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Chapter 4

Placer-Type Rare Earth Element Deposits

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Abstract

Ancient and modern types of sedimentary placer deposits formed in both alluvial and coastal environments

have been signficant sources of the rare earth elements (REEs). The REE-bearing minerals in placer-type

deposits are primarily monazite [(Ce,La,Nd,Th)PO4] and sometimes xenotime (YPO4), which are high-density

(heavy) minerals that accumulate with the suite of heavy minerals. Monazite has been extracted from many

heavy mineral placers as a coproduct of the economic recovery of associated industrial minerals, such as titanium

oxide minerals (ilmenite, rutile), zircon, sillimanite, garnet, staurolite, and others. Xenotime has been

produced from some alluvial deposits as a coproduct of tin (cassiterite) placer mining.

Placers are mineral deposits formed by the mechanical concentration of minerals from weathered debris.

Placers can be classified as eluvial, alluvial, eolian, beach, and fossil (paleo) deposit types. Monazite-bearing

placer-type deposits can occur in residual weathering zones, beaches, rivers and streams, dunes, and offshore

areas. The detrital mixture of sand, silt, clays, and heavy (dense) minerals deposited in placers are derived primarily

from the erosion of crystalline rocks, mainly igneous rocks and moderate- to high-grade metamorphic

rocks (amphibolite facies and higher). In fluvial settings, slope is an important factor for the concentration of

heavy minerals from detritus. In coastal settings, the actions of waves, currents, tides, and wind are forces that

concentrate and sort mineral particles based on size and density.

Placer deposits containing monazite are known on all continents. In the past, by-product monazite has been

recovered from placers in Australia, Brazil, India, Malaysia, Thailand, China, New Zealand, Sri Lanka, Indonesia,

Zaire, Korea, and the United States. More recently, monazite has been recovered from coastal and alluvial

placers in India, Malaysia, Sri Lanka, Thailand, and Brazil. In particular, along the southwestern and southeastern

coasts of India, beach deposits rich in heavy minerals have experienced renewed exploration and development,

partly to recover monazite for its REEs as well as its Th, to be used as a nuclear fuel source.

Exploration designed to locate heavy mineral placers in coastal environments should identify bedrock terranes

containing abundant high-grade metamorphic rocks or igneous rocks and identify ancient or modern

coastal plains sourced by streams and rivers that drain these terranes. Trace elements associated with heavy

mineral placers, useful as pathfinder elements, primarily include Ti, Hf, the REEs, Th, and U. Radiometric

methods of geophysical exploration are useful in discovering and delineating deposits of heavy mineral sands.

Several minerals in these deposits can produce a radiometric anomaly, but especially monazite, due to its high

thorium content. Some beach districts in India and Brazil have been demonstrated as areas of high background

radiation with potential dose exposure to humans and others, primarily due to the Th and U in detrital grains

of monazite and zircon.

Monazite- or xenotime-bearing placers offer several advantages as sources of REEs. Ancient and modern

deposits of heavy mineral sands that formed in coastal settings can be voluminous with individual deposits as

much as about 1 km wide and more than 5 km long. Grains of monazite or xenotime in placer deposits are

mingled with other heavy minerals of industrial value. Monazite and xenotime are durable and often the heaviest

minerals within the sand-silt deposit, which makes them relatively easy to mechanically separate. Thus, the

REE ore minerals, monazite or xenotime, can be recovered from heavy mineral placers as a low-cost coproduct

along with the economic production of the associated industrial minerals.

Introduction

Alluvial and coastal placer deposits have been, and continue

to be, important sources of many mineral commodities, such

as gold, tin (in cassiterite), titanium oxide (in ilmenite, rutile,

leucoxene), and zirconium (in zircons), as well as additional

industrial minerals (sand and gravel, sillimanite, garnet,

staurolite, as examples). Placers are also sources of the rare

earth elements (REEs), chiefly via the minerals monazite

[(Ce,La,Nd,Th)PO4] and sometimes xenotime (YPO4). In

fact, until the mid-1960s, when full-scale production of rare

earths began at the Mountain Pass carbonatite deposit in

southeastern California, placer mines recovering monazite as

a coproduct were the world’s principal source of the REEs

(Tse, 2011; Fig. 1).

With the increasing demand for REEs in modern technologies,

combined with potential supply restrictions for specific

REEs, placer deposits have reemerged as viable sources of

rare earths, specifically through the recovery of monazite and/

or xenotime from placers composed of heavy mineral-rich

sands. Presently, the purposeful recovery of monazite occurs

from heavy mineral beach deposits mined and processed at

several coastal sites along the southwestern and southeastern

shores of India. These operations recover ilmenite, rutile,

leucoxene, rutile, sillimanite, garnet, and sometimes other

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industrial minerals as primary commodities, and also separate

monazite as a coproduct. The REEs within the monazite

are extracted for sale, and the thorium (Th) in the mineral is

sought as a fuel source for a nationally coordinated program in

India to develop thorium-based nuclear power.

Ancient and modern coastal deposits of heavy mineral sands

offer several advantages as ore deposits. As examples, these

deposits are relatively easy to mine because they are weakly

to poorly consolidated, and likewise are relatively easy to process.

Examples of heavy mineral sands deposits are known on

every continent and most likely also exist in Antartica. Ancient

and modern deposits of heavy mineral sands that formed in

coastal environments can be voluminous. Individual bodies of

heavy mineral-rich sands are typically about 1 km wide and

more than 5 km long. Many heavy mineral sands districts

extend for more than 10 km, encompassing several individual

deposits that are spread along an ancient or modern strandline.

Reported thicknesses of economic deposits range from

3 to 45 m. Individual ore deposits typically comprise at least

10 million metric tons (Mt) of ore (the total size of the individual

sand-silt body), with an overall heavy mineral content

of 2 to >10%.

This paper describes examples of alluvial and coastal placer

deposits known to host economic concentrations of monazite

or xenotime (economic in the past or present). Descriptions

of these deposits and their geologic setting provide insights

into source rocks, transport mechanisms, and the depositional

environments that form potentially economic REE placer

deposits. Separately discussed is a classification scheme for

placer deposits in general, followed by explanations of oregangue

mineralogy and geochemistry characteristic of REEbearing

placers. These insights contribute to discussions on

genetic models and exploration criteria relevant to monazite-

or xenotime-bearing placers, particulary coastal placer

deposits. Next, the aspect of radiation exposures from these

deposits is discussed; relatively high levels of natural radioactivity,

produced by monazite and zircon in some coastal sands,

have been studied, particular in India. Finally, the significance

of monazite-bearing placers is reemphasized—monazite in

placers can contribute much-needed REEs to the global supply

as well as thorium, obtaining the monazite (and/or xenotime)

as a coproduct of the economic production of titanium

oxide minerals, zircons, and other industrial minerals.

Terminology

Much of the terminology used to describe placer deposits is

not commonly used in geologic discussions. To aid the reader

and avoid confusion, some terms often used in discussions of

this general deposit type are as follows.

“Heavy minerals” are generally defined as dense minerals

that have a specific gravity greater than 2.85. For comparison,

quartz has a specific gravity of approximately 2.65.

“Heavy mineral suite” is a term that refers to the entire

group of heavy minerals identified within a particular deposit.

Fig. 1. Global map showing significant placer districts (red squares) that produced monazite and/or xenotime in the past

or presently; these minerals were recovered as by- or coproduct commodities with other economic heavy minerals. Current

monazite production occurs at modern beach placers in India and coastal placers at the Buena district, Brazil.

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“Grade,” in reference to a heavy mineral sands deposit,

most often refers to the average heavy mineral content of the

deposit (usually reported in wt %).

As noted earlier, placers are sedimentary deposits formed

by the physical-mechanical concentration of minerals orginally

derived from weathered debris. Some of these deposits

can contain economic (or potentially economic) concentrations

of heavy minerals; in addition to “placer,” this deposit

type is also commonly referred to as “heavy mineral sands.” In

the context of this discussion, placer and heavy mineral sands

are interchangeable.

General geology

Placers are mineral deposits formed by the mechanical concentration

of minerals from weathered debris. Examples of

placer deposits occur in beaches, rivers and streams, dunes

and offshore areas. The economic minerals hosted by placer

deposits are very resistant to chemical and physical breakdown

(durable), and typically have high density. The detrital

mixture of sand, silt, clays, and “heavy” (dense) minerals

deposited in placers are primarily derived from the erosion

of crystalline rocks. The source rocks include a wide variety

of igneous rocks and moderate- to high-grade metamorphic

rocks (amphibolite facies and higher), and some

sandstones and conglomerates. This detritus is transported

by mechanisms such as moving water and aeolian activity,

carrying the dense minerals in a mixture of sand, silt, and

clay to downgradient areas where they are deposited and

further concentrated. It is important to note that the processes

of major concentration of heavy minerals are due to

flowing waters in rivers or streams and wind. In fluvial settings,

slope provides an important factor for the concentration

heavy mineral placers. In coastal settings, the actions

of waves, currents, tides, and wind are forces that concentrate

the heavy dense minerals, including the minerals of

economic value.

The major thorium deposits in various parts of coastal Asia

and South America are classified as sedimentary thorium

deposits (Dill, 2010), which could also be described as thorium

placers (Table 1). Both modern placer and paleoplacer

deposits could cater to the world demand of thorium. Thorium-

bearing minerals are widely known to accumulate in

modern coastal placer deposits, with examples in India, Brazil,

Sri Lanka, and Malaysia, to name a few (Fig. 1, Table 1). In

India, shoreline-parallel concentrations of monazite in coastal

sands in the States of Kerala, Tamil Nadu, and the recently

discovered deposits in Orissa (Fig. 2; Mohanty et al., 2003a, b)

have pushed India to the top level in production of thorium.

These placer deposits resulted from fluvial drainage systems

during the Quaternary. These monazite sands are of interest

as a resource for economic recovery of the REEs, primarily

cerium (Ce), obtained as a coproduct of titanium (Ti) oxide

production in the form of ilmenite and rutile and zirconium

(Zr) recovery from zircon.

Fig. 2. Index map of southern India and northern Sri Lanka, showing locations of (1) historic and active heavy mineral sands

operations discussed in this report, and (2) areas of Quaternary and Neogene sediments.

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Table 1. Major Coastal and Fluvial Thorium (Monazite) Placer Deposits

Country State Placer district Latitude Longitude Comments References

Australia Western Australia Eneabba, Perth basin –29.79 115.30 About 2,500 t of monazite produced Sheppard (1990);

annually as a coproduct prior to 1995 Castor and Hedrick (2006)

Brazil Bahia Alcobaça –17.26 –39.22 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Brazil Espírito Santo Anchieta (Parati, Imbiri, –20.77 –40.57 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Pipa de Viho, Mãebá)

Brazil Espírito Santo Aracruz –19.95 –40.15 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Brazil Sergipe Brejo Grande - Pacatuba –10.43 –36.47 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Brazil Rio de Janeiro Buena (Buena Norte, Buena Sol) –21.52 –41.07 Active producer of monazite from beach placers Indústrias Nucleares do Brasil SA (2013)

Brazil Rio Grande do Norte Camaratuba –6.89 –34.89 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Brazil Bahia Cumuruxatiba (Curumuxatiba, –18.31 –39.66 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Comoxatiba)

Brazil Espírito Santo Guarapari (Praia do Vaz, Vila Velha, –20.70 –40.51 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Rastinga, Canto do Riacho,

Praia de Diogo)

Brazil Espírito Santo Itapemirim (Boa Vista, Siri) –21.17 –40.91 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Brazil Paraiba Mataraca –6.48 –34.97 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Brazil Bahia Porto Seguro district –16.43 –39.08 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Brazil Bahia Prado area –17.39 –39.21 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Brazil Rio de Janeiro Sao Joao de Barra (Barra Sao Joao) –21.40 –41.00 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Brazil Espírito Santo Serra (Jacareipe) –20.17 –40.19 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

Brazil Bahia, Espirito Santo Vitoria –18.33 –39.66 Coastal placer; past producer of monazite Overstreet (1967); Orris and Grauch (2002)

China Guangxi Beihei 21.48 109.10 River and coastal placers; byproduct monazite Jackson and Christiansen (1993);

Orris and Grauch (2002)

China Guangdong Dianbai 21.50 111.02 Coastal placers; by-product monazite Jackson and Christiansen (1993);

Orris and Grauch (2002)

China Guangdong Haikang 20.98 110.07 River and coastal placers; by-product monazite Jackson and Christiansen (1993);

Orris and Grauch (2002)

China Guangdong Nanshanhai 21.55 111.67 Coastal placers; by-product monazite Jackson and Christiansen (1993);

Orris and Grauch (2002)

China Hainan Island Sai-Lao, Wuzhaung, and 18.68 110.38 Coastal placers; by-product monazite Jackson and Christiansen (1993);

Xinglong districts Orris and Grauch (2002)

China Guangxi Xun Jiang 23.50 110.83 River placers; by-product monazite Jackson and Christiansen (1993);

Orris and Grauch (2002)

India Orissa Erasama 20.15 86.51 Coastal placers containing monazite Mohanty et al. (2003a, b, 2004)

India Orissa Chhatrapur 19.34 85.01 Coastal placers containing monazite Mohanty et al. (2003a, b, 2004)

India Andhra Pradesh Visakhapatnam 17.66 83.27 Coastal placers containing monazite Raju et al. (2001)

India Kerala Manavalakurichi 8.14 77.30 Coastal placers containing monazite Tipper (1914); Raju et al. (2001)

India Kerala Chavara 8.99 76.52 Coastal placers containing monazite Prakash et al. (1991)

India Maharashtra Ratnagiri 17.02 73.28 Coastal placers containing monazite Raju et al. (2001)

Malaysia Selangor Batang Berjuntai 3.39 101.42 Fluvial tin placers; by-product monazite Orris and Grauch (2002)

and xenotime

Sri Lanka Eastern Province Pulmoddai 8.95 80.99 Coastal placers containing monazite Lanka Mineral Sands Limited (2013)

Thailand Phang-nga Takua-Pa 8.87 98.35 Fluvial tin placers; by-product monazite Economic and Social Commission

and xenotime for Asia and the Pacific (2001)

United States Idaho Central Idaho fluvial placers 44.42 –116.02 Fluvial placers; by-product monazite Staatz et al. (1980)

United States North Carolina and Piedmont region fluvial placers 35.31 –81.54 5,000 t of monazite produced from Overstreet et. al. (1968); Staatz et al. (1979)

South Carolina 1887 to 1917

United States Florida Mineral City 30.24 –81.39 About 1 t of monazite produced in 1925 Staatz et al. (1980)

United States Florida Rutile Mining Co. mine 30.34 –81.60 Small amounts of monazite recovered Staatz et al. (1980)

from beach sands

United States Florida Riz Mining Co. mine 27.64 –80.35 Dune sands; monazite as by-product from Staatz et al. (1980)

1940s to 1955

United States Florida Green Cove Springs 29.87 –81.71 Beach deposits; monazite recovered as coproduct Staatz et al. (1980);

Castor and Hedrick (2006)

United States Florida Boulogne 30.77 –81.98 Beach deposits; monazite recovered as coproduct Staatz et al. (1980)

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Classification of Placer Deposits

Based on their mode of transportation and the site of deposition,

placers are classified as (1) eluvial, (2) alluvial or fluvial,

(3) eolian, (4) beach, and (5) fossil placers.

1. Eluvial placers are formed upon the release of minerals

from the rock matrix, caused by the decomposition of rock

in place from weathered deposits primarily due to precipitation

and aeolian activity. This is the embryonic stage in

the development of placers (Gupta, 2003). Notable Indian

examples are the cassiterite, columbite, and tantalite

placer deposits in the Bastar district in the state of Madhya

Pradesh in central India (Fig. 2; Suryanarayan et al., 1979).

2. Alluvial placers represent the next stage in the placer formation.

The heavy minerals are introduced into the fluvial

system by the action of runoff, gravity, and/or by the erosive

action of the stream itself. Renowned examples are the

gold-bearing alluvial placer deposits that fed the famous

California (United States) gold rush in the 19th century.

Economic examples of xenotime-bearing fluvial placer

deposits occur in India (Rai et al., 1991), Malaysia (Castor

and Hedrick, 2006), and Thailand (Economic and Social

Commission for Asia and the Pacific, 2001, p. 72–74).

3. Eolian deposits, formed by the actions of winds, can hold

concentrations of heavy minerals. These types of deposits

occur in arid/semiarid regions, where the influence of wind

is strong and sufficient vegetation does not exist to cover

the soil. Wind action progressively concentrates the heavy

minerals by blowing away the associated light minerals over

time (Nikiforova et al., 2005, 2007). Prominent examples

are eolian gold deposits of Australia. The Teri deposits of

Tamil Nadu (Fig. 2) are aeolian in origin. The Trail Ridge

deposit of north-central Florida is a Pliocene-age complex

of aeolian sands, from which DuPont produces titanium

minerals, zircon, and staurolite (Dupont, 2014). The sand

dunes of the Richards Bay area (Richards Bay Minerals,

2013) on the east coast of South Africa have been a highly

productive source of zircon, rutile, and ilmenite.

4. Beach placers are formed by the interaction of terrestrial

processess with coastal hydrodynamics. The heavy minerals

are carried in sediments, transported to the coastal area

by various processes of detrital transport, then selectively

panned, sorted and deposited at suitable locations by the

action of waves and currents. The factors controlling the

formation of beach placers are complex and include geomorphology

of the area, climate, drainage pattern, coastal

processes, and neotectonics. The heavy minerals are concentrated

by a combination of these processes in the upper

part of the beach, where the actions of the wind may erode

them and form heavy mineral-rich coastal dune deposits

(deposit type 3 above; Kudrass, 2000). Most of the important

deposits of ilmenite, rutile, zircon, monazite, and garnet

occur in the form of beach placers. India has some of

the world’s largest placer deposits along its long southeast

and southwest coastlines.

5. Fossil (paleo) placers formed in the geologic past due

to processes similar to modern deposits. Fossil placers

become exposed by factors such as climate change and/

orepirogenic movements and eustasy. Along the coasts of

India and adjoining areas of Sri Lanka (Singhvi et al., 1986)

there are considerable reserves of fossil placers known to

exist (Ali et al., 2001); these deposits formed during previous

low stands of sea level. Other examples of fossil placers

are discussed in this article. Fossil placers can be reworked

by erosion and act as sources of recent deposits.

Examples of Monazite-Bearing Placer Districts

By-product monazite has been recovered in the past from placer

deposits in Australia, Brazil, India, Malaysia, Thailand, China,

New Zealand, Sri Lanka, Indonesia, Zaire, Korea, and the

United States. Until the mid-1960s, with the advent of full rare

earth production from the Mountain Pass carbonatite deposit

in southeastern California, monazite placers were the world’s

principal source of REE production (Tse, 2011, Fig. 1). Monazite

has recently been recovered from beach and alluvial placers

in India, Malaysia, Sri Lanka, Thailand, and Brazil (Table

1). Indian beach placers are the principal source for ongoing

production of monazite and for this reason the Indian deposits

are described in more detail as examples of this deposit type.

Heavy mineral sands deposits (placers) occur on every continent,

likely including Antarctica. The REE deposit dataset of

Orris and Grauch (2002) lists 369 REE-bearing placer deposits

and occurrences, including 264 shoreline placers, 78 alluvial

placers, 13 paleoplacers, and 14 unclassified placers. The

examples of monazite-bearing placers that follow should not

be regarded as a complete listing of all known occurrences of

this deposit type throughout the world. Rather, the deposits

described here are examples of significant deposits of monazite-

rich, heavy mineral sands that have been worked in the

past or are being mined at this time.

Australia

The vast majority of the heavy mineral and associated monazite

resources of Australia are hosted by ancient beach and

sand dune deposits that formed along middle Eocene to Pleistocene

strandlines (Hoatson et al., 2011). Significant fossil

beach deposits of heavy minerals occur in three inland Cenozoic-

age sedimentary basins of western and southern Australia,

which are the Canning, Perth, Murray, and Eucla basins

(Fig. 3). In the northeastern part of the Canning basin in the

northeastern part of Western Australia, heavy mineral sands

are currently (2014) mined inland of the coast near Derby.

The Perth basin, in the southwestern part of Western Australia,

hosts substantial deposits of heavy minerals within Cenozoic

strandline strata that parallel the coast north and south of

Perth. The heavy mineral beach deposits of the Murray basin

occur in Cenozoic paleostrandlines in New South Wales, Victoria,

and South Australia. The Eucla basin bounds the coast

of the southwestern part of South Australia and southeastern

part of Western Australia.

Heavy mineral-rich beach and dune sand deposits in the

Perth basin of Western Australia have been extensively mined

since the 1970s. The sands were deposited along strandlines

from the Pliocene to early Pleistocene. The Eneabba mining

district in the northern part of the Perth basin (north of

Perth, Fig. 3) has been a substantial producer of heavy minerals,

principally rutile, zircon, and ilmenite, as well as a former

producer of monazite as a coproduct. Reportedly, prior

to 1995 about 2,500 t of monazite were recovered annually

as a coproduct of titanium minerals and zircon processing

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in the Eneabba district (Castor and Hedrick, 2006; Hoatson

et al., 2011). Production of monazite in the district peaked

between 1975 and 1985 (Shepherd, 1990). The source of the

monazite in the ancient dune and beach sands of the Eneabba

district are thought to be underlying Mesozoic sedimentary

rocks, with Archean crystalline rocks of the basement being

the original source (Shepherd, 1990). In the Eneabba deposits,

monazite concentrations can be as much as 7% near the

southern end of the barrier complex, deposited in the direction

of the longshore drift near a relic headland (Shepherd,

1990). On average, heavy minerals compose about 6% of the

paleoshore sands mined in this district, with monazite composing

0.5 to 7.0% of this heavy mineral suite (Shepherd,

1990). Heavy mineral production remains active today in the

district, but monazite is not currently recovered as a product

and is returned to the mined site. As an example of recent

heavy mineral production capacity, in 2010 Iluka Resources

reported a mining and processing output from their Perth

basin operations of 41,500 t of rutile, 347,500 t of synthetic

rutile, 255,800 t of ilmenite, and 46,200 t of zircon (Geoscience

Australia, 2012).

Within the Murray basin, near Horsham in the Wimmera

region of western Victoria, the WIM150 mineral sands deposit

(Fig. 3) reportedly contains substantial resources of monazite

and xenotime, associated with titanium minerals and zircon

in the heavy mineral suite. The deposit is about 14 m thick,

comprises titanium-zircon-rich sand bodies formed along

a late Tertiary strandline. The mineral sands project here is

in an advanced stage of premining development and permitting,

with plans to recover the titanium minerals and zircon.

It appears that the associated monazite and xenotime will not

be exploited in the foreseeable future of this project; however,

the deposit reportedly contains more than 580,000 t of monazite

and 170,000 t of xenotime (O’Driscoll, 1988).

Roy and Whitehouse (2003) attributed the high concentrations

of heavy minerals in strandline sands in the Murray basin

to barrier sand complexes, totaling 400 km in length, which

formed during Pliocene seashore progradation driven by sealevel

oscillations. They suggest that the heavy minerals in the

sand deposits were derived from storm and wave reworking

of underlying heavy mineral-bearing Miocene sands, and that

erosion and deposition were aided by growth faults.

Brazil

The monazite placers of the Brazilian coast include elevated

paleobeaches, modern beaches, sand dunes, and the banks,

Fig. 3. Index map of Australia showing the Cenozoic sedimentary basins and other districts (red dots; Tiwi Islands, Cape

York, North Stradbroke Island) that host deposits of heavy mineral sands that are currently being mined.

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channels, and bars of streams that deposit sediments near

the shore. Cretaceous and Tertiary sandstones that formed

along paleostrandlines crop out near the modern beach; some

sandstone intervals are rich in monazite, ilmenite, and zircon.

These sandstones are eroded and disaggregated by high-tide

waves and storm surges. These processes redeposit sand and

heavy minerals into the surf zone, where the heavy minerals

are again reworked and sorted by waves, longshore drift,

and tides. Thus, the Cretaceous-Tertiary strandline deposits,

which occur in slightly higher outcrops near the modern

beach, are another source (often richer source) of monazite.

According to the study of Leonardos (1974), the principal

inland sources of detrital monazite along the central Brazilian

coast are Archean amphibolite-granulite rocks and Cretaceous

and Tertiary sedimentary rocks derived from erosion of

these Archean rocks.

More than a dozen mined monazite-bearing placer districts

occur intermittently along the central coast of Brazil

(Overstreet, 1967; Orris and Grauch, 2002). Coastal placers

that were past producers of monazite occur scattered along

the coast between the city of Campos in the state of Rio de

Janeiro on the southern end to the southernmost area of the

coast in the state of Rio Grande do Norte on the north end

(Fig. 4). Monazite was recovered as a coproduct of the more

profitable titanium minerals (ilmenite, rutile) and zircon. In

contrast to most heavy mineral sands operations, many of the

Brazilian deposits were mined primarily for their monazite,

sought foremost as a source of thorium. According to Overstreet

(1967), from 1900 to 1947 Brazil exported 62,115 short

tons (56,350 t) of monazite concentrate, with the monazite

recovered from beach placers. Since the early 1990s, the

Buena placer district (Fig. 4), which includes the Buena Norte

and Buena Sol deposits, has been the only active Brazilian

producer of monazite through a state-administered program

(Indústrias Nucleares do Brasil SA (INB), 2013).

The coastal sand deposits of Brazil have some of the highest

monazite concentrations known in the world, with as much

as 8% average monazite content in some sand bodies (Overstreet,

1967). The Guarapari coastline of Espiroto Santo, near

Campos (Fig. 4), is a popular tourist destination known for

its white sand beaches, but this shoreline is also known for its

very high level of background radioactivity due to abundant

monazite. In this area, the recently and historically mined

Buena Norte deposit has a reported monazite content of

0.83% (Jackson and Christiansen, 1993). Analyses of Brazilian

monazites suggest that their average REE oxide content

is typically around 57 to 60%, with preferential enrichment in

the light REEs (Overstreet, 1967; Orris and Grauch, 2002).

Summarizing the monazite endowment in Brazil’s coastal

deposits state-by-state, Hedrick (1997, p. 61.4) reported the

following “measured reserves” of monazite (more properly

stated, “measured resources”): “Measured reserves were

16,622 tons [metric tons] grading 53.88% REOs in Bahia,

29,210 tons grading 57% REOs in Ceara, 697,382 tons

grading 60% REOs in Espirito Santo, 326,766 tons grading

59.72% REOs in Minas Gerais, and 17,166 tons grading 60%

REOs in the state of Rio De Janeiro.” Most of these monazite

resources remain. The proximity of many of these mineralrich

beach deposits to resorts and other population centers

has been a major factor in restricting their development.

China

China has considerable resources of monazite within placer

deposits; however, scant information on the characteristics

and production of these resources has been published. Jackson

and Christiansen (1993) reported that China produced

10,200 t REOs from placer deposits in 1989. Since that

time, rare earth production from placer deposits in China is

unavailable.

Some of the productive monazite-bearing placer districts

in China (Jackson and Christiansen, 1993; Orris and Grauch,

2002) are as follows:

1. Beihei district, located near 21° 29' N, 109° 06' E in the

Guangxi province. A mixture of river and marine placers

along the coast, containing about 1.5% heavy minerals

comprised of ilmenite, rutile, zircon, and monazite. A producer

of by-product monazite.

2. Dianbai district, located near 21° 30' N, 111° 01' E in the

Guangdong province. Placers on the coast, containing

about 2.3% heavy minerals comprise ilmenite, rutile, zircon,

and monazite. A producer of by-product monazite.

3. Haikang district, located near 20° 56' N, 110° 04' E in

the Guangdong province. A mixture of river and marine

placers that contain ilmenite, zircon, rutile, monazite, and

xenotime. A producer of by-product monazite.

4. Nanshanhai district, located near 21° 32' 45" N, 111°

40' 00" E in the Guangdong province. Coastal placers that

contain ilmenite, zircon, rutile, monazite, and xenotime. A

producer of by-product monazite.

5. Sai-Lao, Wuzhaung, and Xinglong placer districts, all located

on Hainan Island (see Orris and Grauch, 2002). These placers

contain ilmenite, zircon, anatase, cassiterite, monazite,

magnetite, and chromite. Producers of by-product monazite.

6. Xun Jiang district, located near 23° 30' N, 110° 50' E in the

Guangxi province. River deposits containing 6.0% heavy

minerals comprise ilmenite, rutile, zircon, and monazite.

India

The history of placer deposits as a source of economic minerals

began with the discovery of monazite in the beach sands of

Manavalakurichi (Tipper, 1914) in southernmost India (Fig.

2). The beach sands were first worked in 1911 and subsequently

were rapidly developed with the establishment of the

TiO2 (titania) pigment industry in Europe and America. However,

by the 1950s ilmenite production saw a sudden decrease

in India. This was in part due to the discoveries of new deposits

in Australia and Canada, compounded by the presence of

undesirable impurities, such as chromium and ferric iron,

in Indian ilmenite. However, after nationalization of all the

major deposits in India, the national production of ilmenite

and rutile has increased over the years. The current production

rate is about 140,000 t of ilmenite and 6,000 t of rutile.

Governmental concerns, such as the Indian Rare Earths Ltd.

and Kerala Minerals and Metals Ltd., are involved in the production

and marketing of the placer minerals.

Over the last few decades new deposits have been discovered

in coastal placers of India, such as Chhatrapur in Orissa

and Visakhapatnam in Andhra Pradesh along the east coast,

and Ratnagiri in Maharashtra on the west coast of the country

(Fig. 2). Along the coastal stretches of Tamil Nadu, deposits

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Fig. 4. Index map showing monazite-producing placer deposits (red squares) along the central coastline of Brazil. The active

monazite producer is the Buena district (Indústrias Nucleares do Brasil SA (INB), 2013), the southernmost placer district

shown in the map.

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of heavy minerals occur in the inland areas in the form of teri

sands, also known as red sands in Tamil Nadu (Babu et al.,

2009). The current reserves of the placer minerals in India

are as follows: 278 Mt ilmenite, 13.49 Mt rutile, 18 Mt zircon,

7 Mt monazite, 84 Mt sillimanite, and 86 Mt garnet (Raju et

al., 2001).

The major placer concentrations of India are located along

the east and west coasts (Fig. 2). For example, detrital monazite

occurs in ilmenite-bearing heavy mineral sands of Chavara

and Manavalakurichi, as well as less extensive detrital

monazite deposits in parts of coastal Orissa, Andhra Pradesh,

and Tamil Nadu. Thus, the Eastern Ghats group of rocks

have been more widely spread, though as localized deposits,

in comparison to sediments derived from the Western Ghats

group, which is mostly concentrated in Kerala. Apart from

these coastal placers, there are numerous inland placers in

Maharashtra. These deposits generally occur in stream segments

with low current velocity, such as point bar deposits,

within ripple marks, around submerged bars, or in narrow

zones at the bottom of a stream.

The heavy mineral content of beach placers along the

southern coast of Orissa primarily depends on the nature of

the hinterland rocks present in the region. The source rocks

are dominated by granulite facies of khondalites, charnockites,

and leptynolites (Mohanty et al., 2003b), plus the presence

of granite intrusions, pegmatites, quartz veins, and

metasediments. Based on the thorium oxide concentration in

the monazite sands, it was inferred that the monazite grains

were derived primarily from the granulite-facies metamorphic

rocks belonging to the Eastern Ghats group of rocks

(Mohanty et al., 2003b). Radioactive elements thorium (Th)

and uranium (U) and rare earth elements (lanthanum (La),

cerium (Ce), praseodymium (Pr), neodymium (Nd), and

samarium (Sm)) are highly enriched in the monazite sands

of coastal Orissa. Ilmenites are the major heavy minerals

and constituite about 65 to 80% of the total heavy mineral

assemblage (Mohanty et al., 2003b). Earlier studies (Mohanty

et al., 2003a) suggest that the ilmenite grains are derived

from higher grade (granulite-facies) metamorphic rocks. The

important feature observed commonly in the monazites is the

abundance of total REE as compared to the actinides; additionally,

the monazites are enriched in La, Ce and Nd. The

greater content of yttrium oxide (Y2O3) has been attributed to

the garnet-free paragenesis (Mohanty et al., 2003a).

In extensive studies undertaken along peninsular India,

especially along the eastern and western coasts, in addition to

the marine regressions and transgressions during the Quartenary

the rivers also play a significant role in beach placer development

(Prakash et al., 1991; Mohanty et al., 2004; Sengupta et

al., 2005). Three factors responsible for placer mineralization,

especially the radioactive minerals, are (1) their distribution

in the hinterland rocks, (2) geologic controls due to presence

of rivers attributed to its morphology, and (3) structures that

control the drainage patterns (Sinha-Roy, 1982). This implies

the significant role of weathering and transport in the formation

of heavy mineral placers. This relationship is true for not

only the placer mineralization along the Western Ghats group

of rocks, especially the southern coast of Kerala, such as the

Chavara placer deposit, but also in the Eastern Ghats (Prakash

et al., 1991). The latter comprises rich placer deposits along

the southern Orissa coast, such as the Erasama (Fig. 5) and

Chhatrapur deposits (Fig. 6). The southern rivers in Kerala,

India, for example, the Neyyar, Karamana, and Vamanapuram

Rivers, carry enhanced concentrations of heavy minerals (that

include radioactive minerals) into the pensisular region, aided

by the southwestern monsoon (Prakash et al., 1991). In Tamil

Nadu, extensive studies of zircons in placer deposits located

along the southern coast show the zircons are enriched in

REEs, especially europium (Eu) and (Ce); this indicates that

the bedrock source for the zircons was primarily charnockites

(Angusamy et al., 2004). In a similar manner, the role

of Rushikulya River, in the Ganjam district, southern coast

of Orissa (Fig. 7), aided in the formation of the rich placer

deposits sourced from the Eastern Ghats group of rocks for

Chhatrapur placers. Additionally, high-grade metasedimentary

rocks along the hinterland, transported by the Mahanadi

River drainage basin, formed the Erasama placer deposit

(Mohanty et al., 2004; Sengupta et al., 2005). For the Eastern

Ghats group of rocks, it has been observed that charckonites

and the khondalites are primarly responsible for the

enhanced concentration of thorium as compared to uranium.

Along the Eastern Ghats there are major and notable heavy

mineral placers, located in the States of Tamil Nadu, Andhra

Pradesh, and Orissa, respectively (Ali et al., 2001; Mohanty

Fig. 5. Map showing the sample locations in the Erasama beach placer

deposit, Orissa, India (after Mohanty et al., 2004).

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et al., 2003b). Recent studies indicate that the Eastern Ghats

group is the major source for the heavy mineral assemblage

observed in the placer deposits (Raju et al., 2001). The heavy

mineral placers both in the eastern and western part of India

are highly enriched in thorium (Mohanty et al., 2003a, b,

2004; Sengupta et al., 2005).

Malaysia

Prior to the domination of global yttrium production by China

in the late 1980s, xenotime-bearing alluvial placer deposits

in Malaysia were the largest sources of yttrium in the world

(Castor and Hedrick, 2006). The sources within Malaysia

are alluvial tin placer deposits, which carry considerable cassiterite

accompanied by ilmenite, monazite, and xenotime.

Recently, tailings produced from past tin placer mining have

been reprocessed to recover monazite and xenotime. In this

manner, 350 t REOs were produced from Malaysia in 2012

(Gambogi, 2013).

Sri Lanka

Modern beach deposits on the northeastern coast of Sri Lanka

have some of the highest concentrations of heavy minerals in

the world. Beach sands of this region are mined and processed

by Lanka Minerals Sands Ltd. (2013), a company owned by the

Government of Sri Lanka, and the successor to Ceylon Mineral

Sands Corp. The company’s primary mining operations

and processing plants are located just east of Pulmoddai on the

northeast coast of Sri Lanka (Fig. 2). Products from the beach

sands are ilmenite, rutile, and zircon; sillimanite, monazite and

garnet also exist, with monazite reportedly composing 0.3% of

the heavy mineral fraction (Herath, 1990). According to the

company, in some stretches of beach the heavy minerals can

compose as much as 90% of the sand deposits; ilmenite forms

65% of the heavies, rutile forms 10%, and zircon forms 10%

(Lanka Minerals Sands Ltd., 2013). Heavy mineral-rich beach

sands extend along the shore about 8 km south from Kokkilai

Lagoon (Fig. 2) and they extend inland from the ocean for

about 370 m. The stretch of beach that extends about 40 km

north and south of Pulmoddai in northeastern Sri Lanka represents

one of the richest deposits of heavy mineral sands in the

world (Lanka Minerals Sands Ltd., 2013).

Monazite-bearing alluvium in southwestern Sri Lanka, specifically

stream sediments of the Bentota River, have been

described as “one of the world’s most thorium rich sediments”

(Rupasinghe et al., 1983, p. 1). Monazite is carried by this

river system into seasonal beach sand deposits at Kaikawala

Fig. 6. Map showing sample locations in the Chhatrapur beach placer deposit, Orissa, India (after Mohanty et al., 2004).

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and Beruwala. Monazite was once mined on a small scale at

Kaikawala beach. Analyses of these monazites by Rupasinghe

et al. (1983) found them to be highly enriched in the light

REEs relative to the heavy REEs, with a negative Eu anomaly

when normalized to chondrite values (Rupasinghe and Dissanayake,

1984).

Thailand

Tin (in cassiterite) has been mined from alluvial placers in

Thailand for over 1,000 years, but much more recently they

initiated by-product recovery of monazite (starting in 1969),

ilmenite (in 1976), and xenotime (in 1977; Economic and

Social Commission for Asia and the Pacific, 2001, p. 72–74).

Production of REOs from Thailand decreased steadily from

the 1980s to 1995, which was their last year of significant

monazite and xenotime production. Similar to the Malaysian

rare-earth resources, in Thailand the monazite and xenotime

are recovered as by-products from the retreatment of earlier

processing plant tailings derived from tin placers. The host tin

placers, those enriched in monazite and xenotime, are alluvial

deposits that were mined by gravel pump; these deposits

occur mainly in southern Thailand (shown in Economic and

Social Commission for Asia and the Pacific, 2001, p. 72–74).

United States

Monazite-bearing, heavy mineral placers of both alluvial and

coastal origins are well known in the United States. Some of

these placers produced modest tonnages of monazite in the

past. A century ago, monazite was produced from alluvial placers

in mountain valleys of North Carolina and South Carolina,

and during the 1950s monazite was recovered from stream

alluvium in mountain valleys of central Idaho. As recently as

1994, heavy mineral sands deposits in Florida, which formed

along Pliocene and Pleistocene strandlines, were worked for

titanium minerals and zircon but also produced monazite as a

coproduct. As of 2014, monazite is not recovered at an active

placer operation in the United States.

Monazite-brearing alluvial placers in North and South Carolina:

In 1887, a few short tons of monazite were produced

from stream deposits in the Piedmont region of North and

South Carolina, giving this region the distinction of being

the world’s first supplier of thorium (Olson and Overstreet,

1964). Monazite-bearing placers of this region were worked

by small-scale sluice operations from 1887 to 1911 and 1915

to 1917, producing a total of about 5,000 t of monazite (Overstreet

et al., 1968). Monazite mining ended here in 1917, not

because reserves had been exhausted, but rather because the

beach deposits of India and Brazil were producing thorium at

lower cost.

The high-grade monazite placers of the Piedmont of North

and South Carolina occur between the Catawba River in the

northeast and the Savannah River in the southwest (Fig. 8).

The stream-sediment deposits across this region are generally

consistent in character; the heavy mineral concentrations

Fig. 7. Index map of the Rushikulya beach placer deposit along the Orissa coast, southeast India, showing sample locations

(after Sulekha Roa et al., 2009).

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are greatest in the headwaters areas. Stacked layers of unconsolidated

sediments of gravel, sand, clay, and clayey silt form

an average total thickness of about 4.5 m (15 ft; Staatz et al.,

1979). Monazite typically occurs in all units, but is generally

most abundant in the basal gravel layers and least abundant

in the clay layers. Dredging in this region between the summers

of 1955 and 1958 (Williams, 1967) found heavy mineral

contents of about 1 to 1.5%, with monazite forming about 8%

of this fraction (Mertie, 1975). Overall, these dredging operations

recovered monazite, ilmenite, rutile, zircon, and staurolite

(Williams, 1967).

According to Staatz et al. (1979), the heavy mineral content

of the placer deposits of the Piedmont region ranges

from 0.15 to 2.0%, with monazite forming about 3.5 to 13% of

the heavy minerals. Other parts of the heavy mineral fraction

include ilmenite, 20 to 70%; garnet, 2 to 50%; rutile, 0.3 to

7%; zircon, trace to 14%; and sillimanite and kyanite together,

trace to 20%. In some Piedmont placer deposits, additional

heavy minerals include epidote, magnetite, xenotime, tourmaline,

sphene, staurolite, andalusite, and an unidentified

black radioactive mineral (Staatz et al., 1979). Analysis of

52 samples of alluvial monazite from this region (Mertie,

1975) found that the monazite contains 60 to 63% total REE

oxides and 2.5 to 7.8% Th oxide content, with a mean value

of 5.67% Th.

The Piedmont region of the southeastern United States

is underlain by crystalline, high-grade metamorphic rocks

intruded by quartz monzonite and pegmatite. The monzonite

and pegmatite intrusions vary from monazite-bearing to

monazite-free. Overstreet (1967) suggested that the primary

Fig. 8. Map of monazite-bearing alluvial placers in North and South Carolina, United States. Modified from Staatz et al.

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source of the alluvial monazite was the high-grade metamorphic

rocks, particularly sillimanite schist.

Monazite alluvial placers in Idaho: At least 11 monazitebearing

placer districts exist in the valleys of a region extending

north of Boise, Idaho, and along the western flank of the

Idaho batholith (Fig. 9). Monazite was first recognized here

in 1896, as the heavy, yellow to brownish-yellow mineral that

collected with other heavy minerals and gold within the sluice

boxes of gold placer operations in the Boise basin near Idaho

City, Centerville, and Placerville (Lindgren, 1897). In 1909, a

mill designed to capture the monazite was built by the Centerville

Mining and Milling Co. Only a small amount of monazite

concentrate was produced for its Th content before the

mill burned down in a forest fire in 1910.

In the 1950s, two areas of west-central Idaho were mined

by dredges for monazite recovery—Long Valley and Bear Valley

(Fig. 9). Beginning in September 1950, Long Valley was

worked by three dredges that were earlier used to recover

gold but later converted to recover monazite. The dredges

were redesigned for monazite recovery with assistance from

the U.S. Bureau of Mines under the sponsorship of the U.S.

Atomic Energy Commission. The history of these dredging

operations is described by Argall (1954) and Staatz et al.

(1980, p. 9–16, and references cited therein). The heavy minerals

recovered in the Long Valley district were dominated by

ilmenite (84% of heavies), followed by monazite (8%), garnet

(5%), and zircon (3%). During this five-year period, Staatz et

al. (1980) estimated that the three dredges recovered 6,430 t

Fig. 9. Generalized map of known monazite-bearing

alluvial placer districts in Idaho. Modified from Staatz

et al. (1980).

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of monazite. The dredging ended here in mid-1955, when the

government stockpile order was fulfilled.

Rare earth elements and thorium were also unintentionally

recovered within the minerals euxenite and monazite

from the Bear Valley placers. The Bear Valley placers were

worked by first one dredge in 1955, then a second in 1956,

with the intent to recover niobium (Nb) and tantalum (Ta)

for another federal government contract. According to Staatz

et al. (1980, p. 10), “from alluvium of Bear Valley, 2,049 short

tons [1,858 metric tons] of euxenite, 83.5 tons [75.7 metric

tons] of columbite, and 54,862 tons [49,760 metric tons] of

ilmenite were recovered.” No records of the monazite recovery

were kept.

The U.S. Geological Survey (Staatz et al., 1980) determined

that the five most important monazite districts in Idaho are

Long Valley, Bear Valley, the Boise basin, the Burgdorf Warren

area, and the Elk City-Newsome area (Fig. 9). The reported

thorium oxide contents of monazite in the Idaho placer deposits

range from 2.2 to 6.24%. Only a few analyses for REE were

conducted on monazites from Idaho placers, which indicated

these monazites contain 63% total REE oxides. Staatz et al.

(1980) calculated thorium reserves for each of the five major

placer districts individually, indicating the five districts have

total reserves of about 9,130 t of Th oxide. The REE resources

of the five placer districts would presumably be at least 10

times the Th resource, because the typical monazite contains

about 63% total REE oxides and 2.2 to 6.24% Th oxide.

The primary source of the resistant REE-thorium-bearing

minerals in the Idaho placers is thought to be the Idaho batholith,

in particular the quartz monzonite and pegmatite phases of

the batholith (Mackin and Schmidt, 1957). The most common

heavy minerals in the alluvial deposits (in generally decreasing

amounts) are ilmenite, magnetite, sphene, garnet, monazite,

euxenite, zircon, and uranothorite (uranium-rich thorite).

Monazite-bearing coastal sands in northeastern Florida:

Modern beach sands near Mineral City (now known as Ponte

Vedra) were mined chiefly for ilmenite from 1916 to 1929

(Staatz et al., 1980), about 1 km west of the ocean and just east

of Jacksonville. Reportedly one short ton (0.9 t) of monazite

was produced in 1925 (Staatz et al., 1980).

From 1943 to 1968, the Rutile Mining Co. recovered

ilmenite, rutile, zircon, and small amounts of monazite from

Pleistocene and Pliocene beach sands just east of Jacksonville.

The Riz Mineral Co. mined dune sands near Vero Beach

from the early 1940s until 1955, recovering ilmenite, rutile,

zircon, and monazite (Staatz et al., 1980).

A variety of companies mined and processed Pleistocene

beach deposits at Green Cove Springs to recover their heavy

minerals, particularly titanium minerals and zircons (the

Duval Upland ridge deposit); these deposits are located south

of Jacksonville and west of St. Johns River. Reportedly, about

500 t of monazite per year were recovered as a coproduct

from the Green Cove Springs deposits (Castor and Hedrick,

2006). Recently, Iluka Resources resumed mining from this

deposit to recover titanium minerals and zircon; they ended

their mining activities there in 2005 and the site is now being

reclaimed by the company. The deposits at Green Cove

Springs contained an average of 3% heavy minerals, which

included ilmenite, leucoxene, rutile, zircon, and monazite

(Staatz et al., 1980).

From 1974 to 1978, Humphrey Minerals mined a Pleistocene

beach deposit near Boulogne in northeastern Florida.

This ore body averaged about 4% heavy minerals; titanium

minerals, zircon, and monazite were recovered. Reportedly,

monazite composes 0.3 to 0.4% of the heavy mineral assemblage

in this deposit (Staatz et al., 1980). This Pleistocene

shoreline facies extends to the north into Georgia, where

this unit was earlier mined by the same company at nearby

Folkston, Georgia.

Industrial Mineral Commodities in

Heavy Mineral Placers

Placer deposits are the main source of titanium feedstock

for the titanium dioxide (TiO2) pigments industry (Murphy

and Frick, 2006), through recovery of the minerals ilmenite

(Fe2+TiO3), rutile (TiO2), and leucoxene (an alteration product

of ilmenite). Heavy mineral sands (placers) are also the

principal source of zircon (ZrSiO4), which is often recovered

as a coproduct. Other heavy minerals produced as coproducts

from some deposits are sillimanite/kyanite, staurolite, monazite,

and garnet.

Prior to full-scale mining and production from the Mountain

Pass carbonatite deposit, California, in the mid-1960s, alluvial

placers were the primary source of rare-earth elements for

the world. Today, deposits of monazite [(Ce,La,Nd,Th)PO4],

mainly in beach placers, are again sought as a source of rare

earth elements as well as thorium, most particularly at several

coastal sand deposits in southern India. The processed Th is

to be used in Th-based nuclear power under development in

India and elsewhere.

Ore and Gangue Mineralogy

Heavy mineral-rich placer deposits encompass a wide range

of minerals with varying values of specific gravity. They have

been generally classified (Emery and Noakes, 1968) as placers

that contain: (1) “very heavy” minerals with specific gravity

between 6.8 and 21, such as cassiterite and native gold;

(2) “light” heavy minerals with specific gravity between 4.2

and 5.3, such as ilmenite, rutile, monazite, xenotime, and zircon;

and (3) minerals with densities between 2.9 and 4.1, such

as garnet, sillimanite, and hypersthene. Folk (1980) divided

the heavy minerals into four groups, based on their physical

and chemical nature—opaques, micas, ultrastables, and

metastables.

The economic heavy minerals in placer deposits are especially

durable and resistant to chemical breakdown, and thus

survive the torturous journey from the bedrock source area

to the site of deposition, as distant as the coast or the sea

(offshore deposition). The suite of heavy minerals most commonly

includes Ti-bearing minerals (ilmenite, rutile, and leucoxene)

and zircon, and can also contain sillimanite/kyanite,

staurolite, monazite, garnets, xenotime, and others. In the vast

majority of economic heavy mineral coastal deposits (“heavy

mineral sands”), ilmenite is the most abundant heavy mineral

and the principal ore mineral, followed by rutile, leucoxene

(“altered ilmenite”), and zircon. Together, ilmenite, rutile, and

zircon often compose more than 80% of the heavy mineral

suite. Other heavy minerals that are sometimes recovered as

economic coproducts include garnets, sillimanite, staurolite,

cassiterite (“tin placers”), monazite, and xenotime. Economic

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deposits can contain less than 1% heavy mineral content, but

composite grades are usually more than 2% and locally can

exceed 10%. The economic viability of a heavy mineral sand

deposit is dependent on the interplay of many factors, such as

its location, depth, size, heavy mineral grade and mineralogy,

and market prices.

Resources of REEs in placer deposits occur principally in

monazite [(Ce,La,Nd,Th)PO4], as a source of light REEs,

and/or xenotime (YPO4), as a potential source of Y and heavy

REEs. The light minerals (gangue) in heavy minerals sands

are dominated by quartz sand, clay minerals, and silt-size

quartz and iron-oxide minerals. Feldspars are typically minor

or absent constituents. Carbonate minerals are rare.

Mineralogical characteristics in beach placer deposits vary

from region to region depending on the host rocks, their

provenance, ambient climate, mechanism of transport, and

the hydraulic conditions during the depositional stage (Borreswara

Rao, 1957; Force, 1976, 1991). The roles of aeolian

and marine processes along with the local hydrodynamic conditions

and coastal geomorphology have a dominant role in

the distribution of the placer minerals, as demonstrated along

coastal Orissa, India (Komar and Wang, 1984).

Geochemistry

Trace elements associated with heavy mineral placers primarily

include Ti, Hf, the REEs (such as La, Ce, Pr, Nd, Sm,

Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) and Y, Th, and U.

These elements have been used from the analyses of stream

sediments to evaluate the presence of heavy mineral sands on

a regional scale (e.g., Grosz, 1993). These pathfinder (exploration)

elements reflect the composition of the potentially economic

heavy minerals of this deposit type, including ilmenite

(FeTiO3), rutile (TiO2), zircon ((Zr,Hf,U)SiO4), monazite

((La,Ce,Th,U)PO4), and xenotime (YPO4). Monazite is preferentially

enriched in the light REEs relative to the heavy

REEs (Fig. 10).

Variation in chemistry at a deposit scale most likely indicates

the variations in heavy mineral content rather than geochemical

gradients due to hypogene, hydrothermal, or supergene

processes. Hydrothermal alteration and other forms of geochemical

diffusion that are typical of most ore deposits are not

associated with heavy mineral sands.

The thorium to uranium ratio is useful in the recognition

of “geochemical facies” (Macfarlane et al., 1990) and a possible

indicator of oxidizing and reducing conditions (Adams

and Weaver, 1958; Anjos et al, 2006). Average equivalent Th/

equivalent U (eTh/eU) ratios for Gopalpur and Rushikulya

beach samples, India (Figs. 6, 7), are observed to be in the

range of 22 to 49 (Fig. 11). Both sets of beach samples lie in

heavy mineral and clay mineral fields, indicating a generally

higher presence of thorium in Gopalpur and higher potassium

in Rushikulya. This could be attributed to adsorption and the

chemical composition in this region (Doveton and Presnky,

1992). The detailed mechanism has been discussed by Sulekha

Rao et al. (2009).

Higher concentrations of radioactive elements (Th, U) and

REEs (La, Ce and Nd) have been observed in the monazite

sands of Chhatrapur, India (Mohanty et al., 2003a). The chondrite-

normalized REE distribution pattern of the monazite

grains indicated uniformly enriched light REEs, which has

been attributed to the preferential incorporation of lighter

lanthanides formed during partial melting. The majority of

the beach samples studied fall in both heavy minerals and

clay mineral fields (Fig. 11). However, samples of beach sands

from Gopalpur fall primarily in the heavy minerals field while

Rushikulya beach samples plot mainly in the clay minerals

field, indicating that both Th and K are associated with

clay minerals due to adsorption and chemical composition

(Doveton and Presnsky, 1992).

Most of the earlier studies on monazite REE chemistry

are either related to igneous or metamorphic rocks, with few

studies reported on placers. Geochemical studies of the REE

Fig. 10. Chondrite-normalized plot showing the REE distribution in selected monazites separated from heavy mineral sands

deposits from a few continents. Chondrite-normalized europium values that lie below the trend of the other REEs are typical

of monazite, but are not universal, as displayed by the monazite sample from a heavy mineral sand deposit in Taiwan. Data

from Mukherjee (2007). Chondrite REE concentrations from Boynton (1984).

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chemistry in placers are important because sustained mining

of placer deposits depletes their reserves. An important

additional aspect is to utilize better techniques for enhanced

recovery of the REEs from beach washings.

Typically, monazite extracted from beach placers is preferentially

enriched in the light REEs. Dawood and El-Naby

(2007) reported light REE enrichment from Sinai beach,

Egypt. This monazite is sourced primarily by pegmatites

and granites. The chondrite-normalized REE pattern from

zircons (Fig. 12) of the Kanayakumari beach areas, located

on the southernmost tip of India, exhibits light REE enrichment

compared to heavy REE as well as Ce and Eu anomalies

(Angusamy et al., 2004); these monazites are thought to

be sourced by charnockites. Chhatrapur monazite placers in

Orissa, on the east coast of India (Fig. 6), also show similar

trends of light REE enrichment in zircons (Fig. 13) relative to

heavy REEs as well as an Eu anomaly (Mohanty et al., 2003b).

Chondrite-normalized REE fractionation patterns for the

lunar and terrestrial monazite indicate that the light REEs

(ie., La to Sm) are highly enriched relative to heavy REEs

(i.e., Gd to Lu; Lovering et al., 1974).

Genesis of Heavy Mineral Placers

Whether the ultimate deposition of the heavy mineral-rich

sediments occurs in an alluvial or coastal setting, the processes

that form these deposits begin inland. High-grade

metamorphic rocks (of amphibolite facies and higher) and a

variety of plutonic igneous rocks are the principal sources of

heavy minerals, including monazite. These bedrocks weather

and erode, contributing detritus composed of sand, silt, clay,

and heavy minerals to fluvial systems. Streams and rivers carry

the detritus to the coast, where they are deposited in a variety

of coastal environments, including deltas, the beach face

(foreshore), nearshore, barrier islands, dunes, or tidal lagoons,

as well as the channels and floodplains of streams and rivers in

the coastal plain. The sediments are worked by the actions of

waves, tides, longshore currents, and wind, which are effective

mechanisms for sorting the mineral grains based on differences

in their size and density. The finest-grained, most dense

heavy minerals are the most effectively sorted. The result is

that heavy minerals accumulate together, forming laminated

or lens-shaped packages of sediments several meters and as

much as tens of meters thick that are rich in heavy minerals.

Generally, economic deposits of heavy mineral sands contain

at least 1% total heavy mineral content. Most economic

deposits of coastal heavy mineral sands (coastal placers) are

Paleogene, Neogene, and Quaternary deposits, as well as

some modern coastal deposits.

Factors influencing the formation of placer deposits

Climate: Climate influences the weathering processes, and

ultimately decomposes the rock matrix and liberates the

minerals. Tropical to subtropical climates promote chemical

weathering, which has given rise to a decomposed stage of

crystalline rocks called laterites. This could be considered as

the preconcentration process of the placer minerals. Most of

the rich, modern placer deposits of the world are in tropical

regions.

Drainage pattern: Fluvial processes act as a conductor of

sediment transport from the source rock to the zone of concentration.

The erosive power of rivers is strong, releasing

heavy minerals from the parent rock and transporting them

downstream. For example, in the Kerala State of southwestern

India, west-flowing rivers with steep gradients were the

major agent of erosion and transportation of sediments to the

Arabian Sea.

Fig. 11. Discrimination diagram plot of eTh/eU vs. eTh/eK in bulk sand samples collected from the Gopalpur and Rushikulya

beach placer deposits, Orissa, India. The vertical bars represent values of eTh/eU = 2 or 7. Diagram modified from Sulekha

Rao et al. (2009).

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Coastal processes: Beach deposits result from the interplay

of coastal hydrodynamics of rivers, waves, and currents. The

direction and strength of the coastal currents along with the

geomorphology of the coast, sometimes influenced by localized

faulting, determine the location of the deposit. Strong, sustained

wave action moves sand from offshore to the shore. Waves sort

out the heavy minerals based on their size and specific gravity,

respectively. Studies suggest that mineral sorting occurs mainly

on the upper part of the high-tide swash (wave) zone. Finegrained

sands and heavy minerals on the foreshore (beach face)

can be remobilized by winds, forming heavy mineral-rich sand

dunes behind the beach. Sea-level changes are a function of

climatic changes, such as ice ages. Rises in regional sea level

(transgression) and fall of sea level (regression) strongly influence

the deposition and preservation of heavy mineral sands,

both along the strandline and inland fluvial deposits. Major episodes

of heavy mineral sands accumulation have been linked to

seaward progradation of the shore during regression events as

well as prolonged transgressive events.

Exploration Considerations

Beach placer deposits—also referred to as “heavy mineral

sands”—are well known from different parts of the world

(Mero, 1965). Discoveries of beach placer deposits occurred

along the Brazilian coast (Da Silva, 1979), China (Highley et

al., 1988), Egypt, France, Bangladesh, and Iran (UNSCEAR,

1993). The beach placer deposits have primarily been investigated

for their economic resources of heavy minerals, in

particular ilmenite, rutile, zircon, sillimanite and garnet,

apart from monazite and zircon and their actinide and rareearth

elements. Two basic criteria provide the foundation for

locating significant deposits of heavy mineral sands (placers)

in coastal environments: (1) identify bedrock terranes that

contain abundant high-grade metamorphic rocks or igneous

rocks; and (2) identify ancient or modern coastal plains

sourced by streams and rivers that drain these terranes.

For several decades, the mineable (economic) deposits of

heavy mineral sands are those formed during the Paleogene,

Fig. 12. Chondrite-normalized pattern of REEs in zircons from Kanyakumari beach placers, showing Ce and Eu anomalies

(Angusamy et al., 2004).

Fig. 13. Chondrite-normalized pattern of the light REEs in zircons from Chhatrapur beach, India, showing LREE enrichment

and Eu anomaly (after Mohanty et al., 2003a).

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Neogene, or Quaternary. Heavy mineral deposits of Cretaceous

age or older are likely to be hosted by lithified, wellcemented

sandstones. Thus, restricting the assessment areas

to unconsolidated Paleogene, Neogene, and Quaternary sediments

deposited in coastal environments is a first-level exploration

and assessment guideline.

Detailed geologic mapping that divides sedimentary units

by time period (such as epoch) can benefit the search for

deposits. For example, during the Pliocene many economic

deposits of heavy mineral sands formed along the cratonic

margins of widely separated continents. Also, within a single

coastal basin, time-equivalent sedimentary units can indicate

the extent of ancient strandlines, and thus the possible locations

of related deposits.

Grosz (1993) described the application of stream sediments

to locate deposits of heavy mineral sands in the mid-Atlantic

coastal plain of the United States. His study analyzed concentrations

of Ti, Hf, the REEs, Th, and U in stream sediments.

These pathfinder (exploration) elements were selected

to detect the presence of the heavy minerals typical of this

deposit type, including ilmenite (FeTiO3), rutile (TiO2), zircon

((Zr,Hf,U)SiO4), monazite ((Ce,La,Y,Th,U)PO4), and xenotime

(YPO4). Grosz (1993) concluded that geochemical data

may be used to locate deposits of heavy minerals, especially

by indicating areas in the mid-Atlantic region of the eastern

United States that merit more detailed sampling and analyses.

Monazite-Bearing Beach Placer Deposits

and Natural Radioactivity

Radiometric methods of geophysical exploration are useful

in discovering and delineating deposits of heavy mineral-rich

beach placers (heavy mineral sands). Several minerals in these

deposits can produce a radiometric anomaly, in particular monazite,

due to its thorium content (Force et al., 1982; Grosz et al.,

1989, 1992; Grosz and Schruben, 1994). Zircon grains may also

generate thorium and uranium anomalies. Potassium-bearing

minerals, such as K-feldspar and micas, can also contribute to

total count surveys, appearing as K highs in the gamma spectra.

A factor that is equally important is the potential radiation

dose to humans and others from some high-grade placers,

specifically, the exposure to natural radioactivity caused by

the radioactive minerals in these deposits, principally monazite

and zircon. The Erasama and Chhtarapur placer districts

in the Orissa State along the east coast of India (Figs. 5–7)

have been shown to be “high background radiation areas,” primarily

due to the presence of thorium and uranium (Mohanty

et al., 2004; Sengupta et al., 2005). Similarly, in Brazil the

Guarapari coastline of Espírito Santo is a popular tourist destination

known for its white sand beaches, but this shoreline is

also known for its very high level of background radioactivity

due to abundant detrital monazite.

The Significance of Monazite Placers

Monazite hosted by placer deposits offers several advantages.

First, it has a two-fold value as an ore mineral—it contains

several rare earth elements as well as thorium. Second, grains

of monazite in placer deposits are mingled with other minerals

of industrial value, such as ilmenite, rutile, zircon, garnet,

sillimanite, and other heavy minerals; thus, monazite is recovered

as a low-cost coproduct. Third, monazite is resistant to

mechanical and chemical degradation and is typically the

heaviest (highest density) mineral in the sand-silt deposit;

these qualities make monazite relatively easy to mechanically

separate and recover from heavy mineral sands.

Thorium has wide applications apart from its potential use

as source of nuclear energy (International Atomic Energy

Agency, 2005; Hongjie, 2012), such as its use in glasses of high

refractive indices and as a source of neutrons. The major applications

of thorium presently are in refractory usage, aerospace

alloys, ceramics, and lighting. Thorium’s host minerals—monazite,

thorite, thorianite, bedafite and zircon—are normally

associated with other minerals that have a better control on

the ore grade rather than thorium itself (Dill, 2010).

Because of the effect of the natural radiation environment

and its enhancement due to the presence of monazite and

the zircon in these placers, there is dire need to quantify the

radiation background and its possible effects on the population.

These studies are more so because quite a large number

of beach placer areas, such as Gopalpur and other adjacent

beaches, are also famous beach resorts of the southern part

of coastal Orissa (east coast of India). Recently, these beach

areas have become important centers of tourism with a large

influx of people throughout the year (Mohanty et al., 2003a).

China, Japan, and the United States constitute about 90%

of global product manufacturing that involves the REEs. The

product distribution differences among the countries are substantial.

Automobile catalytic converters accounted for 32%

of rare earth use in the United States in 2007; the second

biggest use was in metallurgical additives and alloys (around

21%). Japan used 28 and 27% of total rare earths in permanent

magnets and polishing powders, and 15% in automobile

catalytic converters. China has experienced the most dramatic

changes in recent REE use. China has traditionally employed

rare earths in applications such as metallurgical additives and

alloys, petroleum refining, and glass and ceramics, but new

applications in China have grown significantly since 2002. The

end-use history demonstrates the dramatic increase in these

new applications, which are primarily permanent magnets,

polishing powders, nickel hydride batteries, phosphors, and

automobile catalytic converters.

PIXE and EDXRF analyses on monazite sands from Chhatrapur

and Erasama (Figs. 5–7) indicate the higher abundance

of the oxides of cerium followed by lanthanum and

neodymium. Cerium has wide applications, mainly in the

fields of specialty glasses and ceramics. In addition, cerium

lasers are used to locate atmospheric pollutants such as

ozone and sulfur dioxide. Cerium compounds are also used

to make phosphors. The primary uses of lanthanum are in

hybrid car batteries, hydrogen sponge alloys, “mischmetal”

(an alloy with approximate composition of 50% Ce, 25% La,

and the remainder mostly Nd and Pr), and in cerium-doped

lanthanum-based scintillators. Lanthanum is also used to

enhance the alkali resistance of glasses, such as infrared

absorbing glasses. Neodymium is useful in crycoolers and

frequently used in countries such as China as a fertilizer. In

addition, neodymium compounds are used in manufacturing

neodymium magnets, which are the strongest permanent

magnets at this time.

The sector with the largest consumption use of REEs is

metallurgical applications—mainly in the form of mischmetal.

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With the growing demand for Nd and Pr in magnets, current

processing methods sometimes recover those elements individually,

leaving a mischmetal composition consisting almost

entirely of Ce and La. The sector with the next highest use

of REEs is computer components, which contain Nd, Pr,

Dy, Gd, and Tb. Automobile catalytic converters rank third

among rare earth consumption, mostly using Ce. Six other

product sectors are also significant users of REEs: audio systems

(mostly Ce), glass additives (Ce and La), nickel metal

hydride batteries for computers (Nd, Pr, Dy, and Tb), catalysts

(predominantly La), automobiles (Nd and Pr), and wind

turbines (Nd and Pr). Together, the consumption of REEs in

these nine product sectors constitutes nearly 88% of the total

REE use (Du and Graedel, 2011).

Heavy mineral placers offer several advantages as sources

of mineral feedstock:

1. The deposits are usually unconsolidated or weakly consolidated

sediments, and thus relatively easy to excavate;

2. These deposits are sizeable, with orebodies of at least 10

Mt;

3. Well-established techniques are used to separate the heavy

minerals from the ore body (mixture of sand-silt-clay);

4. A single deposit and operation can produce multiple salable

products, such a Ti oxide minerals (ilmenite, rutile),

zircons, garnet, staurolite, tourmaline, kyanite, and/or sillimanite,

as well as monazite, a potential source of the light

REEs and thorium.

An aspect of utmost significance is the depletion of heavy

mineral content and the associated rare earth minerals due

to continuous mining of the beach placers. Thus, additional

deposits of heavy minerals (including inland paleodeposits)

will be needed to fill increasing world demand for many

industrial minerals, REEs, and perhaps thorium.

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