Coastal deposits of heavy mineral sands; Global significance and US resources

by Bradley S. Van Gosen, Donald I. Bleiwas, George M. Bedinger, Karl J. Ellefsen and Anjana K. Shah

Ancient and modern coastal deposits of heavy mineral sands (HMS) are the principal source of several heavy industrial minerals, with mining and processing operations on every continent except Antarctica. For example, HMS deposits are the main source of titanium feedstock for the titanium dioxide (TiO_2) pigments industry, obtained from the minerals ilmenite (Fe_2+TiO_3), rutile (TiO_2) and leucoxene (an alteration product of ilmenite). HMS deposits are also the principal source of zircon ($ZrSiO_4$), from which zirconium dioxide (ZrO_2) is obtained for uses mostly in refractory products. Sometimes monazite [(Ce,La,Nd,Th)PO_4] is recovered as a byproduct mineral, sought for its rare earth elements, and thorium (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 the heavy minerals (Fig. 1). Economic (mined) HMS deposits include Holocene sediments on modern coasts, such as examples in India and Brazil, as well as coastal deposits formed by transgressions and regressions of the seas during intervals in the Quaternary, Tertiary and Cretaceous, such as in Australia and the southeastern United States. Economic deposits typically contain heavy-mineral concentrations of at least two percent.

Individual heavy minerals are commonly defined as minerals with a specific gravity greater than approximately 2.9 g/cm^3. 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, sulfides, anatase, monazite, cassiterite and xenotime. Of these, ilmenite, leucoxene, rutile and zircon are the primary economic minerals. Garnet, monazite, cassiterite and xenotime are occasionally recovered as byproducts. The heavy minerals as a suite typically make up no more than 15 weight percent of a deposit and usually much less. Quartz and clay minerals form the bulk of the sediment. The geology of HMS deposits and examples of significant districts are summarized in Van Gosen and others (2014) and Hou and Keeling (2016).

To form HMS deposits, heavy minerals are liberated 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

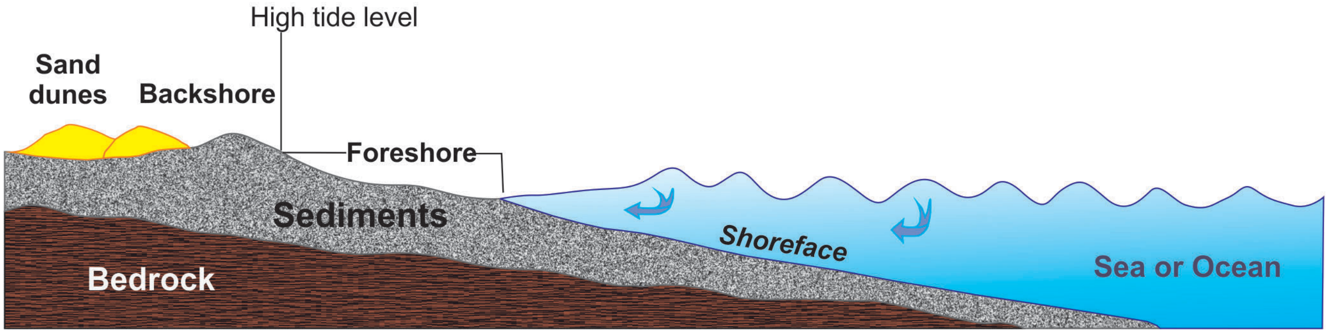
Figure 1

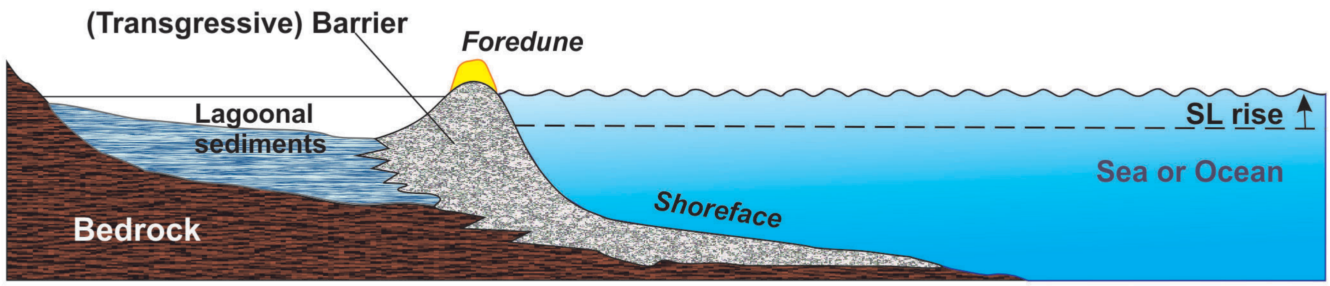
Layers of heavy minerals in quartz beach sand (heavy mineral sands, HMS), Trivandrum, India. Photograph courtesy of B. Hou, Geological Survey of South Australia. ("HMs," heavy mineral content.)

Bradley S. Van Gosen, Donald I. Bleiwas, George M. Bedinger, Karl J. Ellefsen and Anjana K. Shah are research geologist, physical scientist, physical scientist and research geophysicist and research geophysicist, respectively, U.S. Geological Survey, email bvangose@usgs.gov.

Figure 2

Schematic cross sections showing the features commonly used to describe shoreline depositional environments associated with heavy mineral sands deposits. Upper cross section: mainland beach depositional environment; lower cross section: barrier-tidal lagoon shoreline depositional environment (modified from Roy and others, 1994). (SL, sea level.)





concentrating the heaviest minerals as layered sediments in a variety of coastal depositional environments (Fig. 1). Typically, approximately 80 percent of the heavy-mineral suite is ilmenite, rutile, iron-oxide minerals and zircon, with lesser amounts of leucoxene, monazite, garnets, sillimanite and staurolite. HMS can accumulate in deltas, the beach face (foreshore), sand dunes behind the shore (backshore area), the offshore (shoreface and farther seaward), in barrier islands (transgressive or regressive barrier) and tidal lagoons (Fig. 2), as well as the channels and floodplains of streams and estuarine channels. These depositional environments are discussed in detail by Hou and Keeling (2016). Processes that one can observe now provide modern analogues to the processes that formed the ancient deposits (Fig. 3). That is, the natural processes that act upon coastal areas today, such as effects of waves, storm surges, tides, longshore drift and sediment supply from inland sources are similar to the processes that formed voluminous deposits of HMS over thousands to millions of years of deposition along ancient shores across the world.

Industrial uses and production of titanium mineral concentrates from heavy mineral sands

Industrial uses of titanium. Most titanium, derived from processing ilmenite, rutile, and leucoxene, is not consumed in its metal form

Figure 3

Heavy minerals (black sands) deposited on a beach along the shoreline of the Atlantic Ocean in Virginia. Storms can bring heavy minerals from the shoreface to the beach (foreshore), where the actions of waves, tidal currents, and wind can mechanically sort the heavy minerals into layered deposits. Photograph courtesy of Rick Berquist, Virginia Division of Geology and Mineral Resources.

Figure 4

Wet concentrator plant (top), early-stage concentrator that separates clay and silt from the sediments (middle photo), and wet stacking of heavy mineral concentrate (bottom photo); Jacinth operation of Iluka Resources Ltd., located in South Australia. Photographs courtesy of B. Hou, Geological Survey of South Australia.

but as titanium dioxide (TiO_2). In powder form, 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). On a gross weight basis, 95 percent of the U.S. domestic consumption of titanium mineral concentrates was used to produce TiO_2 pigment in 2015 (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 is blended to produce high-grade titanium with a TiO_2 content of 70 to 95 percent (HiTi), 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. The estimated value of titanium mineral concentrates consumed in the United States in 2015 was $670 million (Bedinger, 2016a).

Production of titanium mineral concentrates. HMS deposits are usually mined by surface operations involving dredging and (or) dry surface mining techniques. Onsite gravity separation operations are used to isolate the heavy-mineral components (Fig. 4), 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 is accomplished using magnetic and electrostatic circuits. 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.

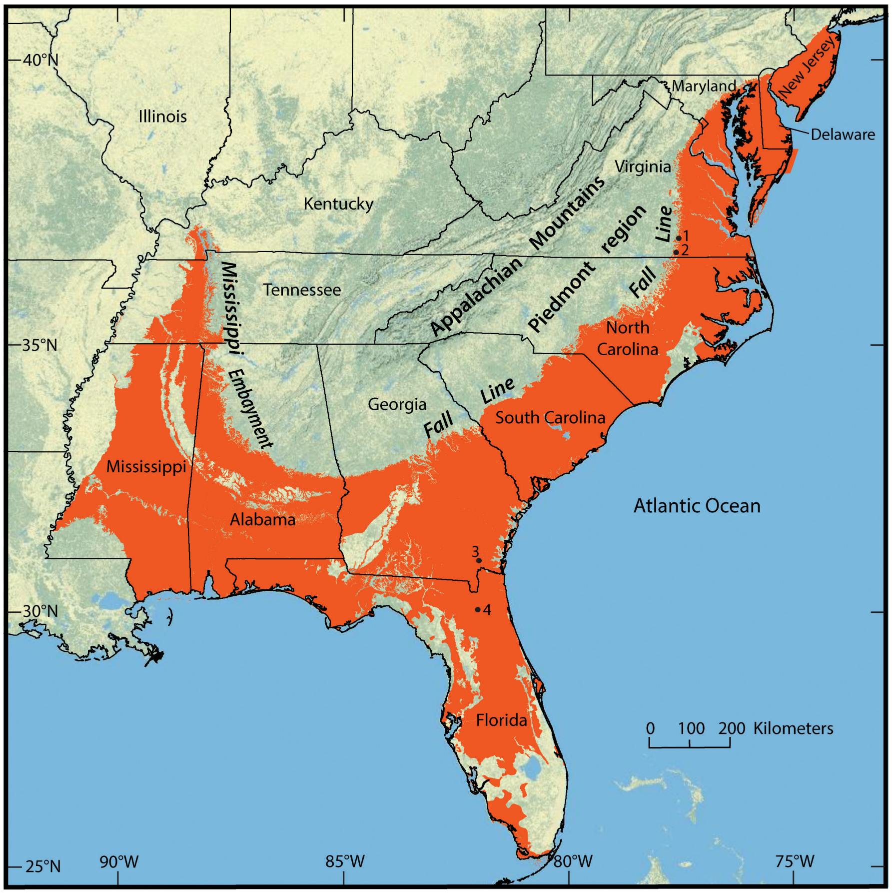
Ilmenite is typically the most abundant titanium mineral in HMS deposits. It has a TiO_2 content of 53 percent, but intercalation and weathering causes the TiO_2 content to vary significantly. After deposition in sediments, weathering enhances the TiO_2 content of some Ti-oxide minerals. In particular, iron is leached from ilmenite by weathering, which thereby upgrades the TiO_2 content of the ilmenite (Force, 1991). Ilmenite is often further processed to produce a titanium concentrate, either as synthetic rutile or titaniferous slag.

Ideal rutile contains about 95 percent TiO_2, but it is usually less abundant than ilmenite in HMS deposits. 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, 2013a).

Dozens of coastal deposits of HMS are being mined and processed to extract heavy minerals, with active operations on every continent except Antarctica, serving as globally important sources of some industrial minerals. For example, in 2001, about 96 percent of the zircon, 90 percent

Figure 5

Index map of the southeastern United States showing the distribution of clastic coastal deposits of the ancient and modern Atlantic Coastal Plain. These sediments, ranging from Late Cretaceous to modern deposits, locally contain heavy mineral sands. Also shown are four recent HMS mining areas in this region: the Concord Mine (1) and the Brink Mine (2) of Iluka Resources Ltd in southeastern Virginia; the Mission Mine (3) of Southern Ionics Inc. in southeastern Georgia and the Trail Ridge deposits (4) of The Chemours Company in northeastern Florida.



of the rutile and diamonds, 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 (Chi and Zheng, 2001). More recent data suggest these percentages have remained similar (Australian Atlas of Mineral Resources, Mines, and Processing Centres, 2013). Australia and China are the major global producers of HMS, recovering mainly ilmenite, rutile and zircon, and in the past, monazite (Australian Atlas of Mineral Resources, Mines, and Processing Centers, 2013). Exploration for HMS deposits is occurring in Australia, India, Kenya, Madagascar, South Africa, Sri Lanka, the United States and other countries (Van Gosen and others, 2014).

From 2000 to 2014, the total world mine production of ilmenite concentrates increased by 30 percent, from an estimated 4.3 to 5.57 Mt (4.7 to 6.14 million st) of TiO_2 contained in concentrate (Gambogi, 2002; Bedinger, 2016a). The increase in production of concentrates was brought about, to a large extent, by increased demand by China.

In 2014, China was the leading world mine producer of TiO_2 in ilmenite concentrates, with approximately 960 kt (1.06 million st) representing 17 percent of global production. This was a significant increase from 2000, when China produced about 150 kt (165,000 st) of TiO_2 contained in ilmenite concentrates, less than 5 percent of global production (USGS records). Australia was the world's leading producer of ilmenite concentrates in 2000, which contained about 1.23 Mt (1.35 million st) of TiO_2, about 29 percent of world production. In 2014, Australia produced 720 kt (793,000 st) of TiO_2 contained in ilmenite concentrates, about 13 percent of global production (Bedinger, 2016a).

Other major producers of TiO_2 contained in ilmenite concentrates in 2014, and their respective share of global ilmenite production, were South Africa (11 percent); Vietnam (10 percent) and Mozambique (9 percent) (Table 1). The future market for titanium mineral concentrates is expected to depend on the demand for TiO_2 pigment (Bedinger, 2016a).

World production of natural rutile concentrates increased from about 390 kt (430,000 st) of TiO_2 contained in concentrate in 2000 to 471 kt (518,000 st) of TiO_2 contained in concentrate in 2014 (Gambogi, 2002; Bedinger, 2016a). The increase in production of natural rutile concentrates resulted from the development of mines in Sierra Leone, beginning in 2006. World production of rutile concentrates was less than ilmenite concentrates over the entire period.

In 2014, Australia was the world leader in mined natural rutile production with about 190 kt (210,000 st) of TiO_2 contained in rutile concentrates, a 40 percent share of world mine production (Bedinger, 2016a). This was a decrease from 2000, when Australia produced an estimated 225 kt (248,000 st) of TiO_2 contained in concentrate, about a 58-percent share of world mine production. In 2014, Sierra Leone produced about 100 kt (120,000 st) of TiO_2 contained in rutile concentrates, representing about 21 percent of 2014 global production of

Heavy Mineral Sands

Table 1

World mine production in 2014. (Ilmenite and rutile reported in thousands of metric tons of TiO_2 contained in ilmenite and rutile concentrates, respectively; zirconium reported in gross weight)

Country	Deposit type	Ilmenite	Rutile	Zirconium
China	HMS	960	nr	150
Australia	HMS	720	190	551
South Africa	HMS	600	53	387
Vietnam	HMS	560	nr	nr
Mozambique	HMS	510	nr	51
Madagascar	HMS	300	9	nr
Ukraine	HMS	250	63	nr
India	HMS	190	17	40
Kenya	HMS	100	22	nr
Brazil	HMS	100	nr	nr
United States	HMS	100	*	**
Senegal	HMS	60	nr	nr
Sierra Leone	HMS	nr	100	nr
Indonesia	HMS	nr	nr	110
Canada	Hard rock	480	nr	nr
Norway	Hard rock	440	nr	nr
Russia	Hard rock	110	nr	nr
Other countries		90	17	130
World total		5,570	471	1,419

natural rutile concentrates (Bedinger, 2016a). Other major natural rutile producers in 2014, and their respective production percentage share of global TiO_2 contained in rutile concentrates, were Ukraine (13 percent), South Africa (11 percent) and Kenya (5 percent) (Bedinger, 2016a) (Table 1).

Industrial uses and production of zircon from heavy mineral sands

Industrial uses of zircon. Zircon ($ZrSiO_4$) is obtained as a coproduct during the separation and recovery of the titanium minerals. Zirconium oxide 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 by the foundry industry (Bedinger, 2013b). Zircon is used as an abrasive. It is an additive to metal alloys, chemicals, pharmaceuticals and medicine and food; and it is used in welding rod coatings, cosmetics, glass faceplates for television tubes, computer disc drives, lightweight warm and protective clothing, ballpoint pens and wear-resistant knives.

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). Other markets, in decreasing order, were zirconia (ZrO_2) and other zirconium chemicals, refractory and foundry applications.

Global production of zirconium. Global mine production of zirconium mineral concentrates was estimated to be about 1.42 Mt (1.56 million st) in 2014, an increase of 37 percent from global zirconium production of 1.04 Mt (1.14 million st) in 2000 (Hedrick, 2002; Bedinger, 2016c). In 2014, the leading zirconium concentrate producing countries were Australia and South Africa (Table 1) with 39 percent and 27 percent of global production, respectively (Bedinger, 2016c). Production was consistent with demand as the three largest global producers of zircon — Iluka Resources Ltd. of Australia, Rio Tinto of the United Kingdom and Tronox Ltd. of Stamford, CT, USA — reported stable market conditions (Bedinger, 2016b).

In February 2016, Iluka announced that it would suspend mining and mineral processing at its Jacinth-Ambrosia Mine in South Australia for 18 to 24 months, beginning in April, in order to draw down existing inventory. MZI Resources Ltd. of Australia completed construction of its Keysbrook Project in Western Australia and produced its first zircon product in November 2015. Other heavy mineral exploration and mining projects with significant zircon resources were underway in Australia, Brazil, Kenya, Madagascar, Mozambique, Senegal and Sri Lanka.

Iluka, the largest global producer of zircon concentrates, was expecting zircon production and sales in 2016 to exceed those of 2015. TZ Minerals International Pty. Ltd. projected an increase in global production in 2016 as new sources in Africa were being developed.

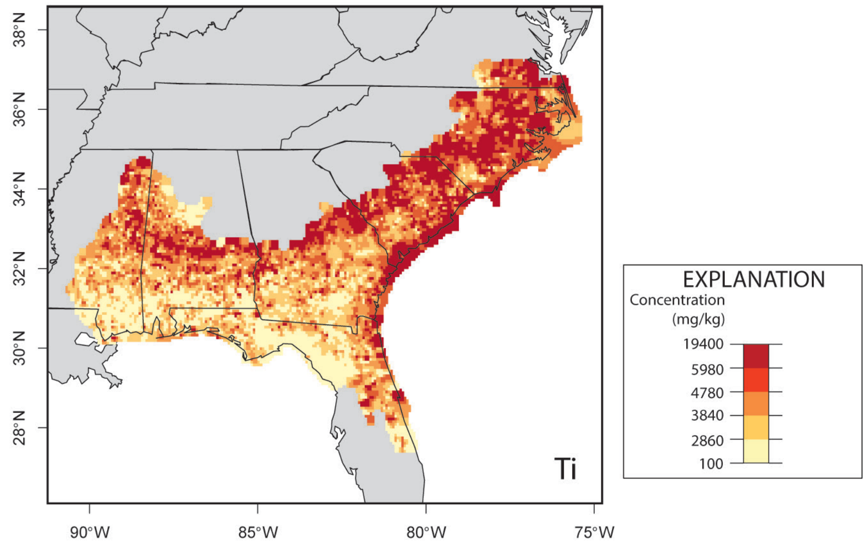
Industrial uses and production of monazite from heavy mineral sands

Until the mid-1960s, monazite extracted from HMS deposits was the primary global source for rare earth elements, with most of this monazite production from Brazil and India. In 1965, when full-scale mining and production of rare earth elements began from the Mountain Pass carbonatite deposit in California, the role of HMS deposits as sources of rare earth elements from monazite in placer deposits was greatly reduced.

Some countries, such as China and India, have ambitious programs in nuclear power. The countries have limited resources of uranium

Figure 6

Map of the southeastern United States showing the distribution of titanium in stream sediment samples. From Ellefsen and others (2015).



and considerably larger resources of thorium. India's sizable resources of thorium, possibly the largest in situ thorium resources in the world (NEA-IAEA, 2014), are in the form of monazite [(Ce,La,Nd,Th)PO_4] in HMS along their eastern and western coastlines. Government-supported projects, in particular in India and China, as well as France, Norway, Canada, Brazil and Russia, have recently devoted research toward the development of thorium-based nuclear power (NEA-IAEA, 2014; NEA-IAEA, 2015; Van Gosen and Tulsidas, 2016).

Monazite concentrate production, as a coproduct of HMS mining for titanium minerals and zircon, has occurred in recent years in India, Malaysia, Thailand, Vietnam and Brazil, in decreasing order of production (Van Gosen and others, 2014). Indian beach placers are the principal present-day source for the production of monazite, mainly obtained from coastal shores in the states of Kerala and Orissa. The monazite is stockpiled to provide source material for future development of thorium-based nuclear power, under a program sponsored by the Department of Atomic Energy of the Indian government (Anantharaman and others, 2008). The typical composition of monazite from the Kerala deposits in India is reportedly 57.5 percent REE oxide and 7.96 percent thorium oxide (ThO_2) (Kerala Minerals & Metals Ltd., 2016). Monazite is currently processed as a stockpile of thorium hydroxide by the Rare Earths Division of Indian Rare Earths Limited (Indian Rare Earths Limited, 2016).

In recent years in the United States, while studies show that monazite can comprise up to 12 percent of the heavy mineral suite (Bern and others, 2016), monazite has not been stockpiled due to concerns about the radiation from thorium within the monazite. Instead, monazite recovered during the gravitational separation of the heavy minerals is typically blended with the waste sands and silts and returned to the pit during remediation, thereby returning the monazite to the ground at proportions similar to the original HMS.

U.S. production and resources of heavy mineral sands

Recent U.S. production. In May 2015, Southern Ionics Inc. completed construction of its mineral sands processing plant near Offerman, GA, to process heavy mineral concentrates from its mining operation in Charlton County. In February 2016, Southern Ionics announced a curtailment of operations owing to a decreased demand for titanium concentrates that was anticipated to extend through most of 2016 (Bedinger, 2016a).

In May 2015, Southern Pines LLC began to build a wet concentrator plant to process existing tailings deposits in New Jersey to produce a zircon-ilmenite concentrate. Completion of the plant was expected in 2016.

Iluka Resources Ltd. concluded operations at its Brink and Concord Mines near Stony Creek, VA, at the end of 2015 (Bedinger, 2016a; Iluka Resources Ltd., 2016). Iluka commenced mining of HMS in this area of southeastern Virginia (Dinwiddie County) in 1998 (at the Old Hickory deposit). Using openpit, dry mining techniques the company has worked unconsolidated, Tertiary-age HMS deposits in this area to recover ilmenite, rutile and zircon (Iluka Resources Ltd, 2013; Van Gosen and others, 2014; Berquist and others, 2015).

Mining and processing of HMS for titanium minerals and zircon continues at The Chemours Co. operations along the Pleistocene-age Trail Ridge deposits, east of Starke, FL. DuPont began mining on the southern end of the Trail Ridge in 1949. Recent operations continue to mine HMS along the trend of Trail Ridge, which now includes mines in Baker, Bradford, Clay and Duval counties.

U.S. heavy mineral sands resources. The coastal plain of the southeastern United States has substantial resource potential for HMS deposits. Clastic sediments have been deposited along the Atlantic Coastal Plain (Fig. 5) from the Late Cretaceous to the present. The sedimentary units are weakly consolidated and locally enriched in heavy minerals, making them candidates for economic deposits of HMS. As a result, large expanses of the Coastal Plain of the southeastern U.S. are permissive for extensive, potentially economic deposits of heavy minerals (Neiheisel, 1962; Carpenter and Carpenter, 1991; Grosz and others, 1992; Grosz, 1993; Grosz and Schruben, 1994; Van Gosen and others, 2014). These deposits are known to include ilmenite, rutile, zircon, and locally minor amounts of monazite and xenotime.

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 deposits, which were subsequently mined by Iluka Resources. The heavy mineral deposits of this belt initially developed in the upper Coastal Plain, just east of the "Fall Line" (Fig. 5) — a regional term used to describe the contact zone between the basement rocks of the Piedmont region on the west and much younger sediments of the Coastal Plain on the east. HMS in the western parts of the Coastal Plain of Virginia and North Carolina, along the Fall Line, are interpreted to be Pliocene sedimentary deposits that formed during worldwide transgression-regression events, which occurred between 3 and 3.5 million years ago (Ma) (Carpenter and Carpenter, 1991). On the basis of heavy-mineral estimates for 19 deposits within this belt, Carpenter and Carpenter (1991) calculated a total regional resource of 22.7 Mt (25 million st) of heavy minerals in 377.8 Mt (416 million st) 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 percent kyanite, 1.3 percent sillimanite and 11.5 percent other heavy minerals (mostly limonite) (Carpenter and Carpenter, 1991).

In addition to Tertiary and Late Cretaceous HMS deposits along the Fall Line, north-south-trending ridges of HMS cross northeastern Florida and southeastern Georgia. An example is the Pleistocene-age Trail Ridge mined by Chemours, east of Starke, FL, located about 65 km (40 miles) inland from the current shoreline. Other Pleistocene and Pliocene ridges of HMS in northeastern Florida lie closer to the coast, such as the Duval Upland ridge deposit at Green Cove Springs, FL, which contains an average of 3 percent heavy minerals that included ilmenite, leucoxene, rutile, zircon and monazite (Staatz and others, 1980). The Green Cove Springs deposit was mined from 1972 to 1978 by Titanium Enterprises, then later by Iluka Resources until 2005. Historical accounts of the early HMS operations in Florida are detailed in Staatz and others (1980), and summarized in Van Gosen and others (2014).

The Atlantic Coastal Plain extends to New Jersey on its north terminus (Fig. 5). HMS deposits of Neogene age have been mined in the area of Lakehurst, NJ, where two companies produced mainly an altered ilmenite (Van Gosen and others, 2014). The deposit's highest-grade intervals are about 5 m (16 ft) thick and contain 5 to 25 percent heavy minerals (Puffer and Cousminer, 1982; Force, 1991), formed in the swash zone along the Neogene shore (Carter, 1978; Puffer and Cousminer, 1982).

On the western part of the ancient Atlantic Coastal Plain, HMS deposits occur in Late Cretaceous sedimentary layers near Bruceton, TN. The McNairy Sand, about 50- to 100-m (164- to 328-ft) thick, is the shoreline facies of a Late Cretaceous transgressive-regressive sequence in the Mississippi embayment (Fig. 5), which extends from Mississippi to southern Illinois (Force, 1991). The basal member of the McNairy Sand, which is as much as 15-m (50-ft) thick, contains concentrations of heavy minerals, which are locally as high as 17 percent (Wilcox, 1971). The heavy mineral suite averages 55 percent ilmenite, 8 percent leucoxene, 2 percent rutile, 10 percent zircon and 1 percent monazite (Force, 1991); staurolite, kyanite, and tourmaline are also present (Wilcox, 1971).

U.S. Geological Survey study of heavy mineral sands of the Atlantic Coastal Plain

A U.S. Geological Survey (USGS) project, scheduled to continue into 2018, is evaluating the coastal plain of the southeastern United States for critical and strategic commodities — particularly titanium and zirconium — that are potentially recoverable from the large, undeveloped deposits of heavy mineral sands in this vast region. This project is a continuation of a recent USGS study that focused on rare earth elements resources in the Atlantic Coastal Plain (Shah and others, 2015). The current project has two basic assessment objectives: determine the regional extent of this resource endowment and evaluate the factors that affect the development of mines for heavy mineral sands.

To address the study's first objective, the project has focused on the spatial distribution of known and potential HMS deposits and the associated geologic processes. This involves mapping the probabilities for high concentrations of heavy mineral sands. The maps generated identify favorable areas where industry might conduct exploration and development. Understanding the processes that formed these deposits will aid in interpreting both the spatial distributions maps and the probability of occurrence maps. To be comprehensive, the study will use multiple, existing earth-science data sets, such as geochemical, geological, geophysical, hydrological and geographical data. Initial analyses of these different data sets were conducted by Ellefsen and others (2015), Shah and others (2015), and Bern and others (2016), which have established the foundation for this investigation. For example, one data set is the geochemical analyses of stream sediments from the National Geochemical Survey (Smith, 1997). Within the study area, there are approximately 5,200 sediment samples, each with chemical analyses for titanium (Fig. 6) and zirconium; these elements serve as proxies for the heavy minerals of high value. Another data set is airborne radiometric data that were collected as part of the National Uranium Resource Evaluation program (Hill and others, 2009). In the study area, there are approximately 1.6×106 measurements of equivalent thorium concentrations, which indicate accumulations of monazite and xenotime, and hence HMS.

To address the second overall objective of the study, the project is conducting a mineral industry analysis and material flow study of HMS deposits, from mine to market. Activities involve:

- Compare the character of undeveloped U.S. deposits to analogous explored deposits and active operations in other parts of the world. This comparison will place into context the economic potential of the U.S. deposits as a potential domestic supply source.
- Examine the estimated lead time requirements for development.
- Examine the potential influence on reduction of import reliance.
- Develop flow figures that display the concept of mine to market and include byproducts, coproducts, and waste products of this deposit type.
- Illustrate the mining and mineral processing requirements, waste generation, resource requirements, and infrastructure requirements. These requirements include land, grade, tonnage, water, energy, site operations, fuel, and other factors.
- Examine the associated environmental factors and social issues affected by competing values that may restrict development. The competing values involve land disturbance, urban development, recreational values, national forest, national seashores, water quality and quantity, radiation issues associated with the sale, stockpiling, and reburial of thorium-bearing monazite and xenotime.

Outlook

HMS deposits will continue to serve as the major source of titanium, zirconium and a few other industrial minerals because these deposits have several advantages:

1. The deposits are usually voluminous, covering large areas.
2. Deposits are usually located at the surface or at shallow depths beneath thin layers of sediments.
3. Individual mined deposits typically comprise >10 Mt (11 million st) of ore (the total size of the individual sand-silt body) often containing >2 or 3 percent heavy mineral content.
4. They are generally easy to excavate. Most HMS deposits mined today vary in coherence from unconsolidated to poorly consolidated; thus, they are generally easily excavated and worked with heavy equipment).
5. Well-established, highly mechanized, and efficient mineral-separation techniques are used in modern heavy-mineral processing plants.
6. Modern plants can control a continuous feed of high volumes of ore materials that thereby maintains an effective pace of mineral separation, which can produce high-purity mineral products within hours.
7. HMS deposits supply several salable minerals as coproducts to the titanium minerals (such as zircon, staurolite, garnets, and (or) monazite).

For these reasons, and because HMS deposits are the major sources of titanium and zirconium in particular, the mining and processing of HMS deposits should remain an important sector of the industrial minerals industry in the future. (References are available from the authors.)■