Geodetic System 1984 (WGS 84)

**Figure 10.** Map showing the mean titanium concentrations in the Atlantic Coastal Plain. Labels A to E designate areas of anomalous concentrations of titanium. A, upper coastal plain along the Fall Zone in Georgia (fig. 12); B, area near the border between South Carolina and North Carolina (fig. 13); C, upper and middle coastal plain of North Carolina (fig. 14); D, The majority of the coastal plain in Virginia (fig. 15); E, the outer coastal plain of South Carolina (fig. 16).



**Figure 11.** Map showing standard deviation of titanium concentrations in the Atlantic Coastal Plain. Labels A to E designate areas of anomalous concentrations of titanium. A, Upper coastal plain along the Fall Zone in Georgia (fig. 12); B, area near the border between South Carolina and North Carolina (fig. 13); C, upper and middle coastal plain of North Carolina (fig. 14); D, the majority of the coastal plain in Virginia (fig. 15); E, the outer coastal plain of South Carolina (fig. 16).



**Figure 12.** Map showing the anomalous titanium concentrations in area A coastal plains sediments that border the Fall Zone in Georgia, from the Columbus area to the Augusta area and contain anomalous concentrations of titanium in Cretaceous and Tertiary sediments of the coastal plain. The standard deviation in the titanium concentrations is generally low across this region of the Atlantic Coastal Plain (see fig. 11), indicating low variation around the mean concentrations. Refer to figure 10 for spatial reference within the larger Atlantic Coastal Plain region. Geologic map units from Horton and others (2017).

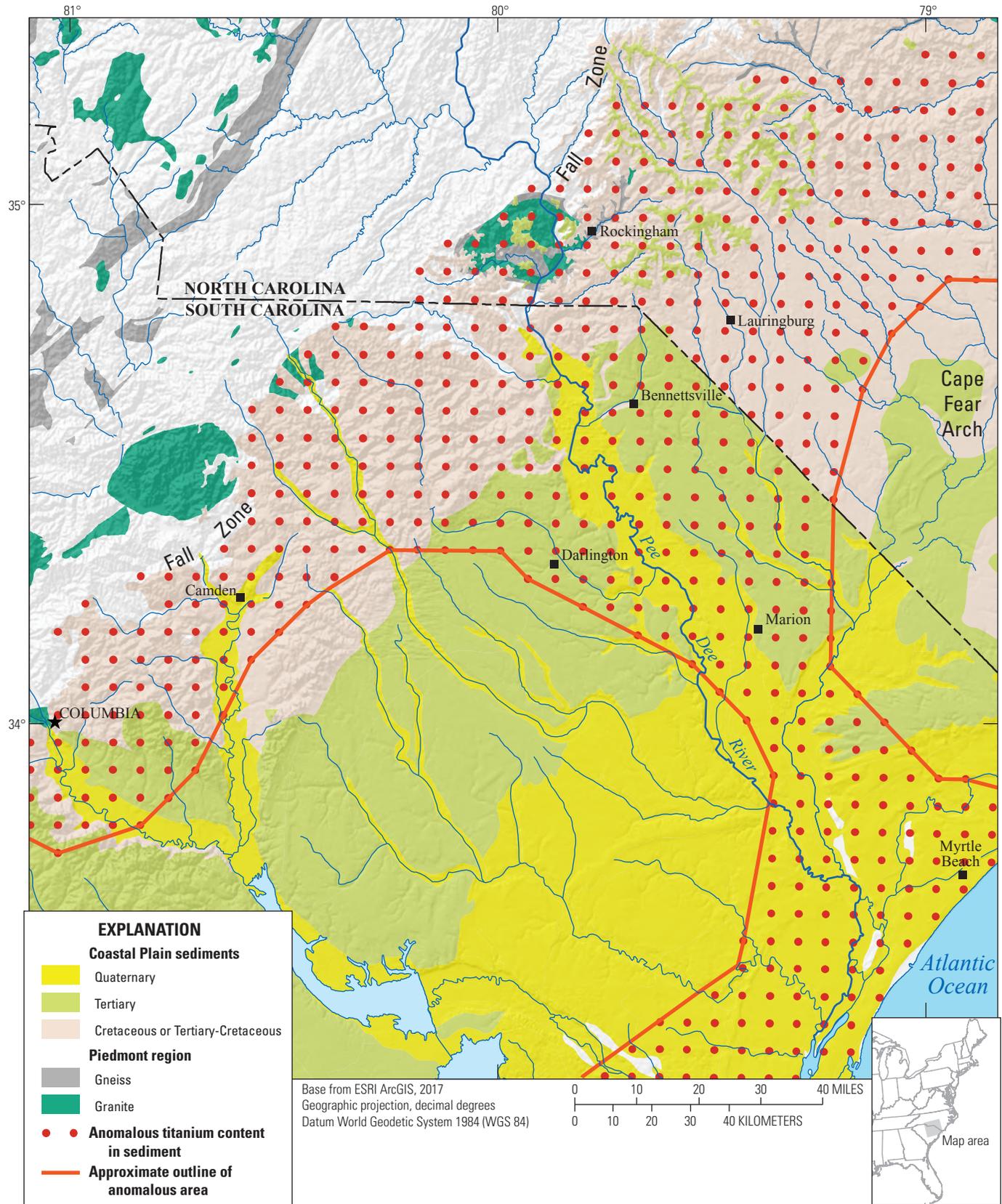


Figure 13 (continued on following page). Map showing the anomalous titanium concentrations in area B, near the border between South Carolina and North Carolina, which contains a zone of anomalous concentrations of titanium in Cretaceous and Tertiary sediments, as well as along a paleovalley that carried titanium minerals from the Piedmont to a Pleistocene-age paleo-shoreline

**Figure 13 (continued from previous page).** in South Carolina. The standard deviation in the titanium concentrations is generally low across this region of the Atlantic Coastal Plain (see fig. 11), indicating low variation around the mean concentrations. Refer to figure 10 for spatial reference within the larger Atlantic Coastal Plain region. Geologic map units from Horton and others (2017). Mismatches in geologic units across the borders of North Carolina and South Carolina reflect interpretive differences between the State geologic maps.

sediments to the lower coastal plain of South Carolina. Numerous Pleistocene-age river terraces exist along this drainage basin, indicating that this river basin was active during the Pleistocene. The terrace sediments contain anomalous titanium concentrations. This large drainage system could have transported grains of ilmenite and rutile for considerable distances to the coastal plain of South Carolina during periods of Pleistocene glaciation, and perhaps more expediently, during periods of glacial melting. The majority of the anomalous titanium concentrations in the lower coastal plain of South Carolina, as shown in figure 13, occur primarily in Pleistocene-age sediments.

### Anomalous Area C

In sediments mapped as Cretaceous and as Tertiary, anomalous titanium concentrations occur in the upper and middle coastal plain of North Carolina (fig. 14). The standard deviation in the titanium concentrations is generally low across this region of the Atlantic Coastal Plain (fig. 11), indicating low variation around the mean concentrations.

Large expanses of gneiss and granite bound the Fall Zone of north-central North Carolina (fig. 14), the likely sources of the ilmenite, leucoxene (altered ilmenite), and rutile grains in this part of the coastal plain. Headward erosion of these Piedmont crystalline rocks near the coasts during the Cretaceous and Tertiary was likely a significant source of the heavy minerals. In addition, during the Pleistocene and thereafter, large river drainage systems further transported and distributed detrital ilmenite and rutile across large areas of the coastal plain of North Carolina.

An exception to the widespread titanium enrichment in sediments in this region is the lack of anomalous titanium in the area that overlies a coastal uplift referred to as the Cape Fear arch (southeastern part of North Carolina, in fig. 14). The Cape Fear arch is a northwest-southeast-trending structural ridge formed in crystalline basement rocks that lie beneath the Atlantic Coastal Plain near the North Carolina-South Carolina border (Gohn, 1988; Klitgord and others, 1988). The crest of the arch (ridge) lies about 500 m beneath the Atlantic Coastal Plain surface of the region and extends into the offshore continental shelf (Gohn, 1988; Klitgord and others, 1988).

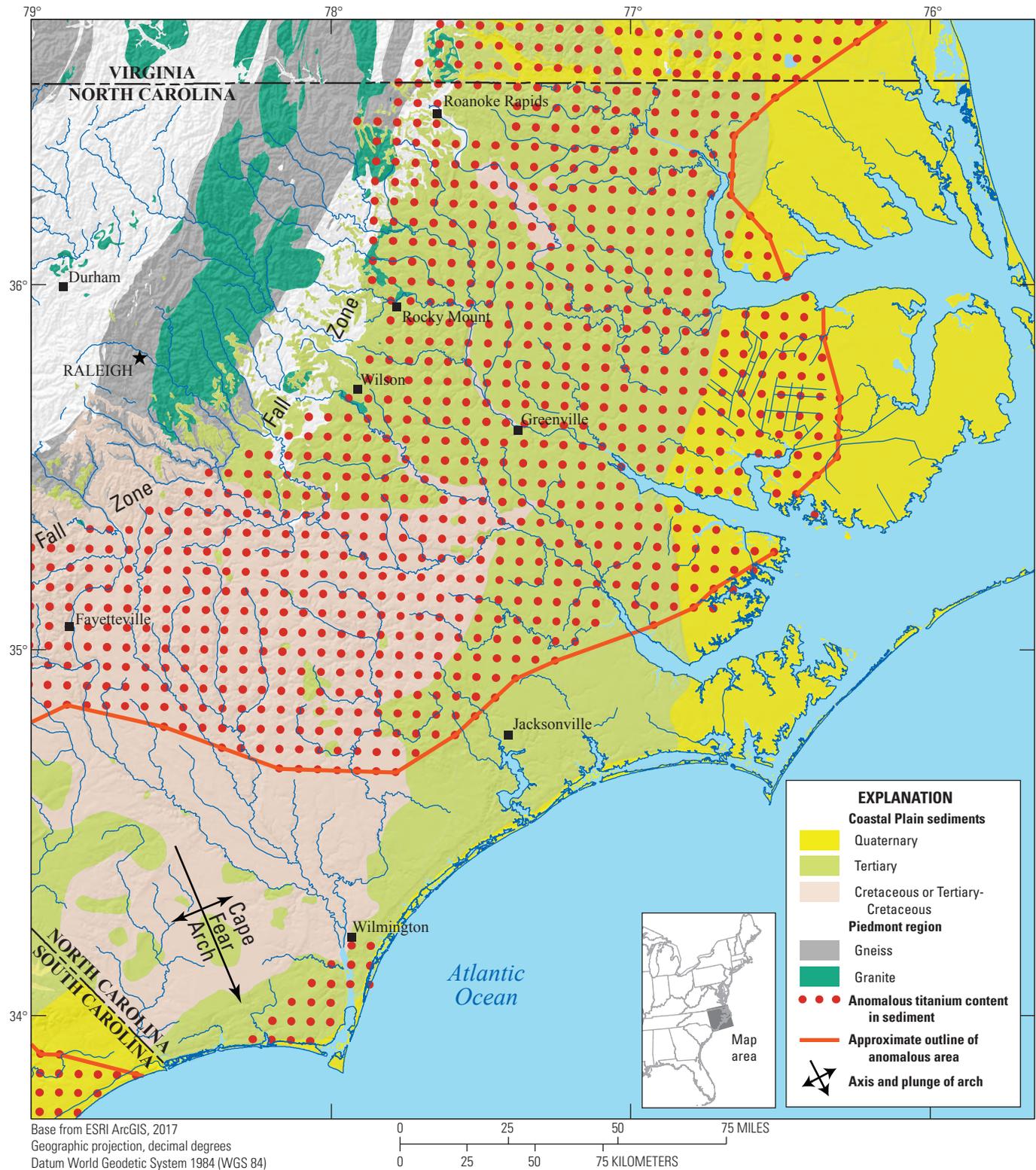
Basins bound each side of the arch. Uplift of the arch has been interpreted to have occurred during the Pliocene and Pleistocene (Soller, 1988). Erosion of the sediments atop the arch, as well as diversion of drainage systems to areas northeast of the arch (Soller, 1988), probably were the main influences for the lack of heavy-mineral deposition (or preservation) across the arch since the late Pliocene.

As noted earlier, Carpenter and Carpenter (1991) identified 19 HMS deposits in the upper Atlantic Coastal Plain along the Fall Zone in southern Virginia and northern North Carolina, a strip of deposits they named the “North Carolina-Virginia heavy mineral belt.” This belt of Pliocene strandline deposits extends north to south from the area of Richmond, Va. (Newton and Romeo, 2006; Berquist and others, 2015) to the vicinity of Wilson, N.C. (figs. 1 and 14). In addition to this “heavy mineral belt,” the results of our study suggest that HMS deposits are not only concentrated along the Fall Zone, but also that similar HMS deposits could be found for several tens of kilometers east of the Fall Zone (fig. 14).

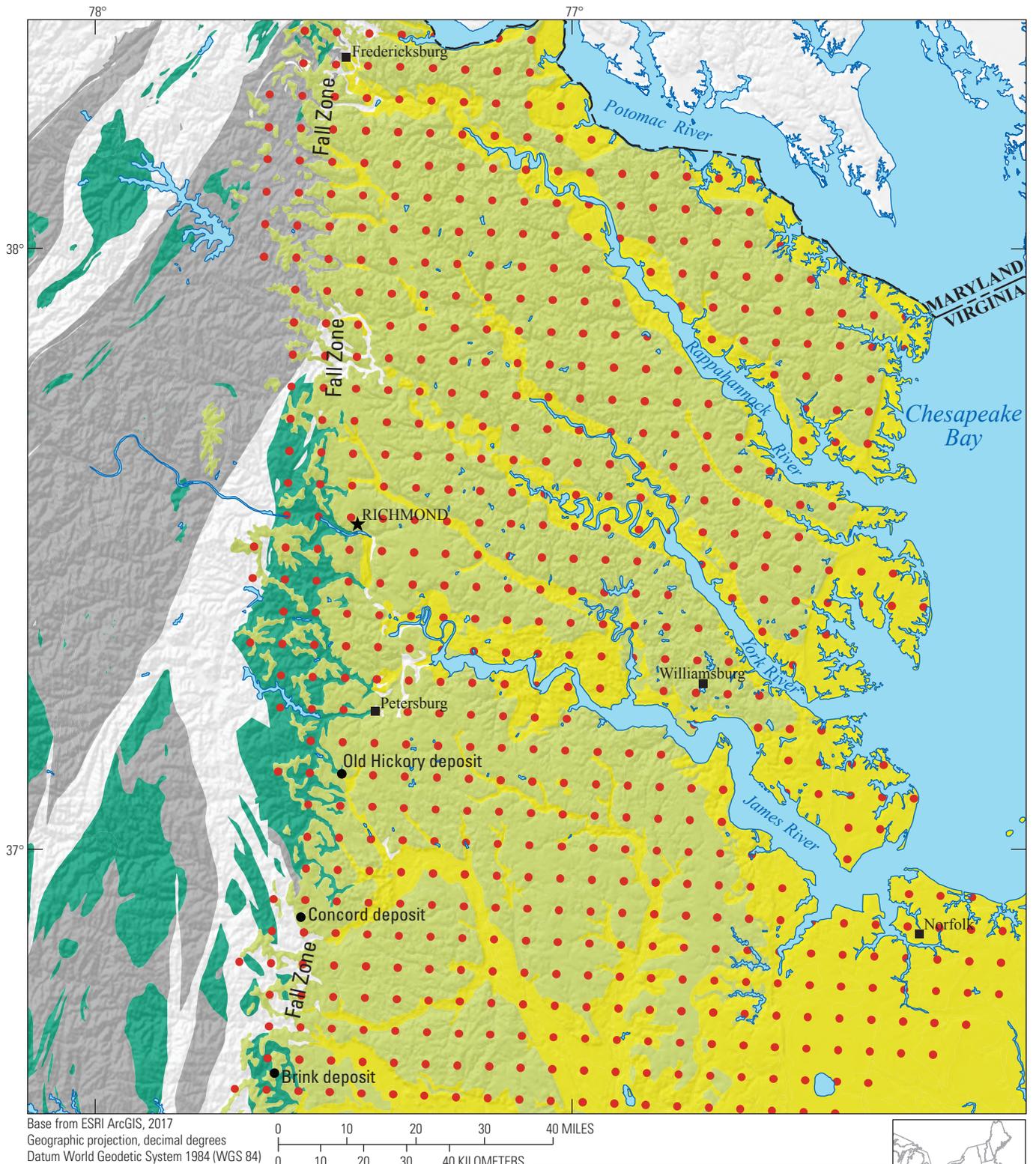
### Anomalous Area D

Our study determined that a majority of the coastal plain of Virginia could have the potential to host titanium-rich deposits of HMS (figs. 10 and 15). Some of the highest titanium concentrations found in our study area of the Atlantic Coastal Plain occur along the western coast of the Chesapeake Bay in Virginia (fig. 15). Although this area also contains some of the highest variability in concentrations (high standard deviation) (fig. 11), the large number of clusters of titanium anomalies indicate that this area may have high potential for HMS.

In particular, the areas between the James and the Potomac Rivers (fig. 15) exhibited some of the highest titanium concentrations in the entire study area. These anomalies occur in Pliocene-Miocene and Pleistocene sedimentary deposits (Berquist and others, 2015; Horton and others, 2017). The highest titanium values occur in the outer coastal plain, the region most distant (eastward) of the Fall Zone (fig. 15). This relationship likely indicates a progressive remobilization, re-concentration, and re-deposition of the heavy minerals along eastward-developing coastlines that existed from the Pliocene to the Pleistocene (Oaks and Coch, 1963, 1973; Bick and Coch, 1969; Johnson, 1969, 1972, 1976; Oaks and others, 1974). Heavy-mineral-rich river terrace deposits of Pleistocene age occur along the major drainages of the Virginia coastal plain, which are well exemplified by the terraces along the James River, York River, and Rappahannock River (Bick and Coch, 1969; Johnson, 1969; Force and Geraci, 1975; Berquist and others, 2015). Headward erosion of bedrock along the Fall Zone was a principal source of ilmenite and rutile during the Pliocene and Miocene, as suggested by Shah and others (2017). Subsequently during the Pleistocene, major drainage systems, represented now by the large modern rivers, transported additional detritus carrying heavy minerals to the Atlantic Coastal Plain from the metamorphic and igneous terranes of the Piedmont Region (Minard and others, 1976).



**Figure 14.** Map showing the anomalous titanium concentrations in area C, the upper and middle coastal plain of North Carolina. Anomalous titanium concentrations occur in sediments mapped as Cretaceous and as Tertiary. The standard deviation in the titanium concentrations is generally low across this region of the Atlantic Coastal Plain (see fig. 11), indicating low variation around the mean concentrations. Refer to figure 10 for spatial reference within the larger Atlantic Coastal Plain region. Geologic map units from Horton and others (2017). Mismatches in geologic units across the borders of North Carolina, South Carolina, and Virginia reflect interpretive differences between the State geologic maps.



**Figure 15 (continued on following page).** Map showing the anomalous titanium concentrations in area D, the coastal plain of Virginia. Some of the highest titanium concentrations found in our study area of the Atlantic Coastal Plain occur along the western coast of the Chesapeake Bay in Virginia. Although this

EXPLANATION	
<span style="background-color: yellow; border: 1px solid black; display: inline-block; width: 15px; height: 10px;"></span> Coastal Plain sediments	<span style="background-color: grey; border: 1px solid black; display: inline-block; width: 15px; height: 10px;"></span> Piedmont region
<span style="background-color: lightgreen; border: 1px solid black; display: inline-block; width: 15px; height: 10px;"></span> Quaternary	<span style="background-color: darkgreen; border: 1px solid black; display: inline-block; width: 15px; height: 10px;"></span> Gneiss
<span style="background-color: yellowgreen; border: 1px solid black; display: inline-block; width: 15px; height: 10px;"></span> Tertiary	<span style="background-color: green; border: 1px solid black; display: inline-block; width: 15px; height: 10px;"></span> Granite
<span style="color: red;">●</span> Anomalous titanium content in sediment	
<span style="color: black;">●</span> Brink deposit	<span style="color: black;">●</span> Heavy-mineral sand (HMS) deposit and identifier

**Figure 15 (continued from previous page).** area also contains some of the highest variability in concentrations (high standard deviation) (see fig. 11), the large number of clusters of titanium anomalies indicate that this area may have high potential for heavy-mineral sands. Refer to figure 10 for spatial reference within the larger Atlantic Coastal Plain region.

Heavy minerals are still being deposited today along the modern coastlines of this region, where they are worked by the actions of waves, longshore currents, and wind (fig. 4).

Grosz (1983) carried out an exploration assessment of the HMS deposits along the coastal plain of Virginia. His study employed total-count aeroradiometric maps followed by field checking of 80 identified anomalies by ground radiometric surveys and sediment samples. The heavy-mineral assemblages of the 80 sediment samples were processed and individual minerals separated to measure the percentage of each heavy mineral (those with a specific gravity >2.85). The majority of the sediment samples contained less than 1 percent total heavy minerals. Grosz (1983, p. 16) concluded from his study that “no currently economic heavy-mineral deposits are at or near the surface in the coastal plain of Virginia.”

Force and Geraci (1975) documented the heavy-mineral content in sands deposited alongside the modern Atlantic Ocean coast and barrier islands of Virginia, as well as in sands of presumed Pleistocene age near the mouths of the James, York, and Rappahannock Rivers. Based on 54 sediment samples distributed across these areas, they found that (1) ilmenite composed 48 to 79 percent of the heavy-mineral concentrate; (2) the  $\text{TiO}_2$  content of the ilmenite ranged from 46 to 55 percent; and (3) the highest heavy-mineral content was only 1.6 percent. Although the heavy-mineral content of the sands is relatively low for most economic deposits, the  $\text{TiO}_2$  content is in the acceptable range for pigment manufacture.

Several types of metamorphic and igneous rocks that may contain ilmenite and (or) rutile occur in the Piedmont Region of central Virginia, dominated by varieties of gneiss and granite (fig. 15). These rock types are volumetrically the most likely sources of the bulk of ilmenite, leucoxene, and rutile grains in the coastal sediments of Virginia (Minard and others, 1976).

## Anomalous Area E

Anomalous concentrations of titanium occur in Quaternary sediments along the entire outer coastal plain of South Carolina (fig. 16). Some of the highest titanium concentrations found in this study of the Atlantic Coastal Plain were found to occur in barrier islands of southeastern South Carolina, in particular on Hilton Head Island and St. Phillips Island (fig. 16). The majority of the high-titanium sediments along the South Carolina coast are in Pleistocene-age deposits. The barrier islands are transgressive features (fig. 2), which presumably formed during sea level rise in tandem with an increase in

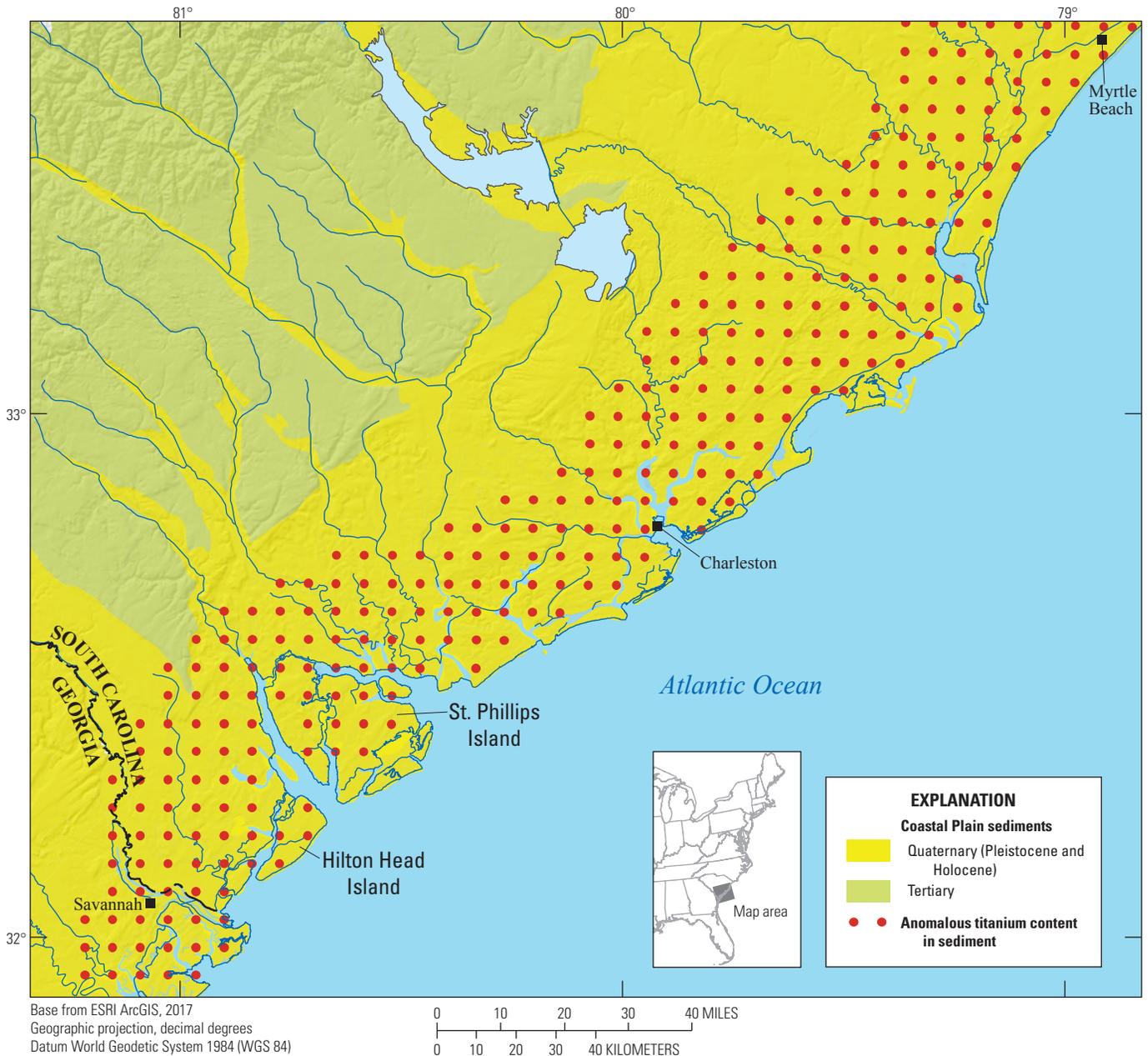
sediment load to the coastal plain. These conditions most likely occurred during periods of melting and retreat of Pleistocene glaciation in the northern U.S. Numerous rivers in South Carolina originate in the Piedmont region and cross the Atlantic Coastal Plain (fig. 16); the alluvial deposits (placers) in many of these rivers can also contain HMS deposits (Williams, 1967; Neiheisel, 1976; Force and others, 1982). The rivers brought heavy minerals to the coast for further concentration by waves, wind, and tides (Pirkle, Pirkle, and Reynolds, 1991; Elsner, 1997). Longshore transport along the coast, which is dominantly from north to south along the South Carolina coast (van Gaalen, 2004), has also redistributed the heavy minerals along coastal strandlines through time.

Hilton Head Island in southeastern South Carolina (fig. 16) has been shown to host several HMS deposits, including some with high heavy-mineral content. In 1954, the U.S. Bureau of Mines reportedly drilled 265 shallow holes (5 to 54 feet [ft] in depth) and 64 auger holes 4.5 to 15 ft in depth into Hilton Head Island to evaluate its HMS potential (McCauley, 1960). According to McCauley (1960, p. 4), their “... analysis revealed an average heavy mineral content of 2.19 percent to an average depth of 11.1 feet.” A HMS deposit that covers about 4,630 acres was calculated to contain an average heavy-mineral content of about 2.3 percent (Williams, 1967). The titanium mineralogy of the heavy-mineral fraction was dominated by ilmenite (about seven times the rutile content). At about the same time period, the National Lead Company drilled 545 holes into Hilton Head Island to a depth of about 40 ft each (McCauley, 1960). They found similar results, “The average percentage of heavy minerals contained in the top 10 feet of the 545 drill holes was 2.24” (McCauley, 1960, p. 5).

Other barrier islands along the South Carolina coast that are located to the northeast of Hilton Head Island also reportedly contain high-grade HMS deposits that are potentially economic. Listed in decreasing order of potential (according to Neiheisel, 1958), these islands (that are too small to show on figure 16) include Bull Island, Capers Island, Isle of Palms, Edisto Island, Fripp Island, and Dewees Island.

## Summary and Conclusions

This study carried out a geospatial analysis of the titanium concentrations measured from 3,457 stream sediment samples distributed across the Atlantic Coastal Plain of the southeastern U.S. The raw data used to carry out the geospatial analyses are provided in the data release that accompanies this report (Ellefsen, 2017). The geospatial analysis involved developing a new Bayesian hierarchical model from which both the mean and the variance of the concentrations are estimated over a region. The mean may be interpreted as an average, and the square root of the variance may be interpreted as the spread of the concentrations around the mean. Maps of these two quantities help delimit regions that might be favorable to mining of titanium-bearing minerals.



Base from ESRI ArcGIS, 2017  
 Geographic projection, decimal degrees  
 Datum World Geodetic System 1984 (WGS 84)

**Figure 16.** Map showing the anomalous titanium concentrations in area E, the outer coastal plain of South Carolina. Some of the highest titanium concentrations found in this study of the Atlantic Coastal Plain were found to occur in barrier islands of southeastern South Carolina, in particular on Hilton Head Island and St. Phillips Island. Refer to figure 10 for spatial reference within the larger Atlantic Coastal Plain region.

The study results indicate that considerable resources of titanium, in the form of detrital grains of ilmenite, leucoxene, and rutile, could exist in large areas of the Atlantic Coastal Plain. These HMS deposits represent possible domestic sources of titanium that have yet to be developed. Identifying potential domestic resources of titanium is useful because titanium has significant industrial applications, and because the great majority of titanium mineral concentrates consumed in the U.S. are imported (91 percent in 2016; Ober, 2017). Only two HMS

mining operations are currently (as of 2017) active in the U.S., due to closure of the HMS mines in southern Virginia.

To assist in the search and discovery of additional HMS deposits in the U.S., our study outlines areas where exploration for such deposits could focus within the Atlantic Coastal Plain. In addition to zones of HMS deposits that parallel the Fall Zone, the results of this study suggest that substantial heavy-mineral resources in a variety of settings could exist some distance from the Fall Zone. Specific areas

with anomalous titanium concentrations, shown regionally in figure 10 and in more detail in figures 12 to 16, might be considered as focus areas for future exploration for HMS deposits.

Many prospective areas for HMS deposits in the Atlantic Coastal Plain occur near the modern shores or on barrier islands, for example, the coasts of South Carolina, southeastern Georgia, and northeastern Florida. Much of the modern coastal areas are covered by infrastructure or designated protected wetlands. Thus, land-use and permitting considerations may limit mineral development along the modern coast.

Shah and others (2017), utilizing regional aeroradiometric data, evaluated the mapping of potential rare earth elements resources in the Atlantic Coastal Plain in the form of monazite and xenotime. Their studies indicate that concentrations of monazite and xenotime are highest near the Fall Zone, and their concentrations remain relatively high for approximately 40 km eastward of the Fall Zone. The phenomenon of higher monazite concentrations in the upper Atlantic Coastal Plain is understandable, because monazite is typically the heaviest (most dense) of the minerals in the sediments, and thereby less amenable to long distance transport. Our study focused on the potential for titanium resources (ilmenite, leucosene, rutile), which our study suggests is more widespread in the Atlantic Coastal Plain than monazite.

The application of stream sediment sampling to identify HMS in coastal plains has some advantages over aeroradiometric surveys. As examples of the limits of aeroradiometric surveys, Grosz (1983) noted several factors can subdue or enhance the radioactivity measured by an airborne survey: (1) high moisture content of the sediment can subdue radioactivity; (2) a small concentration of radioactive minerals (monazite, zircon) can prevent detection of HMS deposits; (3) fertilizers applied in agricultural lands can be radioactive because of their potash and phosphate; (4) radioactivity can be contributed by some clay-sized minerals (as also described by Force and Bose, 1977); (5) thick vegetation cover can subdue radioactivity; and (6) some cultural features contribute radioactivity, such as buildings made of granite or road gravels of crushed gneiss or granite.

While this study was able to map the distribution of titanium-rich sediments, it also revealed limitations of using stream sediment samples to locate HMS deposits. One limitation is that the stream sediment samples are representative of the soils and sediments near the land surface. Consequently, economically profitable deposits that are well beneath the land surface will not be detected using this method. Another limitation is spatial resolution; maps of titanium concentrations show regional-scale features, not deposit-scale features.

This study demonstrates an application of Bayesian hierarchical modeling for mapping titanium concentrations on a regional scale. Mapping titanium concentration in the Atlantic Coastal Plain area of the U.S. (fig. 10) indicates where the average concentration is high; such areas might be suitable for exploration. The map of the standard deviation in titanium concentrations in the Atlantic Coastal Plain area of the U.S.

(fig. 11) indicates how the concentrations vary about the average; areas with high average concentration and low variability may be less risky than areas with high average concentration and high variability. Mapping these data could help mining companies delimit areas for exploration.

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