CHAPTER - II

REVIEW OF LITERATURE

2.1 General

Owing to the increasing importance of titanium mineral mining, many government and research institutions have sponsored and supported several studies on the different aspects of ilmenite deposits and mining. In this section, an attempt is made to examine the relevant literature in order to arrive at the focus of the present study. Here, the past studies are broadly classified into ilmenite, rutile, titanium minerals and their relevance of economics.

2.2 Studies Related to Ilmenite Minerals

Siddique et al. (1982) have undertaken exploratory surveys for offshore ilmenite placer off Konkan Coast in the West Coast. The surveys indicate the presence of ilmenite sand on the seabed over an area of 96 sq. km, and the sands contain 11 per cent to 57 per cent ilmenite, Titanomagnetite and Hematite. The thickness of the ilmenite bearing sands ranges from 2m to 10m., and these extend to a water depth of about 20m. Ilmenite placers are found to extend approximately for 2km. to 5km. offshore. The reserves of ilmenite are inferred to be 12.5 million tonnes. Thus, the probable reserves in the area will be many times more than the onshore reserves of four million tonnes.
Rajamanickam et al., (1983) has undertaken a detailed placer mineral exploration in the Jaigad, Ambwah, and Varvada bays of the Konkan Coast. The study shows that sizeable placer deposits of magnetite and ilmenite are found covering an area of about 24.37 sq. km., 8 sq. km., 4.02 sq. km., in Jaigad, Ambwah, and Varvada bays, respectively. The probable reserve of ilmenite to a subsurface depth of 1m. is 21.08 million tonnes. They also concluded that the ilmenite rich sands are paleo-placers, because the mineral concentrate and the nature of the coastal rocks do not match well. The ilmenite reserves in the surveyed area are inferred to be about 21 million tonnes.

Mir Azam Ali et al. (1989) have conducted an investigation for the beach placer in the Ratnagiri district of Maharashtra, India. They have identified the occurrence of significant deposits of ilmenite free from magnetite and limonite / hematite in parts of Kalbadevi, Newra and Varvada Coast. The presence of ilmenite deposits with considerable amounts of magnetite, limonite / nematicite is noticed in parts of Bhatya, Purangad and Goankhade. The ilmenite forms 92% wt. of total heavies (15% to 80% wt.) of raw sand in the former deposits with a chemical assay of 50-52 TiO₂ wt.% 0.5 wt. % Cr₂O₃, 0.1 wt. % V₂O₅, 21.2 wt. % FeO and 23.9 wt. %, Fe₂O₃. In the latter case, the magnetite share is high (40-60 wt. %). The deposit contains 25-35 wt. % of limonite / hematite and 5-25 wt. % of ilmenite in the raw sand. The occurrence of higher content of placer in Kalbadevi,
Newra and Varvada with a rich ilmenite reserve opens a new area along with Ratnagiri Coast for exploration of beach placers.

Chandrasekar (1992) has studied the heavy minerals in Central Tamil Nadu Coast. He divided the coastal zone, according to the concentration of heavy minerals, into two viz., the lean zone and enriched zone. The enriched zone, namely the area between Nagoore and Thirumullaivasal has been found to contain 1.74 million tonnes of zircon, 2.45 million tonnes of garnet and 5.97 million tonnes of ilmenite and the lean zone is estimated to contain 0.48 million tonnes of zircon, 1.22 million tonnes of garnet and 0.45 million tonnes of ilmenite.

Angusamy et al. (1992) have estimated 0.49 million tonnes of zircon, 6.13 million tonnes of garnet, 6.01 million tonnes of ilmenite, 0.10 million tonnes of magnetite and 0.84 million tonnes of monazite in the coast between Mandapam and Kanyakumari in Tamil Nadu.

Sengupta et al. (1992) have estimated placer reserves along the Orissa Coast up to a depth of 1m. They have estimated 17.28 million tonnes of ilmenite, 6.8 million tonnes of sillimanite, 4.86 million tonnes of garnet, 1.62 million tonnes of monazite and the presence of zircon and rutile.

The beach placer mineral exploration project headed by Victor Rajamanickam (1994) surveyed the coastal tract between Mandapam and Kanyakumari stretching for about 350 km. The estimated heavy mineral content in the five blocks of the study area are 8.81 per cent (Mandapam block), 15.2 per
cent (Valinokkam block), 36.7 per cent (Tuticorin block), 17.44 per cent (Manappad block), and 48.12 per cent (Kanyakumari block). High concentrations have been observed only in the blocks B3 and B5. The project has estimated inferred reserves of zircon, garnet, ilmenite, magnetite and monazite, in Kanyakumari region to be of 0.490079, 6.127306, 6.012375, 0.099551 and 0.8436 million tonnes, respectively. In Kallar-Vaippar region, the reserves of zircon, garnet, ilmenite, and magnetite are estimated at 0.0142089, 2.587945, 2.130044 and 0.51499 million tonnes respectively.

Angusamy (1995) has studied about the granulometric, geomorphological structures and tectonics of the southern Tamil Nadu coast, subtended between Mandapam and Kanyakumari. His study established the existence of five different blocks, namely Mandapam (B1), Valinokkam (B2), Tuticorin (B3), Manappad (B4) and Kanyakumari (B5). He found the enrichment of heavy minerals like ilmenite, garnet and zircon only in two selective zones, viz., Kanyakumari-Kuttankuli and Kallar-Vaippar river mouths. He evaluated the total reserves of zircon, garnet and ilmenite to be at 0.632168 million tonne (million tonnes) 8.715251 million tonnes, 8.14419 million tonnes and 0.034498 million tonnes, 0.508244 million tonnes, 0.029195 million tonnes respectively.

Murthy et al. (1998) have surveyed the Coastal area between Koyyam and the Nagavali River, Srikakulam District, Andhra Pradesh, spans over 20 km. in length with an average width of 800 meter. The concentration is 8-22 per cent in
the central sector of the study region, and 12-33 per cent and 2-21 per cent in the southern and northern sectors, respectively. Of the total Indian ilmenite reserve of about 278 million tonnes, the northern coast of Andhra Pradesh alone contains 50 million tonnes. This deposit contains 2 million tonnes of ilmenite with a working grade of 10 per cent, 1.5 million tonnes of garnet, 1.9 million tonnes of sillimanite, 0.15 million tonnes of rutile, 0.15 million tonnes of leucoxene, 0.08 million tonnes of zircon, and 0.62 million tonnes of monazite. The chemical analysis of ilmenite reveals that it contains 50 per cent TiO₂ with significantly low levels of CaO, MgO, V₂O₃ and Cr.

Chandrasekaran et al. (1998) identified heavy mineral concentration at Manavalakurichi near Kanyakumari, Tamil Nadu. The deposits are found to contain 15.5 per cent of ilmenite, 2.6 per cent of sillimanite, 2.4 per cent of garnet, 1.2 per cent of zircon, 0.9 per cent of rutile, 0.7 per cent of leucoxene, 0.7 per cent of monazite and 0.1 per cent of kyanite. A stretch of 7 km long bay between Muttam and Colachal has been found with high concentrations of heavy minerals (15.6 to 39.2 per cent with a thickness of 7.5m) when compared to other areas of the region.

Viswanathan et al., (1998) in their study estimated that the deposits between Pallithoppu-Rajakkamangalam contain 50 per cent of ilmenite in the heavies followed by sillimanite (28.3 per cent), garnet (10.8 per cent), zircon (4.7 per cent), rutile (3.6 per cent), monazite (1.74 per cent) and pyribole (0.32 per
cent). Here the total heavy mineral reserves are estimated at 1.21 million tonnes with an average grade of 6.32 per cent permeated upto a thickness of 6.35 m.

Chandrasekaran et al. (1999) have found the presence of ilmenite dominant placer heavy mineral concentrations upto 35 per cent, in the unconsolidated, fine to medium beach and dune sands, in the form of two line bands over a stretch of 3,800 m paralleling the east-west trending shoreline. Mineralisation is identified upto a depth of 10.5 m over an area of 2000x100-499 m and 3800x100-400 m with an average total heavy mineral content of 10.3 per cent and 5.5 per cent respectively. Among the heavies, ilmenite is the dominant one, forming 63 per cent, followed by sillimanite (18 per cent), zircon (6 per cent), garnet (4.4 per cent), rutile (3 per cent), monazite (1.2 per cent), magnetite (0.3 per cent) and leucoxene (3.8 per cent). Here, the heavy mineral reserves are estimated at 2.98 million tonnes, and this could serve as an additional source for the existing heavy mineral separation plant at Manavalakurichi.

Mohan et al. (1999) have conducted a study of placer minerals along the coast between Vedaranyam and Rameswaram on the east coast of India, extending upto 150 km length and one km width. This area is expected to contain ilmenite (4.9 million tonnes), magnetite (4.3 million tonnes) and garnet (6 million tonnes). The authors inferred the presence of buried placers in and around the study area. The buried placer deposits are expected to have a high concentration of magnetite (11 per cent), ilmenite (9.8 per cent) and garnet (12.6 per cent) with expected
reserves of 87.9 million tonnes, 98.6 million tonnes, and 120.5 million tonnes, respectively. Victor Rajamanickam (1996) argued that no proper investigations were undertaken to locate the buried placers and hence the author advocated for further studies in this line.

Mohapatra et al. (1999) have found the distribution of heavy minerals on the mid-continental shelf off Cauvery delta, southern part of the eastern continental shelf of India. The heavy mineral content is found between 2.3 per cent to 40.56 per cent in the terrigenous sands and 0.03 per cent to 2.96 per cent in the carbonate sands.

Suthanantham (1999) has carried out a preliminary investigation for placer gold in the Krishnagiri area of Tamilnadu. The study has found colluvium in the Maharajagadai block over an area of about 0.2 sq.km. The old alluvium along the major streams such as Veppahapalli Nadhi, Nachikuppam Aar, and Karkanda Nadhi and the paleo-channels are the promising sources of placer gold concentrations. The samples over a stretch of 2 km from Tadatarai to Dasirapalli have been found to have economic concentration of gold values ranging from 0.044 to 0.226 g/cu.m over an area of about one sq.km. It has also been indicated that the incidence of visible gold specks are found over a cumulative length of about 50 km.

Mohan and Victor Rajamanickam (2000) conceded that wherever eight per cent heavy mineral concentration in the first one-meter depth exists between
Chennai and Pondicherry, such places are favourable zones for the concentration of buried placers along the coast. They have also confirmed the presence of buried placers around 2 to 4 meter depth along the strandline of the coast.

Angusamy and Victor Rajamanickam (2000) surveyed the southern Tamil Nadu coast for a length of about 360 km. Among the five sectors identified viz., Mandapam, Valinokkam, Tuticorin, Manappad and Kanyakumari, they found that Kallar-Vaippar region in Tuticorin sector stretching for about 20km is concentrated with heavies to an extent of 64 per cent, Kanyakumari with 80-86 per cent, Manappad sector with 8.46 to 80.72 per cent, Valinokkam sector with 5.05 to 64.4 per cent and Mandapam with a lowest of 5.47 to 10.87 per cent. The heavies are primarily from the offshore. The highest concentration in Tuticorin sector is due to the arcuate nature of the coastline. The least concentration in Mandapam sector is due to the prevailing low energy and divergent waves.

Victor Rajamanickam (2000) has pointed out that in Thanjavur district of Tamil Nadu, titanium rich beach sand area has been identified over a length of 12 km distance, along the Cauvery river delta between Sirkali and Kaveripattinam. According to him, this deposit contains a higher percentage of zircon along with monazite and ilmenite, than the deposits of Manavalakurichi.

Arumugam et al. (2000) have attempted a preliminary study on placer minerals on Gadilam river basin, Tamilnadu, South India. The area of study extends over 1394 sq.km, which emerges from the foot of Kalvarayan hills and
comprises parts of Viluppuram and Cuddalore districts. The estimated heavy mineral percentages of the representative samples have shown encouraging results and provide the promise to conduct further detailed exploration.

Manickam et al. (2001) estimated the linear trends for the world and Indian production of ilmenite. From the estimated trends, ilmenite production for the world and India are projected to 11.22 million tonnes and 4.3 lakhs tonnes for the year 2010. The model has also projected the Indian ilmenite consumption for 2010 to be 1.62 lakh tonnes. A multiple linear regression has also been estimated by having Indian ilmenite production as the dependent and export price and Indian ilmenite consumption as independent variables. This model has explained 81 per cent of the variations in the dependent variable. In another multiple linear regression model, the lagged price is found to have a significant influence upon Indian consumption.

Ganapathi (2002) has presented the manufacturing process of Titanium Dioxide, its outstanding properties and application. The basic raw material used for the manufacture of titanium dioxide is ilmenite. The cost of ilmenite is about `3/- per kg while that of titanium dioxide is of much higher value. In recent years, the cost of manufacturing of titanium dioxide has gone up due to increase in the cost of key raw materials, fuel and power. 2.5 tonnes of ilmenite is required to produce one tonne of TiO₂. The worldwide demand for TiO₂ arises from paints (62.3%), plastics (15.2%), paper (12.1%), fibers (2.7%) and others (7.7%). In
India, the estimated demand for rutile grade, is 50,000 tonnes to 55,000 tonnes and anatase grade TiO₂ is worked out to around 24,000 tonnes per annum against the actual production of 21,000 and 21,017 tonnes respectively. Finally he has concluded that the demand for titanium dioxide in India has been increased by about 26 per cent in every five years. However, the paint industry is growing at the rate of 10 per cent and plastic industry is growing at 15 per cent per annum, which are the major consumers of TiO₂. Therefore, the demand for TiO₂ in the future may grow even further.

Manickam et al., (2005) suggested that ilmenite, a major source mineral for titanium, is abundantly available in Indian beaches. After the liberalisation of the coastal mining in India, it provides great opportunities for the transformation of the coastal economy. The world production is showing a falling trend and its international price seems to be increasing at as low rate. As the world production takes a downtrend and as the price of ilmenite in the global market is found to be relatively inelastic, it is suggested that the Indian producers implement a cautious mining plan.

2.3 Studies Related to Rutile Minerals

Mallik (1974) in his review of the world placer mineral resources, has pointed out that placer deposits occur in different parts of the world. Diamonds are found on the Southwest African beaches and in the offshore areas upto a depth of 34 m. Tin resources off West Thailand have been formed as drowned deposits.
Gold has been mined from the beaches near Nome, Alaska and iron ore have been identified from the offshore beach sands in the Ariake Bay. Ceylon beach sand is estimated to contain 75-80 per cent ilmenite, 6-10 per cent rutile, 6-7 per cent zircon, and 2-3 per cent magnetite. The Tugum beach, Queensland contains an average of 42 per cent zircon, 32 per cent rutile and 25 per cent ilmenite. Indian monazite occurs (Tipper, 1914) in five important stretches in the western coasts of India–Cape Comerin to Lipuram, Muttam to Pudur, Kollam, Anjengo-Warkali, and Neendakara. The beach deposits and the neighbouring dunes between Neendakara and Kayankulam are estimated to contain about 20 lakhs tonnes of mineral bearing sands.

Aplan (1985) has indicated that rutile is being mined from placer deposits largely from the beach sands on the east coast of Australia, Norway, USSR and Canada. They are also the leading producers of ilmenite. Minor amounts of ilmenite are produced from Finland, Malaysia, India, Sri Lanka and Sierra Leone. In the USA, Quebec Iron and Titanium Corporation has been mining ilmenite deposits at Allard Lake and the company is producing 70 per cent TiO2 titaniferous slag through smelting process. Several companies are mining along the eastern coast from New Jersey to Florida.

Nagamallaswara Rao (1998) has identified a high potential of economic minerals like garnet, ilmenite, zircon, rutile and monazite in Visakhapatnam-Bhimunipatnam Sector (VB). In this region the content of heavy minerals in the
beach and dune deposits are 90 per cent and 35 per cent respectively. In Itamsaladi-Manginipudi (HM) region, the placer minerals are abundant with magnetite (45%), ilmenite (28%), avgite (19%) and other minor minerals. In Vashishta Godavari-Upputeru (VGU) region ilmenite and magnetite are in equal proportions (34%-35%) and others are to be less than 10 per cent.

Anil Kumar et al. (1998) have pointed out that India is endowed with vast resources of beach placers consisting of 278 million tonnes (million tonnes) of ilmenite, 13 million tonnes of rutile, seven million tonnes of monazite, 18 million tonnes of zircon, 86 million tonnes of garnet and 84 million tonnes of sillimanite. India’s ilmenite resources constitute about 15 per cent of the world’s resources, and garnet 50 per cent. According to them, placer deposits occur at various places along the east and west coasts of India. Important deposits are reported at Ratnagiri in Maharashtra, Quilon in Kerala, Manavalakurichi and Ovari in Tamil Nadu, Kakinada and Bhimilipatnam in Andhra Pradesh and Chhattapur in Orissa.

Indian Bureau of Mines (2000, 2001) has estimated the world production of garnet to be at the order of 160,000 tonne during 1996-97. The other producers of garnet during 1997 were the USA (73,000 tonne), Australia (40,000 tonne) and China and India (15,000 tonnes each). The production of garnet in India has increased from 27,246 tonnes in the year 1990-91 to 274,000 tonnes during 2001 with a rise of about 1005 per cent. During the year 2000-01, 22 mines were reported with an average daily employment of 1,179 and it shows an increased of
42 per cent as compared to that of 1999-2000. Victor Rajamanickam (2001) noted that zircon has been produced largely by Australia, followed by South Africa and USA. Production of zircon is not much high in India as compared to ilmenite (378,000 tonnes in 1999) and rutile (16,000 tonnes in 1999). Major portions of these minerals are being exported to many world countries.

2.4 Studies Related to Titanium Minerals

Gambogi (2000) has reported that India’s ilmenite contributed only six per cent of the USA’s import demand next to South Africa (53 per cent), and Australia (29 per cent). In the USA, during 1999, two largest producers merged together and the newly emerged company supplied up to 32 per cent of the USA’s feedstock. In Australia, a major ilmenite producing company was closed due to acute operational difficulties. In 1999 - 00, the world market for heavy mineral sands was relatively upbeat. In Europe and USA in particular, despite continuing growth in their economies, demand for mineral sands products at the beginning of 1999-00 remained relatively static while Asian demand fell. Japanese pigment producers faced a slump in the construction, engineering and automobile production sectors, which reduced demand. However, by the end of 1999 and into 2000, demand for titanium dioxide pigments strengthened in the Asian region whilst in Europe and the USA the market remained tight www.heavymineralsands. 2001).
Acharya et al. (2001) have stated that the Regional Research Laboratory (RRL), Bhubaneswar has developed a process to separate iron from the ilmenite by plasma smelting of ilmenite. The plasma smelting has increased the titania content to 80-85 per cent in the slag. Another process developed to produce titania slag is the incipient fusion of 80-85 per cent metalised ilmenite. The slag thus, produced contains 80-85 per cent titania slag. The advantage of plasma smelting is that it helps to prepare blue peach and yellow colour zircon based pigments. These pigments are used in the production of coloured tiles.

In Placer Mining Industry, Kenmare Resources (2001) has been granted a mining right by the Mozambican government with an initial mining license over an area of 15,240 hectares. The government has also granted tax concessions in the form of no corporation tax, a minimum of 1 per cent turnover tax and three per cent royalty charges payable on the value of mining production. The Kenmare has completed a feasibility study on its Moma Titanium Mineral Project in Mozambique for the extraction of titanium dioxide at a planned production rate of 625,000 tonnes per annum for a period of 20 years. The after tax NPV, discount rate and IRR are estimated to be $ 200 million, 10 per cent and 23.3 per cent, respectively. The cash flow is calculated to be over $ 55 million per annum (www.kenmareindustries.com).

In Thoothukudi District of Tamil Nadu (2002), the titanium and zirconium sponge metal production was started in the year 2002 and it is being managed by
the Nuclear Fuel Complex, Hyderabad, with a production capacity of 1000 tonnes per annum of titanium and 300 tonnes per annum of zirconium (Indian Bureau of Mines, 2002).

Behera (2003) in his article concluded that, selective sand samples were collected from Gopalpur and Paradeep beaches and studied for their heavy mineral assemblage. Beachsands of both the areas contain heavy mineral ores like sillimanite, ilmenite, garnet, pyroxene, rutile, sphene, biotite, hornblende, zircon and monazite. At Gopalpur, the percentage of concentration of sillimanite is the highest followed by limonite, garnet, pyroxene, rutile, sphene, biotite, hornblende, zircon and monazite. At Paradeep, almost similar trend was observed with some exceptions, i.e., concentration of pyroxene and biotite is more here. The mineral sphene was absent at Paradeep, whereas tourmaline was negligible at Gopalpur. Higher grade percentage of heavies at Gopalpur is linked with many favourable factors and is being mined by IREL whereas low grade percentage at Paradeep discourages mining.

Surender (2004) has concluded that India’s status as the premier country processing the richer reserves of coastal placer minerals is not reflected in its ability to play a leading role in value added products. The globalization of economy and the opening of the placer mineral sector to public participation has provided a great opportunity to rectify this anomaly. There is a growing trend in titanium mineral possessing countries such as South Africa and Australia that innovative processes capable of being globally competitive and country wise
relevant is the need of the hour. It is an opportune time for India to adopt this strategy but with sustainable processes as the template which calls for radically new and out of the box approach. The significant scientific and engineering expertise available at RRL (T) has been reviewed with specific case histories and examples. It is recommended that a national programme adopting a mission mode be undertaken to realize the full potential of wealth creation through sustainable exploitation of the coastal placer minerals (Surender, 2004).

Titanium is a unique metal which belongs to the group of rare reactive or exotic metals consisting of tantalum, zirconium, niobium and tungsten. These are modern engineering materials of construction. Out of these metals titanium is more popular because of its comparatively lower price, availability in abundance and compatibility with systems and areas such as aerospace and aircraft, chemical and metallurgical, petroleum and petro chemical industries etc. (Jeyananth and Thangappan, 1995) etc. Titanium is the ninth most abundant element and constitutes about 0.86 percent of the earth’s crust. Primary titanium minerals are ilmenite, rutile, lecocoxena, etc (Dwivedy, 1995). In these minerals ilmenite supplies about 90 percent of the world’s demand for titanium mineral and it is the feedstock sources for producing TiO₂ pigment, titanium metal and welding rod coating (USGS, 2005).

Strnad et. al., (2005) in their study showed that the sodium titanate layer formation and subsequent apatite precipitation is affected by titanium processing prior to the alkali treatment. Sand blasted, abraded and machined titanium samples
were treated with NaOH solution and soaked in SBF. The precipitation of apatite was evaluated using thin film x-ray diffraction (TF-XRD). While the precipitation rates on the sand blasted and abraded surfaces were comparable the apatite formation on machined samples exhibited low reproducibility and the incidence of apatite spherulites was scarce. During the alkali treatment the protective oxide layer dissolves and dissolution of titanium in an active state occurs. In their study the time dependence of the corrosion potential of titanium during the treatment in NaOH was measured. They found that a heat treatment of titanium at 300°C for 15 minutes can prevent the oxide layer from dissolving and thus inhibit the sodium titanate layer formation. It is known that even higher temperatures can be reached locally during the machining especially when sufficient cooling is not ensured.

The surface profiles of sand blasted, abraded and machined samples were also measured and parameters characterizing the surface roughness were evaluated. The average roughness parameter Ra and the mean spacing of adjacent local peaks S showed that abrasion and sand-blasting produce micro rough surfaces whereas machined surface having higher values of both Rₐ and S consists of larger peaks and valleys. This difference can significantly affect the reactivity of the surface and subsequently the sodium titanate layer formation and the apatite precipitation.
2.5 Studies Related to Economics of Titanium Mining

Sadoon Morad et al., (1982) in their study concluded that the authigenic titanium minerals-rutile, anatase, brookite, and sphene-are recorded in two sequences of sedimentary rocks of proterozoic age, the Visingsoe Group and the Dala Sandstone Formation. Due to diagenesis of the Visingsoe Group and diagenesis to low-grade metamorphism of the Dala Sandstone Formation, the unstable titanium-bearing minerals, mostly biotite and ilmenite, released their titanium. This titanium was involved in the formation of different titanium minerals either on the altered detrital particles, mostly biotite and ilmenite, or in pore spaces. These titanium minerals are often found to attack silicate minerals such as quartz and feldspars. Due to higher temperature and pressure, euhedral sphene and rutile are more common in the Dala Sandstone Formation.

Sureshkumar et al., (1991) have pointed out that the TiO₂ pigment supply was deficient when compared to its demand in India. Its production was 23,000 tonnes in 1980-90 and the demand was nearly double the amount of production. The demand was expected to increase up to 72,000 tonnes in 1994 and upto 115,000 tonnes in 2000.

Elangovan et al. (1998) have discussed the economic viability of garnet along the coast between Kanyakumari and Mandapam in Tamil Nadu. This study applied the capital budgeting techniques such as, Net Present Value (NPV), Internal Rate of Return (IRR), and simple payback period and sensitivity analysis.
This study concludes that garnet mining is economically feasible. The authors have estimated that the capital cost of a garnet mining plant with a capacity of 100 tonnes throughput per day is `2.5 crores for the base case. The operating cost has been worked out to the extent of 20 per cent of the capital cost. The annual revenue and net cash flow are estimated at `1.732 crores and `1.232 crores, respectively. The pay back period and life of the projects are worked out to 2.5 years and 20 years, respectively. The sensitivity analysis showed that a 10 per cent change in capital cost and operating costs does not affect the profitability of garnet mining industry in the study area.

Mukherjee (1998), in his study about the excellent corrosion resistance and resistance to oxidation, good cryogenic performance and many other special properties of titanium and its alloys, treats titanium a highly sought after commodity. The use of titanium in the manufacture of white pigment is only too well known. Economically exploitable titanium minerals are ilmenite and rutile, which occur in the beach sand deposits in fully liberated, and easily recoverable form. The beach sand deposits are repositories of several other minerals of atomic and industrial importance also, like monazite, zircon, sillimanite, garnet and quartz. India, with its vast coast line on both the western and eastern sides of the southern peninsula, is one of the leading countries in mineral production from beach sand deposits and in export of the leading countries in mineral production from beach sand deposits and in the export to the mineral concentrates and value
added products, thus earning valuable foreign exchange for the country. Value addition of the more abundant mineral, ilmenite is being carried out by other public sector companies and private companies which produce the chemically beneficiated ilmenite, known popularly as synthetic rutile. Titanium dioxide pigment is another attractive value added product being produced on a small scale by Defence Metallurgical Research Laboratory and Mishra Dhatu Nigam Limited. The main points since demand for this metal in the pure and alloy forms and also for other value added products like TiO₂ pigment is sure to go up in demand which cannot be met by IRE alone. And hence collaboration with Indian and foreign companies will have to be seriously considered. They concluded that the ilmenite is the most abundant titanium mineral, when ilmenite is partially oxidized with the consequent natural leaching out of iron, the proportion of FeO in it decreases and TiO₂ increases. This altered ilmenite, known as leucoxene, therefore, contains variable and higher amount of TiO₂ rutile. The titanium and its alloys have special properties and hence find extensive use in modern science and technology. India is reasonably well endowed with the ore mineral of this valuable metal. IRE and a few other concerns in India have been extending a valuable service by exploiting the resources of this metal. A number of value added minerals is expected to grow in the near future, and India is having the capability to rise up to the indigenous and world demands.

Manickam et al. (2001) has carried out a geological exploratory study and economic feasibility study of garnet mineral, currently in great demand for export,
along the coast between Chennai and Pondicherry. The heavy mineral deposits with higher garnet content are found around Mahabalipuram and Madras. In this zone, about 23.2 per cent of non-magnetic heavies are found, in which, one third is garnet. They have worked out the economic feasibility of garnet mining by making use of capital budgeting techniques such as, Net Present Value (NPV), Internal Rate of Return (IRR) and simple pay-back period in December 1999 prices. Sensitivity analysis is employed with a view to accommodate the risks associated with different factors of the beach placer mining viz., capital cost, operating cost and annual revenue of garnet mining. The capital cost of a plant with a capacity of 100 tonnes throughput per day is given as `140.30 lakhs, the annual operating cost is `70.01 lakhs, with annual revenue of `104.3 lakhs. The life of the project, internal rate of return and payback period for the base case are computed to be of 25 years, 18.6 per cent and 4.1 years, respectively. The study has concluded that the exploitation of garnet in the coastal area between Chennai and Pondicherry is profitable.

AME (2001) has worked out the mine costs in the production of ilmenite. The cash production costs averaged $29.9 / tonne for the world’s heavy mineral sand miners. The lowest cost producer of ilmenite from heavy minerals sands was Richards Bay Minerals at $16.6 / tonne, well below the average operating cost for the Australian ilmenite producers ($36.8 / tonne). The average cost of production for rutile for the world stood at US $218 / tonne. Richards Bay Minerals was the
producer of rutile with the world’s lowest cost of $141 /tonne well ahead of the Australian average of $240 / tonne. The average cost of natural rutile cost stood at $217 / tonne. In the production of TiO₂ pigments, chloride process remained cheaper than sulphate process. During 1996, the weighted average operating cost for the sulphate plants was $1,424 / tonne compared with $1,165 / tonne for chloride plants.

Gambogi (2003) in his survey, found that the US Geological Survey (USGS) through its Minerals Information Team is the primary source of information on the domestic supply and demand for Ti metal as well as all of the other nonfuel minerals that are of such critical importance to the US economy. In its quarterly Mineral Industry Surveys and Annual Minerals Yearbook, the USGS publishes production, consumption, exports, imports, and stocks of Ti sponge, ingot, mill products, and castings. Decreased demand for Ti from the commercial aircraft industry caused domestic production and consumption of Ti metal products to decrease significantly in 2002 compared with those of 2001. In 2002, consumption of Ti sponge and scrap melted to produce Ti ingot, decreased by 34% and 32%, respectively compared with those of 2001.

Krishnamurthi Rao (2007) Chairman of Titanium Equipment and Anode Manufacturing Company Limited, said that titanium metal is a non-corrosive metal having the “great advantage” of strength-to-weight ratio and high temperature heat resistance. It is the preferred structural material in aircraft, jet
engines, missiles and satellites. DCW Limited manufactures upgraded ilmenite or synthetic rutile, which has 95 per cent of titanium dioxide content. It is only a raw material used in the manufacture of the dioxide. DCW (Dhrangadhara Chemical Works Limited) produces around 42,000 tonnes of upgraded synthetic rutile. Informing that titanium dioxide is manufactured by the chlorination of the ilmenite, Rao said that Kerala Minerals and Metals manufactures the dioxide through the rutile process, wherein ilmenite ore is upgraded to make synthetic rutile, which is further upgraded to titanium tetrachloride. This is used in making titanium dioxide of rutile grade. Kerala Minerals and Metals produces around 36,000 tonnes of titanium dioxide. There are, however, environmental issues, especially relating to effluents.

The Indian Rare Minerals Research Centre and Tamil Nadu Minerals Research Centre have estimated that huge deposits of rare minerals are there in Sathankulam region of Thoothukudi District. Titanium Dioxide Project is proposed to be started by TATA consultancy with an estimated cost of `2,500 crores. In this dry region this project is anticipated to provide direct employment to 800 persons and indirect employment to 2,500 persons. The TATA consultancy wants to acquire 20,000 acres of land for this purpose. The land of this region remained unused and uncultivated for about 20 years due to scarcity of rainwater. But during the last two years there is abundant rainfall in this region and so farmers are hesitant to part with their lands. TATA consultancy is not ready to
pay higher price for land. Danina project of Denmark has planted 1000s of plants in this region to conserve water. If this titanium dioxide project is started here, land will be dug for 30 to 35 feet to separate the rare minerals. This will definitely cause environmental problem. As farmers demand higher price for their land there is a fear that this project may be shifted to Kerala or Orissa (Thina Malar, 8 April 2008).

Titanium dioxide (TiO₂) pigments are white inorganic pigments used primarily in the production of paints, printing inks, paper and plastic products. TiO₂ is also used in many white or coloured products including food, cosmetics, UV skin protection products, ceramics, fibres, rubber products and more.

TiO₂ pigments are inert, do not react with other materials and are thermally stable, non-flammable and non toxic. Titanium dioxide has a remarkably high refractive index and an exceedingly high reflectance. It offers maximum opacity or hiding power as well as imparting whiteness and brightness to the products in which it is used. It helps paint to cover or mask other materials. It is what makes plastic packages pure white and opaque. It prevents show-through on printed paper materials, making it easy to read brochures and literature. It also affords protection from UV degradation.

TiO₂ pigments are made from one of two chemical processes - the chloride process which produces TiO₂ products by reacting titanium ores with chlorine gas; and the sulphate process which produces TiO₂ products by reacting titanium ores
with sulphuric acid. 70 per cent of European production (1.5 million tonnes per annum) is from the sulphate route and 30 per cent from chloride.

Chloride and sulphate pigments are both used in a wide range of applications. There are some preferred end uses for pigments from each process. In Europe, all TDMA TiO₂ companies are signatories to ‘Responsible Care’. Many have achieved, or will soon achieve, ISO 14001 or EMAS, demonstrating their commitment to continuous environmental improvement.

The manufacture of TiO₂ by the chloride and sulphate processes is already covered by its own specific EU directive which stipulates stringent limits for liquid and gaseous emissions. Treatment processes to comply with the EU directive have been implemented in the last decade and use the best available techniques. Over the past 20 years, the European TiO₂ industry has invested about € 1.4 billion in environmental improvement (Paul Anselme, 2008).

Dhana Raju (2008) concluded that sector-wise mining of heavy-mineral sand bodies after taking the local population into confidence, should be large scale and by mobile-floating plants, with hydraulic or bucket-line dredging for the dislodgement and lifting up of heavy mineral sand in leased areas, followed by quick back-filling of the site with the left out, dominantly light mineral sand, so as to minimize the environmental impact of mining. Processing of heavy-mineral sand should aim not only at the separation of individual heavy minerals for export, as is presently the case with the processing plants of Indian Rare Earths Limited and Kerala Minerals and Metals Ltd but more of value-addition (to the maximum
extent possible) from each of the heavy minerals, like manufacturing of Ti-sponge from ilmenite.

2.6 Overview

What seems to emerge from the discussion of above stated literature is that India is endowed with high grade ilmenite, rutile and titanium minerals. The studies on the economics of titanium minerals also point out the viability of titanium mining activity and also indicate the increasing trend in the market for the minerals. The review of the previous studies brings to light many concepts and factors related to and required in the estimation of economic return analysis. The most important factor that has enlightened the researcher is that of the data needed for the estimation of the capital and operating costs and annual revenue of the limonite, rutile and titanium mining venture. However, the studies indicate that geological exploratory analysis are given importance and the other aspect of the research which is equally important, that is, the economics of titanium has not been adequately undertaken. This research tries to focus on this aspect and in the next chapter concepts and methods necessary for this analysis are discussed.