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Non-marine heavy-mineral placers in the Gulf of Thailand

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Abstract: Exploration for mineral deposits in the Gulf of Thailand has been conducted for more than ten years in the joint project between the government of Thailand and the United Nations. Geophysical surveys were carried out along boat track lines with a total distance of several thousands of kilometers. Minerals were extracted from several thousands of drillholes samples recovered from coastal plains and shallow marine areas.

Minerals found in the Gulf of Thailand are titanium minerals (ilmenite, rutile, leucoxene), abrasive minerals (zircon, garnet, staurolite) and tin mineral (cassiterite). A total ore reserve of the assorted heavy minerals is more than one million metric tonnes.

Occurrence of the mineral deposits is interpreted from characteristics of the sediments by comparison with the sediments found on nearby coastal plains. Depositional periods of the mineral deposits were estimated by comparison with global sea-level curves. The unconsolidated sediments in the Gulf of Thailand are deposited in several environments of deposition, including marine, non-marine, and coastal environments. The minerals are concentrated in coarse-grained alluvium and alluvial gravel bed which were deposited under non-marine conditions.

The mineral deposits in the Gulf of Thailand were formed by materials transported from granitic mountains in the coastal areas, as non-marine heavy-mineral placers in the shallow marine areas, during periods of sea-level low-stands when the Gulf of Thailand was a dry land, in the Pleistocene Epoch between 10,000–1,600,000 years before present.

INTRODUCTION

Exploration for mineral resources in the shallow marine areas of the Gulf of Thailand has been conducted between 1987–1997 by the Department of Mineral Resources of Thailand. The exploration was concentrated in 3 major areas, covering 8,110, 2,975, and 11,412 square kilometers (Fig. 1). Seismic profiles and magnetic intensities were recorded on survey lines with a total distance of 19,862 line kilometers. Mineralogical and sedimentological data were analyzed from thousands of sediment samples from 392 drillholes with a total penetration depth of 6,670 meters.

The survey was started with marine geophysical surveys, sea-bottom sampling, coastal mapping, and coastal drilling between 1987–1993, followed by detailed geophysical surveys and offshore drilling between 1994–1997. Results of the first stage of exploration suggested a further exploration in 7 target areas. Area 1A, Area 1C, Area 1D, 1E were selected from Area 1. Area 2 remained unchanged. Area 3B and Area 3C were selected from Area 3 (Fig. 1). Area 1E was the only area selected for gemstone deposits which is not included in this paper. The remaining 6 target areas were selected for exploration for heavy mineral deposits which are discussed in this paper. The data include 231 drillholes offshore with a total penetration depth of 3,607 meters.

The mineral resources were estimated. Environment of deposition of the drillhole sediments was interpreted. A stratigraphic sequence was compiled from drillholes. Ages of sediment sequences were estimated in comparison with sea-level curves.

EXPLORATION METHODS

Coastal geological mapping was conducted to classify surface sediments of the coastal zones using aerial photographs. A field check was undertaken by drilling down to 4 meters into the surface sediments.

Coastal drilling was carried out in the coastal zones of Area-3. A total number of 28 holes was drilled and resulting a total penetration depth of 537 meters. The drilling was undertaken by using

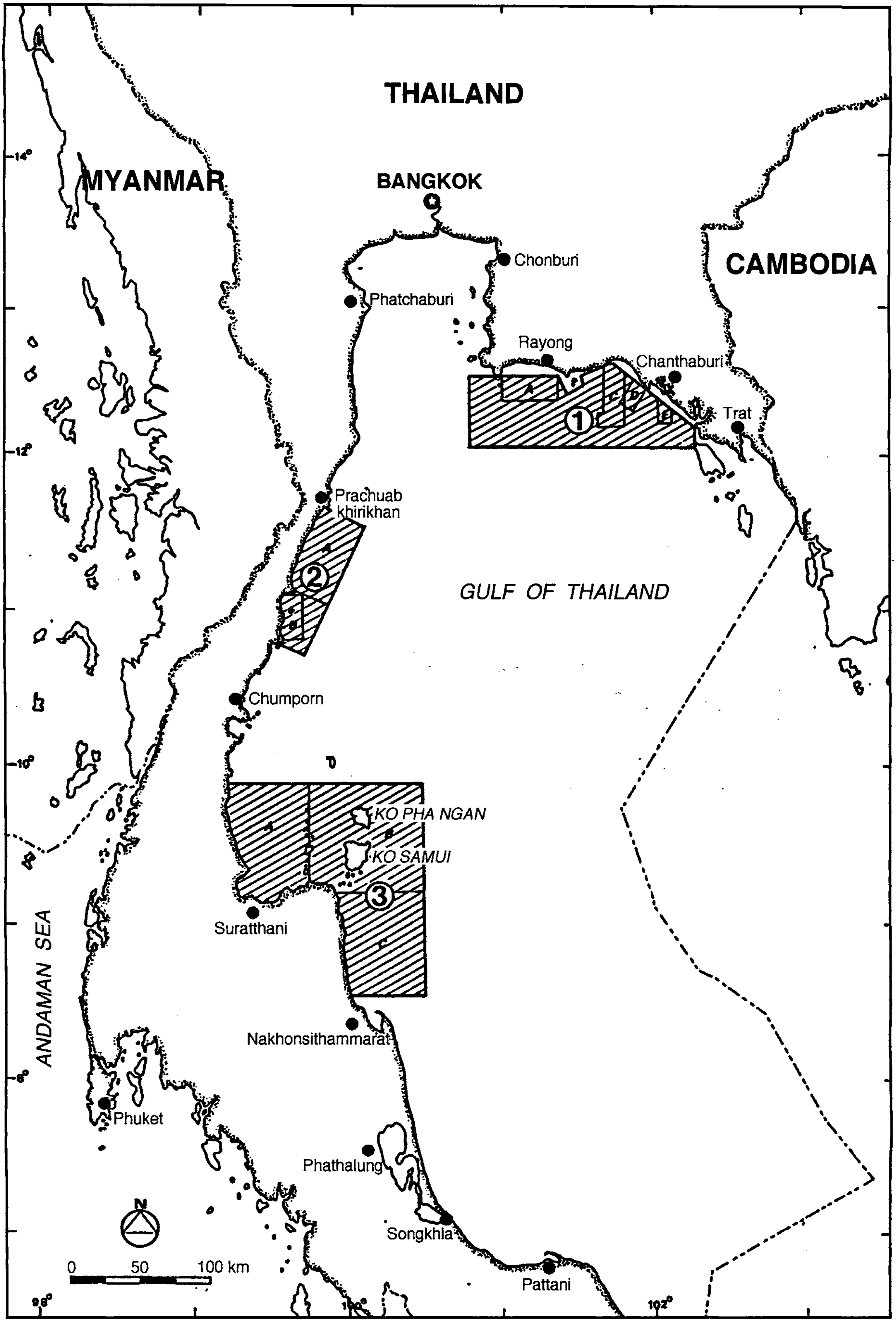


Figure 1. Survey areas for mineral resources in the Gulf of Thailand Project between 1987–1997. Exploration was started in 3 major areas in which 6 target areas were selected for detailed exploration for heavy-mineral deposits and 1 target area for corundum deposits (Area-1E).

the Bangka Drill with a hole diameter of 3 inches to a maximum depth of 90 feet. A sediment sample was collected at a depth interval of every 5-feet or less if the sediment type changes. Samples were analyzed for heavy minerals and sedimentological properties (Kohpina, Pokawanvit and Chiemchindaratana, 1994). The obtained data were very useful for the offshore drilling.

Seafloor sampling was conducted on a vessel by two simple tools. A gravity corer was employed in muddy sediments and a sand dredge was used in sandy bottoms. The gravity corer can penetrate down to a depth of 1 meter. The sand dredge can penetrate down to a few centimeters.

Seismic profiling and magnetic survey were operated on a vessel along grid lines in North-South and East-West directions. The seismic profiling was operated in order to illustrate sediment structures under the seafloor by sending a sound wave to penetrate the sediment layers and receive the reflected sound and process. By using a set of very sophisticated electrical equipment, the data can be processed and a seabed profile can be illustrated on a paper showing a picture of the seabed profile. Boundaries of sediment layers are shown as major reflectors and sediment types as a pattern of reflected sound intensity. Significant features on the seismic profiles obtained are various major reflectors, abundant buried channels, a few sediment layers with different intensities and bedrocks. Marine mud and alluvium can be classified on seismic profiles. Buried channels can be observed as an indicator of riverine origin of the alluvium.

The magnetic survey was carried out in order to measure intensity of the Earth's magnetic field in order to locate high-intensity magnetic mass under the seafloor. Rocks or materials with high iron contents usually induce high intensities of the Earth's magnetic field. A profile of magnetic intensity can be drawn showing bedrocks with various magnetic susceptibilities. Results form the magnetic measurement in all 6 target areas showed no significant variations in the magnetic intensities. The plots of magnetic intensities along profiles showed almost flat magnetic curves. These data suggest no magnetic bodies buried under the seabed. Results of the drilling in the final have proved that the seafloor sediments contain very little magnetic minerals and the bedrocks are composed of sedimentary rocks, metasedimentary rocks and granite which generally contain very little magnetic minerals.

The drilling in 6 target offshore areas in the Gulf of Thailand Project was conducted by using a drilling barge equipped with a drilling system. A total number of 231 drillholes was accomplished between 1994 and 1997 and a total penetration depth of 3,607 meters was obtained. The drilling is a measure to obtain sediment samples down to the maximum depth of 40 meters from the seafloor. A sediment sample was collected at every depth interval of 3 meters or where sediment type changes. Each sample was analyzed for economic heavy minerals.

Thousands of sediment samples were analyzed between 1987–1997 using the conventional heavy mineral processing method. Minerals were extracted from sediment samples by panning in a conical pan. The heavy-mineral concentrate obtained from the panning was purified in bromoform (specific gravity 2.82) where light minerals would float and heavy minerals would sink in this liquid. The heavy minerals were separated on a filter paper to be cleaned and dried.

Mineral grains were inspected under a microscope for percentages of minerals. This inspection was done after magnetic separation which groups minerals into small groups of a fewer mineral types. Weight of minerals was measured in every procedure. Abundance of mineral was calculated from the percentage, weight, specific gravity, and volume of bulk sample.

Prior to the mineral processing, a sample was inspected for sedimentological properties, including colour, stiffness, texture, abundances of shells, wood fragments, riverine pebbles, rock fragments, and laterites. These parameters were found to be good indicators for environment of deposition of the sediments and mineral deposits. A sample was washed in water to discard mud and clay. Gravels were separated from sands by a 2-mm screen. Volume of every fraction in each step is measured to obtain percentages of mud, sand and gravels. Environment of deposition of the drillhole sediments was interpreted by using the parameters in comparison with the sediments on the coastal zones based on Walker (1984), Davis (1985) and Roy (1989). Non-marine environments are indicated by laterite, reddish and yellowish clay, and poorly sorted sands and rounded pebbles. Marine environments are indicated by greenish-gray marine mud with marine shells and corals. Estuarine and intertidal environments indicated by dark-gray and dark-brown peaty clay, wood fragments, and petrified worm burrows.

MINERAL DEPOSITS

Economic heavy minerals found in 6 target areas are ilmenite, rutile, leucoxene, monazite, zircon, garnet, staurolite and cassiterite (The Gulf of Thailand Project, 1994). Ilmenite ($FeTiO_3$) is a low grade titanium mineral. Rutile (TiO_2) and leucoxene

(TiO_2) are high grade titanium minerals. These titanium minerals are major sources of pigment (TiO_2) and titanium metal. Monazite (Ce, La, Nd, Th) (PO_4) SiO_4) is the principle source of thorium and some rare-earth elements. Zircon, garnet, and staurolite are high grade abrasive minerals. Cassiterite (SnO_2) is the major source of tin metal. A total reserve of 991,180 metric tonnes of these heavy minerals was estimated in the sediments of 14,784 millions cubic meters (Kohpina and Saisuthichai, 1996).

These minerals are concentrated in alluvium which is ranging in thickness from 10 to more than 40 meters. This layer is located in water depths of 0–30 meters and is capped with a layer of marine mud which is ranging in thickness from 0.5–5 meters. Superiors of these offshore mineral deposits are the massive extents and homogeneity of the ore bodies, no obstructions to the mining equipment, and these lands belong to no one but the government of Thailand. Inferiors of the deposits are the low mineral abundances and the muddy ore bodies which make them not favourable for economic purpose at the present but in the future.

MINERAL OCCURRENCE

Environments of deposition of the sediments in the coastal zones from land to the sea, can be classified into 4 environments; including alluvium (or riverine), intertidal, beach, and marine (Chotikasathien and Kohpina, 1993). Results from the seafloor sediment sampling showed that the seafloor sediments in the Gulf of Thailand are mostly soft, greenish-gray marine mud and very locally sandy and shelly sediments.

A stratigraphic sequence compiled from the offshore drillholes is as follows:-

Water depth:	0–30 meters.
Top sequence:	Marine mud, 0.5–5 meters.
Bottom sequence:	Alluvium interbedded with lens of Peaty Clay, 10 to over 40 meters.
Bedrocks:	Shale, siltstone, sandstone, phyllite, schist, gneiss, or granite.

(Roy, 1994, and Kohpina and Chiemchindaratana, 1997)

It can be concluded from results of various studies worldwide, that sea-level rose and dropped several times in the Quaternary Period, or a time period between present and 1.6 million years ago. The main cause of these sea-level fluctuations is believed to be periodically depletion and refilling of ocean by meltwater from glaciation and deglaciation (Tija, 1986).

The sea-level curves (Fig. 2) suggest that sea-level rose and dropped in a cycle from the high stands at present datum to an elevation of 150 meters lower than present datum, with a wavelength of about 120,000 years. The sea-level in the Gulf of Thailand must have fluctuated in the same manner. The Gulf of Thailand has been tectonically stable throughout the Quaternary Period (Tija, 1986). This implies that the Gulf of Thailand, which has a maximum depth of 90–100 meters, was a dry continent a few times and was as the present condition a few times. Environment of sediment deposition would have changed from open marine during sea-level high stands to coastal environment and non-marine environments during low stands.

The pattern of sea-level changes corresponds well with drillhole sediments. The alternation of alluvium and estuarine and intertidal sediments can be correlated with the sea-level fluctuations in the Pleistocene or the period of time between 6,000 years and 1.6 million years in the past. A layer of marine mud is obtained during the last sea-level high stand or the period of time in the last 6,000 years. This marine mud should have been deposited in the Gulf of Thailand at every high sea-level high stand. However, because of its very soft texture, it is too weak to be preserved in the sediment sequence. Beach sand is not preserved in the sediment sequence because of its loose texture.

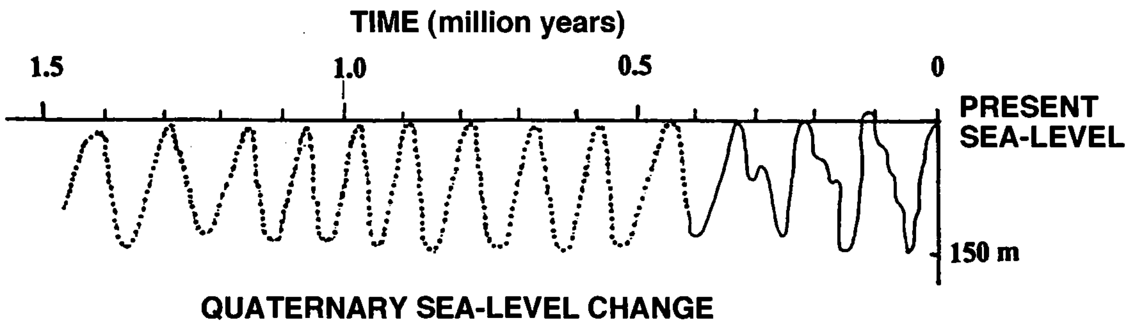
Indications of the last glacial period can be observed as buried channels (Fig. 3) which are generally found on many of the seismic profiles recorded along a total distance of over ten thousands of line kilometers in water depths of 0–30 meters and at depths of 0–30 meters from the seafloor. These buried channels may not be a good indication of the last glacial maximum because the sea-level of the glacial maximum is estimated at 150 meters below present level.

Indications of the last interglacial period can be observed as ancient beach ridges which were extensively found on the coastal plains of the Gulf (Fig. 4) which were well described in Roy (1989), Roy (1990), Roy (1991) and Chotikasathien and Kohpina (1993). These beach ridges (120,000 years old) were clearly distinguished from the Holocene beach ridges (6,000 years old) by the eroded surfaces. Although these ridges have not been dated, but similar ridges in Eastern Australia were dated by the thermoluminescence method and found to be Pleistocene in age (Roy, Per. Com., 1991).

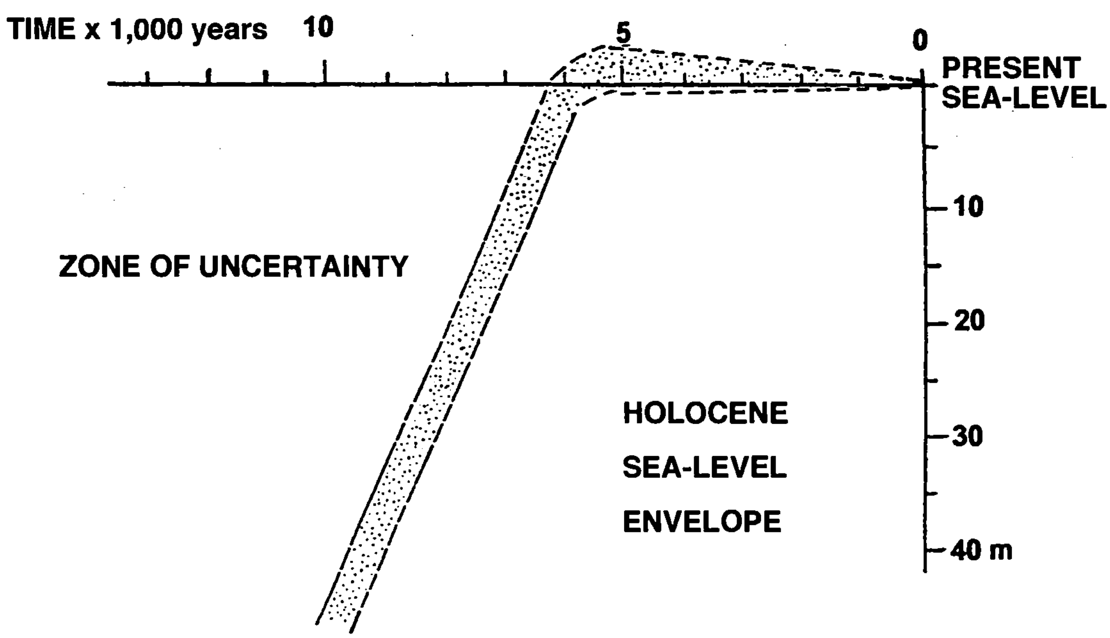
Models of mineral occurrence can be constructed from geology of the coastal zones and offshore areas (Figs. 5, 6 and 7). Coastal zones of these areas comprise granitic and sedimentary rocks in the mountains. Granitic rocks are the major source of the heavy minerals. Many heavy-mineral deposits on the coastal areas are associated with these rocks. The heavy minerals were weathered, distributed by rivers and deposited in the survey areas in a non-marine condition when the Gulf of Thailand became a dry land several times in the Pleistocene, or in the last 1.6 million years.

ACKNOWLEDGEMENT

This report is compiled from a great deal of geological data collected in a period of 10 years by hardship of many scientists, engineers and other personnel in the Gulf of Thailand Project and great encouragement from project organizers in Department of Mineral Resources, United Nations Development Program and Department of Technical and Educational Cooperation. Without these distinguished people and the remarkable project, this report would be impossible. The authors would like to express their sincere gratitude to Mr. Samai Chiemchindaratana, the manager of the Gulf of Thailand Project; Mr. Suvit Sampattavanija, the director of the Economic Geology Division; Mr. Nopadon Mantajit, the director general of the Department of Mineral Resources, and many other people involved in this project.



A. Glacial-interglacial oscillations of intervals about 100,000 years, amplitude 150 m (Roy, 1989).



B. Sea-level changes in the Holocene on a tectonically stable margin base on data from SE Australia (Thom and Roy, 1985).

Figure 2. Sea-level curves in the Pleistocene (after Roy, 1989). The sea-level was changed several times in almost a uniform cycle from present level to a 150 meters below present level at every 120,000 years. The sea-level remains at present level about 6,000 years ago.

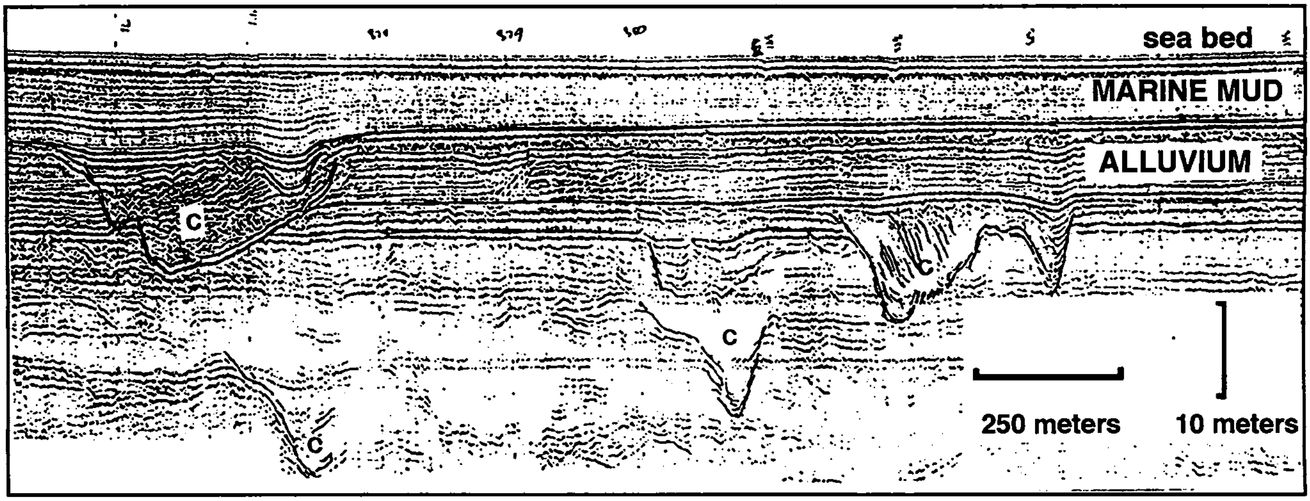


Figure 3. Buried channels on a seismic profile. Buried channel are frequently associated with the alluvium. None have been found in the marine mud, at top layer.

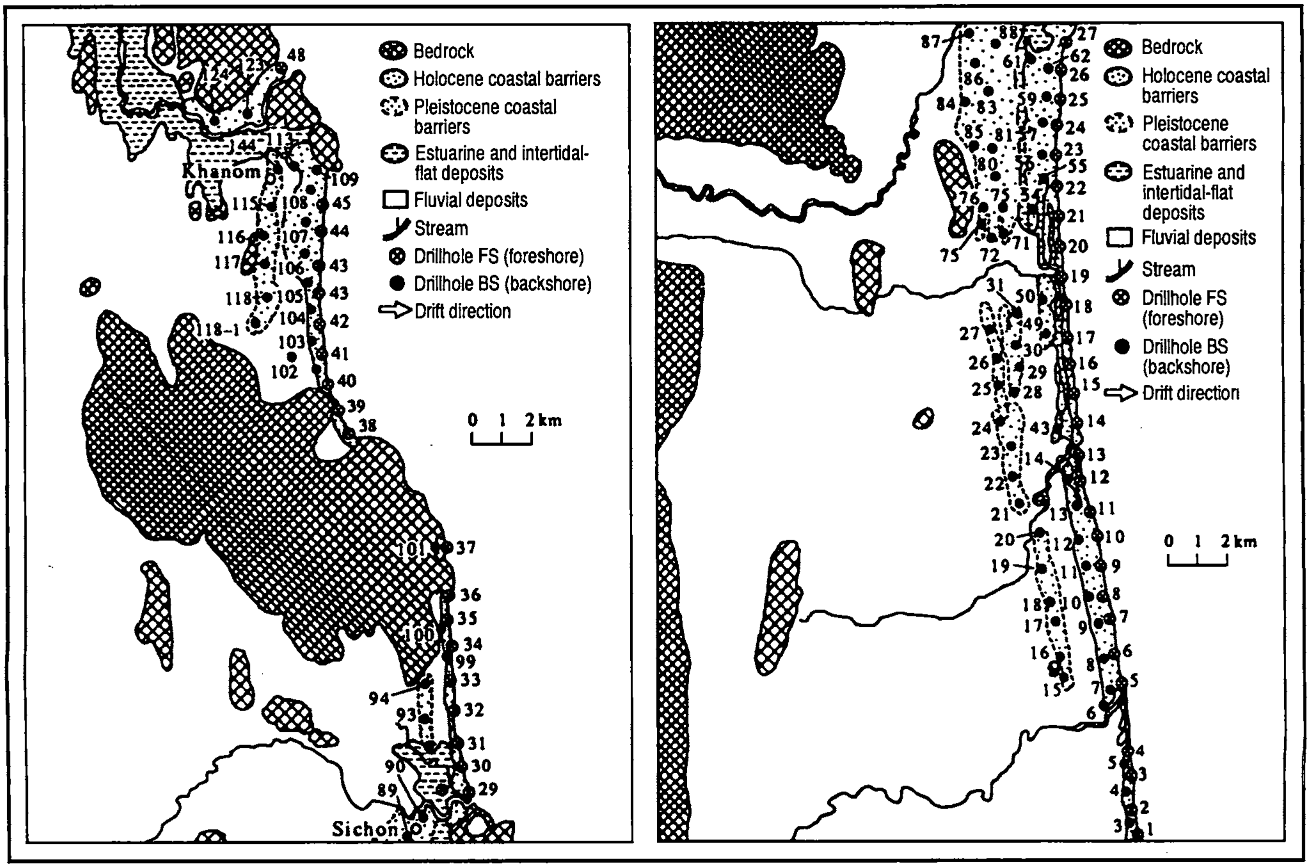


Figure 4. Pleistocene and Holocene beach ridges (or in Australian term "coastal barrier"). Pleistocene beach ridges around the Gulf of Thailand can be distinguished from the Holocene beach ridges by their eroded surface, absence of shells, and sometimes contain glass-sand deposits (After Chotikasathien and Kohpina 1993).

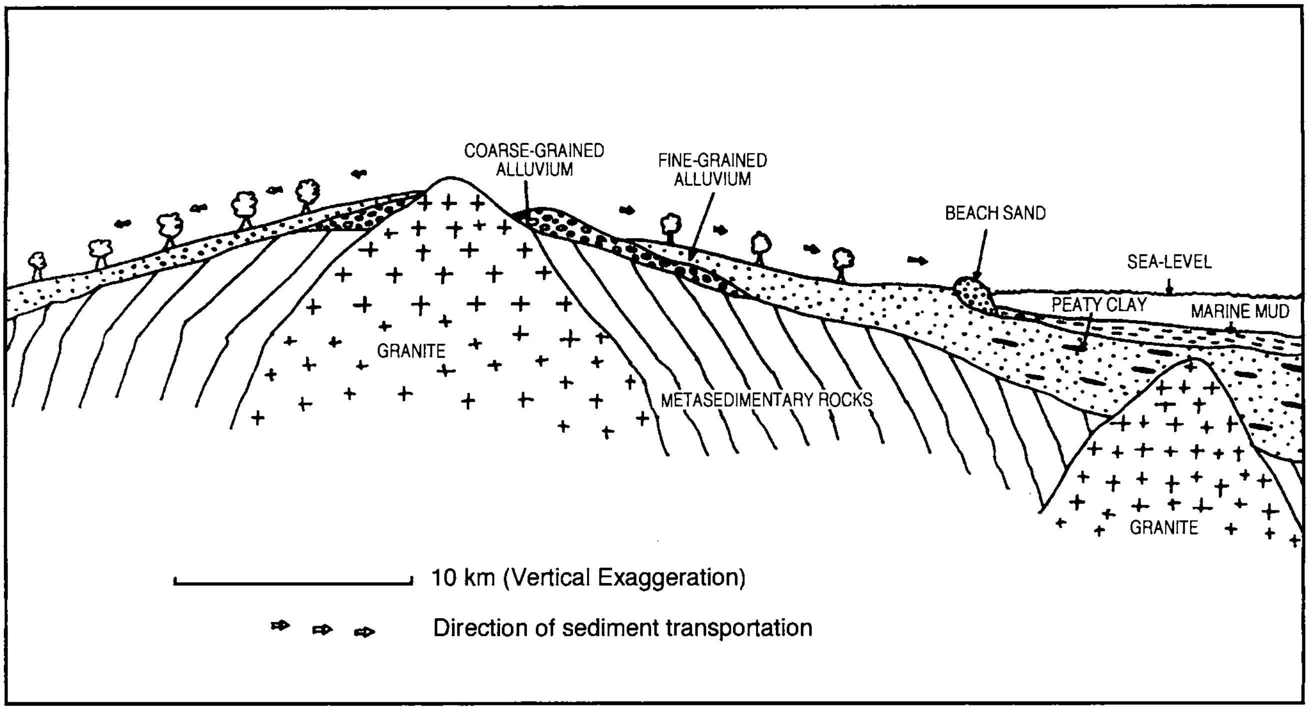


Figure 5. Model of heavy-mineral deposits in Area-1A, Area-1C and Area-1D. Granitic bodies were found on land and under the seabed. Although, rare mineral deposits are found on the coast, a heavy mineral reserve is found in the seabed sediments. Water depth 0–15 meters. Thickness of marine mud 0.5–2 meters, alluvium 10 to more than 30 meters.

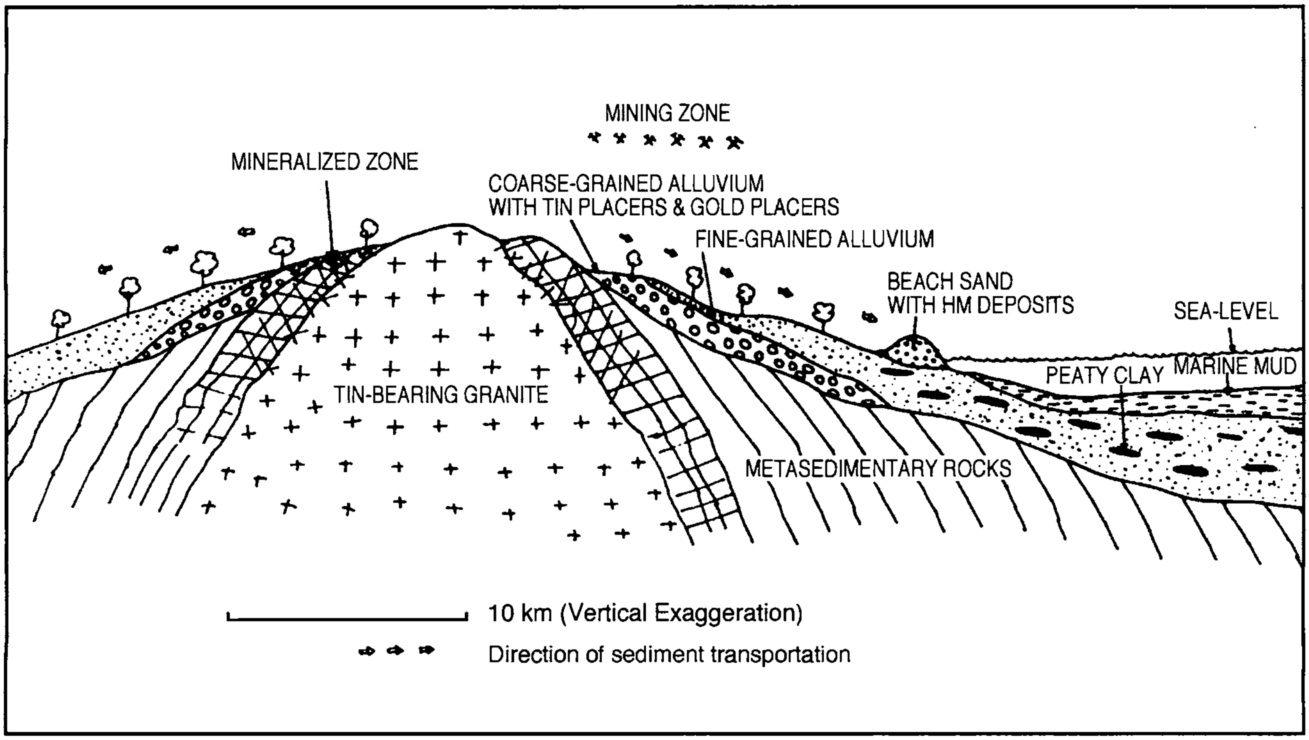


Figure 6. Model of heavy-mineral deposits in Area-2 and Area-3C. Abundant mineral deposits are associated with granitic rocks near the border line between Myanmar and Thailand. Heavy minerals and cassiterite are found in the seabed sediments. Water depth ranges 0–20 meters. Thickness of marine mud ranges 1–3 meters, alluvium ranges 20 to more than 40 meters.

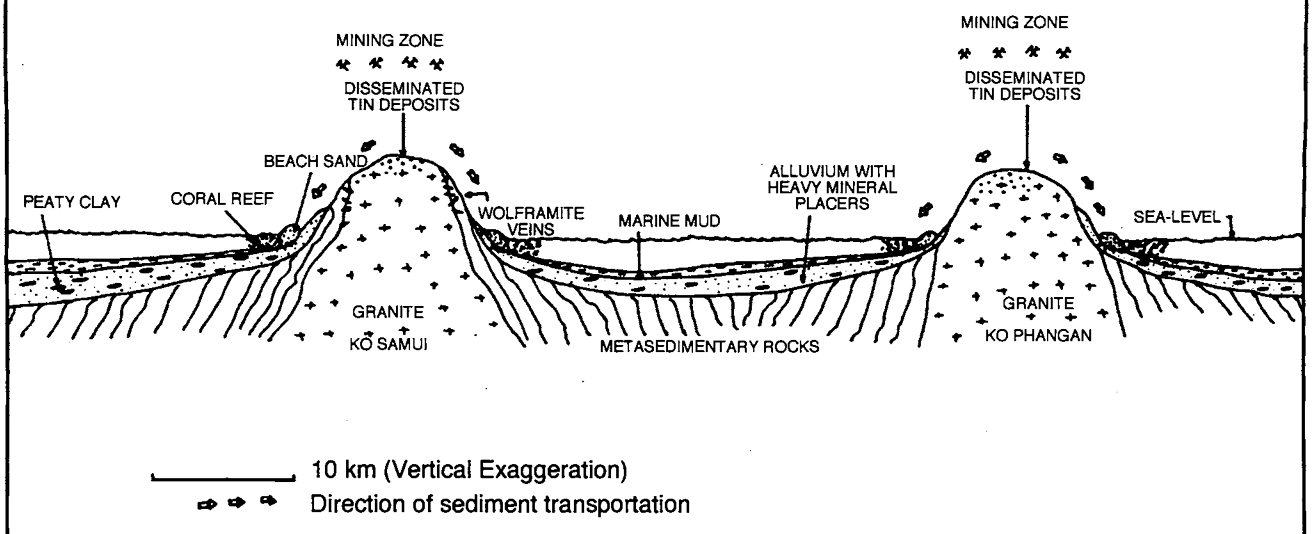


Figure 7. Model of heavy-mineral deposits in Area-3B around Samui and Phangan Islands. A few tin and wolframite deposits are associated with granitic rocks on the islands. Heavy minerals and cassiterite are found in the seabed sediments. Water depth ranges 0–30 meters. Thickness of marine mud ranges 1–5 meters, alluvium ranges 10 to more than 40 meters.

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