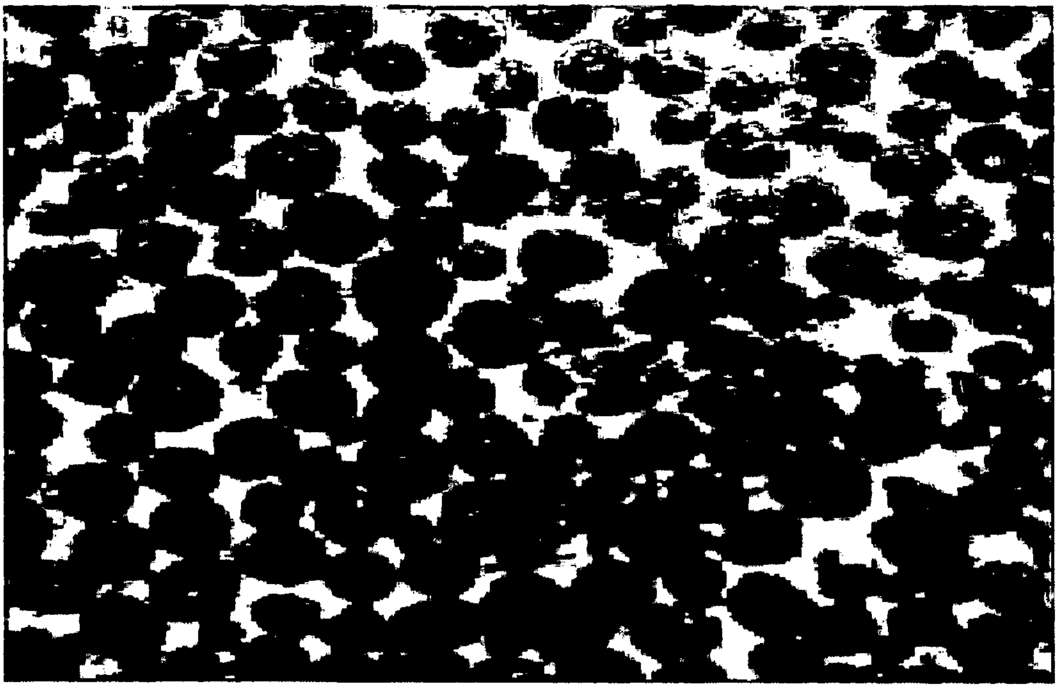
A COMPREHENSIVE STUDY AND ANALYSIS OF POLYMETALLIC NODULE DEPOSITS IN INDIAN OCEAN WITH AN EMPHASIS ON ECONOMIC, ENVIRONMENTAL AND MINING ASPECTS



Ph. D. THESIS

By

SYAMAL KANTI DAS

August – 2006

A COMPREHENSIVE STUDY AND ANALYSIS OF POLYMETALLIC NODULE DEPOSITS IN INDIAN OCEAN WITH AN EMPHASIS ON ECONOMIC, ENVIRONMENTAL AND MINING ASPECTS

THESIS

SUBMITTED TO THE GOA UNIVERSITY
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
MARINE SCIENCE

By
SYAMAL KANTI DAS

UNDER THE GUIDANCE OF

Dr. G. N. NAYAK and **Dr. M. SUDHAKAR**

Professor of Marine Science,
Department of Marine Sciences,
Goa University,
Taleigao Plateau,
Goa 403 206 - India

Scientist 'F',
National Centre for Antarctic & Ocean Research (NCAOR),
Ministry of Earth Sciences (MoES),
Headland Sada, Vasco da Gama,
Goa 403 804 – India

August - 2006

TO

MY WIFE JAYANTI

STATEMENT

As required under the University ordinance O. 19.8(vi), I state that the present thesis entitled ***"A COMPREHENSIVE STUDY AND ANALYSIS OF POLYMETALLIC NODULE DEPOSITS IN INDIAN OCEAN WITH AN EMPHASIS ON ECONOMIC, ENVIRONMENTAL AND MINING ASPECTS"*** is my original contribution and the same has not been submitted on any previous occasion. For the best of my knowledge, the present study is the first comprehensive work of its kind from the central Indian Ocean Basin.

The literature related to the problems analyzed and investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

Place: Goa, India

Date: 20-11-2006.

Das.

Syamal Kanti Das

<u>***CERTIFICATE***</u>

This is to certify that the thesis entitled ***"A COMPREHENSIVE STUDY AND ANALYSIS OF POLYMETALLIC NODULE DEPOSITS IN INDIAN OCEAN WITH AN EMPHASIS ON ECONOMIC, ENVIRONMENTAL AND MINING ASPECTS"*** submitted by Mr. Syamal Kanti Das for the award of the Degree of Doctor of Philosophy in Marine Science is based on his original studies carried out by him under our supervision. The thesis or any part thereof has not been previously submitted for any other degree or diploma in any University or institutions.

Place: Goa, India
Date: 20-11-2006

Dr. G. N. Nayak
(Research Guide)
Professor of Marine Sciences
Head, Dept. of Marine Sciences
Goa University.
Goa 403 206
India.

Dr. M. Sudhakar
(Research Co-Guide)
Scientist "F"
National Centre for Antarctic and
Ocean Research.
Headland Sada
Goa 403804
India.

All the corrections suggested by the Examiner have been incorporated in this thesis.

20/11/06

CONTENTS

ACKNOWLEDGEMENTS

This work has been accomplished under the joint guidance of Dr. G. N. Nayak Professor and Head, Department of Marine Sciences, Goa University, Goa and Dr. M. Sudhakar, Scientist, National Centre for Antarctic and Ocean Research (NCAOR), Goa. I offer deep sense of gratitude to my research guide and Co-guide for their invaluable guidance and constant encouragement and support, at every stage right from the starting of this research work.

My sincere thanks to Dr. R. Nigam, Scientist 'F', National Institute of Oceanography, Goa and Vice Chancellor's nominee in the Faculty Research Committee (FRC), for his constant support and encouragement.

My sincere thanks to the then Director and acting Director, National Centre for Antarctic and Ocean Research, Goa for giving me the institutional support to work on this topics.

My sincere thanks to PadmaShri, Dr. Harsh. K. Gupta former Secretary, Department of Ocean Development (DOD) and PadmaShri, Dr. P. S. Goel, present Secretary, Ministry of Ocean Development (MoOD) for granting me the permission and their encouragement. I specially place on record my gratitude to PadmaVibhushan, Dr.S.Z.Qasim, former Member, Planning Commission and Secretary, DOD for encouraging me to pursue my Ph.D. work. I am grateful to

Prof. P. K. Banerjee Sr. DDG (Rtd) from GSI and former Professor of School of Oceanography, Jadavpur University, Kolkatta. I record my sincere appreciation for all round help rendered by my friends and colleagues from Ministry Ocean Development at various stages of work. My sincere thanks to all staff members of MoOD working with me specifically, Ms. Jaya Laxmi, Mr. Santosh Kumar who rendered assistance in the typing, photocopy, etc.

I am thankful to Mr. N. K. Mittal manager M/S EIL, R&D Centre who has helped me in this work as and when required. I am also very much thankful to Mr. V. Sankar and Dr. Ravi Mishra of NCAOR for helping me to prepare graphs, sketches etc.

It is my immense pleasure to sincerely acknowledge my late parents blessings, in-laws for their support for carrying out this work. It is my immense pleasure and thanks to all my near and dear once again.

This work remains incomplete if I ever miss to acknowledge my loving wife Jayanti, who deserves all the appreciation for her love, continuous support and encouragement to complete this work.

Syamal Kanti Das.

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PREFACE

Manganese nodules also popularly known as polymetallic nodules and are the major mineral deposits on the seabed beyond continental shelf and slope. These deposits have attracted the attention of the world community way back in 1965 and a regulatory body has been established through negotiation in the United Nations Law of the Sea Conference (UNCLOS III). The International Seabed Authority (ISBA) at Jamaica has been the body that controls the licensing for exploitation of these deposits in seas beyond Exclusive Economic Zone. Since 1981 India initiated systematic surveys for mapping and exploration of polymetallic nodules in Indian Ocean for resource potential. The efforts of the country culminated in India getting an area of 150, 000 sq. km. beyond EEZ in Indian Ocean by UNCLOS along with other nations like USSR, France, and Japan. Subsequently Inter Ocean Metal (Consortia of Poland, USSR, Bulgaria, Czechoslovakia etc.), China, South Korea were recognized as the pioneer investors.

The polymetallic nodules in Indian Ocean have been extensively studied on various aspects and studies include mineralogy, morphology, chemistry and other related aspects such as the environment, topography of the region, sediment characteristics, sea bed conditions nodule potential and distribution. For nearly two and half decades the nodule deposits in Indian Ocean have attracted the attention of scientists from this country both for resource potential and basic science of formation of these deposits. However, there is no systematic documentation on the economic, environmental and feasibility of mining aspects and their viability in Indian Ocean that are future resources of the country for alternate exploitation to terrestrial deposits.

The Assembly of ISBA adopted regulation on exploration of polymetallic nodules to facilitate the exploitation activities in the area. In order to obtain production authorization, it is obligatory on the part of India to the ISBA to provide data sets on environmental aspects by conducting prototype mining experiments in the area. Currently India conducted experiment in the Pioneer Area and continuous monitoring is in progress, to understand the likely affects of mining on the environment prevailing in the area. The results are being documented as the work is in progress.

The results of the studies carried out on "A Comprehensive Study And Analysis Of Polymetallic Nodule Deposits In Indian Ocean With An Emphasis On Economic, Environmental And Mining Aspects" the basis of available data in the Indian ocean site, models were used for selection of promising site, demand perspectives have been brought out and cost model has been arrived at for the Indian Ocean Site. The thesis is presented in eight chapters.

Chapter 1: gives a general introduction, global scenario, metal resources of polymetallic nodules, nodule recovery in world Oceans, international efforts on deep sea mining, Indian activities etc. Also includes Objectives of the study, and reviews of previous work.

Chapter 2: Detailed reviews have been carried out on manganese nodule resources, and their global distribution. This chapter also provides analyses of the Indian interests vis-à-vis global interest followed by the Indian activities for polymetallic nodules.

Chapter 3: Presents systematic surveys at regular grid interval over the entire area in the Central Indian Basin at various grid intervals as the prospecting was in progress. Thus resulted in a large database of polymetallic nodules deposits in the Indian Ocean. These data formed a basis for a comprehensive geostatistical evaluation of the resources of manganese nodules and their spatial distribution in the area of study.

Chapter 4: gives the grade-tonnage relationship as a function of Cut-off grades has been evaluated. First, a general statistical approach of computing such curves for a three parameters log normal distribution model has been suggested and graphic solutions are presented. This is followed by computing the grade-tonnage curves based on two different dimensions. There are two relative objectives of the investigations for the nodule study area. First it is intended to demonstrate the dependence of the curve on the block size and second, to develop a practical decision tool to select areas having greater potential in terms of abundance and grade. The results of the study area are presented in terms of evaluation of impact of cut-off values on resultant values. These studies have been made with reference to station wise mean values as well as block wise estimated values. The two results produced, represent the limiting values of selection if it was based on nodule abundance and metal values only. Based on the above studies, the overall estimates and the estimates of resources for the study area are presented.

Chapter 5: Comprises the status of development of various mining technologies globally. A comprehensive review of past & present mining technology perceptions for exploitation of polymetallic nodules has been carried out. The comparison has been made considering the various technologies and their impact on environment and economic aspects. The strength and weakness of various systems have been analyzed in order to optimize a design and propose an environmentally safe commercial mining system. The requirement of various parameters for environmentally safe mining system has been drawn up. The modes of transportation of nodules from the mine site to the land based processing plant have also been dealt in this chapter. An environmentally friendly mining system has been proposed on the basis of analyses of various available technologies and forecasting the future seabed mining developments.

Chapter 6: In this chapter, a review has been carried out on global and Indian studies on environmental impact likely to be caused due to mining. In addition specific investigation have been carried out on granulometric analysis and heavy metals in water column based on prototype studies carried out and the data generated specific to Central Indian Basin.

Chapter 7: Presents the detailed review of demand supply position of four metals of interest from polymetallic nodules. They are Copper(Cu), Nickel(Ni), Cobalt(Co) and Manganese(Mn). The compounded growth rate in demand from 1950 to 2003 for various metals has been analyzed. While reviewing and analyzing the demand-supply growth both globally and in Indian context, an analysis has also been made for the trend in prices of these metals (Cu, Ni & Co) for the last century.

Finally considering the growth in demand supply and the trends in price variations, the expected level of demand-supply of Cu, Ni, Co & Mn for the year 2020 has been projected. Although, the metal prices are very volatile and governed by the market forces though the demand and supply plays an important role, an expected long-term metal prices increase has been projected on the basis of average price growth rate of these metals over the coming years.

Chapter 8: Presents the review of studies made by various state parties in this regime. A cost model has been prepared on the basis of promising exploitation technology, extractive metallurgy considering a promising process package already developed by India. Based on this a cost model has been prepared in respect of mining system, transportation, processing. The net present value at different discounted rates for base case of the model has been worked out. A number of critical parameters (Capital cost revenue, metal prices and grade of nodules) have been considered for analyzing the sensitivity of the project and impacts on profitability of the project. The cost model finally concluded that the polymetallic nodule mining would be economical by 2015 considering the present price trends of Cu, Ni, Co, & Mn with the proposed mining technology application in the selected first generation mining site.

Based on the above chapters suitable conclusions are drawn with an emphasis on economic, environmental and mining aspects related to polymetallic nodule deposits in Indian Ocean.

CHAPTER - 1

INTRODUCTION

Manganese nodules available in the World Oceans have attracted the attention of the world community in the mid sixties. A regulatory body has been established through negotiation in the United Nations Law of the Sea Conference (UNCLOS III). The International Seabed Authority (ISBA) at Jamica has started functioning from 1994 to oversee various issues related to various mineral deposits available in the international water. The regulation on exploitation of polymetallic nodules in the area has been adopted by Assembly of ISBA in 1998 followed by adoption of environmental guidelines on the basis of available information. Environmental guidelines can be reviewed from time to time. Nodules in the Indian Ocean area vary from centimeter to 10 cm in diameter and potato like shape.

Nodules contain important strategic metals like copper (Cu), Nickel (Ni) and Cobalt (Co). India is the first pioneer investor in the Indian Ocean and the only player in Indian Ocean so far in this regime. The area 150, 000 sq. km allotted to India by pre-com under UNCLOS in 1987. After fulfilling the obligation as a pioneer investor i.e., relinquishment of 50 % of the allotted area in March 2002, India retained 75,000 sq. km. for various research and development work. This thesis is to prepare a cost model for a first generation ocean mining project located in the retained area in the Central Indian Ocean Basin.

1.1 Global scenario

It is generally believed that commercial seabed mining will not take place before the middle of this century because of varied reasons. These broadly include the legal negotiations for an internationally acceptable universal regime for the exploitation of deep seabed resources, the state of the world economy and the demand perspective of the metal markets. Nevertheless, the state of art of the deep seabed mining technology and the extractive metallurgy too, play an important role in deciding the future commercial exploitation of these resources. The third United Nations Conference on the Law of the Sea, while adopting the United Nations Convention on the Law of the Sea, established the Preparatory Commission (Prep COM) for the International Seabed Authority (ISBA) and for the International Tribunal for the Law of the Sea (ITLOS) in April, 1982.

For state parties registered as pioneer investor and allotted site for various developmental activities under UNCLOS. India is one of the first registered pioneer investor. Subsequently Three parties (China, Inter Ocean Metal and Korea) also become pioneer investors. All sites except Indian Ocean site were allocated in Clarion Cliperton Fone (CCFZ) in Pacific Ocean. International Seabed Authority (ISBA) started its function at Jamaica as head quarters from 1994. ISBA is monitoring activities of all pioneer investors. The regulation on exploration of Polymetallic Nodules in the area has come into effect from 13th July 1998. Seven pioneer investors signed 15 years contract with ISBA for carrying out various developmental activities in the Area. Subsequently environmental guidelines for carrying out exploration activities at the area have also been adopted by the assembly of ISBA. Germany was likely to sign the contract soon.

1.2 Metal resources in polymetallic nodules

During the last quarter of the century it has been recognized that deep-sea nodules may be regarded as a major potential economic source of metals such as nickel, copper, cobalt, and manganese. These metals are vital for industries and are strategically important. Prosperity of mankind depends much on these resources.

The occurrence of nodules and encrustations on the deep seafloor have been first reported more than 100 years ago in the findings of the research cruise of the British Vessel – HMS Challenger (1872 - 76). The unique results obtained on this deep-sea expedition led to the thinking that marine nodules are an important source of metals. Since then nodules have been extensively sampled and photographed by a number of oceanographic expeditions. The composition and origin of nodules were largely studied as a scientific curiosity till early 1960's when their economic potential was recognized and since then detailed exploration and studies on exploitation have been carried out.

Mero [1965] has been the first to collate and publish data on nodules and to study the economic feasibility of manganese nodule exploitation. He noted that ferromanganese deposits may be a potentially valuable source of important industrial metals. Subsequently, a coherent hypothesis of nodules as a resource began to appear. Both Industrialized and developing countries have become increasingly aware of the economic importance of these recoverable resources. There is now, little doubt that the nodules form an important source for Ni, Cu and Co and possibly other elements (Mn, Fe, Zn, Mo, Pb, V, Au, Pt, Ti, Zr, Ag, P and Cd). The increasing demand for minerals and technology advances has now made ferro-manganese nodules a prime target of a massive international effort for deep seabed mining. The formation of OPEC in the early seventies and the apprehension of the developed countries about the interruption of supplies of raw materials from the developing countries provided an added impetus to these efforts. Since then, the feasibility of exploration and exploitation of the manganese nodule deposits has been demonstrated. The possible mining of these deposits has caused a profound concern of the nations, especially in the developing nations, because of the envisaged impact of these materials on the world market and economy. Therefore, during the deliberations of the UN Law of the Sea Convention, the deep seabed beyond the national jurisdiction has been declared "Common Heritage of Mankind" [Pardo, 1967]. First time that such a proposal is put forward to the General Assembly at the United Nations. Pardo's initiative is both timely and well conceived [Zuleta, 1982]. Barkenbus [1979] regards the role of pardo as that of a "legal catalyst".

Since 1965, extensive exploration activities have been carried out by a number of companies, universities and governmental institutions from countries such as the United States of America, the Federal Republic of Germany, the United Kingdom, France, Japan, Australia, New Zealand, the then USSR, India and China. The result is an abundance of published papers and articles on manganese nodules [e.g. Glasby and Hubred, 1976]. In early 70's, major commercial companies of the Western Countries, Japan and the United States of America formed into various Multinational Consortia and began prospecting for the nodules mostly in the Pacific Ocean. Simultaneously the technology for the extractive metallurgy of nodule ores and the designing of mining system was initiated.

Manganese nodules generally occur between 3500 m and 6000 m water depth in all ocean basins. In order to determine the quality and coverage density of nodule fields and also with an aim to demarcate areas favorable for deep-seabed mining, research vessels investigated the deep-seabed in the pacific and the Indian Oceans, especially the area of high seas beyond national jurisdiction. The results of these numerous efforts established that the large areas of the seabed measuring thousands of square kilometers have nodule coverage up to and occasionally even exceeding 10 Kg/sq. m., equivalent to 10, 000 metric tons/sq. m., the vast resources perceived are mostly confined to the Pacific and the Indian Oceans. The Atlantic Ocean does not appear to be a promising area for ore grade nodule fields [Moore and Cruickshank, 1973].

1.3 Nodule resources in world oceans

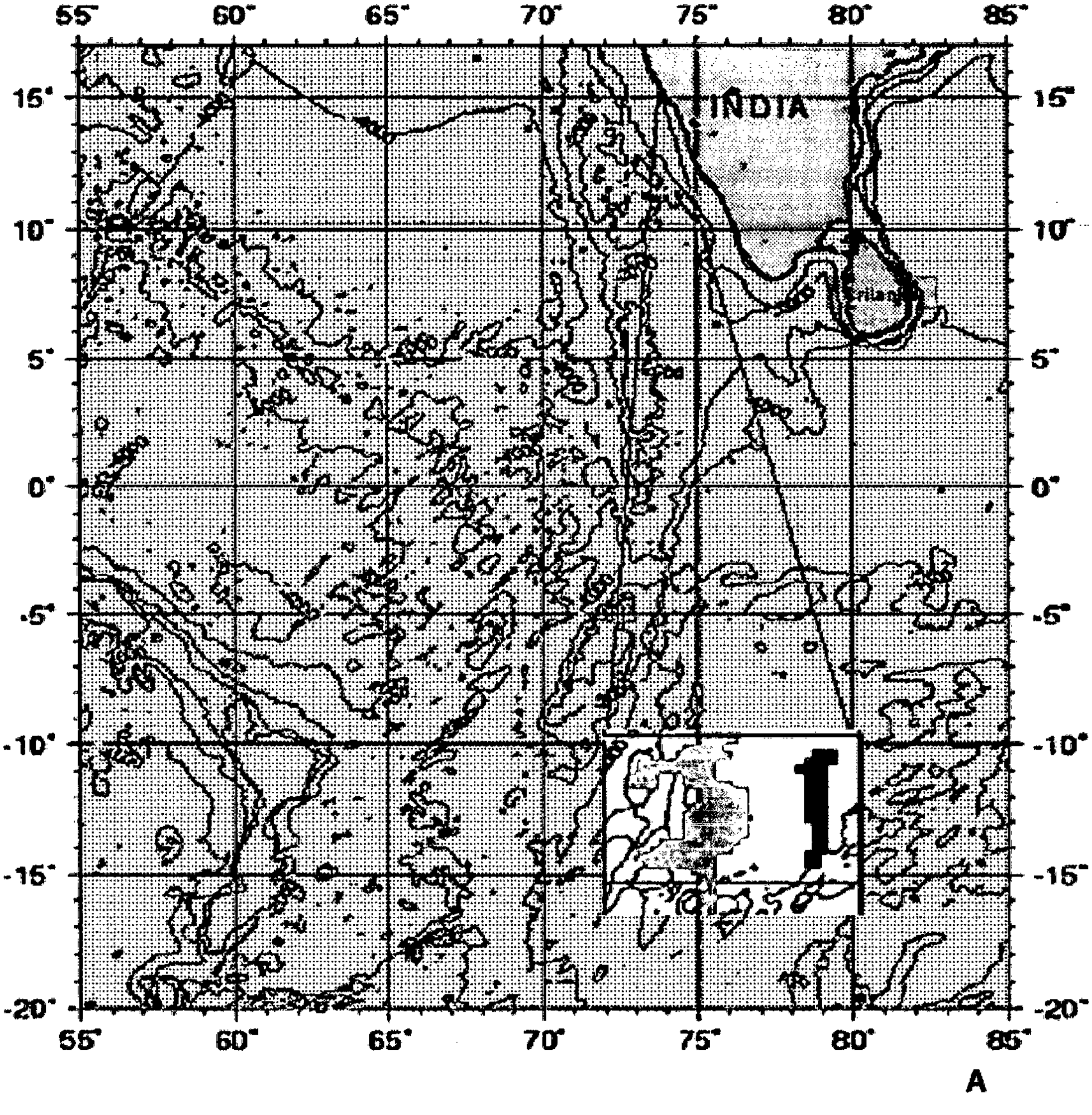
Nodules cover an area of approximately 46×10^6 sq. km., in the world oceans [Moore and Cruickshank, 1973]. Later, the revised estimates suggested that nodules are present in a total area of about 54×10^6 sq. km., [Archer, 1985]. The estimated area covered in the Pacific Ocean is about 23×10^6 sq. km., in the Atlantic Ocean 8×10^6 sq. km., and for the Indian Ocean between 10 and 15×10^6 sq. km. The estimated total resources of manganese nodules in the world oceans range from 1.7 to 3×10^{12} tonnes of nodules, The Indian Ocean 0.15 x

10^{12} tonnes and Atlantic Ocean 0.005 x 10^{12} tonnes of nodules. Pasho [1979] quantified the existing prime areas suitable for first generation mining of manganese nodules. He estimated 5.20 x 10^6 sq. km., in the Pacific Ocean, 0.50 x 10^6 sq. km., in the Indian Ocean and 0.85 x 10^6 sq. km., in the Atlantic Ocean and explored areas. Archer [1979] defined Prime Areas as areas at least part of which there are deposits of relatively abundant nodules with significantly higher grades than elsewhere. Prime Areas are often referred to yield more than one first generation mine-site. The boundaries of these areas are demarcated after detailed exploration and evaluation of data. To qualify as first generation mine-site, a nodule deposit should provide an average combined Ni and Cu content of 2.25% (at 1.81% cut - off) and an average abundance of 10 Kg/sq. m., (at 5 Kg/m^2 Cut - off). The nodule field needs to have a capacity to sustain a production level of 1.5 x 10^6 tons of dry nodules per year and the mining need to last for at least 20 to 25 years. The site may encompass an area of at least 10, 000 sq. km with a more or less uniform or even topography. The area may yield about 60 x 10^6 tons of such nodules to describe as first generation mine-site [Archer, 1979]. Prime areas account for only a small proportion of the seabed. The largest, about 3.5 x 10^6 sq. km., being between the Clarion and Clipperton fracture zones and another in the North Pacific covering about 0.8 x 10^6 sq.m., to the southwest of Hawaii [Archer, 1979].

Fraze and Wilson [1980] indicated that the paramarginal and sub-marginal grades of nodules cover an area of 0.7 x 10^6 sq. km., between 10°S to 16° S in the Central Indian Basin. Based on the grades, the deposits are classified and referred to as 'paramarginal, submarginal and low grade deposits'. Those nodule deposits provide a grade more than 2.47% are called 'paramarginal', and grades falling between 2.47% and 1.63% are called 'submarginal'. Below 1.63% grades, the deposits are referred as 'low grade'. As of March, 1980, the Scripps Sediment Data Bank contained chemical analyses of nodules from 2,401 stations. More than 400 stations are located in the Clarion-Clipperton zone in the northeastern equatorial Pacific Ocean area of about 2.5 million sq. km. in which nodules average 25.43 % manganese, 6.66 % iron, 1.27 % nickel, 1.02 % copper, and % 0.22 cobalt (Heye and Marching, 1977) reported almost identical averages for the several thousand samples collected from the Clarion-Clipperton zone by the Centre National pour l'Exploration des Oceans - namely 25.56 % manganese, 6.40 % iron, 1.25 % nickel, 1.05 % copper, and 0.24 % cobalt. As the comparison in table 1.1 shows, exclusion of Clarion-Clipperton zone values from the world averages decreases somewhat the average nickel, copper, and manganese contents, increases iron content, and has no effect on cobalt content. The world averages estimated by Cronan (1980, slightly revised from 1976, 1977) are even lower in manganese, nickel and copper and higher in iron and cobalt (Table 1.1). In the Indian Ocean only the nodules of the Central Indian Basin (hereafter referred to as 'CIB') meet the criteria for first generation mining [e.g. Fraze and Wilson, 1980; Cronan and Moorby, 1981; Sudhakar, 1989a]. However available data on the grade and abundance until the end of eighties has been inadequate for the identification of a Prime Area and for the estimation of resources. Later reports based on the India's continued exploration programme for nodules confirmed that the ore grade nodule resources are mainly concentrated between 10° S and 16° S in the Central Indian Basin [Sudhakar, 1989 a]. At 2% cut-off grade, nearly 1/3 of the explored area in the Central Indian Basin provides high grade regions [Sudhakar, 1989 a, b]. The data on abundance, grade and resources in two Application Areas (Fig. 1.1) in the CIB is shown in table 1.2. The Indian Ocean is often ranked second to the Pacific Ocean, both in terms of the area covered by nodules and their estimated resources. India's interest in polymetallic nodules and its nodule programme are detailed in the second chapter.

Table 1.1: Comparison of the world average metal content of manganese nodules listed with the values reported by Cronan (1980)
(The Clarion-Clipperton zone is taken to the area defined by 70 to 150 N, 1140 to 1530 W)

	World	World excluding clarion-clipperton zone	World values reported by cronan(in per cent)
Mn	18.60	17.45	16.8740
Fe	12.47	13.63	15.608
Ni	0.66	0.55	0.4888
Cu	0.45	0.34	0.2561
Ni+Cu	1.12	0.90	0.7449
Co	0.27	0.27	0.2987



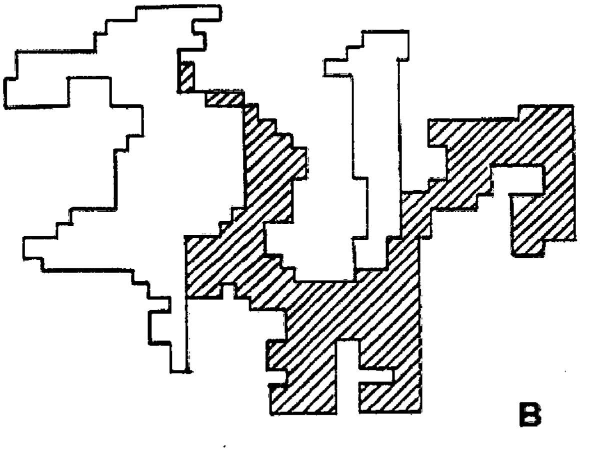


Fig. 1.1: A: Mine site area
B: Mine site allotted to India (Area not hatch marked In the Central Indian Ocean Basin)

Table 1. 2: Indian land reserves and marine reserves in the retained area

(Figures in million tones)

Metals	**Indian land resources**	**Reserves in Application areas**		**Reserved in retained area**
Manganese(Mn)	142.00 (approx)	247.00	478.00	92.59
Copper(Cu)	9.44	9.51	17.07	4.291
Nickel(Ni)	No proven reserve	10.47	20.81	4.702
Cobalt(Co)	No proven reserve	1.82	3.87	0.549

1.4 Earlier explorations

Starting from the British Oceanographic Expedition with HMS CHALLENGER, various scientific ocean explorations were undertaken and these explorations were able to provide valuable information on various aspects of marine minerals. The foremost of the significant explorations namely of that of HMS CHALLENGER was conducted by the British Oceanographic **Expedition** during 1872 - 76. It was during the expedition that deep-sea polymetallic nodules were recovered for the first time in 1873 at a location about 300 km south west of the island Ferro in the Canary group in the Pacific Ocean. A more extensive exploration was made by the ALBATROSS Expedition during 1899 -1900 and 1904 -1905, during which the extent of nodule distribution in the equatorial Pacific was mapped and an extensive collection of nodules was also made. Thereafter, the explorative activities were sporadic-the MURRAY expedition (1925 -1927), the CARNEGIE expedition (1928 -1929) being some of the important milestones in the deep sea exploration.

During 1947- 48, the Swedish Deep Sea Expedition collected sediment samples, the chemical investigations of which established the inter-relationship between manganese, nickel and cobalt. In 1965, Jonn Mero collected data on the regional variation of nodule composition throughout the pacific and this set the pace for compilation of literature on polymetallic nodules.

During 1971, RSS SHACKLETON conducted an extensive cruise of the Indian Ocean In planning this cruise, a specified location was selected where both polymetallic nodules and metalliferous sediments were known to exist in variable composition and abundance. The cruise route was designed to cover four major physiographic features in the north-west Indian Ocean - the Arabian Abyssal Plain, the Carlsberg Ridge, the Somali Basin and the Seychelles Plateau. It has been indicated that poly metallic nodules are most abundant in the basin area far *from* the land and *on* either side of Ninety East ridge. High nodule concentrations are said to *occur* locally *on* and at the foot of some submarine ridges and occasionally in the vicinity of major fault zones.

1.5 Demand of metals

The Consumptions/Demands of metals (Cu, Ni, Co and Mn) are basically depends on six forces which may change the topography of the market. They are increased globalization, sustainability, financial performance (profitability and capital productivity), customer expectations, changing work force requirements, and increased collaboration.

Copper is one of the most useful and versatile metals and is used in both pure form and in alloys such as brass, bronze and nickel – silver. The most important use for nickel is in the steel industry, mainly in the production of stainless steels and other alloys. Electro-plating, chemical and other industrial uses also represent important applications. Cobalt has a number of specialized uses in heat corrosion-resistant and tool-steels, in hard facing material for drilling equipment, in the manufacture of permanent magnets and in the chemical industry. It is especially useful in missiles and jet engines. Most of the world Manganese output is consumed by steel plants and foundries and a small percent is used by chemical and dry cell industries.

The percentage growth rate per year for copper was 2.15 % during 1980-2003, however the rate of growth during 1990-2003 was 2.85 %. Similarly Nickel consumption rate increased to 3.33 % during last decade. In case of cobalt the average growth per annum was 2.79 % and that of Manganese was approximately 3 %.

For many years the consumption of manganese has been correlated with steel production. Manganese production is mainly confined to six countries viz., South Africa, the then USSR, Brazil, Gabon, Australia and India; with 80 % of all land reserves being located in the then USSR and South Africa Technological innovations call for a smaller input of manganese in near future. However, now there is increase in demand in steel mostly due to very high demand in some of the Asian countries.

In the case of manganese recovery from nodules, Nickel and Manganese represent major part of the revenue. Nickel's annual compound growth rate of price increase is 12.47 % during 2000-04. The average compound price growth has been found from the historical data in respect of Cu, Ni, Co, and Mn is 2.49 %, 2.97 %, 3.56 %, and 2.56 %. (USGS., Mineral Commodity Summaries, January 2004.)The present concentration of land reserves are largely located in Canada, New Caledonia (France), Cuba, the then USSR, Indonesia, Philippines and Australia. It is forecasted that the nickel production from the seabed sources shall not affect the nickel price - may be less than or up to 10 percent [Schmidt, 1989].

The volume of nodule metals on the seabed has been a subject of much speculation. Archer [1985] concluded that manganese nodules probably cover about 15% of the ocean floor. He asserts that if, these estimates reflect the actual magnitude, then, the potentially recoverable economic resources of Ni, Cu, Co and Mn in nodules are neither enormously more nor less than economic resources on land. Economic resources of Ni, Cu, Co and Mn on land area are shown in following table 1.3. It is evident that seabed reserves are, in a general approximation and with the exception of Cu, are of the lesser magnitude as those on land. Even though the figures indicate that the earlier market situation of metals does not encourage investment in nodule mining and profitable exploitation, the apparent wealth of the nodule resources makes an obvious target for all the nations to show an active interest Nevertheless, the nodules of relatively dense coverage and 'high metal grade occurring in other parts of the Pacific and the Indian Oceans, makes them the biggest resources of Ni, Co and Mn ores on our globe.

Table 1.3: Comparative global reserves of metal from land and nodules.

	(Million tones)	
	Land	**Nodules**
Cu	940	175
Ni	140	215
Co	13	40
Mn	5000	5000

If we consider the present price of metal values in the Indian reserved area, the estimated value of metals is of the order of about 50 billion thousand rupees, which is very attractive from investment point of view. However the demands and prices of these metals are very volatile, technological, economical, and societal factors influence the supply-demand of metals.

1.6 International efforts on deep sea mining

The polymetallic nodules generally *occur* beyond the continental rise *or* outside the continental margin. Earlier explorations have indicated that these nodules *occur* at water depths ranging from 4000 m to 6000 m and the deposits are reported to be spread over a total ocean floor area of about 46 million square km. Mining of the nodules at such deep oceans require new technological approach and hence special mining systems have to be evolved. To achieve this, different agencies from different countries of the world have grouped them selves into various consortia thereby pooling financial and technological resources. These consortia have been engaged in various activities connected with intensive exploration and pilot mining studies *on* different systems for commercial exploitation These consortia are concentrating their activities in CLARION-CLIPPERTON-ZONE of Pacific Ocean considered to be one of the potential areas of commercial mining.

In the late seventies there were four North American organizations developing deep ocean mining systems – Deepsea Ventures, Kennnecott Coper, International Nickel, and Lockheed Ocean Systems, a division of Lockheed Missiles Space Corporation. All four have formed consortia with domestic and foreign companies. All have selected the same basic design of a mining system, i.e., a bottom miner on the ocean floor connected to a surface ship by a nearly vertical pipe. Both a hydraulic air lift system and a mechanical pump system are being examined by the consortia. In addition, one other group, Ocean Resources, Inc., a syndicate of over twenty mineral and energy companies, is developing the technology of continuous line bucket lift system.

The Deepsea Ventures group consists of U.S. Steel (Essex Minerals), Union Miniere (Union Seas), and Sun Ocean Ventures, Inc., with Deepsea Ventures as the project manager. This group has filed a mine site claim and has completed pilot test evaluations of the lift recovery and hydro-metallurgical processing systems.

The Kennecott Copper consortium consists of Kennecott Copper, Rio Tinto Zinc, Consolidated Goldfields, Noranda Mines, Mitsubishi, and Bp Minerals, with

Kennecott designed as the project manager. This group has completed pilot scale evaluations of the sea floor mining vehicles and the hydrometallurgical processing systems. Further unspecified research and development is scheduled.

The international Nickel group consists of INCO, Arbetisgemeinschaft Meerestechnisch-Gwinnbare Rohstoffe (AMR), Sedco, INC., Deep Ocean mining Company, and Ocean Management, Inc., as the management contractor. This group is continuing development of its processing technology and had reportedly scheduled late 1977 at-sea tests using the Sedco 445 drill ship and the R/V Valdivia exploration data.

The Ocean Minerals Company consists of Lockheed Ocean Systems, Amoco Minerals Company, Billiton International Metals, B.V. (a subsidiary of Royal Dutch Shell), and Bos Kalis Westminister Ocean Minerals, B. V., with Lockheed as project manager. The group has conducted on - land evaluation of some components of the mining system and laboratory evaluations of the hydrometallurgical processing system. The group planned to start at-sea tests in late 1977.

The technology surrounding the mining system, comprising the bottom miner, lift system, and surface system is probably known with least certainty. While some technology can be drawn from current offshore drilling operations, government research and development programs, and land mining systems, many of the technical uncertainties must remain until actual on-site experience is gained. The collector head's capability to separate bottom clay, the stability of the pipestring, the optimal depth of the lift pump, the maneuverability of the dredge head, and the impact of surface discharge on the environment of the ocean are all likely to remain question marks until the system is operating on station.

Many patents of various components of mining system have already been obtained. The mechanisms of various concepts, their development, their strength and weakness of the system have been examined. As per the UNIDO study in 1982, total 19 components out 388 components were considered for extensive research and development. These areas were for various components of collector, riser pipe.

The engineering concepts in respect of above systems were developed with varying degrees of complexities during last four decades covering above four concepts.

The efforts for developments of prototype mining system by some of the Pioneer Investors/Contractors are still going on. A Group of Experts from COMRA (Chinese Ocean Mining Research Administration) developed mining system based on all considerations of main principles of designing of deep sea mining system. COMRA has already designed and developed the system and planned to test up to 4000 m and then up to 6000 m.

IFREMER's latest endeavor was to use unmanned submersibles to mine nodules from seabed but could not be used to mine nodules economically. They reoriented the programme but further development not reported.

Japan also planned a comprehensive mining test in 1995. Due to change in the sociological, the perspectives of technologies in the future, cost effectiveness and so forth, the plan was changed. In 1997, ocean test carried out to verify selected common elemental technologies that could contribute to overall ocean development in future. The test was carried out in an area of seamount at a depth of 2200 m particularly with reference to test of collector with a mother vessel, hybrid deep sea cable with optical fibers and power supply, wire rope, underwater positioning and navigation system.

Korea's deep sea mining programme also aimed at development of various system in phases. They have carried out various laboratory design and test in respect of nodule collectors and collector vehicles. The work of insitu test of pilot mining system was in progress.

Indian also has the plan to design, develop and demonstrate a prototype mining system during 11th plan. The development of metallurgical process route for extraction of metals (Cu, Ni, Co and Mn) has been successfully demonstrated in a pilot scale of 500 kg/day throughput capacity.

Various studies on the feasibility of eventual exploitation of the polymetallic modules from the seabed have been carried out by Australia, France (IFREMER) and MIT. No such study has yet been carried out by India.

1.7 Scope of the study

The objective of the present study is

1. To analyze grade tonnage relationship of the Indian mine site and evaluate the impact of cut-off values on resultant values to help in decision making for site selection.
2. To prepare environmental friendly deep seabed mining system.
3. To predict the likely demand of the metals (Cu, Ni, Co and Mn) by 2020.
4. To prepare the cost model and evaluate the possible economics of deep seabed polymetallic nodule mining.

The scope of the study was defined keeping the above stated objectives in mind. Thus, the scope includes:

- Review of global scenario in deep seabed resources exploration, mining and environment studies.
- Review of metal demands to identify future requirements.
- Optimal estimation methodology and its application for identifying progressively potential areas in terms of polymetallic nodule resources.
- Comprehensive investigation of grade-tonnage relationship leading to the estimates of nodule abundance and metal grades for final mine site selection after meeting pre-specified criteria.
- Comprehensive review of deep seabed mining technologies and a proposed emerging concept meeting the environment requirements.
- Environmental impact of deep seabed mining-an appraisal.
- Demand, supply and price trends of metals in nodules.
- Economic model to evaluate the financial viability of deep seabed mining.

CHAPTER - 2

POLYMETALLIC NODULES

Manganese nodules are concentrations of iron and manganese oxides, ranging from millimeters to tens of centimeters in diameter. They contain economically valuable concentrations of nickel, copper and cobalt (together, making up to three weight percent). They occur mainly on the deep-seafloor. Apart from manganese and iron oxide, nickel, copper and cobalt, the nodules include trace amounts of molybdenum, platinum and other base metals (Cronan, 1980). Manganese nodules were first dredged by the HMS Challenger Expedition in the Pacific Ocean in 1872-76 (Murray and Renard, 1891)

2.1 Polymetallic Nodules

2.1.1 Mineralogy of manganese nodules

Nodules consist predominantly of amorphous and very find grained hydrated manganese and iron oxide minerals with variable amounts of silica, carbonate, detrital and biological materials. The major mineral phases of iron and manganese oxides control the uptake and retention in the nodules of minor elements such as nickel, copper, cobalt, molybdenum and rare earth elements (Cronan, 1977). Identification of specific mineral phases is difficult because of the intimate intergrowth of the different mineral phases and associated detrital material. Of the large number of complex hydrous manganese oxide mineral phases identified in the nodules, todorokite and birnessite, are the most common.

In addition to the iron and manganese minerals, nodules contain a variety of non-metallic minerals, amorphous material and biological debris that may comprise up to 25 wt. % of their (dry) mass. These include clay minerals, quartz, feldspar and chlorite, mostly of detrital origin along with silica gels, chalcedony, calcareous and phosphate components in varied proportions.

In central Indian Ocean Basin (CIOB), todorokite is the dominant mineral phase in the nodules. These nodules are associated with siliceous sediment rich in montmorillonite, chlorite, and illite. MnO_2 is dominant in nodules from the southern CIOB. They are associated with pelagic clay sediments containing keels of foraminifera, zeolites, chlorite, and illite. The intensity of X-ray peak of todorokite changes with nodule size class within the same sediments. The abundance of todorokite decreases with increasing size class, whereas - MnO_2 behaves independently.

2.1.2 Chemical composition of manganese nodules

Gross and McLeod (1987) reported that the major elements in dry nodules are oxygen, manganese, iron, silica, lesser amounts of aluminium, calcium, sodium and magnesium and trace elements of which nickel, copper and cobalt are of greatest economic interest. The amounts and proportions of constituents vary considerably within single nodules, in nodules of different sizes, and in nodules from different regions and ocean basins (Haynes et al., 1985). There are four elements of economic importance in these deposits. They are manganese, copper, nickel and cobalt.

The metal ratios also differ considerably. Not only is the manganese-iron ratio much lower in Atlantic and Indian nodules, but the copper-nickel ratio in Atlantic nodules is also appreciably lower than the copper-nickel ratios in Pacific and Indian nodules. The moderate negative correlation between manganese and iron in Pacific nodules is much weaker in Indian Ocean samples and is nearly absent in Atlantic nodules. The strong positive correlation between nickel and copper and the negative correlation between combined nickel and copper and iron found in the Pacific nodules are weaker in Atlantic and Indian nodules.

2.1.3 Formation of manganese nodules

Manganese nodules have formed through sedimentary, concretionary and biogenic processes. The metals contained in them are derived from hydrothermal, diagenetic, halmyrolytic and sedimentary sources (Cronan, 1980). At the present time, nodules are forming at a slow rate of a one to a few tens of millimeters per million years. Their formation appears to be related to active tectonic belts such as spreading ridges and deep-ocean trenches. They are found chiefly below the carbonate compensation depth in areas with low clastic sedimentation and high biological activity in overlying surface waters. Nodules with high nickel and copper contents are found in some of the deep ocean basins at depth of 4000 to 5000 m.

The development and distribution of nodules are influenced by a variety of regional and local factors (Burns and Burns, 1977). These include -

a) Their size, morphology, mineralogy, age and rate of growth;
b) The availability, size and composition of nuclei
c) Bathymetry, paleo-bathymetry and seabed topography
d) The carbonate compensation depth
e) Seawater composition
f) Bottom currents and paleo-currents
g) Redox potential at the sediment-water interface
h) Composition, thickness and age of underlying sediments
i) Thermal gradients in the sediment column
j) Rates of detrital or chemical sedimentation, and biological productivity in the water column
k) Activity of bottom organisms and
l) The proximity to volcanic, hydrothermal-effusive and tectonic activity.

2.1.4 Distribution of manganese nodules

Manganese nodules occur in many different environments including freshwater lakes, fiords, continental shelves, seamounts or abyssal plains and basins. The most extensive nodule fields are on oceanic crust that is Mesozoic or younger in age.

Metal concentration in the manganese nodules seems to relate to the circulation of the Antarctic Bottom Water currents. Generally, cobalt content in the manganese nodules is higher in the southern and central regions, where the nodule abundance is also higher, than in the northern region. Conversely, copper and nickel contents are higher in the northern region, where nodule abundance is lower.

2.2 Indian Ocean

2.2.1 Morphology

The Indian Ocean is bounded by Africa in the West, India on the North, the ninety east ridge in the east, the Kerguelen - Heard Plateau in the South East and the Antarctic continent in the south mark the limits of the western Indian Ocean. The western Indian Ocean has active mid oceanic ridges and down south to the Carlsberg ridge and the Central Indian ridge. The Central Indian ridge bifurcates into two distinct branches. The South Indian ridge and the South West Indian ridge separate the African and the Indian plates from Antarctica.

Indian Ocean characterizes various topographical features like banks, plateaus, ridges, seamount chairs, etc. These may be continental, which have been separated from main continental blocks by sea floor spreading or uplifted, blocks of oceanic in nature. The volcanic features interpreting the magnetic limitation pattern of the surrounding normal oceanic crust (eg. Afanasy Nikitin Seamounts, Rodgriques Ridge, etc.) do not appear to have been created by simple seafloor spreading process and their origin and crustal structure ore too complex and remain only partially explained (Schlich, 1982). The Central Indian Ocean Basin is one of the deep ocean basins like Arabian Sea, Somali Basin, the Mascarene and Madagascar Basins, the Mozanbique Basin, etc. The geomorphology of the Indian Ocean is characterized by basins, ridges (seismic and aseismic) and plateaus. the Indian Ocean consists of Central Indian, Arabian, Somali, Madagascar, Mozambique, Carlsberg, Central Indian ridge, South West Indian, South East Indian, Central Indian. The Central Indian basin and Arabian Basin lie on the eastern side of these ridges whereas other basins lie on the western part of Carlsberg ridge, Central Indian Ridge, South West Indian Ridges. The Indian Ocean basins (CIOB) have low topographic variations and thin sediment covers except the Central Indian Basin and the Bay of Bengal where sediment cover is several km. thick.

2.2.2 Bathymetry

The bathymetry of the CIOB shows considerable variation. The minimum water depth on the Ninety East Ridge at the equator is 2270 m. However, a depth of 4543 m has been recorded in the immediate vicinity. Though the deepest part in this sector of the basin is 4995 near equator and it shallows in the westward near Chagos – Laccadive ridge to about 3000 m. Around 18^0 S and 83^0 E, the maximum water depth recorded at 6090 m. In general, the water depth of CIOB shows gradual increase from North to South. A number of submarine plateaus and hills are present in this basin between 10^0 S and 20^0 S where minimum water depth has been recorded up to 2950 m. There is a deep trench lying parallel to the eastern margin of the north south trending Chagos - Laccadive Ridge that attains 5408 on depth off the island of diego Garcia. In the Northern part of the CIOB, shallow areas of Ceylon abyssal plain are seen on both sides of equator but in the eastern margin gradually deepens to 4500 m and continuous till the fort of the 900 E ridge. The presence of Afanasy, Nikitin seamount (located at 3^0 S 83^0E) is significant because of its depth at the top rises up to 1549 m water depth of its base is at a depth of 5000 m at the southern margin. In addition, there are several smaller seamounts of 1000 m height from ocean floor of CIOB, reported after single beam echo-sounding data by Kodagali, 1989; Mukhopadhyay and Khadge, 1990 and Kamesh Raju, et al., 1993. Bathymetry and major physiographic features of the study area in the Central Indian Basin is presented in Fig. 2.1.

2.2.3 Sediment

The CIOB has five distinguishable sediment type (i) Terrigeneous sediments from the northernmost part of the basin with illite, kaolinite and chlorite

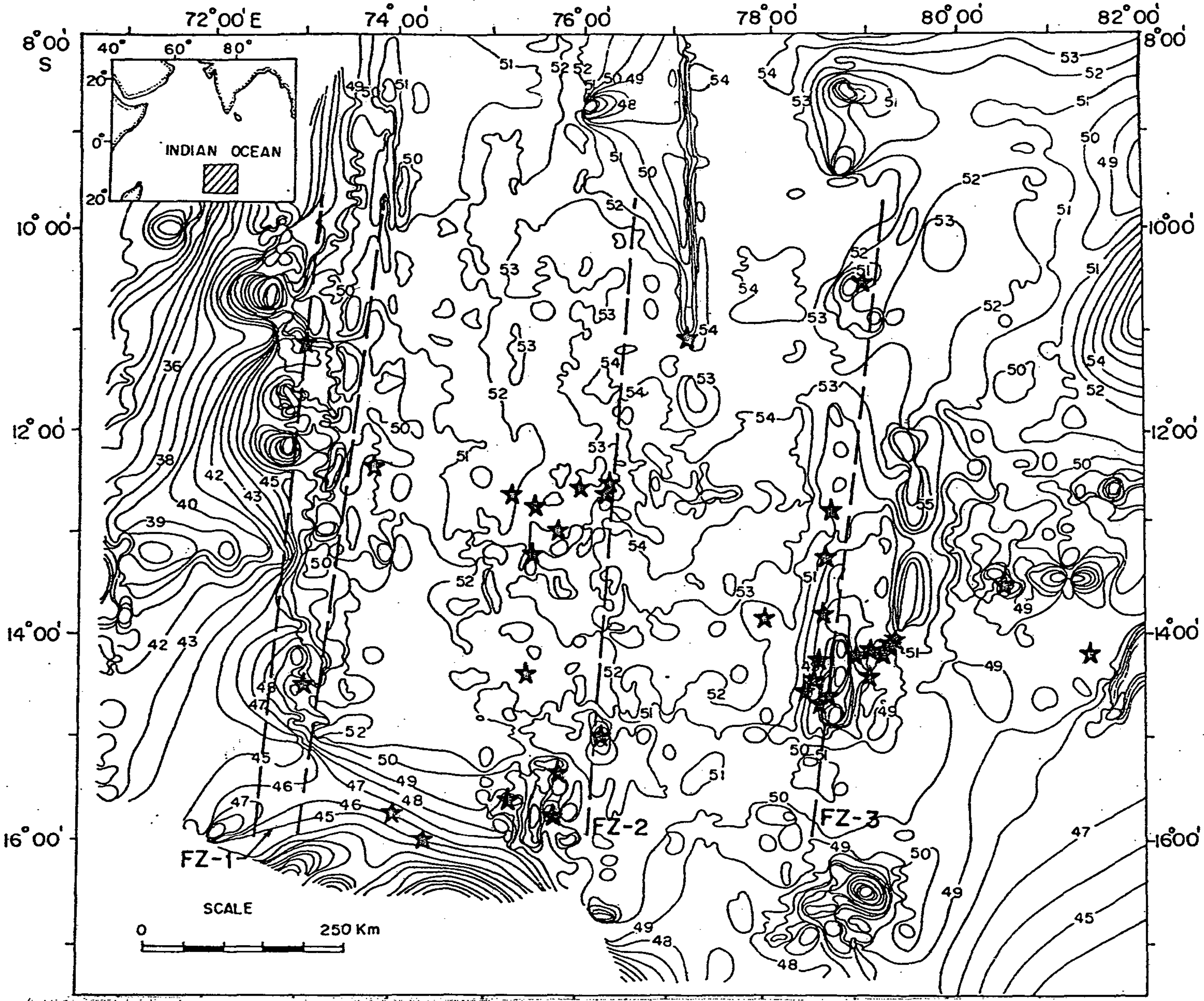


Fig. 2.1 **Map showing bathymetry and major physiographic features of the study area in the Central Indian Basin .Contour values are expressed in x 1000 m. The stars represent major seamounts and fracture zones are represented by dashed lines (FZ-1, FZ-2 and FZ-3) [Source: Iyer and Sudhakar, 1992]**

constituting 90% of the clay minerals (ii) Siliceous sediments from the northern central part of the basin, which are not overlain by nodules and are affected by terrigeneous sedimentation (iii) Siliceous sediments from the southern central part of CIOB with abundant nodule coverage (Sudhakar, 1989a) and an average sedimentation rate of 2 mm / ka (Banakar et al., 1991) (iv) Calcareous sediments from Southern most part of the CIOB. The general surface sediment types of the Indian Ocean floor, based on quantitative descriptions of grab and core samples can be broadly grouped into categories like (a) terrigenous sediment (b) biogenic sediment (c) Pelagic red clays.

2.2.4 Growth rates

Growth rates have been determined in two nodules from the basin by Banakar. Based on the exponential depth decay profile of Th activity and the Th. Th activity ratio, the accretion rates obtained for nodule tops were 1.2 to 1.3 mm / my, and for the bottom layers, 1.9 to 3.2 mm / my. The nearly three times higher accretion rates on the nodule undersides compared to their tops reflects the fixed position of the nodules throughout their growth history. The accumulation rates of sediments in the basin average 2 mm / ka. This suggests that nodules overlying the sediments accrete nearly 1,000 tonnes slower than the sediments.

2.2.5 Elemental variations

It has been reported that nodules of CIOB consist of about 52 elements (major, trace and near earth element). The metal concentration of the nodules of the

CIOB is comparable to reported metal concentration in the other basins of world oceans. Manganese concentration reported highest in plains (25.6 %) and lowest on hilltops (22.4 %). In case of iron, the concentration is highest at the hill top and lowest in the plain. Cobalt concentration varies from 0.12 to 0.15 show much variation in nodules from different areas of CIOB. Nickel and copper concentrations are highest in plains and lowest in valleys and on hill tops. It has also been reported that Ni and Cu contents consistently increase with an increase in the Mn/ Fe ratio where as co decreases. Concentrations of rare earth element (REE) in nodules in CIOB have been reported as a wide variation from 398 to 2020 ppm.

In order to identify the blocks for relinquishment in phases, following broad criteria have been considered.

a) Cut - off values of abundance (> 5 kg / sq. m), grade (> 2%) and individual metals such as copper and nickel (> 1% each) have been considered for the identification of potential blocks and rejecting others.
b) Major topograhic features such as fracture zones and seamounts have been identified to demarcate exactly these areas as the priority blocks for relinquishment. These areas often resulted as partial blocks in the Pioneer Area.
c) A rigorous cut-off criteria was adopted where the blocks with high local gradients (slope angles more than 3^0) have been examined for rejection at the first instance. Such blocks having abundance and grade values below

the desired levels of cut-off (5 kg / sq. m and 2% respectively) have been demarcated for relinquishment on priority.

d) Less explored blocks (where the number of sampling stations are fewer compared to other blocks), but showing higher values of abundance and grades were retained.

e) Hanging blocks (one or few blocks occurring as patches), with low values of abundance are rejected, irrespective of their grades.

f) Blocks occurring below 15^0 S have been re-examined for their potentiality, as these blocks are underlain by pelagic brown clays and the results of many academic studies have shown low grade nodules in this part. Similar inference is supported by the present database of blockwise values.

2.2.6 Abundance and grade

Regional surveys at a spacing of 100 km. were carried out to narrow down the area for further surveys. Based on the regional exploration, further surveys were carried out at a spacing of 50 km. and over 4 million sq. km. have been surveyed in this basin. Efforts to locate a mine site were concentrated in the Central Indian Ocean Basin over an area of 4.24 million sq. km. with the help of various research vessels of the Department and chartered vessel. It was found that ore grade nodules occur only in the central part of the basin by the siliceous sediments. Maximum occurrence of nodules is on the red pelagic clays. The survey (sampling grid) was subsequently narrowed down to 25 km. The sample spacing have further been reduced to 12.5 km. to further refinement of data and to have reliability on the resource estimates. Three/ four sets of data were collected at each station to calculate the wet abundance of nodules in kg /sq. m, the grade (Cu + Ni + Co) of the nodule and topography of the seabed. The data base in respect of the stationwise means of abundance and grades were used or statistical and geostatistical analysis. It was established that there is an inverse relationship between grade and abundance.

The ocean floor where the nodules occur is not a smooth featureless plain. There are mountains, ridges, hills, scarps, troughs and basalt outcrops, geological faults and other irregularities and obstacles such as micro-topographic features. Generally, the sediments on which the nodules rest are soft, fine-grained, water-saturated, clay or ooze. Different types of currents are encountered at various depths of the water. Such conditions present a very difficult environment for mining operations dependent on remotely controlled mechanical apparatus.

2.3 India's interest in polymetallic nodules

The measured, indicated and inferred reserves of manganese ore on land are not likely to last more than 5 to 25 years at the present rate of production. The position in regard to nickel, copper and cobalt is also not satisfactory. A large portion of country's requirement of copper and almost the entire requirement of nickel and cobalt are imported. In addition, the United Nations studies also indicate that the land reserves of manganese, nickel, copper and cobalt are meager when compared to the potential reserves in the manganese nodules. It is with this background that efforts have been initiated in the country in late 1970's for a systematic scientific study of the ferro-manganese nodules and their resource potential. It is estimated that a single mine-site, from which about 1.5 X 10^6 tonnes of dry nodules recovered every year, is likely to yield approximately 16836 tonnes of Ni, 15151.5 tonnes of Cu, and 1440.0 tonnes of Co and 31160 tonnes of Mn, such a rate of production not only meet the Indian requirements but also leave a substantial portion for exports.

Results, based on an initial evaluation of the data (nodule coverage at little more than 600 sites and nodule abundance at 44 locations) available in the Indian Ocean basins, some workers suggested (e.g. Fraze and Wilson, 1980; Cronan and Moorby, 1981) that the CIOB will be most promising area of the Indian Ocean basins for the first-generation mine-sites and paramarginal grade resources. With this background, the Central Indian Basin has been selected as the target basin for the surveys and exploration of manganese nodules in the Indian Ocean.

2.4 India's polymetallic nodules programme

A national programme on polymetallic manganese nodule was formulated by the Department of Ocean Development in early 1980s for identifying an appropriate area from the target basin for applying to the Preparatory. Commission or a site for developmental activities. The National Institute of Oceanography (NIO), Goa was entrusted with the work of executing the Survey and Exploration work. An area of 4.2 million sq. km. was surveyed in detail for all the parameters for identifying areas of potential. A systematic grid - wise sampling, along with the single beam echo- ' sounder was first carried out as a part of this programme.

The data collected in the first phase was the basis for identifying the two areas of potential nodule deposits, which form India's application to the Preparatory Commission (in the International Seabed Authority) and International Tribunal for the Law of the Sea (ITLOS) for grant of the pioneer area. Two areas of 150,000 sq. km. each with comparable nodule grade, abundance and topography were selected on the basis of survey work carried out by India (Fig. 1.1).

India was registered as a Pioneer Investor on 17th August, 1987 as the first Pioneer Investor under certain obligation under Resolution II of the UNCLOS III. The Department has fulfilled all the obligations so far including the training of the personnel from the developing countries. Entire area of 150,000 sq. km. was thoroughly surveyed with the help of Multibeam system. The sampling work has also been completed at a grid interval of 25 km X 25 km, 12.5 km X 12.5 km for refinement for the assessment of nodule abundance, grade, etc. In partial fulfillment of the obligation to the International Seabed Authority, the Department of Ocean Development relinquished 50 % of the allocated area to the International Seabed Authority. Various vessels like ORV Sagar Kanya, M.V. Skandi, M.B. Farnella, M.G. GA Reay, D.S.B. Nandr Rachit and RV A.A. Sidorenko were used for Survey and Exploration work. The data basically contain two main data sets i.e., the data component coordinates of the sampling, type of sampler deployed, data depth, abundance of nodule recovery and the chemical data containing analytical data of nodules, including Mn, Fe, Co, Ni, Cu. The abundance of nodules was exclusively recorded based on the freefall grabs, photography sampling devices. The scientists used the ocean grab sampling at the time of survey work by R.V.A.A. Sidorenko. The data on the basis of the exclusive survey work carried out by the scientists of NIO, the abundance data, and chemical data and bathymetry data were analyzed in detail.

2.5 Indian campaign for polymetallic nodules in central Indian Ocean basin

The considerable investments of the ocean mining consortia before the adoption of the Third United Nations Conventions on the Law of the sea (hereafter referred to as UNCLOS III) had given raise to the demand by some of the industrialized countries for the integration of the nationally recognized claims of those consortia with the regime envisaged in the UNCLOS III text (Ogley, 1984) (UNCLOS III text is also referred to as convention). The major protests to the acceptance of the provisions envisaged in part XI and annex III of the UNCLOS III text by the United States of America was lack of protection said to exist for investments which had already taken place in deep seabed mining. Such a question of preparatory investment protection was not discussed in the conference until the last session in March 1982. However, the group 77, as an important concession accepted the adoption of an interim regime for such protection. In a final effort to compromise all, the UNCLOS III established rules in favor of 'Pioneer Investors' (UN conventions, 1982). These rules are contained in two resolutions (Resolution I and II), which are annexed to the Final Act of the Conference in the UNCLOS III text. Resolution I provides for the establishment of 'Preparatory Commission' (hereafter referred to as PrepCom), whose primary objective is to ensure the entry into effective operation of the International Seabed Authority (ISBA) and the International Tribunal for the Law of the Sea (ITLOS).

Manganese nodules are concentration of iron and manganese oxide ranging from millimeters to tens of centimeters in diameters. They occur mainly on the deep-ocean floor. Apart from manganese and iron oxide, nickel, copper and cobalt the nodules include traces amount of molybdenum, platinum and other base metals. Some researchers suggested (Frazer and Wilson, 1980; Cronan and Moorby, 1981) that the central Indian Ocean basin (CIOB) will be most promising area in the Indian Ocean basin for first generation mine sites and paramarginal grade sources.

The department of ocean development (now ministry of ocean development) government of India entrusted National Institute of Oceanography (NIO, Goa) to undertake necessary exploration for polymetallic nodules in central Indian ocean with prime objectives of identifying a prime area and subsequently application areas.

Primarily NIO used two chartered vessels namely MV Skandi Surveyor and MV Farnella. The third vessel RV Gavenshani (owned by NIO) was also used in initial stages.

First reconnaissance surveys and site specifying detailed investigations were carried out for identifying the target areas in the Indian Ocean. The reconnaissance survey area is between 0° to 21° S latitude and 70° to 88° E longitude. About 4.2 million sq. km area was covered during reconnaissance survey. Target area has been selected between latitudes 10° S and 18° S and longitude 72.5° E and 82.5° E based on the data collected during reconnaissance survey. The sampling was carried out by using grabs, corers, box corers, spade corers; boomerang/free fall samples and dredges. Detailed survey has been carried out in the target area for demarcation of prime Area of nodules and two application Areas. As a part of the principal requirement for application of claims following actives were carried out:-

- Mapping of the seafloor
- Sampling and characterization of nodules and seafloor by geochemical methods
- Delineation of major structures and tectonic features by geophysical methods
- Deposit evaluation

Various equipment were used for the investigation and they are classified in to four major groups

I. Navigation and position fixing equipment

II. Echo sounding and Multiyear sonar

III. Seabed samplers and freefall grabs

IV. Evaluation tools and methods

The sampling was initially carried out at a spacing of about 1°, which is being progressively reduced to 0.25°. First, a preliminary geostatistical analysis was carried out by M/S Engineers India Limited (EIL). This work was entrusted by the department of ocean development on the basis of abundance values from 467 stations and chemical analysis data from 166 stations. Two application areas each of 1, 50, 000 sq. km were identified in Aug' 1983 on the basis of preliminary survey.

CHAPTER-3

PROGRESSIVE AREA SELECTION AND RESOURCE DISTRIBUTION

This chapter documents the results of comprehensive evaluation of polymetallic nodules resources of the Central Indian basin based on the sampling data that was generated during the exploration campaign at various stages. The total area that was targeted in the Central Indian Basin for reconnaissance survey covers a few million sq km, starting from the Equator in the North to 21 deg South latitudes and 70 deg East to 85 deg East longitudes, The detailed exploration campaign however, was confined to an area of approximately 0.1 million sq km. broadly designated as the "Target Area" roughly bounded by the latitudes 10 deg. South to 18 deg. South, and longitudes 72.5 deg. East to 82.5 deg. East. As the sampling densities increased during the campaign into specific sites, the area was further designed as the "Prime Area", where the spatial distribution of nodules and their quality was evaluated by various models that included the conventional statistical techniques as well as the geostatistical models having a greater reliability of estimation compared to the former. Finally, the exploration data and the geostatistical techniques employed lead to the firming up of the coordinates of the two areas of 150,000 sq km each termed as the "Pioneer Area and the Reserved Area". A schematic representation showing the progressive selection of areas based on varying sampling densities is shown in Fig. 3.1.The influence of varying grid size leading to the delineation of potential areas and the subsequent demarcation of the two resources areas have been discussed in this chapter. Therefore, the progressive resource distribution in relation to increasing sampling densities during the comprehensive exploration campaigns and its evaluation of nodules resources in the Pioneer Area of 150,000 sq km allocated to India by the United Nations for its exclusive development efforts forms a part of the results presented in this chapter.

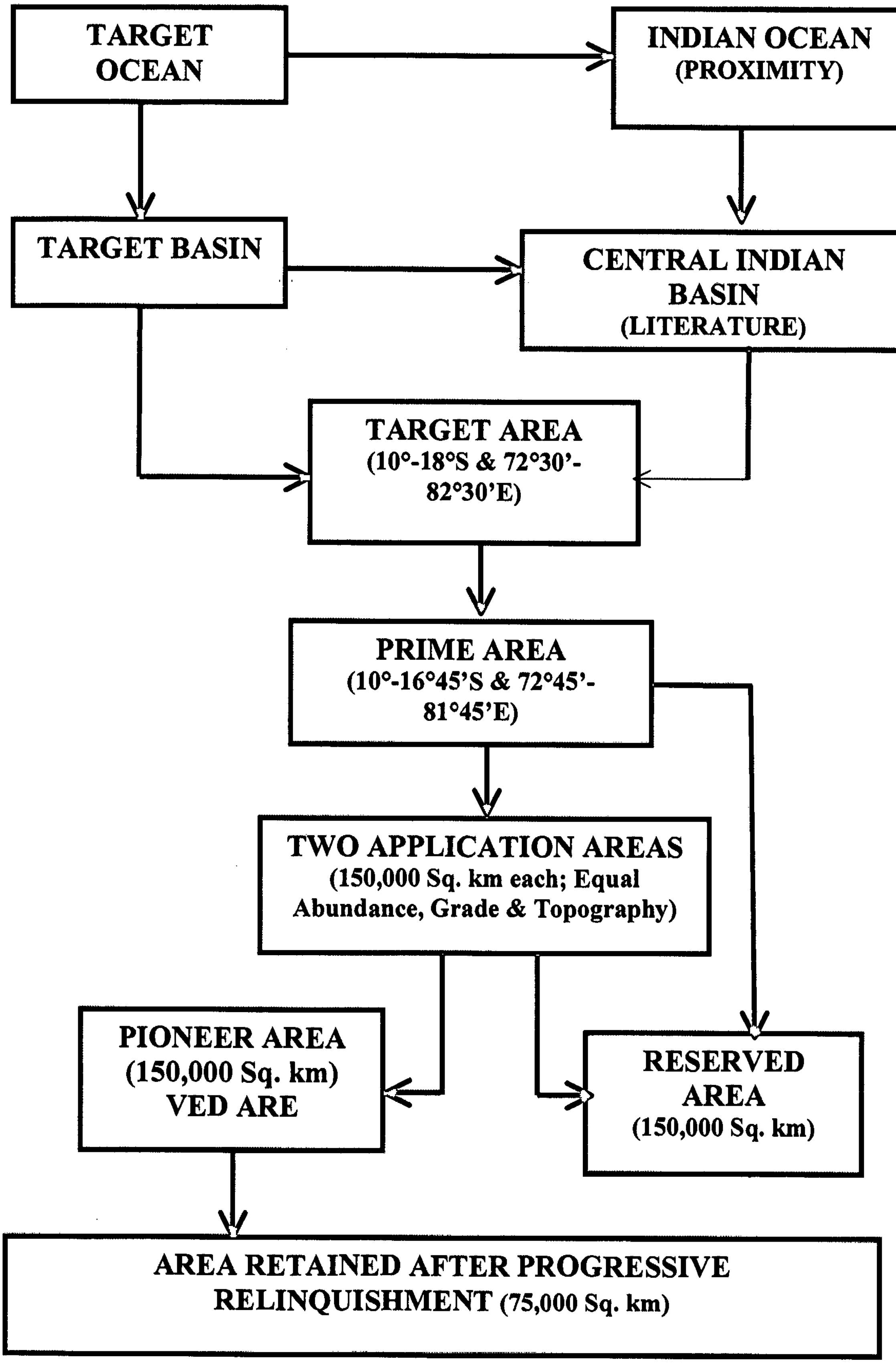


Fig. 3.1 : A schematic representation showing the progressive selection of areas based on varying sampling densities

3.1 Data Base

The exploration data generated during the campaigns contained a large data base consisting of 3 to 7 samples collected at each survey station for abundance measurements. Abundance of nodules on seafloor is measured and expressed in weight of nodules (in kilograms) per a unit area (in square meter). Therefore the measurement of abundance is expressed in kg/sq.m. Each of these 3 to 7 samples from a given station were analyzed for their chemical constituents (expressed in weight percent), and five metals namely, Manganese (Mn), Iron (Fe), Cobalt (Co), Nickel (Ni) and Copper (Cu) were considered for evaluation. Each of the samples was divided into four aliquots, of which 2 to 3 analyses was carried out.

The data so generated was put in two distinct files. The first data file, named as "Abundance File" that contained the following information for each sample:-

- Ship identifier
- Station number
- Sample number
- Location of Station in terms of its Latitude and Longitude
- Water depth at which the sample was collected (expressed in meters)
- Type of Sampler deployed/ used.
- Weight of nodules collected (wet weight in kilograms)
- Abundance of nodules (expressed in kg/sq.m.)

The second data filed, named as "Chemical File" that contained the following information for each sample:-

- Ship identifier
- Station number
- Sample number
- Laboratory identifier
- Latitude of station location
- Longitude of station location
- Chemical analysis (% Mn, Fe, Co, Ni, Cu)

The above two files were considered as the raw database for further evaluation. The raw database for chemical values contained laboratory wise chemical analysis for each sample of the station. The laboratory wise data were first averaged out to generate a sample wise mean grades which, in turn, were weighted by the corresponding abundance values to produce stationwise weighted average of grades. Following the above method, the resultant was the merged data that contained the "Processed database" for grades as

- Station number
- Coordinates of the Station
- Mean abundance of the Station for given samples
- Weighted means of Mn, Fe, Co, Ni, Cu and Total Metal (TM)

  (TM has been defined as TM = Co + Ni + Cu)

The steps involved in generating the processed data base are schematically shown in Fig. 3.2. The processed data base thus contained stationwise means of abundance and grades of nodules.

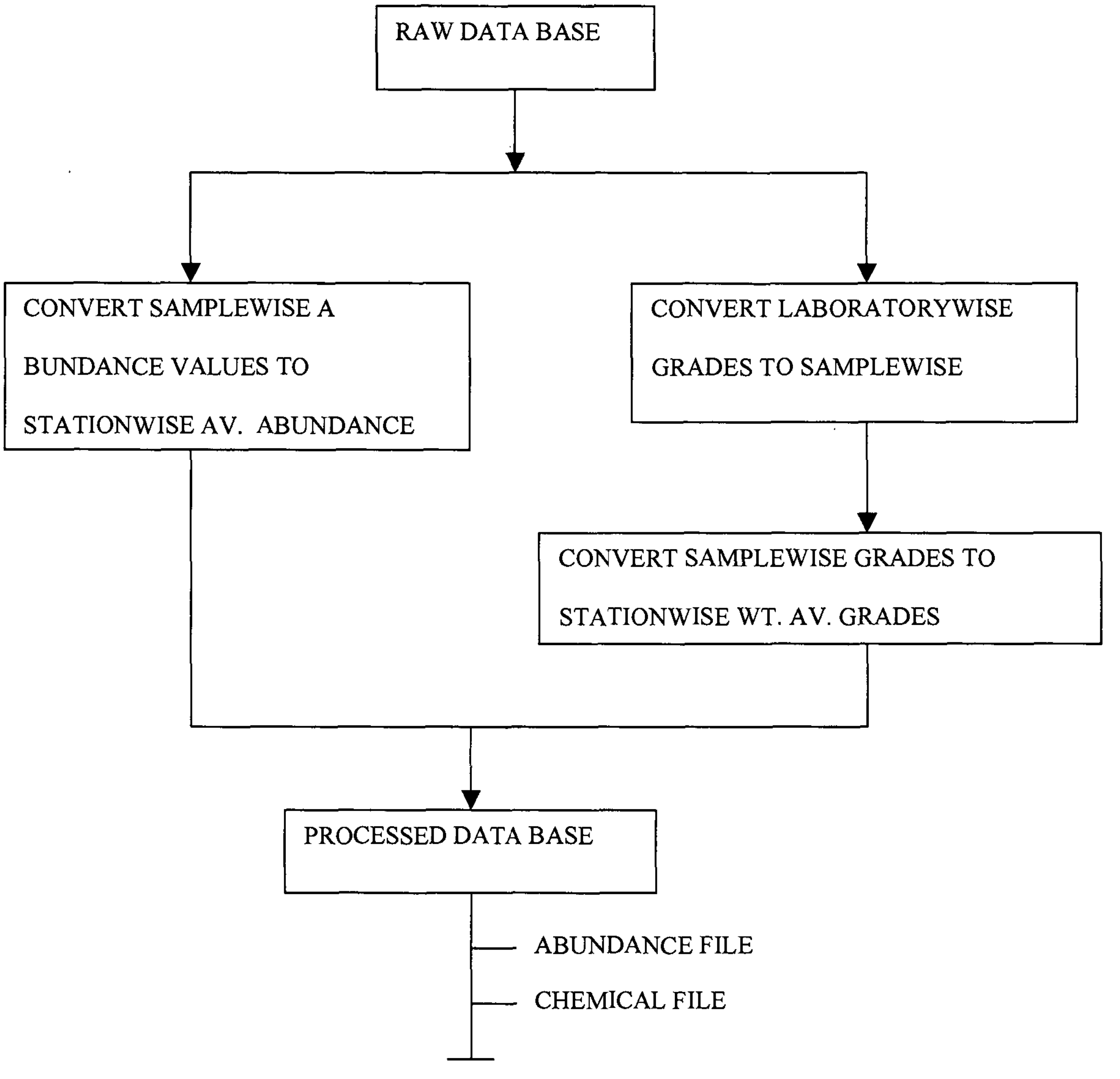


Fig. 3.2: A schematic representation of Processed Database Generation.

3.2 Model Studies

The conventional statistical parameters, such as the stationwise mean values, their frequency distributions and the correlation studies have been computed and evaluated for resources in the area. Besides this, the spatial distribution of nodules and their quality have been approximated by variographic models and the results of which have been used to generate optimal estimates of abundance and grades. Typically, the unit block size varied from 0.5 x 0.5 deg. to 0.25 X 0.25 deg. within the Target Area and Prime Areas that supported the sampling grid spacing. The optimization technique called "kriging" typically used for low-grade terrestrial deposits was employed here considering the character and distribution of polymetallic nodules on the seafloor. Stationwise mean values, blockwise Kriged estimates, frequency distribution results, cut-off value- resultant value curves and the broad bathymetric datas have been used in deciding on progressive selection of blocks. Thus, the Target Area was first reduced to Prime Area out of which two allocation areas (including Pioneer Area), each of 150,000 sq. km. area were demarcated.

3.2.1 Selection of Estimation Model

For estimation of a variable on the basis of available information, the most generalized model may be written as,

Z (x) = T(x) + R (x) + E (x)

where

Z (x) is the functional value at location x

T (x) is the trend surface component

R (x) is the stochastic component

E (x) is the random component

In the present analysis, the component T (x) was dropped on account of

- insignificant trend component

  (R^2 = 4% for abundance)

- statistical equivalence of means over the entire area

The model thus retained is

$Z(x) = R(x) + E(x)$

Under this model the function $Z(x)$ is fully described by a variogram function. Using the available stationwise values on abundance, individual element/ metals and grade (Total Metal), the variograms were computed for abundance and Mn, Co, Ni, Cu and TM in different directions. The experimental results showed tat the variograms were by and large, similar in different directions and that they may be approximated by models with sill (Sudhakar et al., 1996). The following mathematical model, called spherical function, was used to approximate the experimental variograms:

$$g(h) = Co + C \frac{3}{2}\left(\frac{h}{a}\right) - \frac{1}{2}\left(\frac{h}{a}\right)^3$$

Where,

g (h) = semi-variogram function at a distance h

Co = nugget variance

C = structured variance

a = ranges of influence

3.2.2 Estimator Used

An optimal estimation technique called "kriging" (Krige,1960)) was used to estimate blockwise abundance and grades. The kriging estimator Z_K has been defined as,

$Z_k = a_i \ Z(x_i)$

Where

$Z(x_i)$ = experimental values at location x_i

a_i = weights given to $Z(x_i)$

The weights a_i are computed such that the estimator Z_k

i) is unbiased, and

ii) has minimum error of variance.

Applying the above technique and using the processed database and the parameters of the variogram, blockwise estimates of abundance and grade accumulations were generated. The kriged estimates for grades were derived by dividing estimated accumulations by estimated abundance. In addition to the blockwise estimates, the kriged variances and hence the kriged standard deviations were also computed for all blocks and in respect of all variables. The results obtained for blockwise estimates of abundance and grades were evaluated for demarcating the resource potential areas.

3.2.3 Unit of Estimation

The whole area under investigation was divided into 0.5^0 blocks resulting in 320 such blocks. This unit was considered suitable for making selections based on its values of abundances and grades. The exploration grid of 0.5^0 to 0.25^0 also supported the selection of such a unit size in the target area at that stage of exploration (Sudhakar, 1993).

accumulation and TM-accumulation. Similar to abundance, mean experimental variograms for these new variables were computed and approximated by spherical models.

3.3.2 Target Area Evaluation based on Sparse Grid

A comprehensive statistics have been computed on the estimated abundance and grade values of 320 blocks considered in the target area for a unit block size of $0.5^{0.}$ Depending on the density of sampling, the standard deviation varied widely and therefore the computed relative standard error of estimate was considered for decision making with respect to the potential of a given block. As a first step of categorization, the blocks with more than 50% relative standard error have been identified and marked. Out of the total 320 blocks, 173 blocks were classified as high error blocks (with more than 50% relative standard error) and the remaining 147 blocks have standard error lower than 50%, which were considered separately for further evaluation. Therefore, these blocks have been grouped in different areas and the blockwise values and their statistics are presented on the following.

1) Total Target Area	320 blocks
2) Area Rejected	173 blocks
3) Reduced Area	147 blocks
4) Two Potential Pioneer Areas	50 blocks each

The summary of statistics of blockwise values for the three areas is presented in table 3.2.

Table 3.2: Summary of statistics of blockwise values

(i) Summary of Statistics for the total Target Area (320 blocks)

	Mean	Std. Dev.	Coeff. Of variation (%)	Minimum	Maximum
Abundance	2.84	1.99	70	0.05	10.91
Mn	22.62	2.85	13	13.36	29.99
Co	0.18	0.05	28	0.09	0.44
Ni	0.97	0.24	25	0.60	1.68
Cu	0.79	0.31	39	0.31	1.50
TM	1.94	0.50	26	1.12	3.26

(ii) Summary of Statistics for the Reduced Area (147 blocks)

	Mean	Std. Dev.	Coeff. Of variation (%)	Minimum	Maximum
Abundance	4.33	1.76	41	1.74	10.91
Mn	22.73	2.38	11	14.30	29.99
Co	0.17	0.04	24	0.10	0.28
Ni	0.98	0.22	22	0.61	1.54
Cu	0.84	0.29	35	0.31	1.50
TM	2.00	0.48	24	1.12	3.13

(iii)Summary of Statistics for the Two Potential Pioneer Areas (2 X 50 blocks)

	Mean	Std. Dev.	Coeff. Of Variation (%)	Minimum	Maximum
Pioneer Area 'A' Abundance	4.51	1.66	36	2.07	10.91
TM	2.02	0.44	22	1.33	2.91
Pioneer Area 'B' Abundance	4.39	1.53	35	1.47	8.30
TM	2.08	0.42	20	1.44	3.10

3.3.3 Target Area Evaluation based on Close Grid

Stationwise average abundances and grades of nodules were computed and the statistics of stationwise averages were arrived. There were 1412 stations considered in the present dataset for evaluation.

Detailed frequency distribution studies have been conducted on the stationwise averages in respect of abundance, Total Metal (Co+Ni+Cu), Mn, Co, Ni and Cu. The results of these studies are presented in Fig 3.3 A and B, and Fig. 3.4 A, B, C, D.

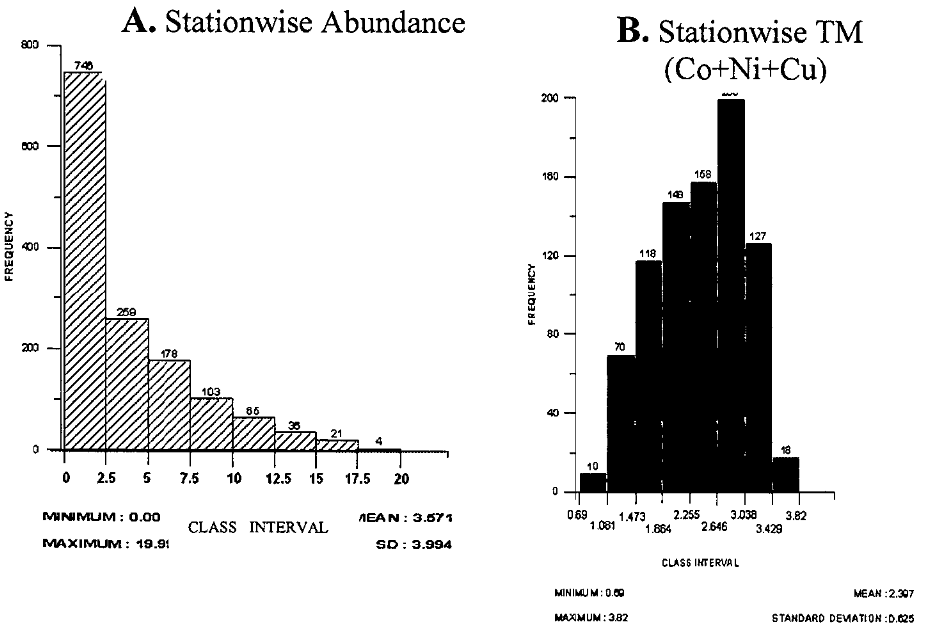


Fig. 3.3: Frequency distributions of A) Stationwise Abundance showing skewed distribution and B) Stationwise Total Metal (Co+Ni+Cu) showing normal distribution

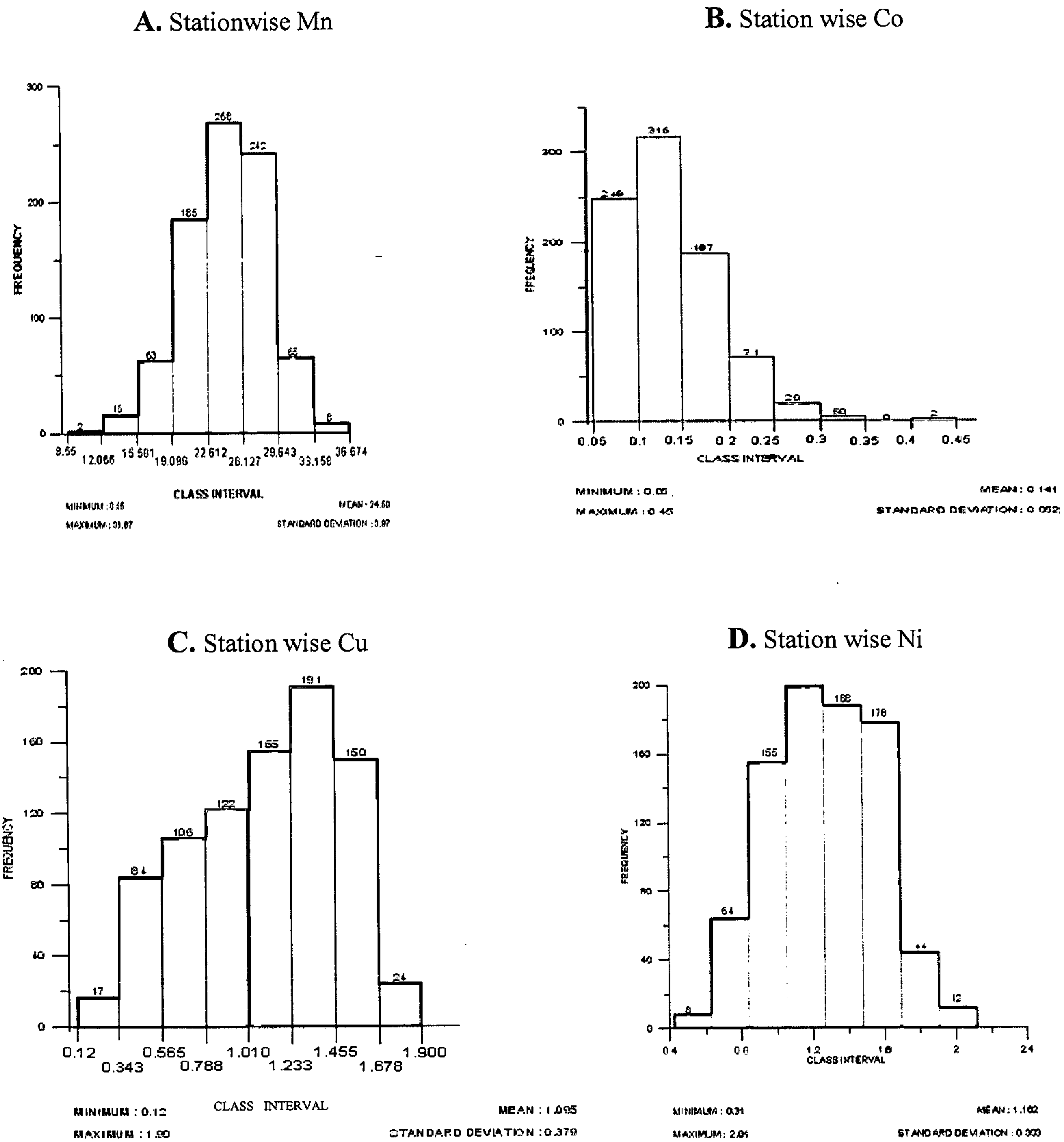


Fig. 3.4: Frequency distributions of A) Stationwise Mn and B) Stationwise Co, C) Stationwise Cu and D) Stationwise Ni. All the metals showing normal distribution.

Based on the Blockwise Estimates of abundance and grades and evaluation of in-situ resources of polymetallic nodules, the estimates for the Target Area is summarized below:

Estimated in-situ Resources in the Target Area

1. Size of Area (sq. km.) : 960,000
2. Mean abundance (kg/m^2) : 3.57
3. Mean grades (%)

Co	Ni	Cu	TM	Mn
0.14	1.16	1.09	2.39	24.5

4. Estimated quantities of wet nodules : 3, 428 MT
5. Estimated quantities of metals (in MT)

Co	Ni	Cu	TM	Mn
3.87	31.87	30.03	65.77	671.92

The target area of 960,000 sq km was delineated and presented in figure 3.5.

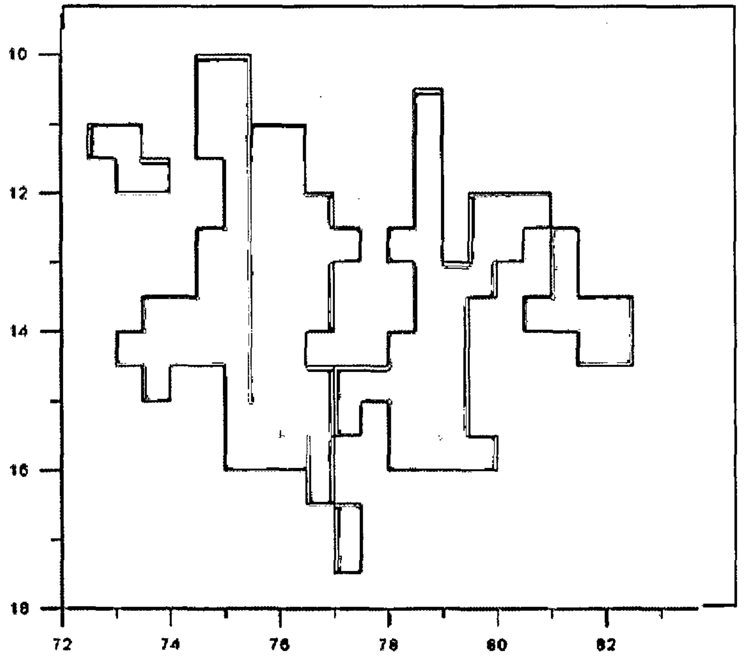


Fig. 3.5: Map showing the Target Area of Nodules in the Central Indian Basin.

3.4 Prime Area Selection

A prime area was selected from out of the target area based on following criteria:

- rejection of blocks with high estimation error for abundances (block with relative kriged standard deviation for abundance greater than 50 % were rejected)
- rejection of blocks with the topographic code 4 (most complex topography).

The prime area so selected on the basis of the above criteria coved an area of 405, 750 sq. km. and contained 541 blocks of 0.25 deg. size. Further selection of blocks was based on the estimated values of abundance and grades of nodules. Thus, the blocks with relatively lower abundance and grades were further rejected leaving an area of 300, 000 sq. km., which constituted the total Application Area for Indian application. As per the requirements of the Preparatory Commission, the total Application was split into two areas, Application Area A and Application Area B, each having an equal area of 150,000 sq. km., containing 200 number of 0.25 deg. size blocks and having equal estimated values of abundance and grades.

3.4.1 Statistics of Blockwise Estimated Values in Prime Area

A detailed analysis was carried out for the prime area based on the blockwise kriged estimates since the selection of the application area was to be made from out of the prime area. It is for this reason that the blockwise values rather than the stationwise values were used for detailed analysis. Thus, in addition to the basic statistics of blockwise values, detailed frequency distribution studies have also been made. Detailed frequency distribution studies have been conducted on the blockwise kriged estimates in respect of abundance, Total Metal (Co+Ni+Cu), Mn, Co, Ni and Cu. The results of these studies are presented in Fig 3.6 A and B, and Fig. 3.7 A, B, C, D.

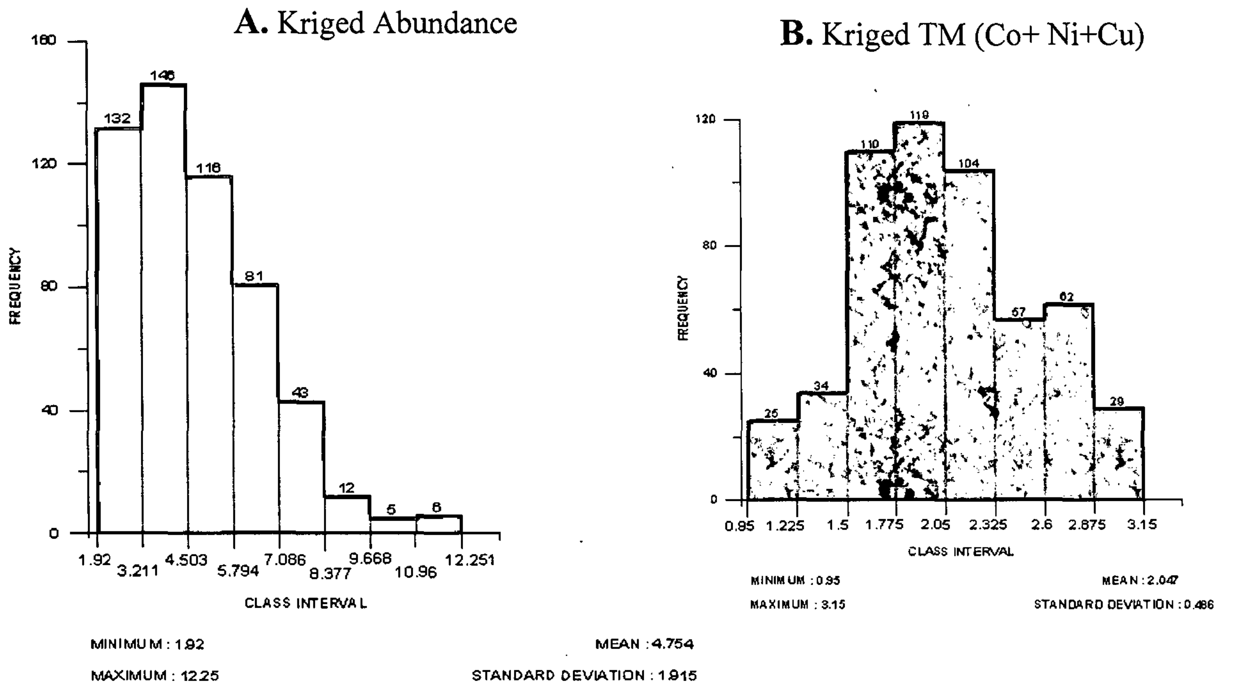


Fig. 3.6: Frequency distributions of A) Blockwise Kriged Abundance and B) Blockwise Kriged Total Metal (Co+Ni+Cu)

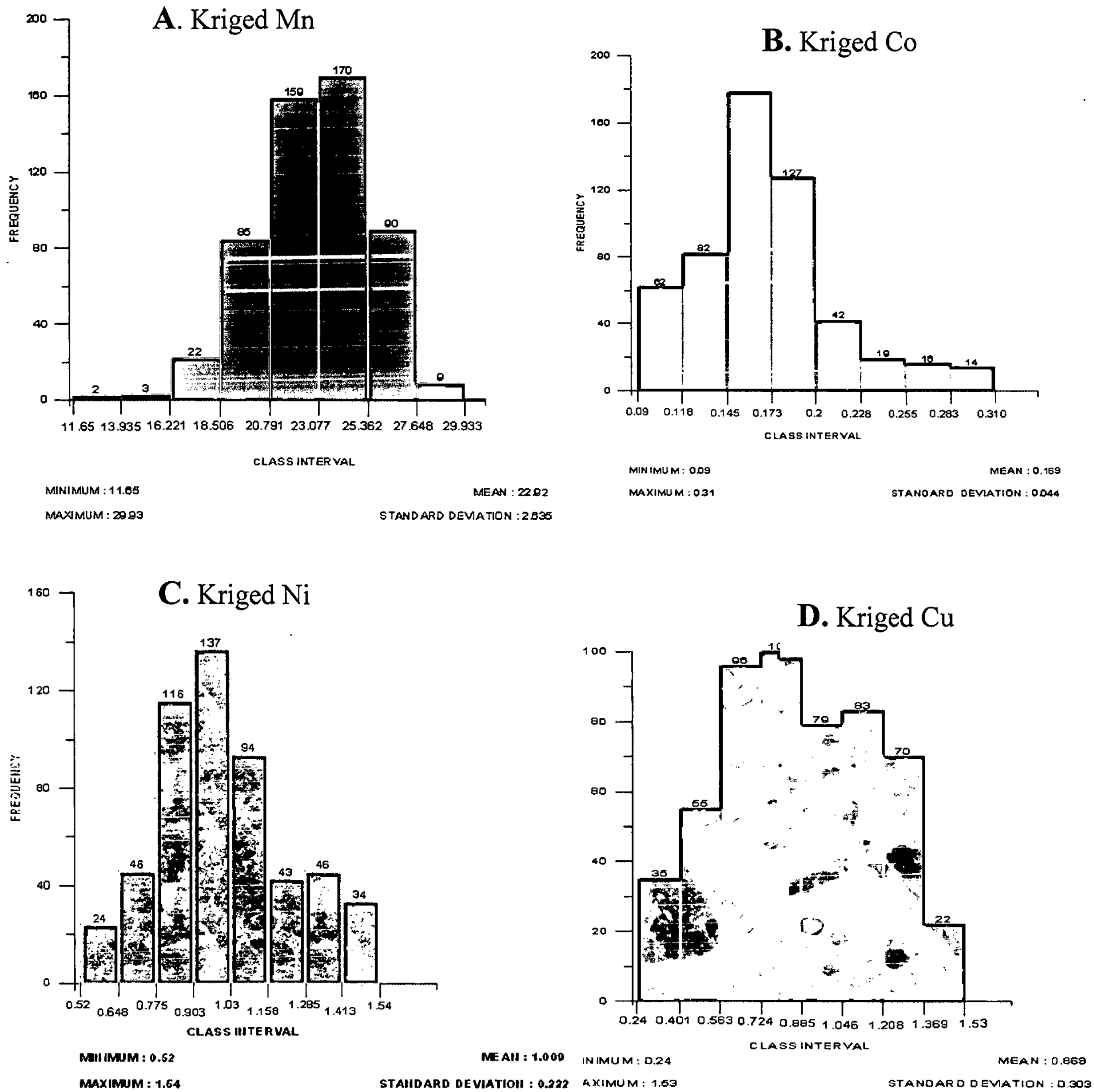


Fig. 3.7: Frequency distributions of A) Blockwise Kriged Mn, B) Blockwise Kriged Co, C) Blockwise Kriged Cu and D) Blockwise Kriged Ni

The summary of statistics of blockwise estimated values of the prime area is presented below

(NO. OF BLOCKS= 541)

	Mean	Std. Dev.	Coeff. Of Variation	Min	Max.
Abundance	4.75	1.9	40	1.9	12.3
Mn	22.92	2.6	11	11.6	29.9
Co	0.17	0.04	24	0.09	0.31
Ni	1.00	0.22	22	0.52	1.54
Cu	0.87	0.30	26	0.24	1.53
TM (Co+Ni+Cu)	2.05	0.48	23	0.95	3.15

The Prime Area of 405,750 sq km was demarcated that formed the basis for application area A and B submitted to the Preparatory Commission for allocation of an area of 150,000 sq km to India, is designated as the "Pioneer Area" and the area retained forms the "Reserved Area" for the International Seabed Authority. The application areas A and B after adjustment were allocated as presented in figure 3.8.

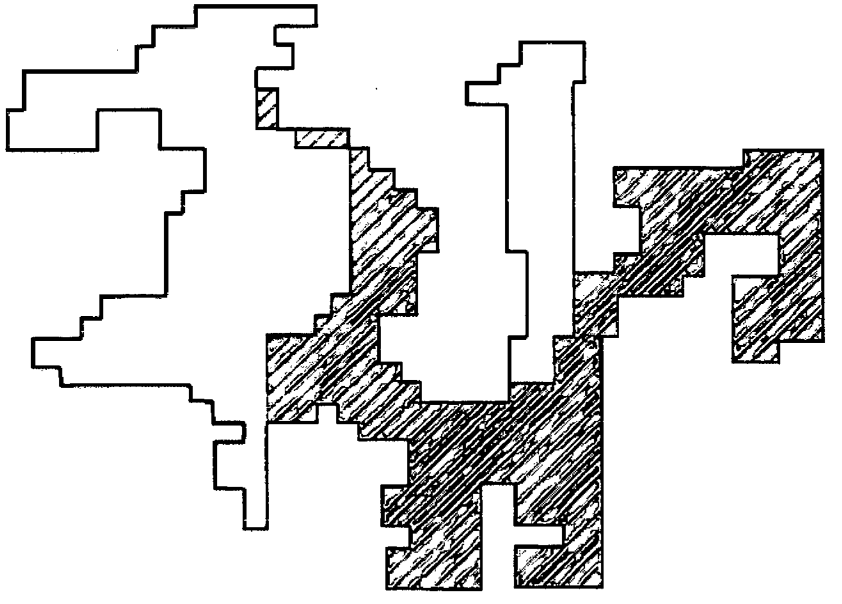


Fig. 3.8: Map showing the Pioneer Area and Reserved Area in the Central Indian Basin.

3.4.2 Prime Area Resource Evaluation

Based on the mean estimates of abundance and metal values of nodules on blockwise estimates and the results of area computations, the total in-situ reserves of nodules and the quantities of metals have been computed for the prime area. The results are summarized below.

Estimated in-situ Resources in the Prime Area:

1. Size of Area (sq. km.) : 405,750
2. Mean abundance (kg/m^2) : 4.75
3. Mean grades (%)

Co	Ni	Cu	TM	Mn
0.17	1.01	0.87	2.05	22.92

4. Estimated quantities of wet nodules : 1,928 MT
5. Estimated quantities of metals (in MT)

Co	Ni	Cu	TM	Mn
2.6	15.6	13.4	31.59	353.7

3.5 Demarcation of Pioneer Area

Fig. 3.9 presents the selection of blocks leading to Pioneer Area allocated to India at the Preparatory Commission for the International Seabed Authority.

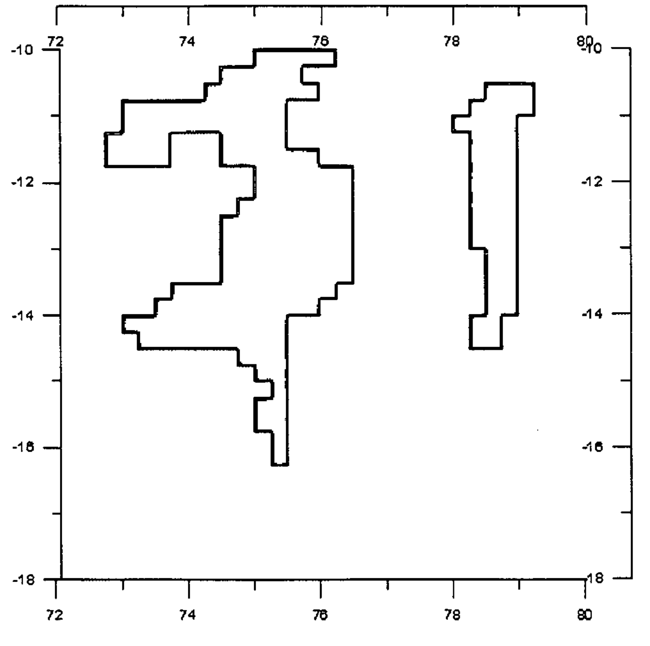


Fig. 3.9: Map showing the Pioneer Area of Nodules in the Central Indian Basin.

The in-situ resources of nodules in the Pioneer Area are summarized below:

Estimated in-situ Resources in the Pioneer Area:

1. Size of area (sq. km.) : 150,000
2. Mean abundance (kg/m^2) : 5.11
3. Mean grades (%)

Co	Ni	Cu	TM	Mn
0.15	1.14	1.06	2.34	23.8

4. Estimated quantities of wet nodules : 768
5. Estimated quantities of metals (in MT)

Co	Ni	Cu	TM	Mn
0.93	7.00	6.51	14.38	146

3.6 ESTIMATION ACCURACY FOR VARYING EXPLORATION GRID

3.6.1 Determination of variable

It may be observed from the summary of statistics for stationwise averages presented earlier that the co-efficient of variation of abundance is much higher (113%) than all the grade variables like Mn, Co, Ni, Cu and TM. It follows, therefore that if a given exploration grid satisfies the requirements of estimation accuracy in respect of abundance, it will also meet the accuracy requirements for grades. Therefore, abundance has been selected as the variable to be used in the context of accuracy in relation to exploration grid.

3.6.2 Effects of varying grid on accuracy of estimation

For the present study, blockwise estimation of abundance and is estimation variance has been made for a block of 0.5^0 size. The present grid in the area is rather heterogeneous ranging from 1^0 in some parts through 0.5^0 and 0.25^0 to 0.1^0 in other parts.

For the purpose of evaluating the effect of increasing grid density on the resultant estimation accuracy, the block size of 0.5^0 has been taken as a constant to facilitate easy comparison.

Using the semi-variogram parameters determined earlier, the effect of the following three grids has been evaluated.

i) 0.5^0 grid

ii) 0.25^0 grid

iii) 0.125^0 grid

For each of the above three grids, the anticipated relative standard deviations of the kriged estimates for abundance have been computed, as abundance is highly variable and negatively skewed when compared to the normal distribution exhibited by the grade parameters. The results are summarized below:

Exploration Grid	Anticipated Relative Std. Dev. of estimate for abundance for 0.5^0 blockwise
0.5^0	50% Approx.
0.25^0	20% Approx.
0.125^0	10% Approx.

The relative standard deviation for an intermediate grid may be approximately computed by interpolation of above results.

CHAPTER - 4

GRADE-TONNAGE RELATIONSHIP

In this chapter, grade – tonnage relationship as a function of cut – off grades of nodules and its application for selection has been presented. Let us consider a nodule deposit with an estimated total tonnage T and an overall mean grade G. Quite often, mining of ore of grade G is not a workable proposition and it becomes necessary to reject some blocks of lower grade with tonnage t, the total exploitable tonnage then decreases to T - t and, its grade improves to G + g. There is thus an inverse relationship between the grade and the tonnage. This relationship is a function of cut - off grade - the grade below which individual blocks are rejected during mining. It is proposed to investigate in this chapter, how the cut-off grade influences the resultant mean grades. The results will also hold for abundance and hence the tonnage. Since the cut off may also be applied on abundance values.

However, before discussing the subject further, it may be in order to summarize here that [David, 1972; 1977] grade - tonnage curve is a function of (a) block size (b) estimation procedure (c) level of information and (d) part of the deposit for which the curve is computed. Further, the cut-off grades may be 'direct' and indirect. The 'direct' grade refers to the valuable constituent while the 'indirect' grade refers to impurities. However, usually and also in the present instance, cut-off grade implies direct grade unless specifically mentioned.

4.1 ESTIMATION OF GRADE – TONNAGE CURVE

For any given block size, at a given level of information the grade-tonnage curve may be computed at least in three distinct ways. They are -

(a) Curve based directly on estimated block values,

(b) Curve based only on statistical properties of estimated block values, and

(c) Curve based on statistical properties of theoretical block value distribution.

We shall discuss each of these three procedures separately:

4.1.1 Curve based directly on estimated block values

The Procedure of computing grade-tonnage curve based on estimated block values is rather straight forward since it consists of eliminating values below the successive cut-off grades and computing the frequency of the remaining values and their grades. The estimated block values themselves may be based on arithmetic means of inside samples, inverse distance weighting of sample values, kriged values and alike.

4.1.2 Curve based on statistical properties of estimated block value distribution

If the mean and variance of the distribution of estimated block values are available, the grade-tonnage curve may be computed using the properties of the distribution. These parameters may have been computed from the original estimates themselves or they may be the only information available without the estimated values. In either case, it is possible to compute such a curve. The prerequisite of such an analysis is the knowledge of the frequency distribution function which approximates the experimental values best. Since in ore deposits, log normal distribution is the most common law, we shall limit our investigations to this model only. However, purely empirical laws like Lasky's laws [Lasky, 1950] based on exponential model of ore distribution are not adequate. The parameters of the distribution must be determined in each case of application. Formery [See, Blais and Carlier, 1967] has provided graphic solution to the problem based on lognormal model. We shall, however, study the problem in some detail and present the results in more convenient forms.

Common logarithmic transformations

While there is no universal transformation that leads to normal distribution of transformed values, we shall consider the commonly used transformation here. Experience has shown that the two major groups of distributions - the positively skewed and the negatively skewed - lend themselves usually to different transformations. Accordingly, we shall briefly mention the commonly used transformations for the two groups.

(a) Group A (Positively skewed distribution):

For positively skewed distributions the logarithmic transformation is usually achieved by writing [Krige, 1960; Sichel, 1966]

$$Z = a + x$$
$$Z' = \log Z$$

Where 'x' is the original variable, say grade (% metal) and 'a' is a constant. The transformed variable Z' approximates normal distribution.

(b) Group B (Negatively skewed distribution):

In case of negatively skewed distributions the logarithmic transformation is often achieved by writing,

$$Z = b - x$$

$$Z' = \log Z$$

Where, 'x' is the original grade (% metal) and 'b' is a constant such that b ≥ x (maximum).

Computation of the curve

(a) Group A (Positively skewed distribution):

Since the newly defined variable Z follows lognormal distribution, we are allowed to use the following two relationships which hold for lognormal distributions [Aitchison and Brown, 1957]

(i) The frequency of values above the pre - given value Z_c is equal to,

$$P(Z > Z_C) = F(W_i) = \frac{1}{\sqrt{2\Pi}} \int_{W_i}^{\infty} \exp\left(-W^2/2\right) dw \qquad (4.1)$$

(ii) The mean value ($\bar{Z}_c$) of all Z value above the value Z_c is equal to,

$$\bar{Z}c = \bar{Z} \, \frac{F\left(w_i - \beta\right)}{F\left(w_i\right)} \qquad (4.2)$$

Where $F\left(w_i - \beta\right)$ represents, in geological terms, metal recovery, and,

$$w_i = \frac{1}{\beta} (\log Z_i - \log G)$$

β = logarithmic standard deviation of Z values,

Z_C = cut-off grade,

$\overline{Z}$ = population mean of z values,

G = geometric mean of Z value.

Using the relationship between G, $\overline{Z}$ and β [Koch and Link, 1971], we may express W_i as,

$$w_i = \frac{1}{\beta} \log\left[\frac{Z_i}{Z}\right] + \beta/2 \quad \text{and}$$

$$w_i - \beta = \frac{1}{\beta} \log\left[\frac{Z_i}{Z}\right] + \beta/2$$

(b) Group B (Negatively skewed distribution):

In view of the transformation discussed earlier for this group, we are concerned herewith the frequency of values below the cut - off value Z_c and not above Z_c. We thus have the following two relations.

(i) The frequency of values below the pre - given value Z_c is equal to

$$P(Z < Z_C) = F'(W_i) = \frac{1}{\sqrt{2\Pi}} \int_{\infty}^{W_i} \exp\left(- W^2 / 2\right) dw \tag{4.3}$$

(ii) The mean value of all Z value above the value Z_c is equal to,

$$\overline{Z}_C = \overline{Z} \frac{F' (w_i - \beta)}{F' (wi)} \tag{4.4}$$

It is evident that the functions $F(W_i)$, $F'(W_i)$. $F(W_i - \beta)$. $F'(W_i - \beta)$ will be a family of straight lines on logarithmic probability paper for different β values and the two F and F' functions are related as.

$$F(W_i) = 100 - F'(W_i)$$
$$F(\overline{W_i} - \beta) = 100 - F'(W_i - \beta)$$

The above functions have been evaluated for varying cut - off grades Z_c and the results are presented in the figures (Fig. 4.1 and 4.2). Figure 4.1 plots $F(w_i)$ and $F'(w_i)$ functions for a set of β^2 values. Thus the curves in figure 4.1 give the % ore tonnage above the cut-off grade expressed in terms of population mean $(Zc\ /\ \overline{Z})$. Figure 4.2 plots the $F(w_i - \beta)$ and $F'(W_i - \beta)$ functions which give the % metal recovery above the cut-off grade $(Zc\ /\ \overline{Z})$. The graphic solutions provided above can be directly used to compute the % ore tonnage above any given cut-off grade and the % metal recovery at that cut - off grade. As may be seen from the figures (Fig. 4.1 and 4.2), the F functions are read on the left hand side which give the % ore tonnage and % metal recovery at given cut - off grades for the group A distributions for the 'direct' grades. The F functions as read on the right hand side of the graph give % ore tonnage and % metal recovery at given cut-off grades for the Group B distributions for the direct grades. However, these curves (right hand side) are also valid for 'indirect' grades which are originally positively skewed but respond to the logarithmic transformations discussed for positively skewed distributions.

It may be remarked that the computations of mean grades above given cut~ off grades are straight forward and is given by,

$$\text{Mean grade above cut-off } (\overline{Z}c) = \frac{\%\text{ metal recovery}}{\%\text{ ore tonnage}} \times \overline{Z} \qquad \text{or}$$

$$\overline{Z}c = \overline{Z}\,\frac{F(w_i)}{F(w_i - \beta)} \text{ for group A,}$$

$$= \overline{Z}\,\frac{F'(w_i)}{F'(w_i - \beta)} \text{ for group B.}$$

4.1.3 Curve based on statistical properties of theoretical block value distribution

The computation of grade - tonnage curve for theoretical (true) block values requires that the mean and the variance parameters of the distribution of true block values be known. With these parameters, the grade - tonnage curve may be computed directly from the graphic solutions discussed in the earlier section. The assumption in this case, however, is that the theoretical block values may be described by the lognormal model discussed earlier.

While the mean of the theoretical value distribution is straight forward to compute, the variance computations are somewhat involved. We may write an expression for the variance of 3-dimensional block as [Matheron, 1963; 1967]

$$\mathrm{Var}(Z_t) = \frac{8}{(a\,b\,c)^2} \int_a \int_b \int_c (a-x)(b-y)(c-z)\, C\left(\sqrt{x^2+Y^2+Z^2}\right) dx\, dy\, dz$$

where a, b and c represent the block dimensions. Thus, once the covariance functions have been estimated in the three principal directions, it is possible to compute the variance of the blocks of given dimensions. With the variance of block means and the population mean known, the grade-tonnage curve may be computed using the graphic solutions (Fig. 4.1 and 4.2) provided.

4.2 Study of grade-tonnage curve for the nodule area under study

The grade - tonnage computations presented in the following sections are based on different block dimensions. The results of studies using different techniques will be discussed separately. There are two relative objectives of the investigations for the nodule study area. First, it is intended to demonstrate the dependence of the curve on the block size and second, to develop a practical decision tool to select areas having greater potential in terms of abundance and grade. The results of the study are presented in terms of evaluation of impact of cut-off values on resultant values.

4.3 Impact of cut-off values on resultant values

It is appropriate to summarize the basis of analysis before the results are presented.

1) The analysis has been made on the stationwise mean values as well as on the blockwise kriged estimates of abundance and the metal grades. This is done to evaluate the response surface relating to extreme volume sizes for selection. Thus, as will be illustrated later, the two sets of results represent

the boundary limits within which the selected area may ultimately fall for a given set of requirements.

2) The cut-off criteria have been applied on abundance as well as each of the metal values separately.

3) For any variable considered for application of cut - off, the resultant values have been computed for all the variables under study corresponding to the stations / blocks selected as per the cut-off criteria.

4) For each variable selected for the cut-off studies, the analysis has been done in two forms. They are -

   - For given categories of limits of abundance as well as metal values, the resultant means of values lying within these limits have been computed in the first form. This is termed as category wise results.

   - In the second form, for specified cut - off limits, the resultant means of all values lying above the limit have been computed. This is termed as cumulative results.

4.4 Results

The results of cut - off value resultant value analysis have been presented in tabular as well as graphic forms. While the analysis has been carried out for all the variables, the presentation of results here is limited to abundance and grade only. Tables 4.1 to 4.4 present the category wise and the cumulative results for abundance and grade corresponding to stationwise values while tables 4.5 to 4.8 present the same results for abundance and grade corresponding to blockwise values. Further graphic presentation of the results is made in figure 4.3 A, B for abundance and grade respectively for sample wise values and in figure 4.4 A, B for blockwise abundance and grade values respectively.

A remark on computation method

All the computations discussed above have been made using stationwise or blockwise values directly. However, the computations based on the parameters of lognormal distribution were also carried out which produced similar results except that the resultant curves were smoother than those based on direct values. For presentation purpose, the direct results only have been used.

4.5 Discussion

Sample wise values

It is clear from the graphic as well as tabular results (Table 4.2 and Fig. 4.3 A) that if the selection had to be based entirely on abundance, 50 % of the samples and hence approximately 50 % of the study area will have an estimated abundance of about 9 kg/sq. m. This provides the upper limit of the mean abundance for 50% of the study area.

\If a similar analysis is made, on the assumption that, the selection is based entirely on grade values (Table 4.4 and Fig. 4.3 B), 50 % of the area is expected to have about 2.9 % of grade. This represents therefore the upper limit of grade value for the 50 % of the study area.

For arriving at an estimate for a combination of abundance and grade values, it appears logical that larger weightage be given to abundance since areas with low abundance are likely to provide poor response to the mining system of the first generation under development. Thus, as a first approximation, the cumulative probability for abundance is taken at 60 % and for grade at 85 %. This combination would result in an overall joint probability of 50 % with the resultant abundance of 8.2 kg/sq. m. and grade of 2.6 % assuming abundance and grade to be independent as first approximation. Thus, a likely scenario that emerges is that with selection on sample wise values, 50 % of the study area is expected to have the following in situ values.

Abundance: 8.2 kg/sq. m.
Grade: 2.6 %

Blockwise values

Just as in case of sample wise values, an analysis based on blockwise values have also been carried out. It is clear from the results presented in tabular as well as graphic forms (Table 4.6, and Fig. 4.4 A) that if the selection had to be based entirely on blockwise abundance values, 50 % of the blocks and hence 50 % of the study area will have an estimated abundance of about 6.5 kg/sq. m. This is the upper limit of the mean abundance for 50 % of the study area with a unit of selection as 0.25°XO.25°. Similarly, if the selection was based entirely on blockwise grade values (Table 4.8 and Fig. 4.4 B), 50 % of the area is expected to have about 2.64 % grade. This is thus the upper limit of grade value for the 50 % of the study area based on block as a selection unit.

However, in order to estimate the combined values of abundance and grade in 50 % of the study area, a cumulative probability of 60 % for abundance and 85 % for grade may be assumed which gives a resultant abundance of 6.2 kg/sq. m. and grade of 2.4 %. Thus, another likely scenario that emerges is that with the selection based on blocks of size 0.25° X 0.25°, 50 % of the study area is expected to have the following in situ values.

Abundance: 6.2 kg/sq. m.
Grade: 2.4%

4.6 Remark on the grade-tonnage curve

A clear difference between the two experimental curves based on stationwise and blockwise values demonstrates the dependence of the curve on block size. The curve dependent on stationwise value is too optimistic and is not realizable in practice. In contrast, the curves based on block values relate to a somewhat larger block size to be considered a "take it" or "leave it" unit. However, if the selection has to be ultimately based on smaller block sizes, the resultant abundance and grade value of selected blocks will fall within the limits developed above.

Table 4.1: Category-wise results for cut-off of station-wise abundance values in the study area.

Abundance category	Resultant values in the abundance category							
	Abundance (Kg/m^2)	Mn (%)	Co (%)	Ni (%)	Cu (%)	Grade (%)	Stations in category No.	(%)
> 10.00	12.874	22.531	0.169	0.943	0.789	1.902	107	16.797
9.00-10.00	9.408	23.788	0.158	1.088	1.017	2.264	29	4.553
8.00-9.00	8.568	24.316	0.135	1.141	1.045	2.321	29	4.553
7.00-8.00	7.488	24.636	0.139	1.178	1.196	2.514	43	6.750
6.00-7.00	6.513	24.971	0.134	1.248	1.175	2.558	59	9.262
5.50-6.00	5.777	25.790	0.115	1.269	1.303	2.688	23	3.611
5.00-5.50	5.222	24.745	0.121	1.304	1.292	2.718	24	3.768
4.50-5.00	4.724	25.490	0.116	1.281	1.275	2.673	22	3.454
4.00-4.50	4.180	26.146	0.102	1.397	1.401	2.902	26	4.082
3.75-4.00	3.857	24.672	0.112	1.201	1.229	2.545	16	2.512
3.50-3.75	3.640	26.122	0.090	1.366	1.417	2.871	11	1.727
3.25-3.50	3.373	22.912	0.136	1.159	1.037	2.333	11	1.727
3.00-3.25	3.122	25.378	0.099	1.344	1.385	2.831	15	2.355
2.75-3.00	2.871	23.719	0.110	1.285	1.277	2.671	15	2.355
2.50-2.75	2.631	25.411	0.100	1.318	1.269	2.687	18	2.826
2.25-2.50	2.385	23.894	0.115	1.280	1.192	2.589	15	2.355
2.00-2.25	2.166	26.250	0.090	1.499	1.549	3.139	7	1.099
1.50-2.00	1.737	26.827	0.104	1.303	1.353	2.760	30	4.710
1.00-1.50	1.242	26.071	0.110	1.253	1.185	2.549	24	3.768
0.00-1.00	0.337	23.853	0.089	1.310	1.287	2.688	113	17.739
Total	**5.531**	**23.932**	**0.144**	**1.117**	**1.037**	**2.299**	**637**	**100.000**

Table 4.2: Cumulative results for cut-off of station-wise abundance values in the study area.

Abundance cut-off	**Resultant values at the cut-off**							
	Abundance (Kg/m^2)	**Mn (%)**	**Co (%)**	**Ni (%)**	**Cu (%)**	**Grade (%)**	**Stations above cut-off No.**	**(%)**
10.00	12.874	22.531	0.169	0.943	0.789	1.902	107	16.797
9.00	12.135	22.745	0.167	0.968	0.828	1.964	136	21.350
8.00	11.508	22.963	0.163	0.992	0.858	2.013	165	25.903
7.00	10.677	23.178	0.160	1.016	0.901	2.078	208	32.653
6.00	9.757	23.448	0.156	1.051	0.942	2.150	267	41.915
5.50	9.441	23.558	0.154	1.061	0.959	2.175	290	45.526
5.00	9.119	23.615	0.152	1.073	0.975	2.201	314	49.294
4.50	8.831	23.690	0.151	1.081	0.987	2.220	336	52.747
4.00	8.497	23.772	0.149	1.092	1.001	2.243	362	56.829
3.75	8.301	23.794	0.148	1.094	1.007	2.250	378	59.341
3.50	8.169	23.828	0.147	1.098	1.013	2.259	389	61.068
3.25	8.037	23.817	0.147	1.099	1.013	2.260	400	62.794
3.00	7.859	23.840	0.147	1.103	1.018	2.269	415	65.149
2.75	7.685	23.839	0.146	1.105	1.022	2.274	430	67.504
2.50	7.482	23.866	0.145	1.109	1.026	2.281	448	70.330
2.25	7.317	23.866	0.145	1.111	1.028	2.285	463	72.684
2.00	7.240	23.874	0.145	1.112	1.030	2.288	470	73.783
1.50	6.910	23.918	0.144	1.115	1.035	2.295	500	78.493
1.00	6.650	23.933	0.144	1.116	1.036	2.296	524	82.261
0.00	5.531	23.932	0.144	1.117	1.037	2.299	637	100.000
Total	**5.531**	**23.932**	**0.144**	**1.117**	**1.037**	**2.299**	**637**	**100.000**

Table 4.3: Category-wise results for cut-off of station-wise grade values in the study area.

Abundance category	Resultant values in the grade category							
	Abundance (Kg/m^2)	Mn (%)	Co (%)	Ni (%)	Cu (%)	Grade (%)	Stations in category No.	(%)
> 2.50	4.851	26.084	0.119	1.380	1.373	2.872	249	56.591
2.40-2.50	5.896	25.321	0.132	1.163	1.156	2.451	23	5.227
2.30-2.40	7.380	25.109	0.141	1.125	1.077	2.345	18	4.091
2.20-2.30	6.291	24.488	0.142	1.063	1.038	2.245	14	3.182
2.10-2.20	6.832	24.071	0.140	1.031	0.960	2.133	26	5.909
2.00-2.10	6.520	23.409	0.151	1.010	0.900	2.061	23	5.227
1.90-2.00	8.422	23.483	0.145	0.937	0.873	1.954	11	2.500
1.80-1.90	7.275	24.585	0.149	0.920	0.771	1.841	8	1.818
1.70-1.80	8.865	20.537	0.186	0.902	0.653	1.745	13	2.955
1.60-1.70	11.191	20.964	0.170	0.841	0.645	1.654	12	2.727
1.50-1.60	10.503	19.291	0.193	0.680	0.464	1.339	43	9.773
Total	**6.236**	**23.950**	**0.144**	**1.117**	**1.039**	**2.301**	**440**	**100.000**

Table 4.4: Cumulative results for cut-off of station-wise grade values in the study area.

Grade cut-off	Resultant values at the cut-off							
	Abundance (Kg/m^2)	Mn (%)	Co (%)	Ni (%)	Cu (%)	Grade (%)	Stations above cut-off No.	(%)
2.50	4.851	26.084	0.119	1.380	1.373	2.872	249	56.591
2.40	4.939	26.007	0.120	1.358	1.351	2.829	272	61.818
2.30	5.091	25.926	0.122	1.337	1.326	2.786	290	65.909
2.20	5.146	25.845	0.123	1.321	1.310	2.755	304	69.091
2.10	5.279	25.664	0.125	1.292	1.274	2.692	330	75.000
2.00	5.360	25.486	0.127	1.269	1.245	2.642	353	80.227
1.90	5.452	25.392	0.128	1.254	1.227	2.610	364	82.727
1.80	5.491	25.369	0.128	1.244	1.214	2.588	372	84.545
1.70	5.605	25.111	0.132	1.226	1.184	2.543	385	87.500
1.60	5.774	24.868	0.134	1.204	1.153	2.491	397	90.227
1.50	6.236	23.950	0.144	1.117	1.039	2.301	440	100.00
Total	**6.236**	**23.950**	**0.144**	**1.117**	**1.039**	**2.301**	**440**	**100.000**

Table 4.5: Category-wise results for cut-off of block-wise kriged abundance values in the study area.

Abundance category	Resultant values in the abundance category							
	Abundance (Kg/m^2)	Mn (%)	Co (%)	Ni (%)	Cu (%)	Grade (%)	Blocks in category No.	(%)
> 5.00	6.718	22.869	0.152	1.062	0.986	2.199	94	46.766
4.50-5.00	4.65	24.429	0.133	1.186	1.135	2.457	18	8.955
4.00-4.50	4.221	24.292	0.134	1.186	1.080	2.402	23	11.443
3.75-4.00	3.843	22.689	0.169	1.041	0.902	2.115	7	3.483
3.50-3.75	3.640	24.873	0.129	1.299	1.171	2.601	8	3.980
3.25-3.50	3.372	25.044	0.113	1.311	1.237	2.661	9	4.478
3.00-3.25	3.129	23.708	0.140	1.166	1.038	2.344	15	7.463
2.75-3.00	2.869	24.615	0.136	1.185	1.067	2.391	8	3.980
2.50-2.75	2.623	25.955	0.118	1.336	1.215	2.666	13	6.468
2.25-2.50	2.348	26.105	0.117	1.299	1.224	2.641	4	1.990
2.00-2.25	1. 860	24.926	0.155	1.028	0.849	2.037	2	0.995
Total	**5.054**	**23.470**	**0.145**	**1.116**	**1.032**	**2.293**	**201**	**100.000**

Table 4.6: Cumulative results for cut-off of block-wise kriged abundance values in the study area.

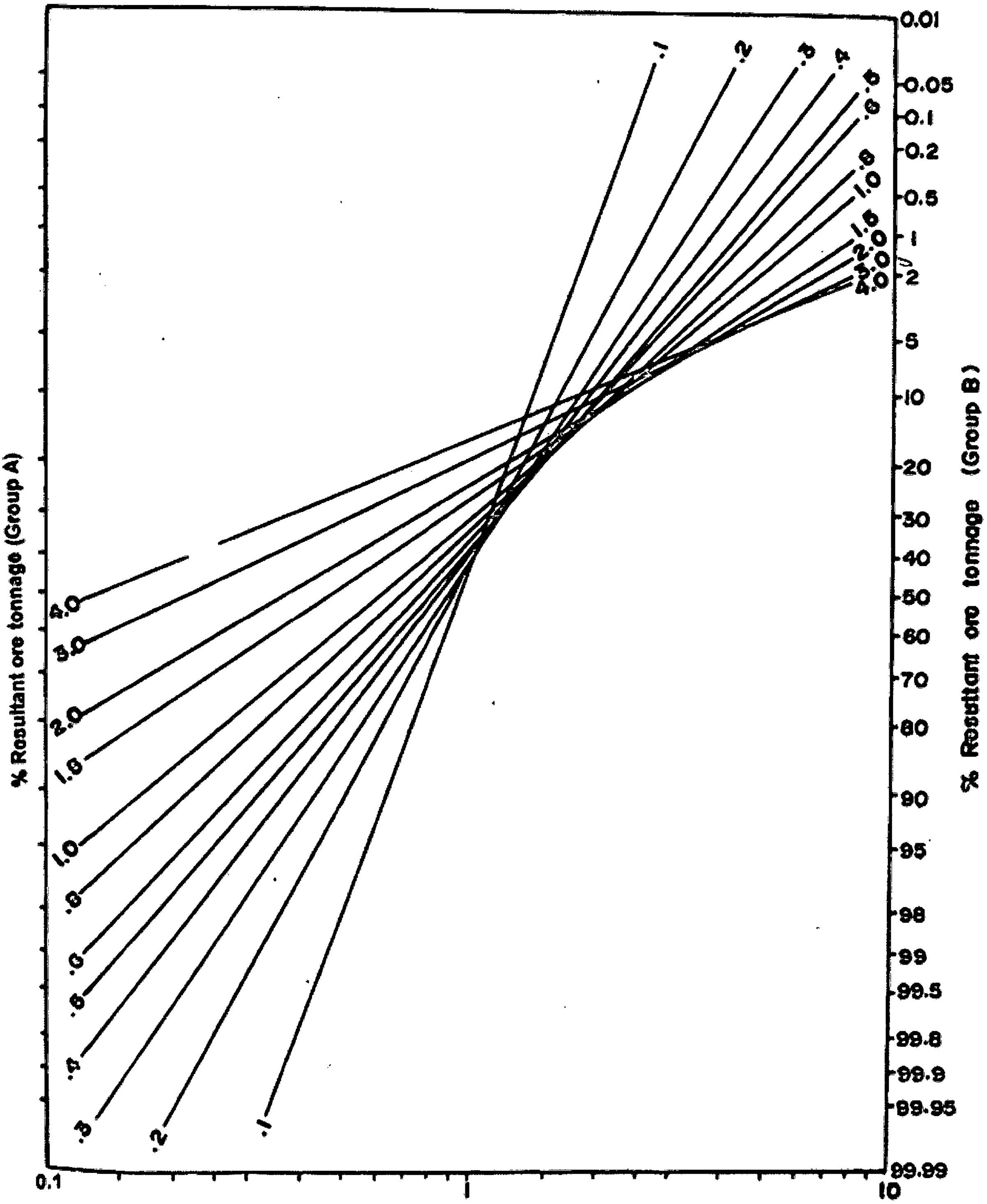
Abundance cut-off	Resultant values in the abundance cut-off							
	Abundance (Kg/m^2)	Mn (%)	Co (%)	Ni (%)	Cu (%)	Grade (%)	Blocks above cut-off No.	(%)
5.00	6.718	22.869	0.152	1.062	0.986	2.199	94	46.766
4.50	6.386	23.051	0.149	1.076	1.004	2.230	112	55.721
4.00	6.017	23.200	0.148	1.089	1.013	2.250	135	67.164
3.75	5.910	23.183	0.148	1.088	1.009	2.246	142	70.647
3.50	5.789	23.240	0.148	1.095	1.015	2.258	150	74.627
3.25	5.652	23.301	0.146	1.102	1.022	2.271	159	79.104
3.00	5.434	23.321	0.146	1.105	1.023	2.275	174	86.567
2.75	5.322	23.352	0.146	1.107	1.024	2.278	182	90.547
2.50	5.142	23.440	0.145	1.115	1.031	2.291	195	97.015
2.25	5.086	23.465	0.145	1.117	1.032	2.294	199	99.005
2.00	5.054	23.470	0.145	1.116	1.032	2.293	201	100.000
Total	**5.054**	**23.470**	**0.145**	**1.116**	**1. 032**	**2.293**	**201**	**100.000**

Table 4.7: Category-wise results for cut-off of block-wise kriged grade values in the study area.

Grade category	Resultant values in the grade category							
	Abundance (Kg/m^2)	Mn (%)	Co (%)	Ni (%)	Cu (%)	Grade (%)	Blocks in category No.	(%)
> 2.50	4.012	25.440	0.115	1.366	1.294	2.775	72	35.821
2.40-2.50	5.797	24.433	0.143	1.188	1.107	2.437	15	7.463
2.30-2.40	5.270	24.579	0.144	1.121	1.086	2.355	21	10.448
2.20-2.30	5.318	23.406	0.150	1.078	1.028	2.258	31	15.423
2.10-2.20	6.732	22.640	0.154	1.032	0.964	2.147	13	6.468
2.00-2.10	6.692	22.685	0.155	0.985	0.918	2.056	9	4.478
1.90-2.00	7.353	21.787	0.171	0.908	0.871	1.950	6	2.985
1.80-1.90	4.553	21.385	0.165	0.900	0.781	1.851	7	3.483
1.70-1.80	4.567	19.623	0.181	0.841	0.704	1.725	6	2.985
1.60-1.70	4.491	20.882	0.188	0.842	0.610	1.640	14	6.965
1.50-1.60	7.207	18.795	0.164	0.793	0.551	1.507	7	3.483
Total	**5.054**	**23.470**	**0.145**	**1.116**	**1.032**	**2.293**	**201**	**100.000**

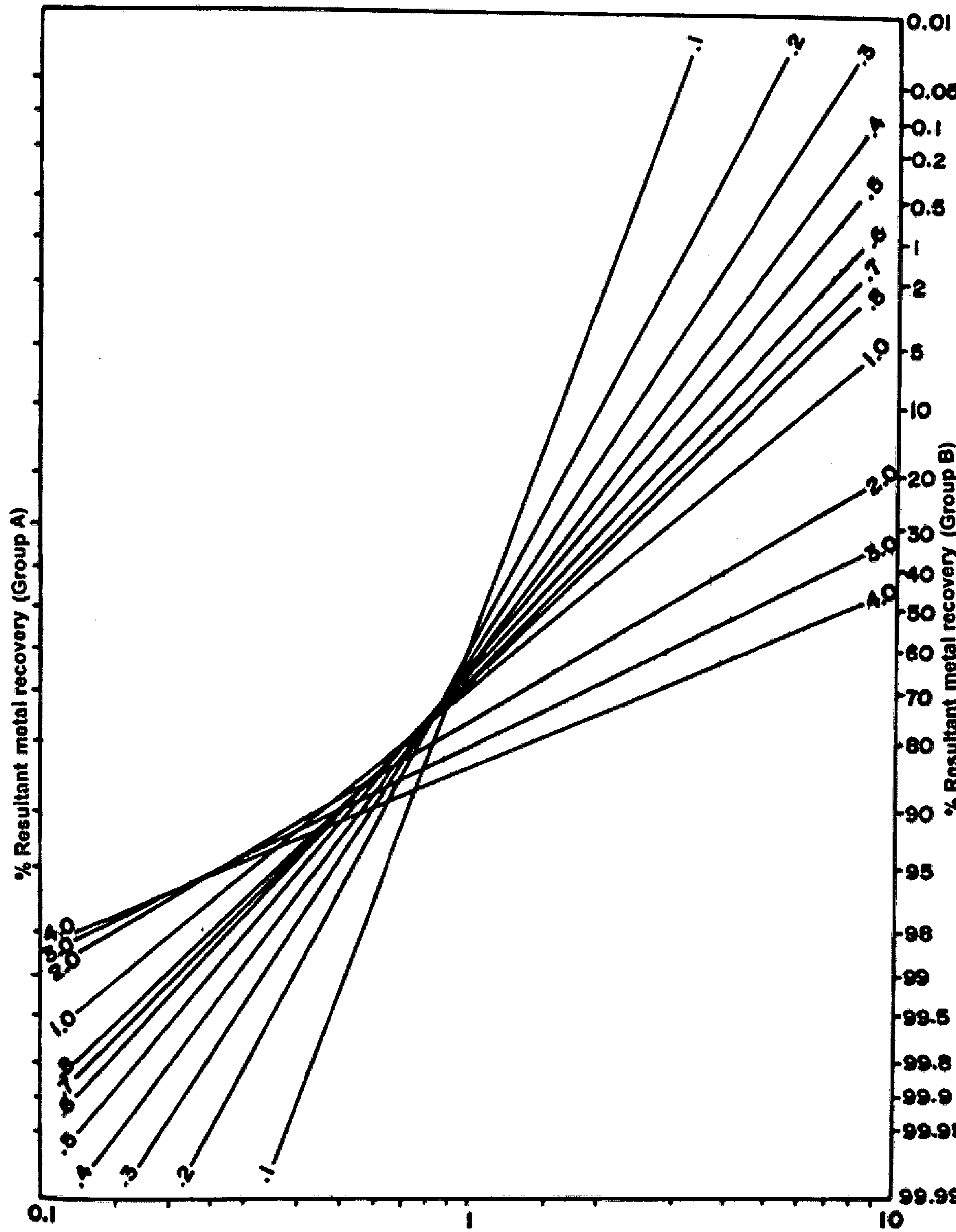
Table 4.8: Cumulative results for cut-off of block-wise kriged grade values in the study area.

Grade cut-off	Resultant values at the cut-off							
	Abundance (Kg/m^2)	Mn (%)	Co (%)	Ni (%)	Cu (%)	Grade (%)	Blocks above cut-off No.	(%)
2.50	4.012	25.440	0.115	1.366	1.294	2.775	72	35.821
2.40	4.319	25.207	0.122	1.325	1.251	2.697	87	43.284
2.30	4.504	25.064	0.127	1.278	1.213	2.619	108	53.731
2.20	4.686	24.644	0.133	1.228	1.166	2.528	139	69.154
2.10	4.861	24.407	0.135	1.205	1.142	2.483	152	75.622
2.00	4.963	24.277	0.137	1.188	1.125	2.450	161	80.100
1.90	5.049	24.147	0.138	1.173	1.112	2.424	167	83.085
1.80	5.029	24.046	0.139	1.163	1.100	2.403	174	86.567
1.70	5.014	23.912	0.141	1.154	1.088	2.383	180	89.552
1.60	4.976	23.715	0.144	1.133	1.057	2.334	194	96.517
1.50	5.054	23.470	0.145	1.116	1.032	2.293	201	100.000
Total	**5.054**	**23.470**	**0.145**	**1.116**	**1. 032**	**2.293**	**201**	**100.000**



Cut off Grade ($Z_c / \overline{Z}$)

Fig. 4.1: Resultant % ore tonnage for varying cut-off grades under log model



Cut off Grade ($Z_c / \overline{Z}$)

Fig. 4.2: Resultant % metal recovery for varying cut-off grades under log model

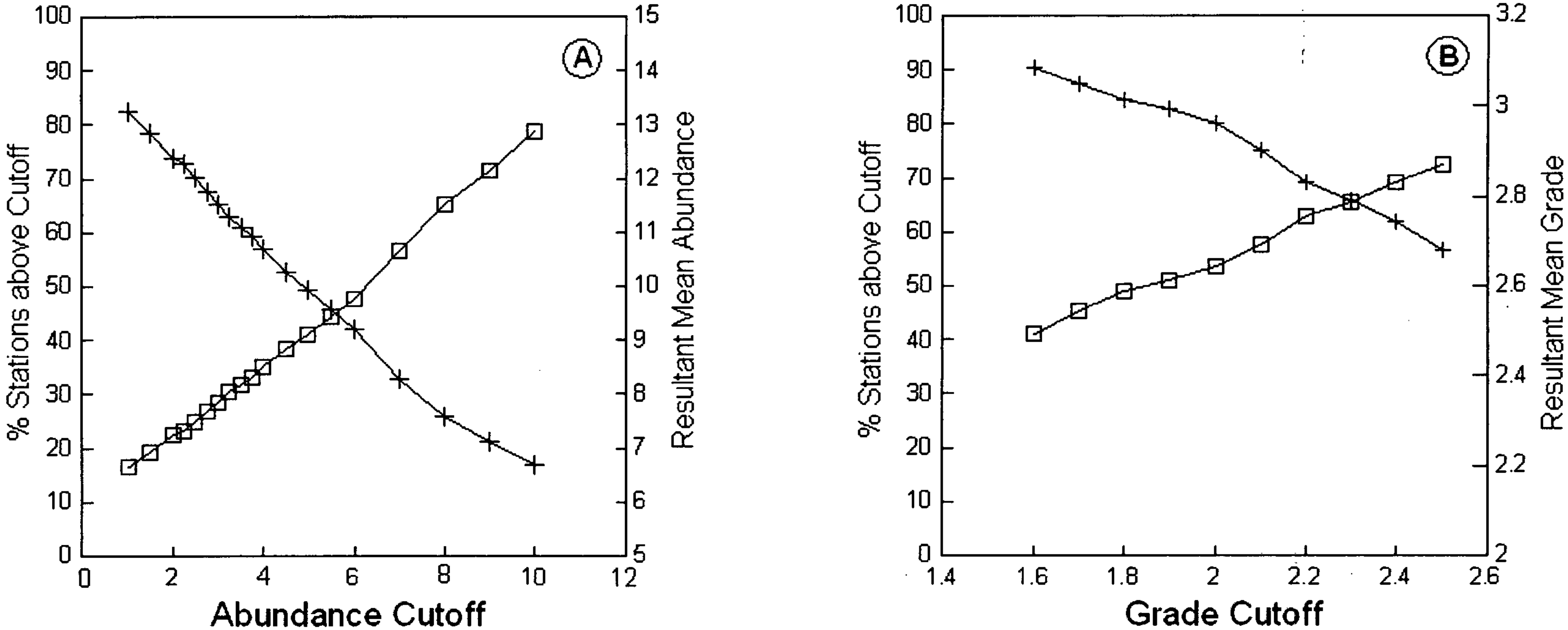


Fig. 4.3: Cut-off value – Resultant value curves for the Study Area.
A) For station-wise Abundance values,
B) For station-wise Grade values.

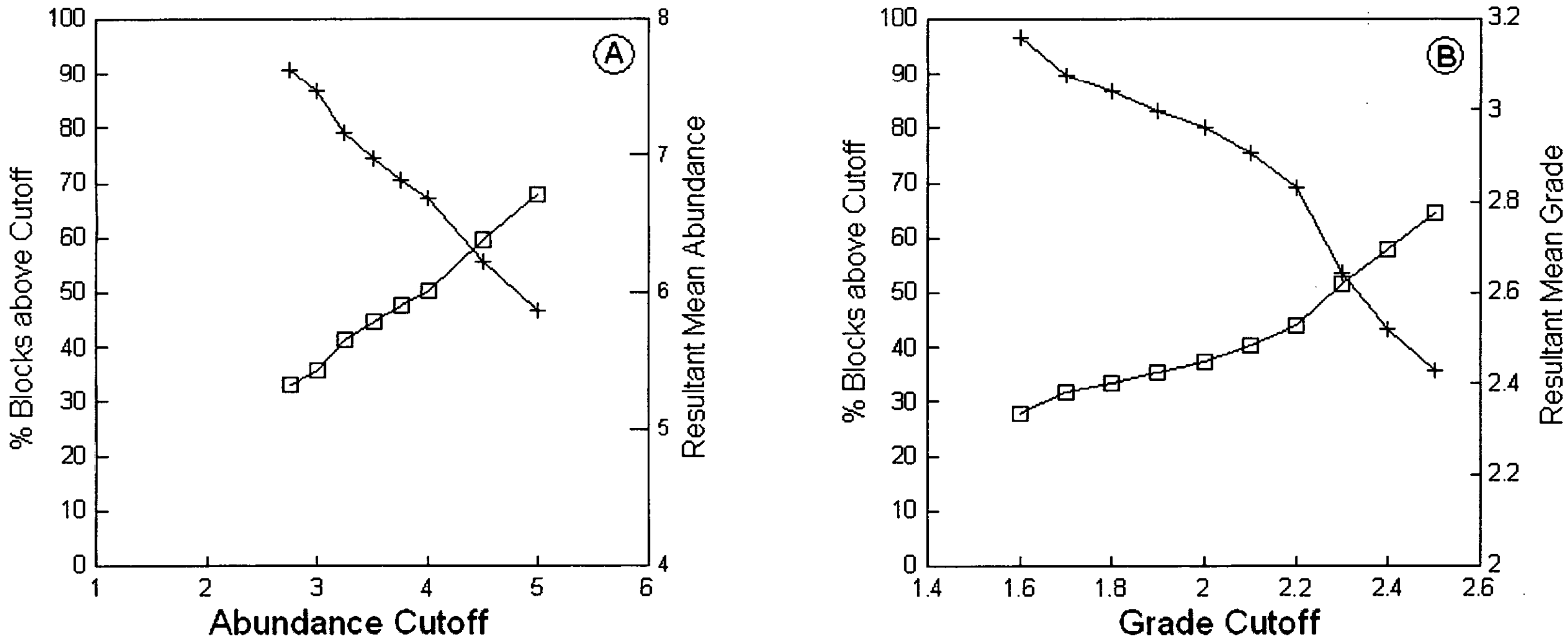


Fig. 4.4: Cut-off value – Resultant value curves for the study Area.
A) For block-wise kriged Abundance values,
B) For block-wise kriged Grade values.

CHAPTER - 5

DEEP SEABED MINING

The deep seabed mining with special reference to developmental status and requirements is presented in this chapter. During last three decades many patents for various components of mining systems have already been issued. The exploration work done so far reveals that although the task is far from being completed, the possibility of commercial mining using first generation equipment and methods is foreseen in near future.

5.1 TYPES OF AVAILABLE MINING SYSTEMS

Nodule mining technology involves picking-up of the nodules from the ocean bed and bringing them to the vessel. Following four alternative design concepts for mining systems have been developed and are being improved further.

- Passive nodule collector with hydraulic lift or air lift system (Fig. 5.1)
- Self propelled active collector with hydraulic lift or air lift system (Fig. 5.2)
- Continuous Line Bucket (CLB) Mining systems (Fig. 5.3)
- Modular or shuttle Mining system (Fig. 5.4)

All the systems have been developed and tested over the years. Broad features of each mining system are outlined in the following paragraphs to provide an overall picture.

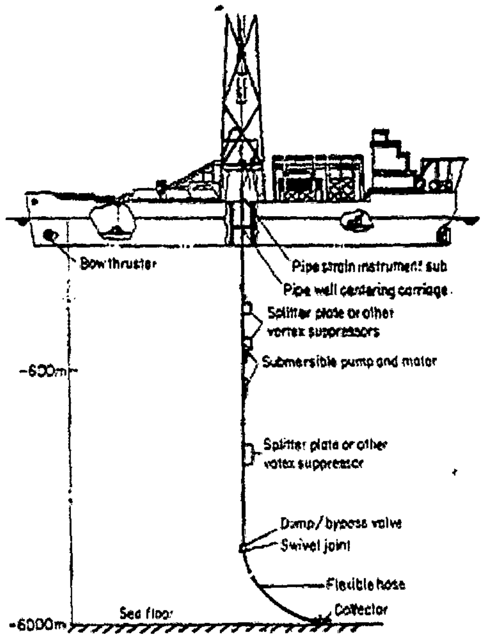


Figure 5.1 The passive towed system

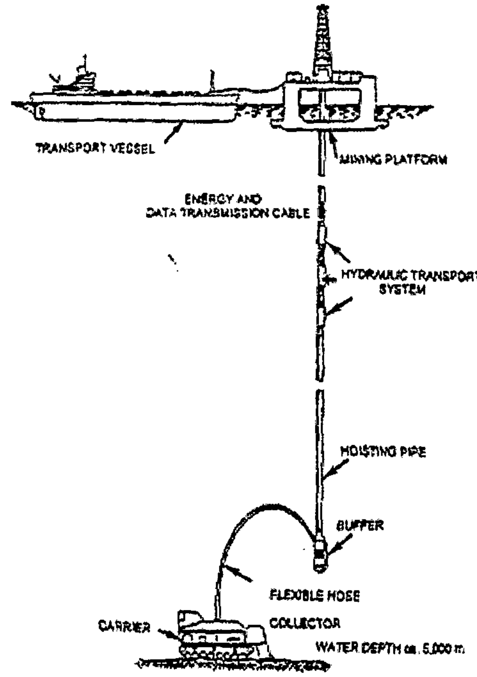


Figure 5.2 The active self-propelled system

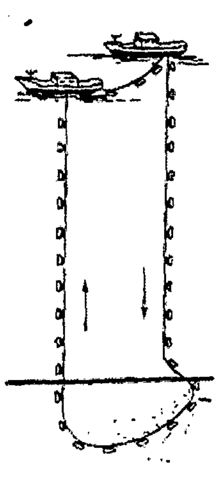


Figure 5.3 The continuous line bucket system

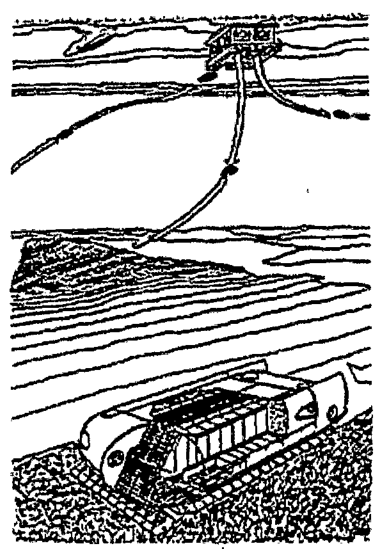


Figure 5.4 The submarine shuttlet system

5.1.1 Hydraulic mining system (pump lift/ air lift)

A lift pipe, fitted to the ship, extends close to the bottom of the seabed. A collector mechanism is linked to the end of the lift pipe and it picks up the nodules and feeds them into the pipe. The nodules are then either pumped up through the pipe by pumps fixed to the pipe, or sucked up through the pipe by compressed air injected into the pipe. Two types of hydraulic mining systems are given in Fig 5.1 and 5.2.

In 1978, Ocean Management Inc's (OMI'S), international team conducted a pilot mining test (PMT) in the eastern equatorial Pacific (Middelhaufe, 1979; Bath, 1989; Oebius, 1993). The international Nickel Co. (INCO) was one of the OMI's partners. The experts from Germany and Japan also participated in this endeavor. The basic elements of the mining system can be divided into following subsystems.

a. Collection sub-system (Passive or Active collector)
b. Lift sub-system
c. Mining ship sub-system

5.1.2 Continuous Line Bucket (CLB) mining system

A long continuous loop of rope, attached with draft buckets, is hung over a surface platform in sea such that end of loop touches the sea floor. When the loop is caused to rotate, the buckets during their passage on sea floor, excavate nodules and carry them to the surface. If the platform moves in a direction of right angles to the plane of the loop, then a path having its width equal to the length of the platform is swept across the ocean floor. This principle of Continuous Line Bucket System (CLB) is represented in Figure 5.2. Japan Ocean Resources Association used their vessel chiyoda Maru No.2 for successful testing of CLB Mining system during 1970 (Masuda et al., 1971). The components of the system consisted of bucket sub-system, rope sub-system and ship sub-system. The end of the main cable is brought from storage in the hold, through the bow friction drive, by passing the outboard idler pulley, over the idler pulleys on the superstructure and through the stern drive in normal fashion. It is then manhandled outboard of the ship to the bow friction drive, where it is secured above the idler pulley. The line is opened out so that the loop falls freely. To compensate for the buoyancy of the rope, weights are added to the bucket loops until line equivalent to about 1.5 times the depth of water is opened out. This is followed by attachment of buckets at regular interval of around 25 M until a total length of line equal to three times the water depth has been let out. The line from the hold is then cut and the two ends are joined to form a continuous loop. As the loop is rotated through the system, weights and buckets are removed at the forward drive; the buckets are emptied and then handled to the stern and placed in the line. The improved version of the system was also tested in 1987, using coastal fishing vessel up to a depth of 50 m (Masuda and Cruickshank, 1994).

5.1.3 Modular mining system

The principle of modular mining system is outlined below.

The collector or shuttle unit is designed to have sufficient buoyancy so that it is weightless in water (Herrouin, 1999). The collector is launched with ballast material such that the weight in water of the ballast material is equal to the weight in water of the nodules to be collected. The thrusters propel the unit down steadily, against hydrodynamic resistance alone, till it touches the seabed. The collector moves on the seabed, and as the collection proceeds, ballast material is simultaneously ejected on the basis of an equal weight in water. Ballast material ejection is continued until the weight of the unit is zero or slightly negative. Finally, the vehicle is propelled by thrusters to the surface, docked with the surface ship, unloaded, serviced, and reballasted for a few mining cycle. Thus, very little onboard power is required to collect the nodules, the major source of energy being the potential energy of the ballast material. The modular mining system comprises two sub-systems viz., the collector unit and the surface platform. The scheme of the system is represented in Figure 5.4.

5.2 EFFORTS BY PIONEER INVESTORS

There are 7 pioneer investors under the Deep sea bed mining regime, only a few pioneer investors (now contractors) are active for research and development of deep sea bed mining technology. A brief summary of their efforts are given below.

France

In 1970 and 1972 - 1976, the French group, AFERNOD (the Association Francaise pour l'E tude et la. Recherche des Nodules) conducted test of CLB system for mining Polymetalic Nodules. During the same period, other mining concepts were also scrutinized. In 1980, AFERNOD studied free shuttle mining concept which proposed the concepts of use of free unmanned submersible to collect nodules from sea bed and lift them to the surface. The program was then reoriented to a hydraulic lifting system with a motorized collector and was implemented in 1984 to 1989. A vehicle known as PLA2-6000 was designed, developed and performed a series of deep water dives in 1987 in the Medterranean Sea demonstrating its capabilities of dynamic flight, landing and moving around at the sea bottom, and finally takeoff to the surface (Herrouin, 1999).

China

COMRA (Chinese Ocean mineral Resources R and D Association) has developed two types of collectors, a hydraulic collector and a hybrid collector, both on a caterpillar track, one with a mechanical and other with a water jet pick up using a Coanda nozzle (Liu, 1995; Liu, 1997; Liu and Ning, 1999). A flexible hose between the collector and a buffer system on the main pipe lift system is part of the total mining system. However no open sea tests have been carried out so far.

Japan

Japan intended to develop a prototype mining system based on the R and D activities before comprehensive Ocean test. In 1995 (Inokuma, 1995), the plan for comprehensive ocean test was reviewed and the plan for full test of the integrated system was changed to four experiments which would contribute to the overall development of the Deep Seabed mining system. After completion of R and D project on nodule mining system, a tow sledge-type collector with a pressurized water jet flow collecting mechanism based on the Coanda effect was designed. The larger nodules are crushed in the collector before lifting. The collector will be towed by a pipe string composed of a flexible hose and lift pipes, collect nodules with water jet, separate seafloor sediments , crush nodules to a desirable size distribution, and feed them to the riser system . A large scale collector test was conducted in 1997 (Chung and Tsurusaki, 1994). The achievement in collecting efficiency was estimated as 87%. Japan does not have any plan right now and all R and D work towards mining technology development was stopped.

Korea

The Korean Ocean Research and Development institute (KORDI) started a 10 year program. As a part of the program nodule collector and integrated recovery system technology aspect was taken up. The work consisted of exploitation technology concept design, enhancement of existing sub systems which include a self propelled collector with flexible umbilical between the collector and the buffer, enhanced buffer function and conventional lift systems. The test collector has been reported as developed however no ocean test has yet been carried out (Hong Sup, 1995).

India

As a part of joint activities with University of Seigen in Germany, a crawler based shallow bed mining system has been developed and tested up to 400 m as a part of developing deep seabed mining system in phases. The system consisted of crawler based collector module, riser module (flexible hose) and control module (Fig 5.5)

The development of nodule collector and crusher along with the flexible hose riser system for a shallow depth is under progress. The data generated from testing at shallow bed has been used for a preliminary design documents for nodule mining up to a depth of 6000 m.

Germany

In 1970's OMI, a consortia of US with the participation of INCO Ltd of Canada, metallyesellschaft A G, preussag A G and salzgitter A G of Germany etc. worked for designing, developing and conducting mining test (Amann, 1991). At present no R and D activity on deep sea mining technology exists.

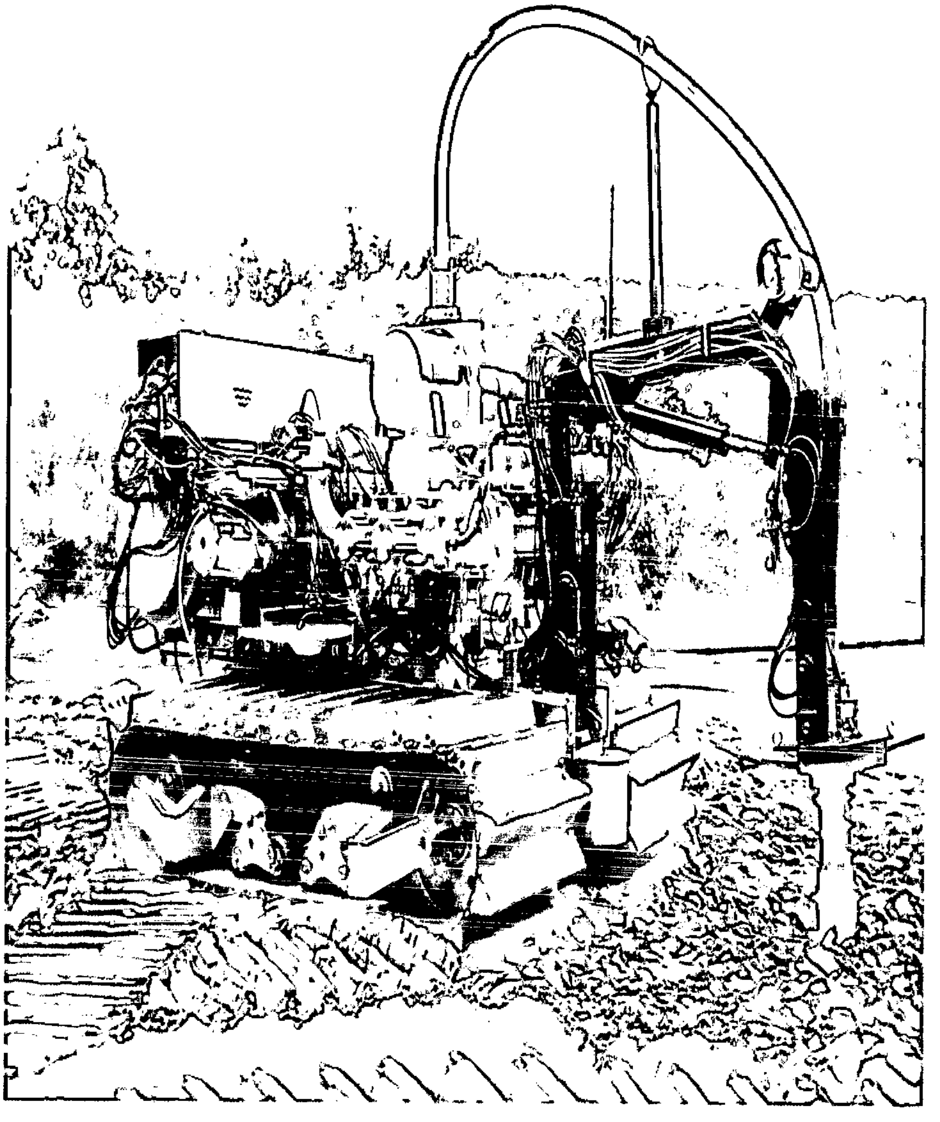


Fig. 5.5 Under water crawler undergoing land tests

5.3 REVIEW OF THE EXISTING SYSTEMS

5.3.1 General

The general assembly of the UN adopted a declaration principle as a come out of negotiations that took place in the seabed sub-committee. The declaration (General Assembly resolution 2749 (xxv)) was "the seabed and ocean floor, and the subsoil thereof, beyond the limits of national jurisdiction as well as resources of the area, are common heritage of mankind". It was also declared that this area" shall be open to use exclusively for peaceful purposes by all states without discrimination ".

In January 1974, private companies in the United kingdom, United states, Canada, Japan, Belgium, Italy and Germany were forming industrial consortia with the expressed purpose of exploring for and mining deposits of these minerals. The Kennecott Consortium (KCON) was formed in January 1974 and included Kennecott corporation parent company being Sohio of the US, Rio Tinto Zinc Corporation of the United Kingdom, British Petroleum Company Ltd. of the United Kingdom, Noranda Mines Ltd. of Canada and the Mitsubishi Group of Japan. In may 1974, Ocean Mining Associates (OMA) was formed as a partnership registered in the United States, with the US steel corporation of the US, Union Miniere of Belgium, Sun Company of the US and Ente Nazionale Idrocorburi of Italy as partners. AFERNOD was also established in 1974 in France and consisted of France's Centre National pour L'Exploitation des Oceans (CNEXO), the Commissariat a l' Energie Atomique, Societe Metallurgique le Nickel and Chantiers de France-Dunkerque. In March 74, Deep Ocean Resources Development (DORD) was formed as a public corporation in Japan. In February 1975 OMI was incorporated in the US with participation of INCO Ltd. Preussage AG of Germany SEDCO, Inc of the US and Deep Ocean

Mining company Ltd. of Japan. The Ocean mineral company (OMCO), consortia formed in November 1977 with Lockheed systems Co. etc.

The development of hydraulic pump lift and hydraulic air lift systems is based on the technology and experience gained in operating oil risers in deep waters and the know-how built in connection with slurry transportation of minerals at sea and on land (Amann, 1994).

The high reliability and survivability associated with various types of collectors designed and developed and tested by various agencies for the last three decades mainly concentrated on collectors which can be divided into passive and active collectors. The passive concept and ability to function without power, qualify them for use as commercial scale collectors. Passive collector is not acceptable for consideration of commercial mining system due to very low nodule collection and sediment rejection efficiency. According to Mr. Brockett CEO, sound oceanic system, USA (former OMI sr. engineer), the passive rake has the highest potential, however it needs further R and D investigation (Brockett and kollwentz, 1977). The passive plow concept should not also be considered due to excessive seafloor interactions.

5.3.2 Hydraulic mining system

The mechanical concept of US consortia has very high collection efficiency but it needs separate hydraulic sediment separating sub-systems. The concept has a large number of moving parts and is most complicated. The mechanical ramp design is more complicated than the drum design, but its ability to eliminate sediments is higher. The survivability and reliability of the system for long operation is doubtful (Brockett, 1999).

The family of hydraulic collectors has the potential for commercial mining operation. There is no substantial difference between design of hydraulic or mechanical ramp collectors from the point of view of collector size, weight, power and handling requirements (Brockett et al., 1979). The two considerations that would significantly influence the decision to use either design are system reliability and maintainability. According to recently published literature on the topic, hydraulic pump/ air lift system appear to be the most promising. As per kauffman, continuous hydraulic dredging approach (using air lift pumps) has been found the most effective system for efficient first generation commercial mining. Compared to CLB system, hydraulic mining system offers far more flexibility for control of the collector sub-system (self-towed collector) and the system can be designed as sufficiently rugged to surmount obstacles of a size, which is readily detected by a previous survey. In view of the relative merits of this system over other mining systems, most of the developmental and experimental works done so far relate to hydraulic mining system only. However, hydraulic mining system has the following limitations.

- It involves bulky and complicated sub-system, which are difficult of handle during operation at sea. A lot of auxiliary handling and controlling equipment are required in addition to the pipe, pump lift/ air lift and the equipment for crushing at seabed.

- Other difficulty with hydraulic mining system is its high reliability requirement. A minimum of 45 - 90 days mean-time-between-failure (MTBF) is considered essential. Further works on design of the propulsion mechanism in a self-propelled collector to achieve smooth movement on the sediment, positioning of the mining ship, the lift pipe and the collector; and the technology of slurry transfer are necessary, before a large-scale system test could be conducted to establish the minimum MTBF defined above.

The relative advantages and disadvantages of Air Lift (AL) and Hydraulic Pump Lift (HP) approaches are given below.

- The capital cost is almost the same for both the designs (AL and HP), while the energy cost is higher for AL, maintenance cost is higher for HP (Herrouin et al., 1989).
- Both the designs are equally reliable (i.e., meantime-between-failure is equal).
- The AL sub-system is likely to present significantly greater handling problems since it is essentially a two-pipe sub-system.

The decision between the two approaches is not readily apparent, therefore, some consortia were planning test of both lift approaches in their large scale demonstrations to choose the final one. But due to uncertainty, the large scale demonstrations did not take place.

5.3.3 CLB mining system

Some of the merits of CLB system are-

- The dredging technology and the operation of the system is simple
- There is high degree of flexibility in working in following respects
- Deposits with any size of nodules can be handled
- Big changes in bottom topography is permitted
- Bottom sediments of varying characteristics in greatly varying water depths can be handled
- System being light weight, can be mounted on any ocean going vessel
- The sediments are washed out during ascent of buckets, hence no separation problems on the surface
- Installation of underwater components is simple and rapid
- The submerged components - fibre rope and buckets, are available for routine checks and maintenance once during each cycle
- The system is potentially energy efficient because the descending line is counter-balanced by the ascending line and no water quantity is required to be transported with the nodules. As per Masuda, CLB system requires, 7,200 HP for a production of 6,000 tonnes per day while a comparable hydraulic dredging system requires 15,000 HP

- The system potentially involves relatively less capital cost compared to hydraulic mining system. As per Masuda, capital expenditure for hydraulic system is as much as several thousand per cent higher compared to CLB (system)
- The operating cost is low (As per Masuda, hydraulic mining system has as much as 50% higher operating cost compared to CLB system)
- Scaling up of the system is easily possible (5 tonnes capacity buckets using 25 tonnes breaking strength cable can produce 5000 tonnes per day at moderate costs)

The limitations of the system are -

- The ascending and descending segments of the line are prone to tangling, which may result-in immediate close-down of operation
- As the segment progress perpendicular to its line of action, the bottom line segment is highly vulnerable to snagging
- The efficiency of nodule pick-up is low (Loose sediments like sand silt and clay tend to fill-up the buckets, which not only affect the efficiency but also lead to serious environmental problems)
- Difficulty in precise tracking lead to insufficient collection from seabed
- There is lack of control of individual buckets (buckets may stay on the bottom long after they are filled and thus unnecessarily obstruct uncollected nodules, or they may be withdrawn before being completely filled)

In view of the above limitations, this system is being looked at in a limited way i.e., only of five consortia.

5.3.4 System Developed/ being developed by Pioneer Investors

COMRAS attempt for developing a mining system is basically for environmental friendly mining system. The design consideration has been taken into consideration of pick up system and transport of clean nodules without sediment. They have further considered, the weight of the collector to minimize the sinking into soft sediment, pipe size to prevent jamming and waste water discharge at a depth least likely to create negative impacts. Other design criteria were optimum collector width and high pick up efficiency.

AFERNOD's study of free shuttle mining concept for nodule mining could not progress much due to its economics for several decades.

JAPAN, though deep sea mining test carried out on the top of a Sea mount in the central-north-western Pacific Ocean, the collection efficiency was 87% with a collector speed between 0.3 and 0.8 knots.

To decrease the down time of the collector the total reliability of the system is the most important. In addition appropriate avoidance methods from stormy weather needs to be developed from the hardware and software point of view to increase overall efficiency, buffer like underwater subsystem perhaps would be appropriate between collector and lift system.

INDIA's mining technology development program is based on crawler based collector with a flexible hose riser facility. Indian systems would be having a large number of moving parts , sensors which may be a bottleneck considering mean time between failures which is most important factor of the success. The Seabed current change due to sub marine storm and suspended sediment floors can cause unexpected difficulties. The absence of catenary may create problem in the event of ship movement. There is need to make a catenary and the two speeds must be synchronized and the tensions are limited by the catenary which must somehow be controlled either by ship or by the crawler. The best possible way to solve the problem perhaps is to provide a buffer system between the collector and riser system.

5.4 Requirements of an environmental friendly mining system

It is suggested that on the basis of extensive analyses of the existing systems that the following basic issues need to be considered for designing and developing environmental friendly deep sea bed mining system(Thiel and Forschungsverbund, 1995; Oebius,1997).

Sediment

It is important to remember that the collector is only one component in the mining system. While it is certainly an important and critical component, it is only one of many and as such it must be compatible with the rest of the components in the system. As a simple example, a collector with a nodule throughout capacity of 100 tonnes per hour will potentially clog and cause to fail a riser system capable of lifting only 80 tonnes per hour. Similarly, the collector must be matched to the forward speed and available power of mining system, and must be compatible with the command and control system that interfaces with the collector.

The top layer sediment will be completely removed by the collector and some of the sediment will be transmitted together with nodules to the mother vessel. The collecting system should be designed and developed such that it should clean the soil from the nodule near the collection point and leave the soil at the seabed. CLB kind of miner may not meet these criteria. A properly designed system may be required to meet these criteria.

Sediment plume

The sediment plume likely to be created by the mining operation is regarded to be responsible for damage to the benthic organism (both flora and fauna). The initial height of the plume generated by a collector will be the decisive factor for spatial dispersion of plume. The heavier one would be settling early near the immediate operation site and lighter sediment plume will disperse according to the currents at the sea bottom. This is a normal phenomenon for sediment plume. It is necessary to minimize the height of the plume for limiting the range of sediment plume.

Mining contour/ track

From engineering point of view, the collector movement on the seabed is likely to be regular in order to optimize the efficiency of the system. The paths of mining system should be perpendicular to the direction of the water current so that the re-suspended bottom sediment can only disperse and resettle in the already mined area and it would avoid burying the nodule area. In this process, sediment re-sedimentation can be contained in the disturbed area by the nodule collector leaving very little quantity of re-suspended soil resetting in the areas beyond mined site. A towed collector will lead to random track on the sea floor causing more environmental hazard. The need for self-propelled collector with an insitu central system would be having comparatively less environmental impact.

Weight of the collector

This is most important criteria to contain the environmental impact. The weight of the collecting system should be as light as possible. It has been reported that Archimedean screw principle self-propelled mining system had tendency to dig the sediment in case of hard obstacle in the front, the cater pillar principle collector may overcome the obstacle if a proper design consideration is given at the initial stage.

Riser system jamming

The riser system jamming may occur due to various reasons. It is necessary to keep a release valve at the pump itself which can be opened in case of jam. The leakage of pipe may create environmental effect on the water column. Appropriate pump with mechanism of release valve should be kept for this purpose.

Discharge of waste water

Mother vessel should have proper storage facility for nodules. The waste water discharge has to be made below the oxygen minimization zone to avoid problem on the sea surface water.

Control system

In order to have good maneuverability of nodule collector, self-propelled vehicle would be the best option taking into consideration of the passive as well as CLB type of collector. Microprocessor based controlled mining / collection system would be preferred option for high recovery rate of the nodule resources.

Reliability

The collector should also be compatible to the environment in which it must operate i.e., high hydrostatic pressure at 5000 / 6000 m depth, sea floor topography, soil bearing strength of seabed sediments and nodule distribution.

As the collector would be at a depth of about 5000/6000 m, it must be reliable and capable of operating for longer duration. Another aspect is equally important that sediments need to be eliminated substantially before sending the nodules to the riser system to avoid likely environmental impact due to discharge back the sediment at a permissible depth of water column.

Redundancy

Redundancy is another key characteristic of the ideal collector. It is important that all critical collector components have redundant or back-up components. It is inevitable that components within the mining system will fail and it is therefore desirable to have redundancy wherever possible. Because it is impractical to have 100% redundant systems, the collector should be designed in such a way that failure of one non-redundant component does not significantly interfere with the primary function of collecting nodules. This idea strongly points towards the concept of modular collector design. The increased complexity associated with modularity is likely overshadowed by the increased flexibility and redundancy provided by modular designs.

5.5 The emerging concept proposed

- During the last three decades, there were several achievements. Electronic advances such as instrumentation, monitoring, data transfer, control capabilities and positioning had greatly improved and reduced the costs. Two issues that require immediate attention are collector and submersible pumps for extensive studies.
- The remoteness of the collecting modules needs to be reliable in the long term and should be as simple as possible.
- There should be minimum moving parts. Mechanically, the collecting system should be simple, rugged, flexible and very light.

- Redundancy of the subsystem is also important so that a component failure should not affect the total system.
- For a commercial system, collector width is critical factor and is a function of nodule coverage, ship speed, collector efficiency and anticipated operating time. A lot of improvement has been made in the pumping system and submersible pump would be superior for use in the riser system.

The extensive analysis of the available design concepts and various developments over the years, the author has formed the basis for the emerging concepts. The **emerging concept** (Fig. 5.6) consists of a simple self propelled collector system, flexible hose connection between buffer systems and riser pipe (hydraulic lifting) with mother vessel. The various parameters relating to different activities are summarized in table 5.1 for design, development of mining system.

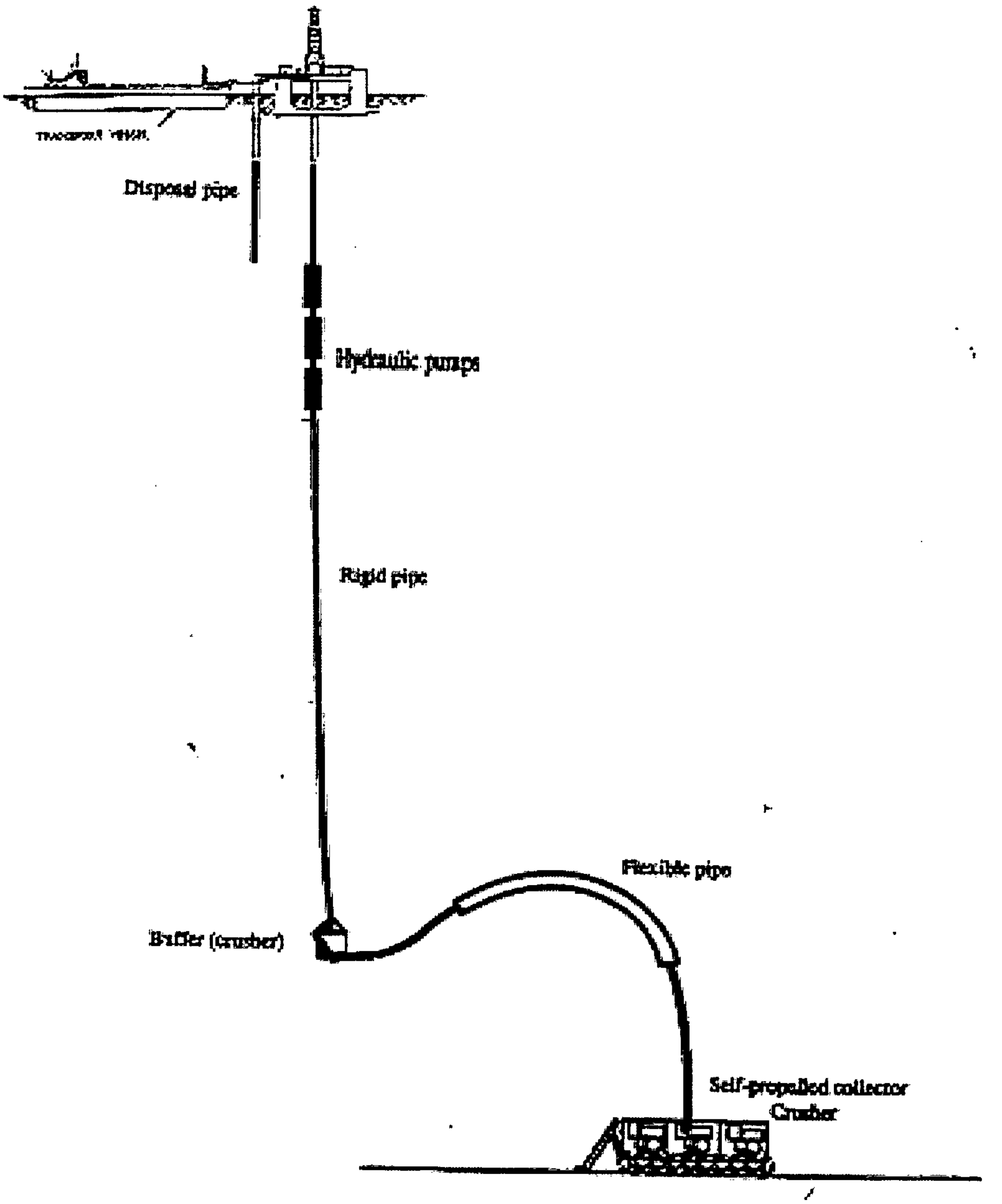


Fig. 5.6: Conceptual model of mining system

Table 5.1: Parameters required for design and development of mining system

Activities	Parameters/sub-systems	Remarks
Exploitation	• Topography • Soil characteristics • Nodule abundance • Meteorological conditions	Comprehensive data must be collected in advance
Exploitation miner Lifting Surface support General positioning of the system	• Miner specific functions (locomotion, collector, crusher) • Miner positioning • Flexible hose • Pipe • Pumps • Handling system (nominal and emergency conditions) • Storage • Ore transfer at sea	Extensive R and D work on the Collector and hydraulic pumps has to be carried out.
Environmental impact	• Knowledge of environmental ecosystem : baseline studies • Water column ecosystem : baseline studies • Consequence of plume of sediment on deep sea ecosystem • Consequence of discharged water on water column ecosystem	Comprehensive study must be carried out well in advance

However author suggests the following critical issues of mining operation which should be kept in mind.

Marine transport

Since the capital investment in the mining component is considerably high, it is not desirable to merge the mining and transportation functions in one vessel. It is economically better to continuously use the mining vessel for maximum possible time (about 300 days per year) for optimum utilization and to use bulk carrier for transport of nodules from mining vessel to shore terminal. The nodules are proposed to be carried from the mine site to the port-based processing plant with the help of two transport vessels.

In order to maintain the production, the vessel should be capable to operate in high sea state and at an arbitrary heading with reference to the weather. The transfer system should be able to operate in high sea state and transfer of nodules needs to be affected at relatively low speed of 2 to 4 knots in a situation where sea states may be changing and the maneuverability of the mining vessel has to be carried out strictly as per predefined planning. The transfer system would be used for transportation of consumables, crews and spares from the shore terminal to mining vessel and brings back unused to shore. The nodules may be transferred in the following way.

a) Slurry transfer

b) Pneumatic or conveyor transfer

There are various advantages, disadvantages in both the modes with respect to stability, relative positioning of the mother-ship and transport ship system during mining operations, connection of transport system with mother ship, etc. The selection and development of transfer at sea concept involves many interdependence decisions. There, it has to be addressed by system engineering approach, which includes development of designs, technical requirements and cost implication of various approaches. The position keeping may be difficult even in moderate sea states. The nodules transfer in large volumes without considering the operation of the mining system poses a major problem and requires further experimentation, which is yet to be attempted by any country/ consortia. However, for the cost estimate purpose, only slurry transportation system is considered.

Shore terminal

The broad functions of the shore terminal would be unloading, storing, transporting of nodule slurry to processing plant, logistic support to the mining operations in terms of supply of crew personnel, technicians, consumables, spares, receipt of unused materials, communication, etc.

Size of the vessel

In order to have 1.5 million tonnes of dry nodules, we have to mine 2.24 m tonnes of wet nodules, which need to be transported to the shore terminal in 300 working days for processing. The size of the vessel has to be based on the following factors.

- Annual quantum of nodules to be transported;
- Availability of draught in Indian port.

The bigger size vessel for transportation would be advantageous for minimizing the capital cost and operating cost. The limiting size of the vessel is determined by the landing limitations of the ports. The mining vessel (mother ship) size needs to be taken into consideration for limiting the size of the vessel. The precaution has also to be taken to ensure continuous operation of the transport vessel to achieve the target. It is assumed to use 75,000 DWT vessels for transportation. The necessary pumping system for transportation of the slurry can be located either on the vessel or on the shore depending on the suitability of working. In case of tankers, pumps are located in the vessel only.

Terminal sites

The approximate distances from the Central Indian Ocean mine site to various possible ports are as under.

Paradeep	-	3980 km.
Madras	-	3150 km.
Goa	-	3390 km.
Cochin	-	2680 km.

The preliminary survey indicates that the Paradeep or Cochin port would be able to meet the requirement. However, dredging would be required to maintain the draught and costing also has been made considering this aspect. Studies on hydraulic model and geo-technical investigations, etc. would be required for final selection.

Number of transport vessel

Assessing the DWT out of the vessel proposed to be used, the number of days required by a vessel for the full trip from Cochin can be calculated as below:

Loading time - 3 - 5 days

$$\text{Travel time (to and fro)} = \frac{3000 \times 2}{25 \times 24} = \frac{3000 \times 2}{600} = 10 \text{ days}$$

Therefore, one vessel can make about 19 trips and would transport about 1425000 tonnes. Total 2 vessels required to meet the target production. If any other port is chosen, the number of vessels required would be more.

Based on the preliminary analysis, either Cochin or Paradeep could be possible alternative choice. The detailed comprehensive investigation is required for selection. For the purpose of costing, Cochin has been taken as the shore terminal.

CHAPTER - 6

ENVIRONMENTAL IMPACTS OF DEEP SEABED MINING

The subject of environmental consequences of deep seabed mining and protection of deep ocean habitats and communities are being considered and analyzed. These issues are under discussion in a number of national and international fora and the same are documented in the Law of the sea treaty.

Mining the deep sea manganese nodules will inevitably disturb the seabed and its communities to a large extent. Therefore, environmental assessments are pre-requisites for risk evaluations, although mining is predicted to begin only in future, considerations and research should be conducted well in advance to evaluate foreseeable environmental effects and to give input for design, development of environmentally friendly mining system.

One of the complex questions to be answered is that of the potential interest in the ecosystem for its recovery i.e., community re-establishment in the mined areas, which occur in areas at depths between 4000 to 6000 m. Due to lack of knowledge on the ecology of the deep sea it is very difficult to make predictions. Faunal abundance in the likely first generation mining areas reported to be varied from 30 - 300 individuals/ 1000 sq. m. of mega fauna, 40 - 200 counts/ sq. m. of micro fauna and 80 - 500 individuals / 10 sq. cm of micro fauna, bacterial numbers will fall in the order of 107 cells/ ml. Several experiments on small scale colonization were carried out in deep sea but their predictive value is rather limited for the case of deep sea mining (Thiel et al., 1993).

In order to prevent serious environmental damage, several critical issues remain to be addressed.

- The likely impacts on the seabed and its community are to be expected as a result of manganese nodule mining
- Whether potential exists for re-colonization and community re-establishment?
- The likely research approach and collaborative mechanism need to be taken up to address these problems.

6.1 Environmental studies carried out by other countries / Contractors

A number of potential Contractors studied environmental impact of deep seabed mining of polymetallic nodules. The contribution of these potential Contractors is very important for the development of guidelines. The various EIA studies carried out at different times are briefly described below.

The benthic impact experiment conducted by the National Oceanic and Atmospheric Administration (NOAA) during 1991 -93 in Pacific Ocean resulted in first baseline data in a Pre-Selected area followed by deep-sea sediment resuspension System (Dssrs). The sampling with CTD, sediment traps and core samples were collected as a part of post disturbance activity to understand the changes in faunal distribution. Assessment of impact study made after 9 months showed a decrease in abundance of meiobenthos, whereas macro benthos showed an increasing trend perhaps due to increase food availability (Trueblood et al., 1997). Though resedimentation would depend on total volume of sediment resuspended along with prevailing current pattern of the area and effect on benthic organism cannot be generalized.

Germany

The German Government has funded a long-term study (ten years) focused on deep sea mining through the Ministry of Science, Education, Research and Technology.

The experimental design of German was to create a large scale disturbance on the sea floor with post- impact studies immediately after the disturbance, after six months, three and seven years. The disturbance was created by ploughing the sea floor with what was termed a plough harrow. A circular area of about 10.8 sq. m. was disturbed by crossing the area 78 times. Approximately 20% of the area is directly affected by the ploughing and the rest by re-sedimentation. The project was initially termed DISCOL for disturbance re-colonization. A continuation programme called ECOBENT for ecology of the benthos which has also been completed.

The scientist observed a highly significant difference between DISCOL 1 (immediately after disturbance) DISCOL 2 (six months) and DISCOL 3 (three years). However, after seven years, no significant difference was detected between the disturbed and undisturbed stations. Reference stations were outside the disturbance area. With regard to functional groups within the biological community of the deep sea, there is strong indication of the disturbance affecting burrowing deposit feeders (Oebius, 1997). The time scale for effects of disturbance is given in table 6.1 on the basis of the study.

Table 6.1: Time scales for effects of disturbance

Short – term (hour - days)	Sedimentation Desoption/ sorption of metals Redox adjustment.
Long term (months - years - decades)	Sedimentation Desorption/ sorption of metals Redox adjustment Surface structure of the sediment Erosion Exchange processes of oxygen and metals Sediment structure of the surface sediment Water content Shear strength Animal stocks: Composition Biomass Diversity

COMRA

The environmental programme of COMRA was carried out in phases. In phase I, geological and geophysical surveys were conducted in 1980s. An additional meteorological data, current and wave data, seawater physical and chemical data, geological data, together with biological and biochemical data were also collected with state-of-the-art instruments during the II phase which lasted for five years, from 1991 to 1995.

Japan

The environmental study consisted of baseline studies and experimental studies. The baseline studies were concerned not only with the benthic environment but also with the surface-ocean environment. Surface - ocean studies involved examination of phytoplankton, zooplankton and heterotrophic bacteria as well as measurement of nutrients and other oceanographic parameters. Benthic studies examined benthic communities and sediment chemistry including pore-water chemistry. The experimental studies focused on three aspects: response of the plankton community to enrichment with bottom water, a benthic disturbance experiment (JET) in 1994 and a nodule collector test in 1997. The Japan Deep Sea Impact Experiment (JET) used a disturber to simulate a nodule collector to re-suspend sediment, creating a sediment plume. JET 1 was sampled just before the disturber operations, JET 2 was immediately after the operation, JET 3 one year after and JET 4 two years after the disturbance. The experiment establishes that certain groups are more susceptible than others to adapt to the changed conditions on seafloor.

IOM

The programme of Inter-Ocean Metal (IOM) was divided into three phases viz., Base line study phase, disturbance phase and monitoring phase.

The IOM Benthic Impact Experiment (BIE) was also subdivided into three stages. The first stage involves the pre-disturbance research on the natural conditions, consisting of acoustic surveys, deployment of mooring systems, sediment sampling and controlled profiling by Conductivity Temperature Depth (CTD) system. Additionally, photographic and video surveys of selected sites were conducted. The disturbance stage involves towing a disturber along predetermined tracks, whereby re-deposition of sediment suspended as a bottom plume took place. A post-disturbance survey and recovery of moored systems provided the first set of samples after the disturbance.

IOM emphasized the importance of getting adequate knowledge on basic environmental conditions and factors prevailing in the claim areas. It also suggested that guidelines should include standardization of methods, comparison of reported results from deep sea experiments and selection of critical parameters for monitoring efforts.

Republic of Korea

The scientific objectives of the programme were to establish an environmental baseline index in the water column and benthic ecosystem to evaluate the environmental impact of an artificial disturbance on the benthic environment, and to provide some basic information towards designing environmentally sensitive mining systems in the future.

Water column studies have focused on bacteria (biomass and productivity), protozoa (composition, biomass and migration pattern) and micro nekton (composition and biomass) as well as physicochemical characterization of the water column (water temperature, salinity and dissolved oxygen, light transmission).

Benthic studies have focused on biological parameters, geochemical processes, geo-technical properties of the deep sea sediment, and physical and geophysical parameters. The studies were planned over a period of four years and no report of results reported so far.

Russia

The State Federal Unitary Geological Enterprise (SGE) "Yuzhmorgeologiya" is the head enterprise for industrial exploitation of the oceanic Fe-Mn-nodule deposits in Russia. The SGE "Yuzhmorgeologiya" developed the National Complex programme for ecological investigations in prospects and mining of mineral resources in the open ocean.

Studies at Pacific Test Site (PTS), during 1984-1987, Russia conducted six cruises on the R/Vs "Akademic Koroljov", Georgiy Ushakov", Professor Khoromov", "Ocean", "Volna", "17 Syezd Profsoyuzov" to the sites in the claim area. The determination of a quantitative relationship between chemical characteristics and biological coefficients within the temperature gradient was one of the most important results of these studies.

The determination of the compensation depth (63 m) was another accomplishment. The compensation depth is the depth at which daily oxygen production, derived from photosynthesis, is compensated or balanced by daily consumption of oxygen by animal respiration and oxidation of organic matter.

6.2 Indian EIA study programme in Central Indian Basin

The Department of Ocean Development, (now Ministry of Ocean Development) Govt. of India has initiated a multi-disciplinary study for assessment and prediction of environmental impact due to mining activity of manganese nodules. The Indian Deep-sea Environment Experiment (INDEX) in Central Indian Basin, under the 'Polymetallic nodule program' was entrusted to National Institute of Oceanography, Goa.

The objectives of the program are -

- To establish baseline conditions of marine environment in the area
- To assess the potential impact of nodule mining on marine ecosystem by simulating a benthic disturbance
- To understand the processes of restoration and decolonization of benthic environment
- To provide scientific inputs for designing and undertaking a deep sea mining operation.

The work carried out in phases is detailed below.

Phase I : Baseline data collection (1995-97)

Five areas of 10 x 10 nautical miles each were surveyed with 1500 km of bathymetry and sub-bottom profiling. In each of the selected areas, 8 Okean grab (0.24 sq. m.) samples with a photograph for nodule data and 5 box cores (50 x 50 x 50 cm) for sediment samples, were operated. The sediment cores were sub-sectioned at different intervals (0.5 - 5 cm) for studying pore water and sediment geochemistry, sediment size analysis and clay mineralogy, biostratigraphy of sediment, geo-technical properties, macro and meiobenthos and sediment microbiology. Data on physical, chemical and biological parameters in water column was collected around the test and reference areas. Lithogenic and biogenic fluxes from the sediment traps at these locations were also evaluated.

On the basis of the baseline data, 2 areas that have similar nodule concentrations, bathymetric variations, as well as benthic biomass, were selected as Test and Reference Areas for conducting the disturbance experiment, and to monitor the undisturbed environment for comparison with the disturbed one, respectively.

Phase II: Benthic disturbance and impact assessment at test site (1997-2001)

Benthic disturbance experiment was carried out during July- August 1997, in a strip of 3000 x 200 m by a hydraulic device in the test area. The site selected for the experiment was located in area A1, between 10° 01' S and 75° 59 E and 10° 03' S, 76° 02' E. Deep sea moorings at 10 locations with current meters, sediment traps and transmissometers were deployed around the area to record the time series data before, during and after the disturbance.

A 'benthic disturber' named as Deep Sea Sediment Resuspension System (DSSRS), developed by the Sound Ocean System Inc. (SOSI), USA was used for suction and discharge of seafloor sediment into the near bottom water column (Brocket and Richards, 1994). The disturber comprises of a tow frame which weighs 3.2 tonnes and has dimensions of 4.8 x 2.4 x 5.0 m. The frame is connected with a coaxial cable that tows as well as transmits signals and power to the disturber unit. It has a discharge stack 5 m high with a 30 cm diameter and is funnel shaped at the bottom, where the sediment is sucked up and discharged from the top.

During the benthic impact experiment conducted over a period of 9 days, the disturber was moved 26 times along the length of the disturbance strip, covering a total distance of 88.3 km, with an effective operation time of 2534 min, resuspending ~ 6000 cu. m. of wet sediment, i.e. ~580 tonnes of dry sediment. Data was collected with deep towed camera systems, sediment corers, sediment traps, current meters and CTD sensors, in different phases of all the experiments. The results showed that there was i) vertical mixing as well as lateral migration of sediment due to resuspension in and around the disturbed zone leading to, ii) changes in physico-chemical changes in the benthic environment and ii) also an overall reduction in benthic biomass in the area.

Phase III: Environmental studies for monitoring of impact

In order to monitor the processes of restoration of benthic environment and re-colonization by the organisms to the level of the baseline conditions in the area, a set of observations on all parameters were undertaken during a cruise onboard RV AA Sidorenko during March - April 2001, 2nd monitoring exercise in 2002, 3rd monitoring exercise was April 2003 and April 2005 after the disturbances experiment. The samples collected using box corer were analyzed for sedimentology, sediment and pure water, geo-chemistry, geotechnical properties, benthic biological parameters for understanding decolonization of benthic environment. The data was collected at the same locations as in the pre-disturbance and post disturbance phases, as well as at reference locations where the baseline data was collected earlier. Deep towed photography showed The above parameters indicate that benthic conditions are steadily moving towards restoration..

In addition sampling at one degree spacing was carried out along with these EIA-monitoring cruises to understand environmental variability in the central Indian basin mine site. The results have shown that there appears to be a distinct difference in distribution parameters of sediment characteristics faunal assemblages and seafloor morphology that influence distribution and association with nodules which is critical for mining.

6.3 Granulometric Analysis

The test and reference areas chosen for the environmental baseline and impact data collection in the Central Indian Basin were studied in great detail for sediment characteristics, seafloor micro-topography/ bathymetry and surface sediments. Sediment cores were analyzed to establish baseline conditions of geochemical, stratigraphic, geotechnical, benthic biomass and microbiological status of the area (Sharma, 2001).

Sediment spade cores (of up to 40 cm long, sub-sectioned at 0.5 to 5 cm length) and surface sediments collected by grabs were subjected to granulometric analysis to determine the sediment size distribution and clay mineralogy of representative sections. The core samples are normally light to dark brown in color, heavily bioturbated in the down core with brownish to grayish intercalations. Smear slides of the sediment samples/ sections suggests pre-dominantly radiolarian assemblages, reported as the siliceous oozes. The granolometric analysis reveals that the sediments are poorly sorted and are clayey or clayey-silt type. The mineralogy is predominantly illites and smectites. These results confirm to the reports by Valsangkar and Ambre(2000) and Khadge (2000).

6.4 Heavy metals in sea water

6.4.1 Method of heavy metals determination

Analysis of the metal reextracts after concentration of elements, made onboard R/V "Yuzhmorgeologiya" cruise, were carried out at the Vernadsky's Institute of

Geochemistry and Analytical Chemistry (GEOKHI), Russia. Mn, Ni and Cu were analyzed by using the ICP- analyzer (inductive-connected plasma). Pb, Cd, Co, Ni and Fe were analyzed by atomic- absorption method with graphite furnace (Perkin Elmer analyzer). Calibration curve was constructed based on the standard samples after element concentration with each sample run.

6.4.2 Distribution of heavy metals in sea water

Data obtained for heavy metals contents (Fe, Mn, Cu, Co, Zn, Pb, Cd) in sea water by extractive method followed by analysis using atomic-absorption spectrophotometer (AAS) with the graphite furnace has been used for interpretation. Metal contents at the oceanic surface obtained in the INDEX-97 cruise are given in table 6.2 and compared with the known published data. The concentration of heavy metals in water column analyzed for the samples collected at various levels till the near bottom and their variations are presented in Figures 6.1 to 6.4 for pre-disturbance samples collected at two stations. Similarly, the concentration of heavy metals in water column analyzed for the samples collected during the post-disturbance at these two stations and their variations are also presented in Figures 6.5 to 6.8.

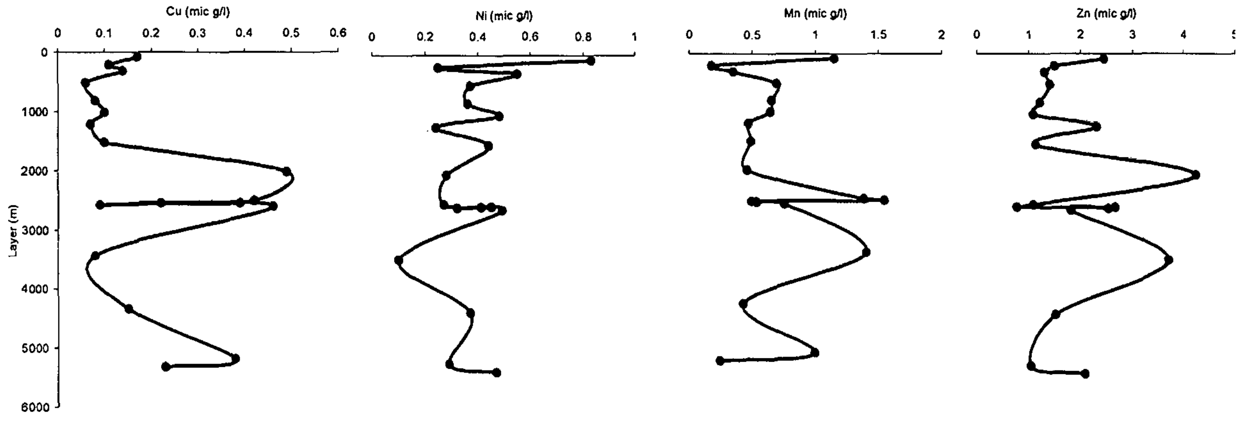


Fig. 6.1: Distribution of heavy metals in water column (pre-disturbance)

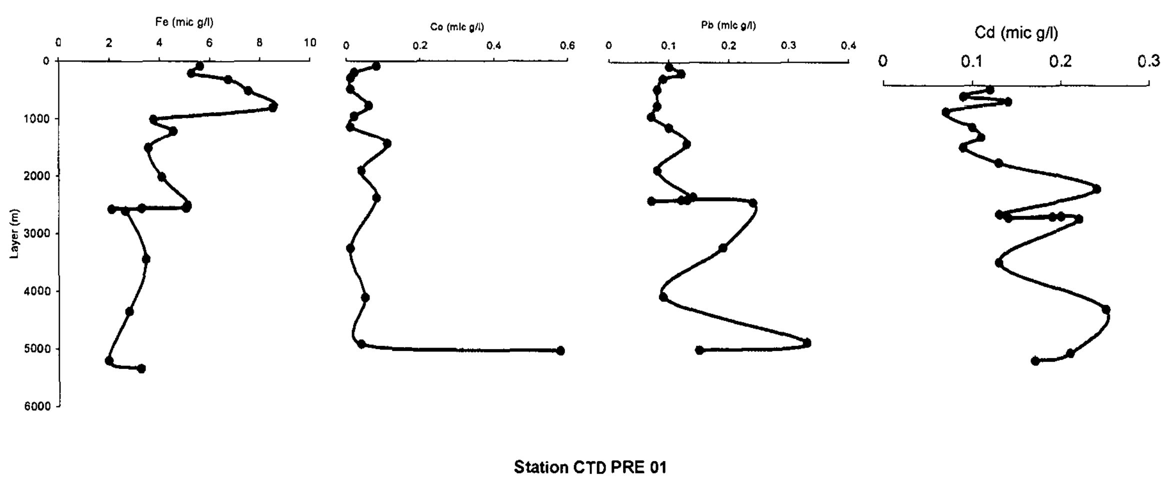


Fig. 6.2: Distribution of heavy metals in water column (pre-disturbance)

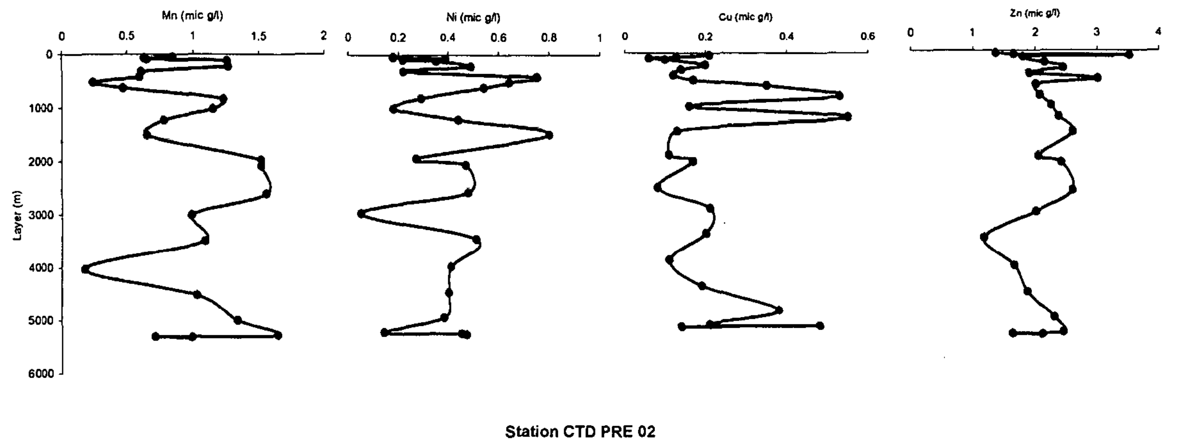


Fig. 6.3: Distribution of heavy metals in water column (pre-disturbance)

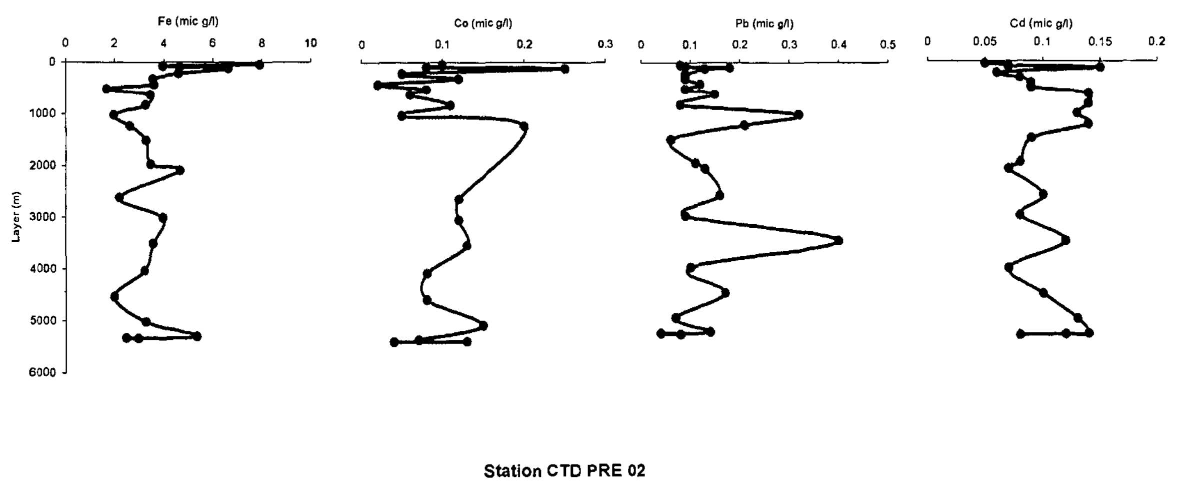


Fig. 6.4: Distribution of heavy metals in water column (pre-disturbance)

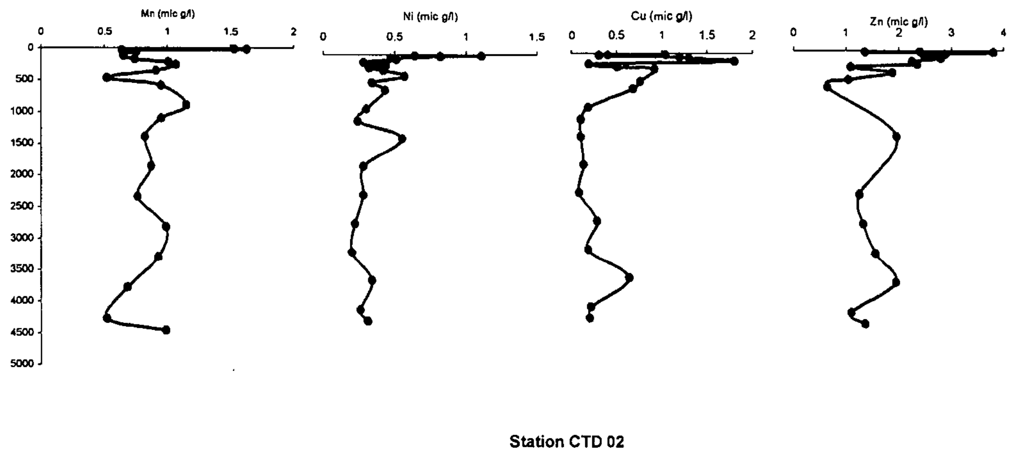


Fig. 6.5: Distribution of heavy metals in water column (post-disturbance)

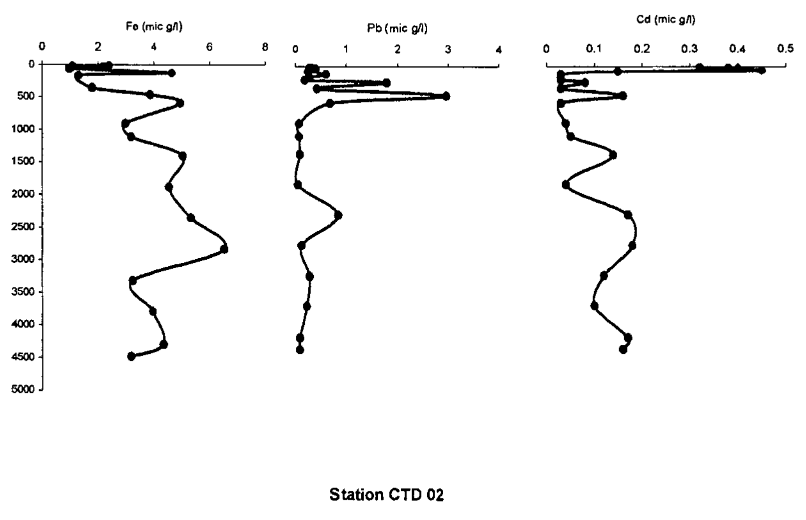


Fig. 6.6: Distribution of heavy metals in water column (post-disturbance)

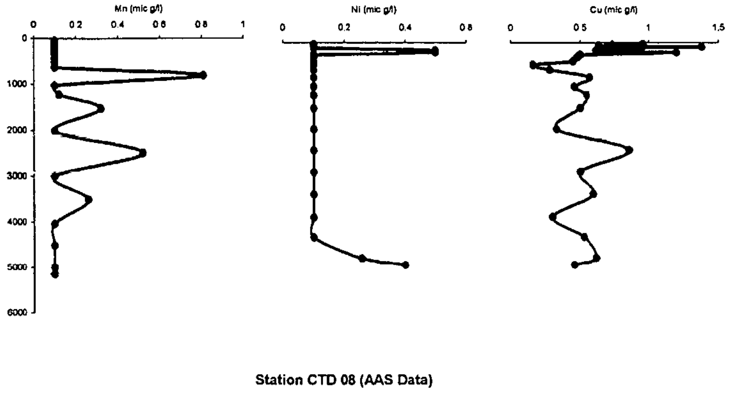


Fig. 6.7: Distribution of heavy metals in water column (post-disturbance)

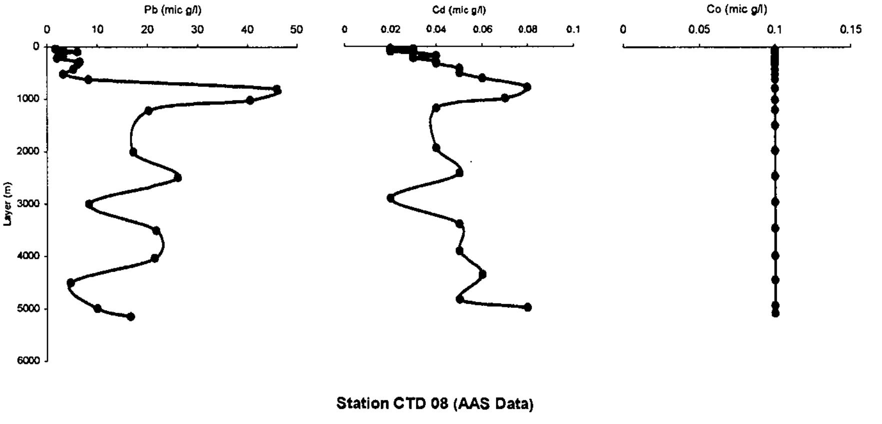


Fig. 6.8: Distribution of heavy metals in water column (post-disturbance)

Table 6.2 Comparison of heavy metal contents (μg/l) for the Indian Test Site (ITS) water surface with other ocean areas.

Metal	INDEX-97 Indian Ocean	Vinogradov, 1967 Pacific Ocean	Moore and Ramamoorthy, 1984 Atlantic Ocean	Bruland 1983 Pacific Ocean	SGE Yuzhmorgeologia 1990 Pacific Ocean
Fe	4.21	5.00	-	0.020	1.00
Mn	1.23	0.40	-	0.030	0.50
Ni	0.51	0.50	-	0.200	0.50
Cu	1.25	1.40	1.00	0.200	1.00
Co	0.02	0.03	-	0.003	0.30
Zn	2.30	5.00	2.00	0.010	5.00
Pb	0.49	0.03	0.01	0.010	1.00
Cd	0.04	0.07	0.02	0.010	0.25

As it is seen from the table 6.2, Fe agrees with the Vinogradov's data (1967) and average Mn contents in the water surface layer (1.23 mkg/l) also coincides with the data of the above investigator (1983), but these data are higher than the content values presented by Bruland (1983); however, the values are near to the data obtained by R/V " Yuzhmorgeologiya" cruise in the Pacific Ocean using the polorographic method.

Average Ni values (0.51 mkg/l) coincide completely with the Vinogradov's data (1967) and the data of "Yuzhmorgeologiya" cruise in the Pacific Ocean. Cu content (1.25 mkg/l) coincides practically with data of all mentioned above investigators except the Bruland's data (1983). Co contents (0.02mkg/l) also agree with data of all authors except the Bruland's data (1983) that show Co contents by an order of magnitude greater. Zn content (2.30 mkg/l) is greater within the limits of presented by the all author's values except the Bruland's data (1983).

Pb contents (0.49 mkg/l) of the water column surface are by an order of magnitude greater to that of other datasets where as Yuzhmorgeologiya cruise in the Pacific Ocean reported values are double in their magnitude. Cd content (0.04mkg/l) is very close to all authors' data except the data of the "Yuzhmorgeologiya" cruise in the Pacific Ocean in 1990.

Based on the data from table 6.2 and 6.3 it may be concluded that the surface layer of water column at ITS has rather high contents for all discussed metals when compared to the deep layers except Cd.

Average values of heavy metal contents for the layers of oceanic water column were calculated in 8 thick layers of the water column: 0-100m, 100-500m, 500-1000m and 1000m intervals for the deeper waters beyond 1000 m (Table 6.3). The last near bottom water layer is of interest because it borders with the distributed sediments during disturber's operation.

The 0-100m layer is also of interest because it coincides with photosynthetic zone, the picnocline's, holocline's and thermocline's boundaries also extend here. This layer is characterized by variability of oxygen, biogenic elements and living benthofauna to a higher degree.

Table 6.3: Average values (μg/l) of heavy metals in the ITS water column

Water column layer (m)	Fe	Mn	Ni	Co	Cu	Zn	Pb	Cd
Surface	4.21	1.23	0.51	0.020	1.25	2.30	0.49	0.042
0-100	4.22	0.99	0.56	0.043	0.47	2.58	0.12	0.042
100-500	4.30	0.79	0.39	0.035	0.32	1.90	0.15	0.049
500-1000	3.71	0.82	0.38	0.027	0.28	0.64	0.13	0.060
1000-2000	4.75	0.73	0.41	0.027	0.28	1.96	0.08	0.071
2000-3000	3.53	0.93	0.28	0.045	0.52	0.88	0.10	0.035
3000-4000	3.22	0.61	0.21	0.032	0.30	0.88	0.13	0.013
4000-5000	3.02	0.79	0.31	0.037	0.39	0.53	0.11	0.069
>5000	3.10	0.60	0.20	0.097	0.23	-	0.09	0.092

Table 6.4: Average values (μg/l) of heavy metals in the ITS water column

Water column layer, (m)	Fe *	Mn *	Ni *	Co	Cu	Zn *	Pb	Cd
Average Content (ITS area)	3.78	0.83	0.36	0.040	0.45	1.46	0.11	0.052
ROS-1	3.02	0.40	0.36	-	0.77	2.36	0.24	0.17
ROS-2 & ROS-3	2.72	0.38	0.27	-	0.80	-	0.25	0.09

The data tabulated and presented in table 6.4 are the average values of heavy metals for the samples of CTD stations carried out during the pre-disturbance. The table also contains the heavy metal data for stations ROS-1, ROS-2 and ROS- 3. ROS-1 represents sampling site before the disturbance operation where as ROS-2 and ROS-3 sampling sites (average values are presented in table 6.4) during the post disturbance. The ROS-2 station was carried out along zone of disturbance and the ROS-3 station transverse to it.

High average contents of Cu- 0.47 mkg/l, Mn- 0.99 mkg/l, Zn- 2.58 mkg/l, Ni-0.56 mkg/l and Co- 0.43 mkg/l are noted for the surface to 100 m level (table 6.3). Decreasing metal contents are observed in the 100-500-m layer, except for Fe (4.30mkg/l). The metal distributions in middle layers of water column are uniform except for a maxima of Fe- 4.75 mkg/l, Zn- 1.96 mkg/l, Cd- 0.071 mkg/l, Cu- 0.52 mkg/l, Mn- 0.93 mkg/l in 1000-2000m layer and so on. Co- 0.045 mkg/l at 2000-3000m water layer is high. If we compare ROS- 2 and ROS- 3 averaged data as the post- disturbance sampling with ROS- 1 data (table 6.4) representing the pre-disturbance, it may be observed that there was a content decrease practically of all the discussed metals in near bottom layer during the post- disturbance where as Cu and Pb contents remain at its previous level. These results suggest that dispersion and suspension of large quantity of fine material (sediment) from the bottom due the disturbance and sorption of dissolved heavy metals on their surfaces may be the causative factor.

In other words, It is very difficult to obtain representative data by micrometal content in sea water and explain their distribution along the vertical of water column. Firstly, oceanic water masses are very mobile system where natural diffusion of dissolved metal forms plays a greater role in leveling the concentrations. If, for example, anomalous water mass structures with high metal content observed may be explained either by hydrothermal discharge of the elements into the water or the land derivation by a laminar flow, or the contamination by the vessel etc. However, no such phenomenon is noticed in the present context.

Certainly, the reliability of the averaged metal contents in sea water of the ITS area not only depends on the sampling and analytical methods, but also from the number of analyzed samples. To have statistical data of high reliability the number of analyzed samples must be more to arrive at a reasonable interpretation.

6.5 Discussion and Conclusion

The physical dynamics of oceanic water and its circulation influence on the dynamics of other processes that involve biological, chemical and sedimentological domains. These physical processes also determine the horizontal and vertical transport of suspended and dissolved chemical matter, mobilization of sediments and their transport near the bottom, and the changes in bio-ecological processes likely to arise as a result of exploration and mining activity in the nodule area. The evolution and consequences of any disturbance of the oceanic environment may therefore depend on hydrodynamic and hydrophysical processes.

To predict and monitor the environmental changes in the nodule area, it is necessary to understand the specifics of ocean water dynamics, its constituents and chemistry throughout the entire water column. However, there are zones of specific interest in the vertical column such as the surface and subsurface layers, mid-depths and near-bottom layers. The upper layers are of critical importance due to the high intensity of biological activity, variability of current velocity and the regional water circulations. Mid-depth characteristics need a special consideration and attention as it is a zone of the main discharge of tailings during nodule mining, and therefore require careful study. The near bottom layer is the column of most intensive impact, and knowledge of near-bottom water dynamics and the structure of the bottom boundary layer are of critical importance for any environmental prediction.

Understanding the main hydrodynamic processes is therefore necessary to address the issues of baseline requirements and to develop basic approaches to select the size and location of test and reserve areas as well as time and space scales of measurements and monitoring.

From the contribution of many major research programmes such as DOMES, DISCOL, JET, BIE and INDEX, a lot of understanding emerged about the deep sea ecosystem, however, the overall knowledge of this environment is still very limited and needs to be pursued on a regional scale before the deep sea mining becomes a reality.

CHAPTER-7

DEMAND, SUPPLY AND PRICE TRENDS OF METALS

The demand, supply and price trends of metals viz. Cu, Ni, Co and Mn of nodules are presented in this chapter. The land resources of the world in respect of four metals viz., manganese, cobalt, nickel and copper are presented and compared with potential metal resources present in deep sea manganese nodules. An attempt has been made to draw some inference on future metal requirements based on present and historical consumption and production pattern. Metal prices have also been forecasted in a similar way.

7.1 Global economic resources on land

Number of studies has been conducted by various national and international agencies to identify global economic resources. Table - 7.1 provides estimates of the global economic resources of land for four metals viz., copper, nickel, cobalt and manganese.

Table-7.1: Global economic resources on land (in million tons)

Manganese (metal content)	5000
Cobalt	13
Nickel	140
Copper	940

(Source: U.S. Geological Survey, Mineral Commodity Summaries, January 2004)

7.2 GLOBAL DISTRIBUTION OF LAND RESOURCES

7.2.1 Manganese

Manganese is the twelfth most abundant element in the earth's crust. Land-based resources are large but irregularly distributed; those of United States are very low grade and have potentially high extraction costs. South Africa accounts for more than 80% of the World's identified resources, and Ukraine for about 10%. Table -7.2 provides information on world manganese reserve base and recent data on mine production..

Table-7.2: World manganese mine production, reserves, and reserve base (metal content) (in thousand metric tons)

Country	Mine production		Reserves	Reserve base
	2002	2003		
United States	-	-	-	-
Australia	983	990	32,000	82,000
Brazil	1,300	950	23,000	51,000
China	900	900	40,000	100,000
Gabon	810	1000	20,000	160,000
India	630	630	15,000	33,000
Mexico	88	85	4,000	9,000
South Africa	1,504	1630	32,000	4,000,000
Ukraine	940	830	140,000	520,000
Other Countries	955	985	Small	Small
World Total	8,100	8000	300,000	5,000,000

(Source: U.S. Geological Survey, Mineral Commodity Summaries, January 2004)

7.2.2 Cobalt

Cobalt is extracted from four chief types of deposit, usually as a by-product of other metals. It occurs in stratabound copper deposits, in nickel-copper sulphide deposits, in nickel laterite deposits and in silver - cobalt sulpharsenide deposits.

Until the 1990s the stratabound copper deposits of Congo DR and Zambia, which occur in sedimentary rocks, were the chief commercial source of cobalt. The grade of cobalt in these deposits, present both as cobalt minerals and in pyrite (iron sulphide), is generally between 0.1 and 0.4 %. The nickel and nickel-copper sulphide deposits in Russia, Canada and Australia, which occur as concentrations in mafic and ultramafic igneous rocks, have cobalt grades of around 0.1 %. Cobalt also occurs as oxide and silicate minerals in nickeliferous laterites derived from the weathering of ultramafic rocks. The cobalt content of these deposits is generally between 0.05 % and 0.15 %. Cuba and New Caledonia are the largest sources of lateritic nickel and cobalt but Western Australia also began production in 1990s. Silver-cobalt sulpharsenide deposits in Canada were formerly important but the Bou Azzer mine in Morocco is now the only producer working on this type of deposit. Table - 7.3 provides information on world cobalt mine production and reserve base.

Table-7.3: World cobalt mine production, reserves, and reserve base (in metric tons)

Country	**Mine production**		**Reserves**	**Reserve base**
	2002	**2003**		
United States	-	-	NA	860,000
Australia	6,700	6,600	1,500,000	1,700,000
Brazil	1,200	1,300	35,000	40,000
Canada	5,100	4,700	90,000	300,000
Congo (Kinshasa)	12,500	10,000	3,400,000	4,700,000
Cuba	3,400	3,200	1,000,000	1,800,000
Morocco	1,300	1,300	20,000	NA
New Caledonia	1,400	1,400	230,000	860,000
Russia	4,600	5,000	250,000	350,000
Zambia	10,000	12,000	270,000	680,000
Other Countries	1,400	1,400	200,000	1,500,000
World Total	47,600	46,900	7,000,000	13,000,000

(Source: U.S. Geological Survey, Mineral Commodity Summaries, January 2004)

7.2.3 Nickel

Identified land-based resources averaging 1 % nickel or greater contain at least 130 million tons of nickel. About 70 % is in laterites and 30 % in sulphide deposits. Nickel laterites occur in present or past zones of the earth that have experienced prolonged tropical weathering of "ultramafic" rocks. The nickel bearing sulphide ores are found mainly in Canada, Russia, Finland, Australia, and Zimbabwe. Lateritic ores generally occur in tropical and subtropical regions, primarily in New Caledonia, Australia, Philippines and Indonesia (Fig. 7.1).

These ores also contains cobalt in addition to nickel. Table - 7.4 provides information on world nickel mine production and reserve base.

Table-7.4: World nickel mine production, reserves, and reserve base (in metric tons)

Country	Mine production		Reserves	Reserve base
	2002	2003		
United States	-	-	-	-
Australia	211,000	220,000	22,000,000	27,000,000
Botswana	20,005	18,000	490,000	920,000
Brazil	45,029	46,000	4,500,000	8,300,000
Canada	178,338	180,000	5,200,000	15,000,000
China	54,500	56,000	1,100,000	7,600,000
Colombia	58,196	65,000	830,000	1,000,000
Cuba	73,000	75,000	5,600,000	23,000,000
Dominican Republic	38,859	39,000	740,000	1,000,000
Greece	22,670	23,000	490,000	900,000
Indonesia	122,000	120,000	3,200,000	13,000,000
New Caledonia	99,650	120,000	4,400,000	12,000,000
Philippines	26,532	27,000	940,000	5,200,000
Russia	310,000	330,000	6,600,000	9,200,000
South Africa	38,546	40,000	3,700,000	12,000,000
Venezuela	18,200	21,000	610,000	610,000
Zimbabwe	8,092	8,000	15,000	260,000
Other Countries	14,000	12,000	1,300,000	5,100,000
World Total	1,340,000	1,400,000	62,000,000	140,000,000

(Source: U.S. geological survey, mineral commodity summaries, January 2004)

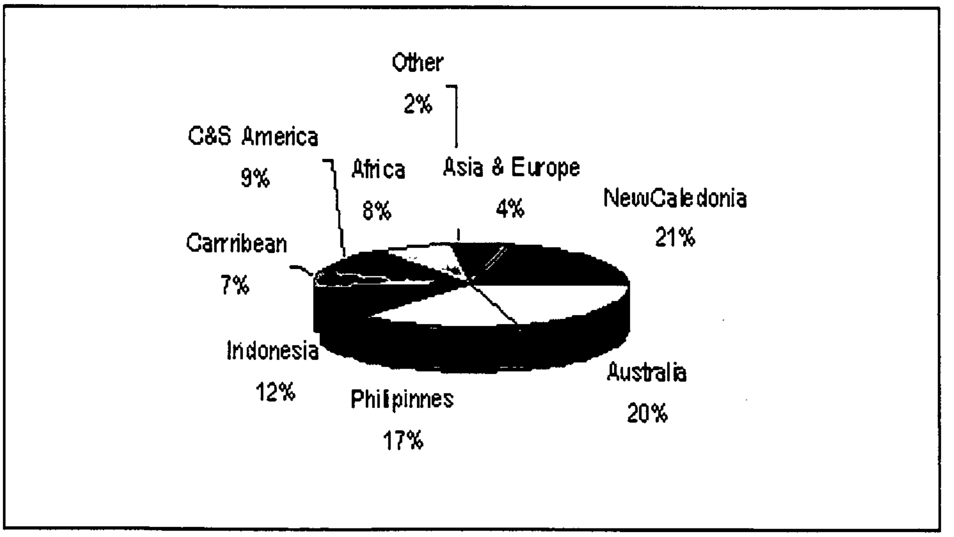


Fig. 7.1: World nickel laterite resources

7.2.4 Copper

Copper deposits are found in a variety of geological environments, depending on the rock-forming processes that occur at a particular location. These deposits can be grouped in the following broad classes:

- Porphyry and related deposits
- Sediment - hosted copper deposits
- Volcanic-hosted massive sulphide deposits
- Veins and replacements bodies associated with metamorphic rocks
- Deposits associated with ultramafic, mafic, ultrabasic, and carbonatite rocks.

Table - 7.5 provides information on world copper mine production and reserve base.

Table-7.5: World copper mine production, reserves, and reserve base (in thousand metric tons)

Country	Mine production		Reserves	Reserve base
	2002	2003		
United States	1,140	1,120	35,000	70,000
Australia	883	870	24,000	43,000
Canada	600	580	7,000	20,000
Chile	4,580	4,860	150,000	360,000
China	585	565	26,000	63,000
Indonesia	1,160	1,170	32,000	38,000
Kazakhstan	490	480	14,000	20,000
Mexico	330	330	27,000	40,000
Peru	843	850	30,000	60,000
Poland	503	500	30,000	48,000
Russia	695	700	20,000	30,000
Zambia	330	330	19,000	35,000
Other Countries	1,500	1,500	60,000	110,000
World Total	13,600	13,900	470,000	940,000

(Source: U.S. Geological Survey, Mineral Commodity Summaries, January 2004)

7.3. Definition of reserve base and reserves

Reserve base is defined as that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the in-place demonstrated (measured plus indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently sub economic (sub economic resources).

Reserves are that part of the reserve base which could be economically extracted or produced at the time of determination.

7.4 RESOURCES OF THE DEEP SEA

7.4.1. Problem of estimation

Resources of the deep sea bed promise to make an enormous contribution to the world's resource base if their potential is realized. At the present time, the resources of the deep sea bed of immediate interest are in the form of manganese nodules which lie on the surface of the ocean floor and contain important metals like copper, nickel, cobalt and manganese. Several estimates have been made on the inventory of elements in manganese nodule deposits based on the world oceanic area covered with manganese mineral, its thickness and mean composition. However, it may be noted that any attempt to estimate the nodule resources in the ocean can only be expected to generate an order of magnitude figure. Nodule deposits that are likely to be worked out by the first generation of mining may presently be described as " potential economic resources".

7.4.2 Potentially economic nodule resources

Studies (Archer, 1985) have indicated that about 55 million sq. km of sea floor area i.e., 15 % of the total 362 million sq. km area is covered with ocean nodules. However, these estimates are hypothetical in the present day context and even in near future since many such deposits contain insignificant quantities of nickel and cobalt. Currently, the economics can at best be order-of-magnitude estimates. Archer defined "prime areas" as those areas within which the abundance and grade of nodules are notably higher than elsewhere. He defined a class of manganese nodule resources as "potential resources" which were characterized by an average of 2.25 % combined Cu, Ni and Co, occurring with abundance of more than 5kg/sq. m. He further defined the areas in which potential reserves occur as "first generation mine-sites", sites to which the economics of first generation mining and processing equipment will apply. Based on this criterion the assumed economics of first generation mining operations is likely to be in the range of 10 to 100 billion tonnes of wet nodules. The more reasonable estimate may be taken at 25 billion tonnes of wet nodules. To convert to dry tonne 0.7 multiplies the wet tonne assuming that nodules contain about 30 % unbound water.

7.4.3 Potentially economic resources of metals

Table - 7.6 gives estimated values for potentially economic resources of metals from nodules. These estimations have been made based on average metal values in first generation mine-sites as indicated in different studies.

Table-7.6: Potentially economic resources of metals form polymetallic nodules

	Metal values range	**Metal values average**	**Metal resources**
		%	million tons
Nodules (Wet)	**	**	25,000
Nodules (Dry)	**	**	17,500
Manganese	25 to 30	27.5	5,000
Cobalt	0.1 to 0.3	0.23	40
Nickel	1 to 2	1.24	215
Copper	1 to 2	1.01	175

7.5 Comparison of metal resources

The comparative data of metal resources (in situ) on land with those in the deep sea nodules are presented in table - 7.7 and figure 7.2. It is clear from the table that metal resources available in polymetallic nodule compares well with land resources. However, the final recovered metals might be quite different and will depend largely on mining and processing efficiency. The processing efficiency for both the cases might be comparable but the mining efficiency for nodules are expected to be lower than land resources.

Table-7.7: Comparative global resources of metal form land and nodules (in situ in million tons)

Metals	Resources on land (In situ)	Nodules
Manganese	5000	5000
Cobalt	13	40
Nickel	140	215
Copper	940	175

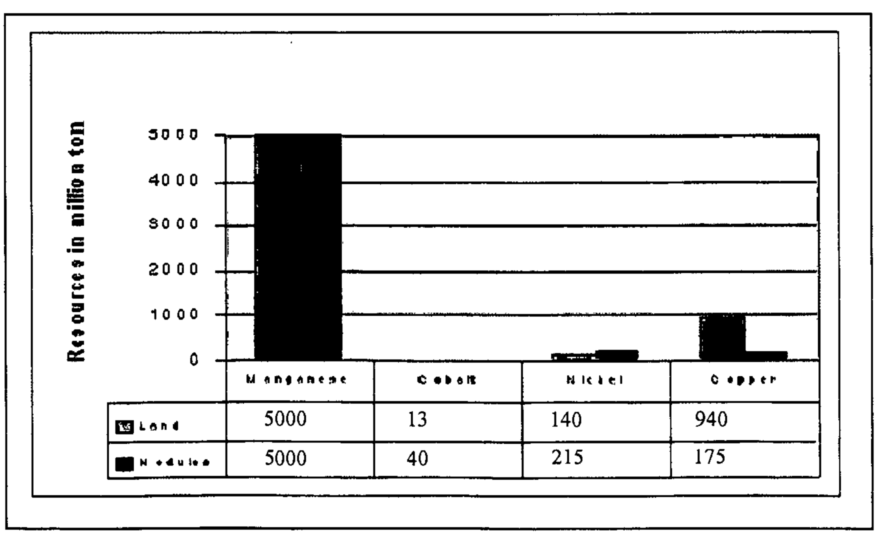


Fig. 7.2: Comparative metal resources

7.6 Comparison of Indian land based resources with metal resources of central Indian ocean basin

In the table - 7.8 comparisons is drawn between available land based metal resources in India with those estimated in the Central Indian Ocean Basin. The exercise may look interesting on account of geographical considerations.

Table-7.8: Metal resources of land in India and in central Indian ocean basin

Metal	**Land reserves (in- situ) (in million tons)**	**Resources of central Indian ocean basin (in million tons)**		
		Explored area 1 million sq km	Total application area 300,000 sq km	Likely mining area 75,000 sq km
Manganese	142 (approximate)	478.00	247.00	73.00
Cobalt	No proven reserves	03.87	01.82	0.49
Nickel	No proven reserves	20.81	10.47	3.20
Copper	9.4	17.07	09.51	3.00

7.7 FORECAST OF GLOBAL DEMAND AND COST STRUCTURE OF METALS

7.7.1 Background

Looking ahead to the 21st century, the following six forces may change the topography of the business landscape.

- Increased globalization
- Sustainability
- Financial Performance (profitability and capital productivity)
- Customer Expectations
- Changing work force requirements, and
- Increased Collaboration.

The two fundamental factors affecting the metal market and ultimately the price are **supply and demand**. Geographic concentrations of metal resources, disparity between developed and developing countries in metal production, consumption and development of substitutes are some of the peculiar features, which impose indirect restrictions on the metal market. Historical data helps in predicting the future requirements. Forecasting real market patterns for periods more than one or two decades away is really complex particularly when an entirely new source of supply from nodule mining may likely to be introduced.

As mentioned earlier an attempt has been made to draw some inference on future metal requirements based on present and historical consumption and production pattern. Metal prices have also been forecasted in a similar way.

7.7.2 Projected growth for metal consumption/demand

Economic, technological and societal factors influence the supply and demand of metal. As society's need for metal increases, new mines and plants are introduced and existing ones expanded. In times of market surplus, existing operations can be scaled back or closed down, while planned expansions can be delayed or cancelled.

a) Manganese

The percentage per annum growth rate for manganese based on ore consumption is summarized in table - 7.9. It can be seen from the table that compounded growth rate per annum from 1950 to 1960 was possibly one of the highest i.e., 8.92 %. After that the average growth rate per annum is approximately 3 %.

Table-7.9: Manganese growth rate profile based on world manganese consumption (% PA)

Year	Consumption	Compounded annual growth rate
	'000 metric tons	% PA
1950	5800	
1960	13625	8.92
1970	18220	2.95
1980	26720	3.90
Average (1950- 1980)		**5.22**

b) Cobalt

The percentage per annum growth rate for cobalt based on cobalt consumption is summarized in table -7.10. The average growth rate per annum for cobalt from 1966 to 1971 was 1.07 %. However, it increased to 3.78 % from 1971 to 1976. The average per annum growth rate from 1976 to 2000 was 2.79 %.

Table-7.10: Cobalt growth rate profile based on world cobalt consumption (% PA)

Year	Consumption	Compounded annual growth rate
	metric tons	% PA
1966	22221	
1971	23430	1.07
1976	28206	3.78
2000	41487	2.79
Average (1966 to2000) **Average(1976 to 2000)**		**2.64** **2.79**

c) Nickel

The percentage per annum growth rate for nickel based on average nickel consumption is summarized in table-7.11. The average growth rate per annum for nickel from 1980 to 2003 was 2.42 %. However, from 1993 to 2003 this rate increased to 3.33 %.

Table-7.11: Nickel growth rate profile based on world nickel consumption (% PA)

Year	**Consumption**	**Compounded annual growth rate**
	'000 metric tonnes	% PA
1973	675.5	
1978	700.5	0.73
1983	691.5	(-) 0.26
1993	803.6	1.51
1998	988.3	4.22
2003	1230.0	5.62
Average (1980 to 2003)		**2.42**
Average (1990 to 2003)		**3.33**

d) Copper

The percentage per annum growth rate for copper based on copper consumption is summarized in table - 7.12. The average growth rate per annum for copper from 1980 to 2003 was 2.15 %. However, during 1990 to 2003 the annual growth rate was 2.85 %.

Table-7.12: Copper growth rate profile based on world copper consumption (% PA)

Year	Consumption	Compounded annual growth rate
	'000 metric tons	% PA
1960	4458	
1965	5734	5.16
1970	9291	10.13
1975	7452	(-) 4.32
1980	9546	5.08
1985	9885	0.70
1990	10791	1.77
1995	11996	2.14
2000	15134	4.76
2003	15555	0.92
Average (1980 to 2003)		**2.15**
Average (1990 to 2003)		**2.85**

7.7.3 Projected growth rates

The projected long term growth rates based on the average of historical data for all the four metals are provided in table - 7.13. It is expected that global manganese consumption will increase @ 3 % per annum while cobalt, nickel and copper consumption will increase @ 2.75, 3.00 and 2.50 % respectively.

Table-7.13: Projected growth rate (% PA)

Metal	Projected growth rate
Manganese	3.0
Cobalt	2.75
Nickel	3.00
Copper	2.75

7.7.4 Expected consumption of metals by 2020

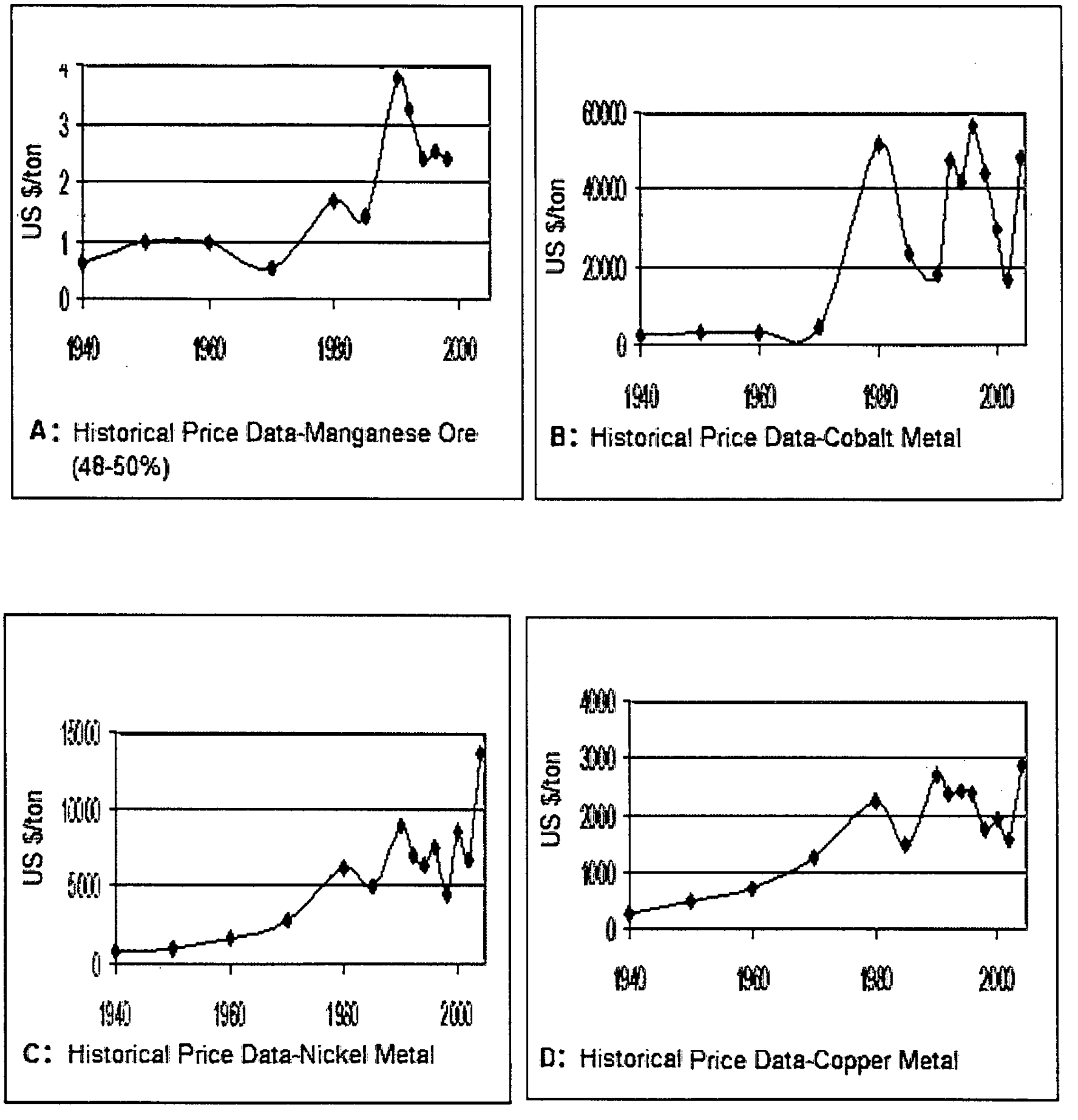
The expected consumption of metals by 2020 based on projected growth rate is summarized in table - 7.14. The expected growth rate for manganese, cobalt, nickel and copper will be 3.0, 2.75, 3.0 and 2.75 % respectively.

Table-7.14: Expected consumption of metal during 2020

Metal	**Present expected consumption, tones**	**Expected consumption during 2020**
Manganese	450,000	810,000
Copper	480,000	865,000
Nickel	30,000	54,000
Cobalt	600	1100

7.7.5 Historical price data

The historical metal price pattern for manganese, cobalt, nickel, and copper are summarized as below at figure 7.3.



A: Historical Price Data-Manganese Ore (48-50%)

B: Historical Price Data-Cobalt Metal

C: Historical Price Data-Nickel Metal

D: Historical Price Data-Copper Metal

Fig. 7.3: Pattern of metal prices over the years

(U.S. geological survey, mineral commodity summary 2004)

7.7.6 Projections of long term metal prices

The long term projections of the demand are essential to determine the long term price, and, therefore are an important factor for investment decisions, as well as for decisions related to the increase or decrease of the production capacity. One of the main parameters related to the income - yield capacity in the mineral and metal industries is the long term price, and therefore the need for long term projections of the demand.

Based on the historical metal prices and the interplay of the various factors, long-term price forecasts beyond 2004 can be made based on average growth in the metal prices. The metal price growth rate since 1910 to 2004 are summarized in table-7.15, 7.16, 7.17 and 7.18 for manganese, cobalt, nickel and copper respectively.

The average compounded price growth rate based on historical prices for manganese ore, cobalt, nickel and copper metal are as follows:

Manganese Ore	:	2.56 %
Cobalt metal	:	3.56 %
Nickel metal	:	2.97 %
Copper metal	:	2.49 %.

Although the metal market is very volatile but it is expected that long term metal prices may increase based on average price growth rate as projected above.

Table 7.15: Manganese ore price growth rate based on real ore price (% PA)

Year	**Real ore price US $/ton ***	**Compounded annual growth rate**
1910	0.26	
1920	0.66	9.76
1930	0.49	(-) 2.93
1940	0.62	2.38
1950	0.96	4.47
1960	0.98	0.21
1970	0.53	(-) 5.96
1980	1.67	12.16
1990	3.78	8.51
1998	2.40	(-) 5.52
Average (1910 to 1998)		**2.56**

* (U.S. geological survey, mineral commodity summary 2004)

Table 7.16: Cobalt metal price growth rate based on real metal price (% PA)

Year	**Real metal price US $/ton ***	**Compounded annual growth rate**
1910	1270	
1920	6150	17.09
1930	4990	(-) 2.07
1940	2620	(-) 6.24
1950	3670	3.43
1960	3390	(-) 0.79
1970	4880	3.71
1980	51600	26.60
1990	18200	(-) 9.90
2000	29700	5.02
Average (1910 to 2000)		**3.56**

* (U.S. geological survey, mineral commodity summary 2004)

Table 7.17: Nickel metal price growth rate based on real metal price (% PA)

Year	Real metal price US $/ton *	Compounded annual growth rate
1910	882	
1920	926	0.49
1930	772	(-) 1.80
1940	772	0.00
1950	992	2.54
1960	1630	5.09
1970	2840	5.71
1980	6230	8.71
1990	8864	3.59
2000	8638	(-) 0.26
2004	13823	12.47
Average (1910 to 2004)		**2.97**

* (U.S. geological survey, mineral commodity summary 2004)

Table 7.18: Copper metal price growth rate based on real metal price (% PA)

Year	Real metal price US $/ton *	Compounded annual growth rate
1910	284	
1920	386	3.12
1930	292	(-) 2.75
1940	254	(-) 1.38
1950	476	6.48
1960	713	4.12
1970	1280	6.03
1980	2234	5.73
1990	2712	1.96
2000	1944	(-) 3.27
2004	2865	10.18
Average (1910 to 2004)		**2.49**

* (U.S. geological survey, mineral commodity summary 2004)

7.8 Observations / Conclusions

To meet the ever-increasing metal demand the land based resources will be fast depleted. More number of primary metal producers will enter the market and possibility of using alternate resources like polymetallic nodules will enhance. It is expected that by 2020 polymetallic nodule may become a commercially viable resource option especially for a country like India, which even today meet its nickel and cobalt demand through imports.

CHAPTER – 8

ECONOMIC MODEL FOR ASSESSING FINANCIAL VIABILITY OF NODULE MINING

The nodule program in India was started in early eighties. After the allocation of the mine site in 1987, India has fulfilled all the obligations to UN as Registered Pioneer Investor. The nodule resources have been estimated on the basis of comprehensive survey.

At present, close - grid survey in selected blocks is under progress and first generation mining site would be selected on the basis of further detailed survey. The comprehensive Environmental Impact Assessment (EIA) has also been commissioned to understand the likely damage of eco-system due to possible mining of nodules in future. The baseline environmental data collection (phase - I) and simulation of mining by creating disturbance at the sea bottom was taken up as a part of comprehensive EIA study at the Central Indian Ocean Basin (CIOB) mine site. Presently, as a part of third phase, i.e., recolonization study (EIA – Monitoring study), every year India is sending a team of scientific expedition to CIOB mine site for collection of samples. India has set up a semi-commercial pilot plant of 500 tonnes per day capacity to validate the process package developed. In the mining sector, attempts have been made for technology development to harness nodules resources from a depth of about 6000 m in phases. The development of mining system for nodule mining would take further time. In this chapter an attempt has been made to prepare a cost model of the nodule mining and metal extraction and their likely viability in the years to come. Three important parameters, nodules grade, abundance and terrain characteristics, determine value and economics of mines site (Welling, 1976).

In this modeling, the structures have been framed by taking into consideration the capital cost, and operating cost of the project during the operating period. The **capital costs** have been divided into three major components i.e., the mining component, the transportation component, shore terminal and extractive metallurgy component.

All these components have been considered in detail while considering the estimation of capital cost.

Investments have been estimated on cost of individual units. The cost of each component / unit is on the basis of equipment cost, their installation, cost due to other services required by equipment and other indirect charges like engineering, supervision, contingencies, etc. In case of mining, transport and terminal components costing, it is based on the present trend in the market for available components and on the basis of some assumptions. In case of extractive metallurgy plant, the estimation is on the basis of pilot plant experience and similar plant elsewhere.

8.1 CAPITAL COST ESTIMATION

8.1.1 Mining

Following major assumptions have been made for cost estimates.

Production capacity of wet nodules	-	2.24 million tonnes/ year for 1.5 million tonnes of dry nodules/ year

- The mother vessel (semi-submersible surface platform) will be supported with hydraulic lift system (steel table) for transporting nodules collected from the seabed to the vessel with wet nodules storage and handling facilities.
- The sizes of the mother vessel and handling system (launching and retrieval system) have been estimated taking into consideration the annual production rate and based on cost estimates for equipment/ facilities like space for power generating unit, storage of flexible riser, space for launching and retrieval system, motion compensating unit, temporary storage for nodules, etc.
- Total number of transport vessel required for transporting the wet nodules to shore terminal has been estimated as two of 75,000 DWT capacities with one mother vessel.
- Slurry transportation has been envisaged for the onshore transport of nodules as well as for disposal of the nodules to process plant.

Comprehensive exploration is required prior to exploitations of the Area (Flipse, 1973). The quantum of the work would be about three months per year. In addition, the same vessel may be used as a supply vessel operating from a base station for crew, scientists and technician's relief and transportation of consumables (Nyhart et al., 1978).

The assumptions made for the cost estimates are as follows -

- Nodule abundance - 8 kg/sq. m.
- Production rate/ year - 1.5 million tonnes (dry nodule)
- Mother vessel (semi-submersible surface platform)
- Average collecting speed – 1 m / sec
- Collector efficiency – 0.80
- Collector width – 15 m
- Depth of working - 6000 m
- Number of working days – 300
- Moisture content = 30 %

The capital costs in respect of mining component is determined from the rate of annual production rate of nodules and are based on the cost model (Nyhart et al., 1978) and from the prototype equipment for ocean mining operation.

Estimated capital expenditure for mining component

	Rs. in crores
Mother ship/platform	570.00
Mining System + Depressor	240.00
Riser pipe along with pumps	200.00
Navigation and control	60.00
Exploration and supply vessel	80.00
Nodule slurry equipment for transferring	30.00
Sub-total – Mining component	**1180.00**

8.1.2 Transportation

The transportation of nodules from mother vessel to shore terminal would be carried out with the help of vessels of adequate size (75,000 DWT in this case) to economize the production. Rapid slurry pipe system is proposed to be used for transfer of nodules from mother vessel to transport vessel and at the terminal from transfer vessel to the shore terminal. The capital cost of the transport system is estimated as the sum of the capital cost of transport vessels and that of slurry system (Frankel and Marcus, 1973). The cost of the transport vessel has been estimated by considering foreign yard construction cost compared to domestic yard construction as the vessel can be constructed faster in foreign yard and cost competitive. The slurry system cost is estimated on the basis of number of pumps required.

The shore terminal capital cost is estimated considering the likely infrastructure including building, associated machinery and dredging.

The rate of loading and unloading is pegged at 3500 tonnes/ hour by using 18 pumps (9 at shore terminal and 9 at mine site). It is assumed that each pump would be able to handle slurry of 7,000 GPM.

The capital cost consists of cost of the vessel and the cost of slurry handling system.

Estimated capital cost for transport component

	Rs. in crores
Vessel including slurry loading system	200.00
Special facility for linking mother vessel and transport vessel	25.00
Sub-total – Transport component	**225.00**
For two vessels total cost	**450.00**

8.1.3 Processing

The processing component cost is estimated by considering all the required operations. It is assumed that the plant would be set up nearer to the site of the port terminal. In the estimate, the sulphur dioxide ammoniacal leach process has been taken into consideration. The basic refining stages (Backhurst and Harker, 1973) are given below in table 8.1.

Table 8.1: Refinery Unit Stages

PROCESS	PURPOSE
Ammonia-Sulfur dioxide pressure leach	To dissolve copper, nickel and cobalt in the nodules in low pressure autoclave
Demanganisation	To remove dissolved manganese as precipitate in low pressure autoclave in presence of oxygen
Ammonia recovery	To recover and recycle ammonia
Neutralization	To neutralize ammonia in solution
Copper solvent extraction	To separate and concentrate copper from nickel and cobalt in solution
Copper electro winning	To produce copper cathode
Bilk sulphide precipitation	To precipitate nickel and cobalt as sulphide from copper raffinate
Bulk sulphide leaching	To dissolve nickel and cobalt sulphide cake in mild acid solution at medium pressure
Secondary copper solvent extraction	To separate copper present as impurity in bulk sulphide solution
Zink solvent extraction	To separate zinc present as impurity in bulk sulphide solution
Cobalt solvent extraction	To separate and concentrate cobalt from nickel in solution
Cobalt electro winning	To produce copper cathode
Nickel solvent extraction	To produce concentrated nickel solution
Nickel electro winning	To produce nickel cathode
Smelting	To produce silico-manganese

The economics of the development of deep seabed manganese nodules have been examined considering a discounted cash flow method. A number of assumptions have been made in this exercise. The assumptions for cost model in respect of processing technology of the cost model are given in table 8.2:

Table 8.2: Assumptions for cost model

Design basis

Plant capacity	1.5 MMTPA Nodules (Dry)
Construction period	3 Years
Plant life	25 years

Financial parameters

Debt equity	1:1
Interest on debt	12 %
Loan repayment period	10 years
Tax rate	20 %
1 $	47 Rs.

Metal recoveries

Copper	91 %
Nickel	92 %
Cobalt	80 %
Manganese	85 %

Nodule feed grade

Copper	1.11 %
Nickel	1.22 %
Cobalt	0.12 %
Manganese	24.44 %

Metal prices ($/tonne)

Copper	3200
Nickel	14000
Cobalt	37528
Manganese alloy	938

The Capital cost for the nodule processing plant (Capacity 1.5 million tonnes / year) has been estimated by taking the cost of pilot plant setup by the depth of ocean development at Hindustan Zink Ltd (Udaipur) as a base cost. The scale up factor has been considered for arriving various components of capital cost. The estimated cost for four metal recovery nodule processing plant is given below.

	Rs. in crores
Engineering	2500.00
Utilities and general facilities	536.00
EPCS	127.00
Waste disposal	179.00
Contingencies	268.00
Sub-total processing	**3610.00**
	= 768.09 M US $ (1 $ = Rs.47)

8.2 OPERATING COST

The component-wise annual operating cost for each of above three components has been estimated in the following heads.

- Employees cost
- Energy cost
- Material cost
- Cost towards insurance, tax, etc.
- Contingencies

8.2.1 Mining

The operation cost like power is calculated from power requirement that is determined by lift optimization section i.e. the length of work days at sea, work year at sea. The labor / personnel is the annual cost of salaries, benefits the cost of materials includes the annual cost of replacement of bottom units, pipes hoses, coupling is determined from the life time of pipe string, maintenance cost includes ship maintains cost, pump using and bottom unit. Insurance charges are 1.5 % of capital cost (Nyhart et al., 1978).

The operating cost for mining component is divided into sub-heads like energy, crew and technicians, supplier and materials (spare parts, administrative expenses, insurance, etc.). The cost of supplies and materials include annual cost of replacement of flexible hose, couplings. The estimated annual operating costs for mining component are summarized below.

	Rs. in crores / year
Personnel	12.48
Fuel and power	32.43
Maintenance	28.50
Exploration and supply	16.60
Overhead	22.60
Sub-total	**112.61**

8.2.2 Transportation

The operating cost consists of POL / fuel, crew maintenance and repairs, personnel, spare components and materials, insurance and contingencies. The fuel cost is estimated by considering its consumption rate while sailing at certain speed and while at port. The speed of the transport vessel pegged at 13 knots, consumption of fuel while sailing and consumption of fuel at ports has been considered for costing. Insurance cost is linked with the vessels size and facility on board and crew onboard. The cost towards crew of the chosen site of vessel is taken as per present practice. Maintenance to repair costs is estimated as percentage of the capital cost of the vessel. Spares and materials are taken as per norms and prevalent practice. Emergency cost has been kept for utilization at the time of any unforeseen circumstances like the production of nodules is held up due to certain reasons. The operating cost of transport sector would be dependent on the sailing speed of the vessel, handling capacity of the slurry system at both ends (mother vessel end and shore terminal end), buffer stock at the terminals. The changes in the slurry system may not have much effect to the total cost system as long as the targeted production of the mining system remains unchanged (Andrews, 1977). The estimated yearly operating cost for transportation system is on the basis of fuel consumption, labor, storage, etc on our vessels.

	Rs. in crores / year
Personnel	5.20
POL/ Fuel	5.04
Spares and materials and maintenance	10.00
Emergency	15.00
Contingencies	6.46
Sub-total	**41.70**
For two vessels	**83.40**

8.2.3 Processing

The process route so far developed by India is one ammoniacal sulphur dioxide leach process route. This process route has been tested thoroughly at the laboratory scale and the flow sheet has been validated in the semi-continuous pilot plant at 500 kg / day capacity. The recovery efficiency achieved is more than the designed parameters of the plant. The processing parameters arrived on the basis of assumptions are given below.

The Operating Cost has been calculated on the basis of the processing parameters taking into consideration of the efficiency and consumables, etc. The operating cost includes salary and wages of manpower, reagent and chemical cost, maintenance cost has been taken as 4.8 % of engineered capital cost, the power cost on the basis of Rs. 3 /- per unit of consumption, overhead includes insurance taxes etc. The details are given below.

	Rs. in crores. / year
Personnel	63.45
Reagent and chemicals	634.50
Power	225.60
Maintenance	119.85
Overhead	119.85
Sub-total – processing	**1163.25**

8.3 Working capital

The fund would be required for meeting initial expenditure towards managing the whole operation. It is taken as three months operating cost of the entire activities. It is estimated as Rs.339.81 crores.

8.4 Capital and operating cost structure

The details of summarized capital cost structure and operating cost structure are given in table 8.3 and 8.4.

Table: 8.3 Summary of capital cost estimates

Area	M. US $	Rs. Crores
Mining		
Mother vessel/platform	121.28	570.00
Collector+Depressor	51.06	240.00
Riser	42.55	200.00
Control	12.77	60.00
Exploration and supply vessel	17.02	80.00
Nodule slurry equipment for transferring	6.38	30.00
Sub-total(A)	**251.06**	**1180.00**
Transportation		
Vessel including slurry loading system (two vessels)	85.11	400.00
Special facility for linking platform and transport vessel (for two vessels)	10.64	50.00
Sub-Total(B)	**95.74**	**450.00**
Processing		
Engineered capital cost	531.91	2500.00
Utilities and general facilities	114.04	536.00
EPCS	27.02	127.00
Waste disposal	38.09	179.00
Contingencies	57.02	268.00
Sub-total(C)	**768.09**	**3610.00**
Total depreciable capital(D)	1114.89(Say 1115)	5240
Working capital(E)	72.30	339.81
Total capital investment(F)	**1187.19**	**5579.81 (Say 5580)**

8.5 Pattern of capital cost

Total capital investment in the polymetallic nodules mining project of 1556.58 M USD is divided into three major components of the cost model – mining, transportations and processing. The cost of each component is further divided into various sub-components. The figure 8.1 and 8.2 depicts the pattern of the capital cost. It is clear that about 65% and 21% of the capital cost is towards processing and mining respectively. Any improvement in the process with reduced stages of operation would be beneficial from economics point of view.

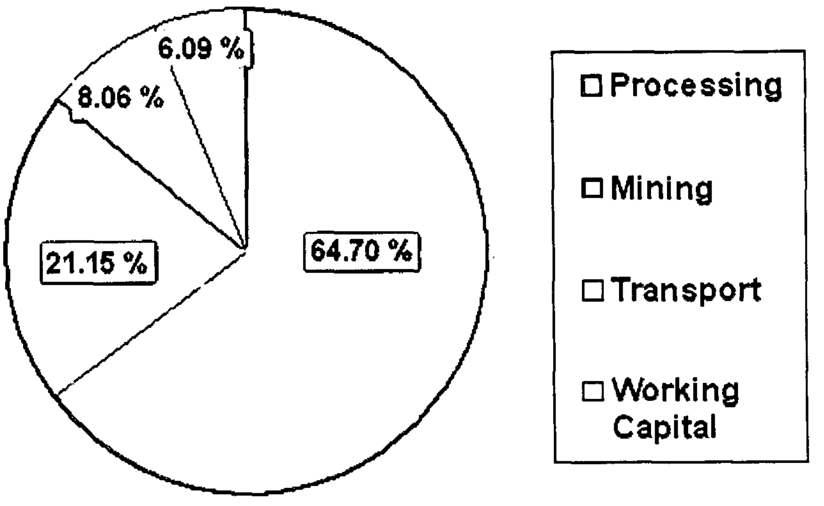


Fig. 8.1: pattern of the capital cost (component wise)

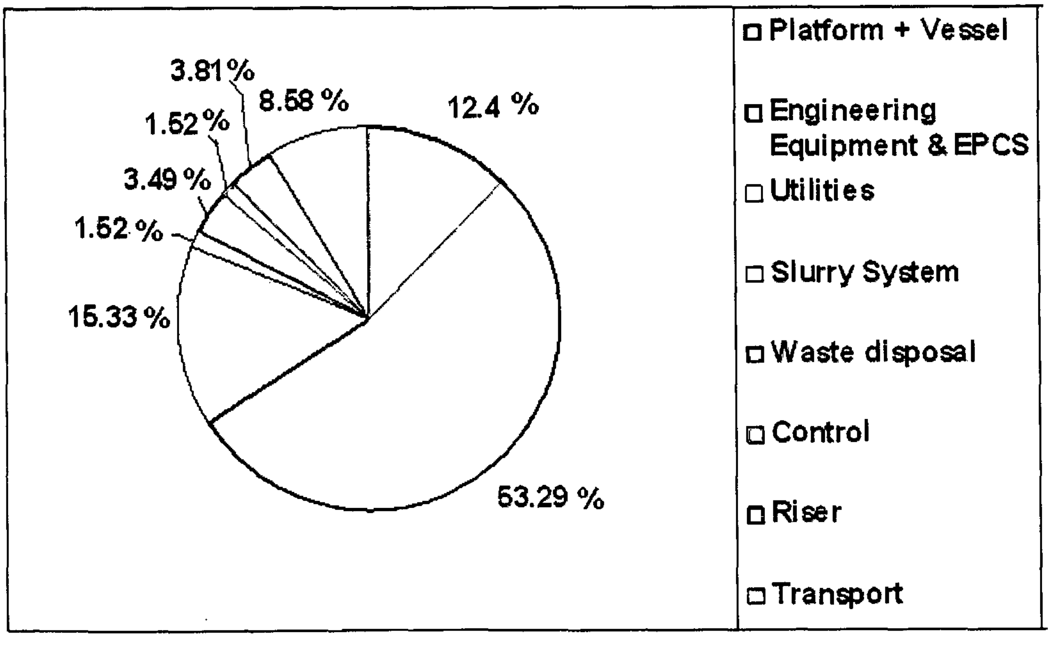


Fig. 8.2: Pattern of capital cost (details)

8.6 Pattern of operating cost

The operating cost calculated as a part of this objective in respect of processing, mining and transportation are 85.57 %, 8.28 %, 6.13 %, respectively. This has been reflected in figure 8.3.

Table 8.4: Operating cost estimates

Area	M. US $	Rs. Crores
Mining		
Personnel	2.66	12.48
Fuel and power	6.90	32.43
Maintenance	6.06	28.5
Exploration and supply	3.53	16.6
Overhead	4.81	22.60
Sub-total(A)	**23.96**	**112.61**
Transportation		
Personnel	2.22	10.40
Fuel	2.14	10.08
Maintenance	4.26	20.00
Emergency fund	6.38	30.00
Overhead	2.76	12.92
Sub-total(B)	**17.74**	**83.40**
Processing		
Personnel	13.50	63.45
Reagents and Chemicals	135.00	634.50
Power	48.00	225.60
Maintenance	25.50	119.85
Overhead	25.50	119.85
Sub-total(C)	**247.50**	**1163.25**
Total	**289.20**	**1359.26**

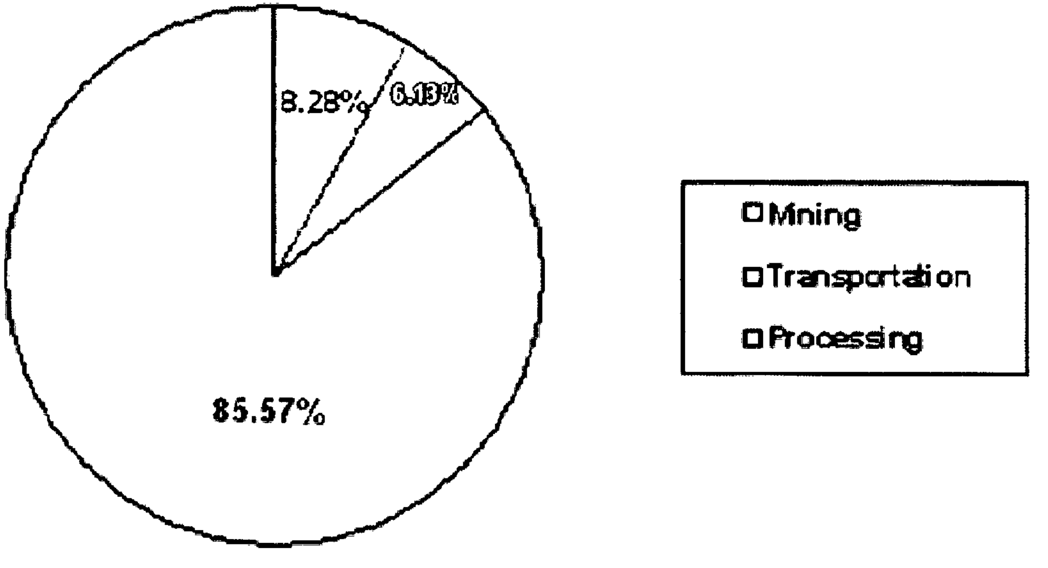


Fig. 8.3 Pattern of operating cost

Table 8.5: Cash flow statement

Basis

Debt:Equity=1:1	RS(crores)
Total Depreciable Capital(TDC)	5240
Working Capital(WC)	329
Total Capital Investment(TCI)	5570
Salvage Value	786

Insurance, Intt and tax rate	%
Insurance on TDC	0.5
Interest on Debt	12
Income Tax Rate	30

	Rs(Crores)/annum
Operating Cost	1358
Sales Revenue	2870
Metal Prices	$/tonne
Copper	3000
Nickel	13000
Cobalt	37528
Manganese	938

Cash Flow Statement

		Construction Period			Operating Period																								
Sr.No.	Description	1	2	3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	Cash In-Flow																												
A	Equity	2455		329																									
B	Debt		1670.9	1113.9																									
C	Operating Revenue				2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870	2870
D	Net Recovery of Salvage Value																												786
	Cash Out-Flow																												
E	Main Investment	2455	1670.9	1443.3																									
F	Financial Charges																												
	Total Investment	2455	1670.9	1443.3																									
G	Operating Cost																												
	Annual Fixed Cost				272	272	272	272	272	272	272	272	272	272	272	272	272	272	272	272	272	272	272	272	272	272	272	272	272
	Annual Variable Cost				1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	1087	1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	1086.6	
	Insurance				26.20	23.97	21.75	19.52	17.29	15.07	12.84	10.61	8.38	6.16	3.93	3.93	3.93	3.93	3.93	3.93	3.93	3.93	3.93	3.93	3.93	3.93	3.93	3.93	3.93
	Total Operating Cost				1385	1382	1380	1378	1376	1373	1371	1369	1367	1364	1362	1362	1362	1362	1362	1362	1362	1362	1362	1362	1362	1362	1362	1362	1362
H	Gross Margin				1486	1488	1490	1493	1495	1497	1499	1501	1504	1506	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	2294
I	Depreciation-St line method				445	445	445	445	445	445	445	445	445	445															
J	Amortization as per sec 35D																												
K	Net Margin				1040	1043	1045	1047	1049	1052	1054	1056	1058	1060	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	2294
L	Interest on Long Term Debt				334	301	267	234	201	167	134	100	67	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	Profit Before Tax				706	742	778	813	849	884	920	956	991	1027	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	2294
N	Tax Liability				212	223	233	244	255	265	276	287	297	308	452	452	452	452	452	452	452	452	452	452	452	452	452	452	688
O	Profit After Tax				494	519	544	569	594	619	644	669	694	719	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1606
P	Long Term Debt Repayment				278	278	278	278	278	278	278	278	278	278	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Net Cash Flow																												
	On Total Capital																												
	Before Taxes	-2455	-1671	-1443	1486	1488	1490	1493	1495	1497	1499	1501	1504	1506	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	2294
	After Taxes(Deducting tax liability)				1274	1265	1257	1249	1240	1232	1223	1215	1206	1198	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1606

IRR (Before tax liability)	14.5%
IRR (After tax liability)	10.7%
NPV Discount Rate	0.1
NPV @ 10 % (Before tax)-crores	2,553
NPV @ 10 % (After tax)-crores	378

Pay Back Period(Before Taxes)*

Pay Back Period(After Taxes)**

*	-2455.4	-1671.9	-1443.3	706	742	778	813	849	884	920	956	991	1027	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	1508	2294
**	-2455.4	-1671.9	-1443.3	494	519	544	569	594	619	644	669	694	719	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1056	1606

8.7 Sensitivity analysis of mining cost module

The projected operational results are summarized and the analysis of the economic return is presented in table 8.5. The annual production and revenues from fourth year is given in table 8.6.

Table 8.6: Annual revenue

	Annual production tonnes/year	**Revenue Rs. crores/year**
Copper	15151.5	213.62
Nickel	16836.0	1028.64
Cobalt	1440.0	253.98
Manganese	311610	1373.76
Total annual revenue		**2870.00**

8.7.1 Impact on profitability of mining cost module due to variation in values of different parameters

In order to present maximum information about profitability, three parameters of economic return have been generated in analyzing the impact of technological choices (Stermole, 1974). They are net present value (NPV), internal rate of return (IRR) and pay back period. The net present value for a range of discount rates from 5% to 25% is applied. A number of critical parameters have been considered for the analysis. They are discount rate capital cost, revenue, metal prices (Cu, Ni, Co and Mn) and grade of nodules.

a) Discount rate

The internal rate of return (IRR) for the base cost of the project is 14.50% and the pay back period is 4 years. The pattern of NPV fluctuation due to upward and downward variation of discount rate from 5% to 25% has been presented in graphical as well as numerical form in table 8.7 and figure 8.4.

Table 8.7: Impact of discount rate on project profitability

Discount rate	NPV before tax
5	9087
7.5	5083
10	2553
12.5	914
15	-170
17.5	-900
20	-1399
22.5	-1741
25	-1978
IRR-B Tax	14.50%
IRR-A Tax	10.70%

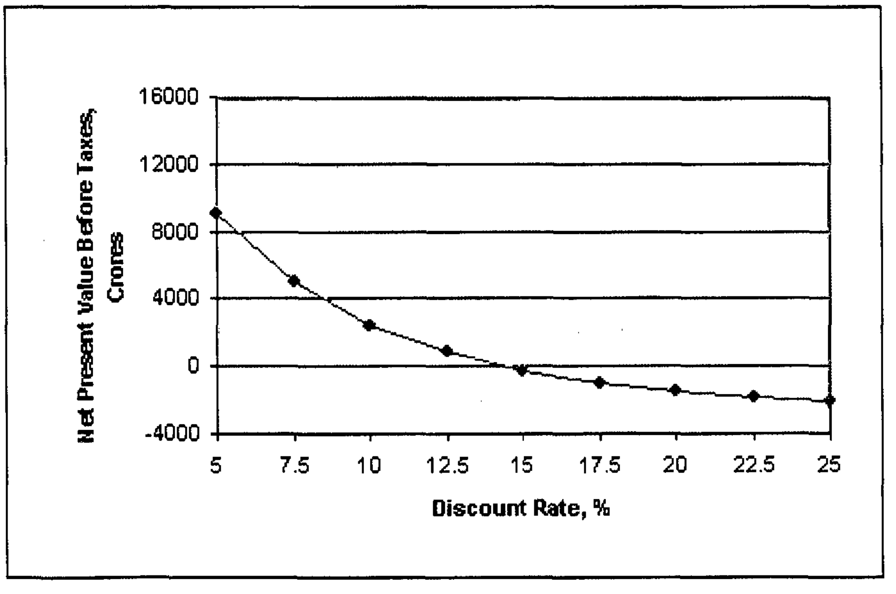


Fig. 8.4: Impact of variation of discount rate on profitability

b) Capital cost

This parameter has been tested in the cost model by increasing and decreasing by 25% from the base line condition. It may be seen in table 8.8 and figure 8.5

that impact is substantial i.e the increase in IRR from 14.50% to 20.40% in case of decrease in capital cost. Similarly increase in capital cost by 25% resulted in decrease in IRR to 10.80%

Table 8.8: Impact of 25% upward and downward shifts in capital costs on NPV

Discount rate	Base	+25%	-25%
5	9087	6703	11470
7.5	5083	2913	7254
10	2553	568	4539
12.5	914	-912	2741
15	-170	-1860	1521
17.5	-900	-2473	673
20	-1399	-2869	72
22.5	-1741	-3123	-360
25	-1978	-3280	-675
IRR-B Tax	14.50%	10.80%	20.40%
IRR-A Tax	10.70%	7.80%	15.45

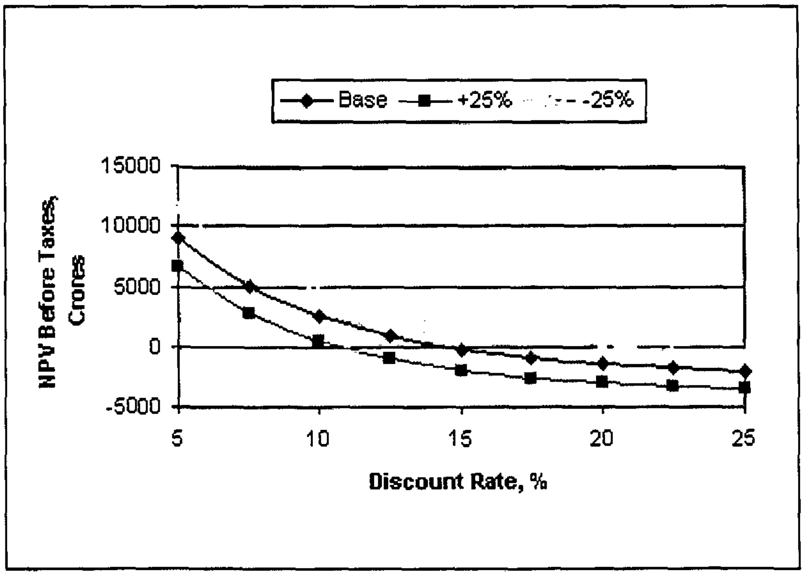


Fig. 8.5: Impact of variation of capital cost on profitability

c) Revenue

By increasing and decreasing the revenue by 25% over the base revenue, it has been found that IRR increase to 22.40% in case of increase revenue by 25%

IRR decrease to 5.4% in case of decrease in revenue by 25%. Details are given in table 8.9 and figure 8.6.

Table 8.9: Impact of 25% upward and downward shift in revenue on project profitability NPV before tax

Discount rate	**Base**	**+25%**	**-25%**
5	9087	17823	350
7.5	5083	11522	-1355
10	2553	7447	-2340
12.5	914	4734	-2905
15	-170	2880	-3220
17.5	-900	1583	-3383
20	-1399	656	-3453
22.5	-1741	-17	-3465
25	-1978	-514	-3442
IRR-B Tax	14.50%	22.40%	5.40%
IRR-A Tax	10.70%	17.00%	3.20%

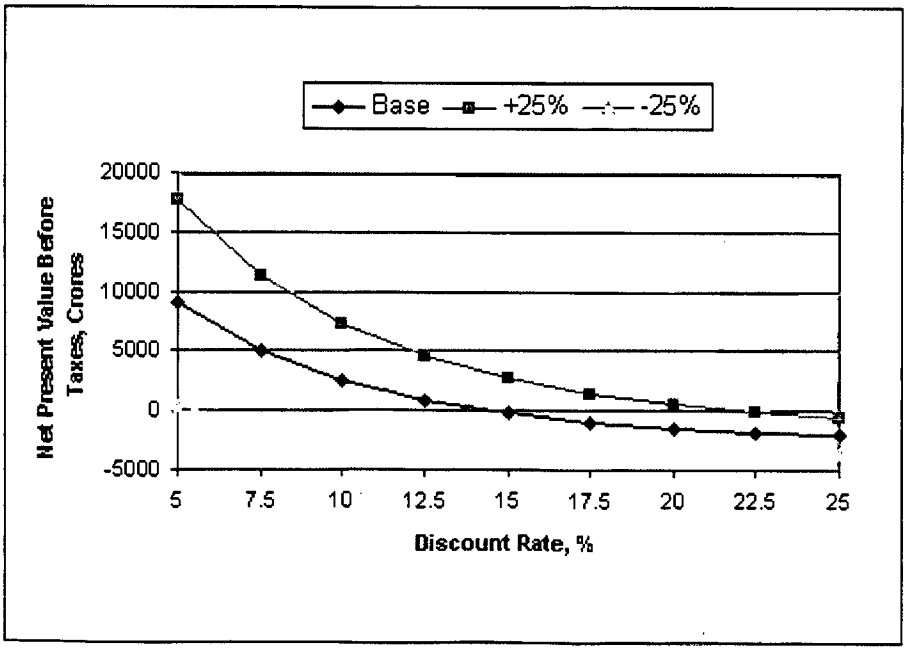


Fig. 8.6: Impact of variation of revenue on profitability

d) Operating cost

The annual operating cost is Rs.1359.26 crores. The model has been tested for knowing the impact of 25% upward and downward shift in annual operating cost on NPV. The IRR has shown a downward trend i.e. 18.40% to 10.40% of IRR- B tax for downward shift (25%) and upward shift (25%) in operating cost. The graphical representation of the impact on NPV is given table 8.10 and figure 8.7.

Table 8.10: Impact of 25% upward and downward shifts in annual operating Costs on NPV

Discount rate	Base	+25%	-25%
5	9087	4953	13221
7.5	5083	2036	8130
10	2553	238	4869
12.5	914	-893	2722
15	-170	-1613	1273
17.5	-900	-2075	275
20	-1399	-2371	-426
22.5	-1741	-2557	-925
25	-1978	-2671	-1285
IRR-B Tax	14.50%	10.40%	18.40%
IRR-A Tax	10.70%	7.40%	13.80%

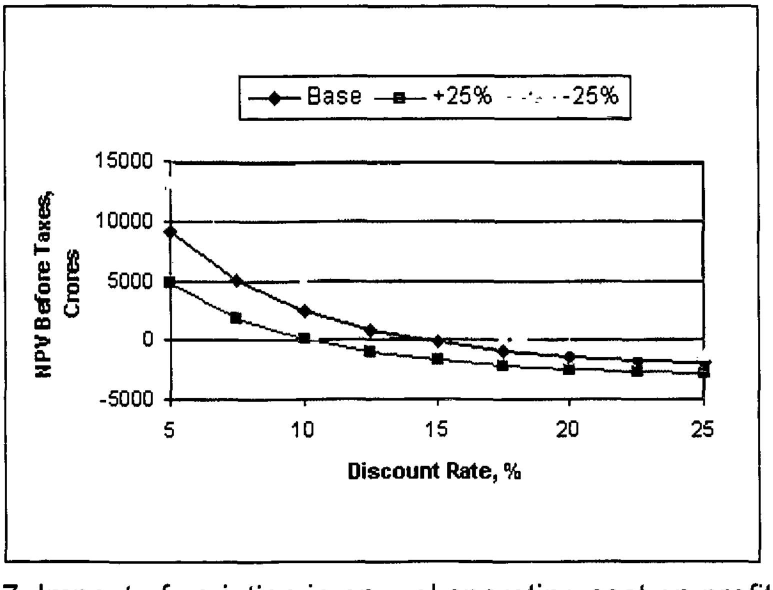


Fig. 8.7: Impact of variation in annual operating cost on profitability

e) Grade

The sensitivity test on the profitability of the project has been carried out by changing the grade of the metal values (Cu + Ni + Co) from 2.45 % to 2 %. The impact on profitability has been reflected by IRR results. i. e. the IRR changes from 14.50 % to 11.30 %. The details of results both in numerical and graphical forms are shown in table 8.11 and figure 8.8.

Table 8.11: Impact of grade (Cu + Ni + Co) on NPV

Discount rate	Base Grade-2.45%	Grade-2%
5	9087	5821
7.5	5083	2676
10	2553	724
12.5	914	-513
15	-170	-1310
17.5	-900	-1828
20	-1399	-2167
22.5	-1741	-2386
25	-1978	-2525
IRR-B Tax	14.50%	11.30%
IRR-A Tax	10.70%	8.20%
Copper	1.11	0.90
Nickel	1.22	1.00
Cobalt	0.12	0.10
Total	2.45	2.00
Manganese	24.44	24.44

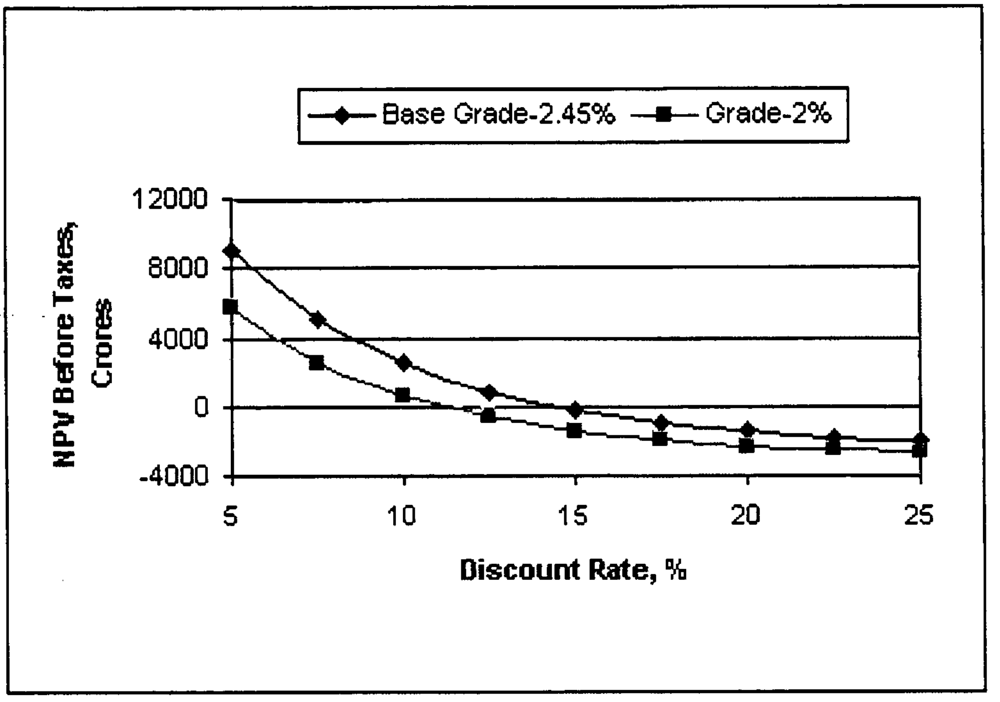


Fig. 8.8: Impact of variation of grade on profitability

f) Metal prices

The cost model has been tested with varied metal prices of Cu, Ni, Co and Mn. It can be seen that change in Prices of manganese affects the profitability substantiality. This metal is one of the major player for profit making nodule mining ventures. The details of test results both in numerical and graphical from are given in tables - 8.12, 8.13, 8.14, 8.15 and figures 8.9, 8.10, 8.11, 8.12.

Table 8.12: Impact of 25% upward and downward shifts in copper prices on NPV

Discount rate	Base	+25%	-25%
5	9087	9737	8437
7.5	5083	5563	4604
10	2553	2918	2189
12.5	914	1199	630
15	-170	57	-397
17.5	-900	-715	-1085
20	-1399	-1246	-1551
22.5	-1741	-1613	-1870
25	-1978	-1869	-2087
IRR-B Tax	14.50%	15.20%	13.90%
IRR-A Tax	10.70%	11.20%	10.20%

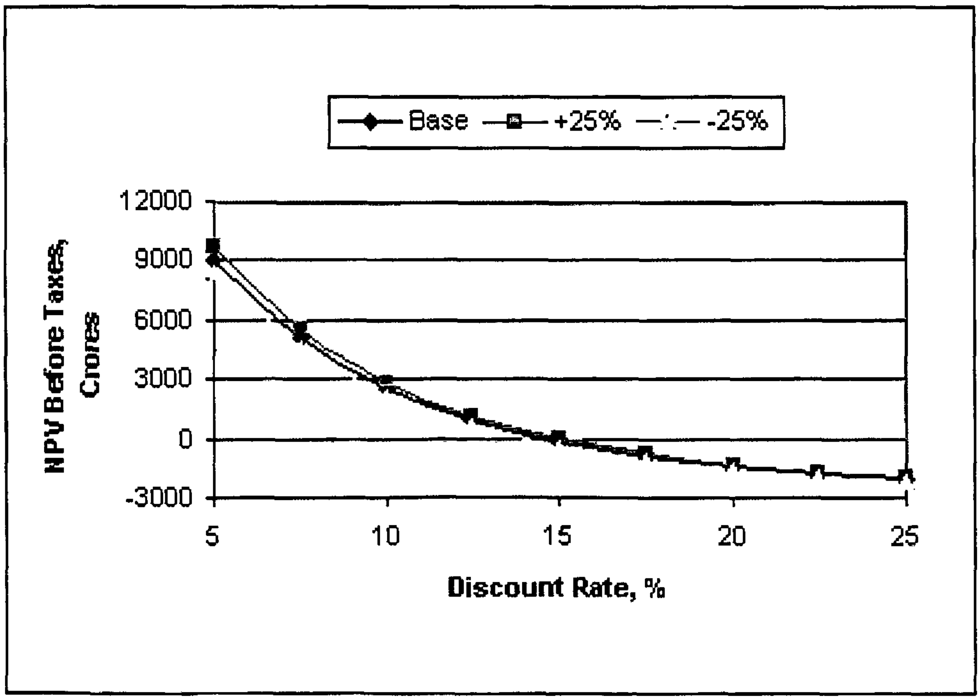


Fig. 8.9: Impact of variation of copper prices on profitability

Table 8.13: Impact of 25% upward and downward shifts in nickel prices on NPV

Discount rate	Base	+25%	-25%
5	9087	12218	5956
7.5	5083	7391	2776
10	2553	4307	799
12.5	914	2283	-454
15	-170	923	-1263
7.5	-900	-10	-1790
20	-1399	-662	-2135
22.5	-1741	-1123	-2359
25	-1978	-1453	-2502
IRR-B Tax	14.50%	17.50%	11.50%
RR-A Tax	10.70%	13.10%	8.30%

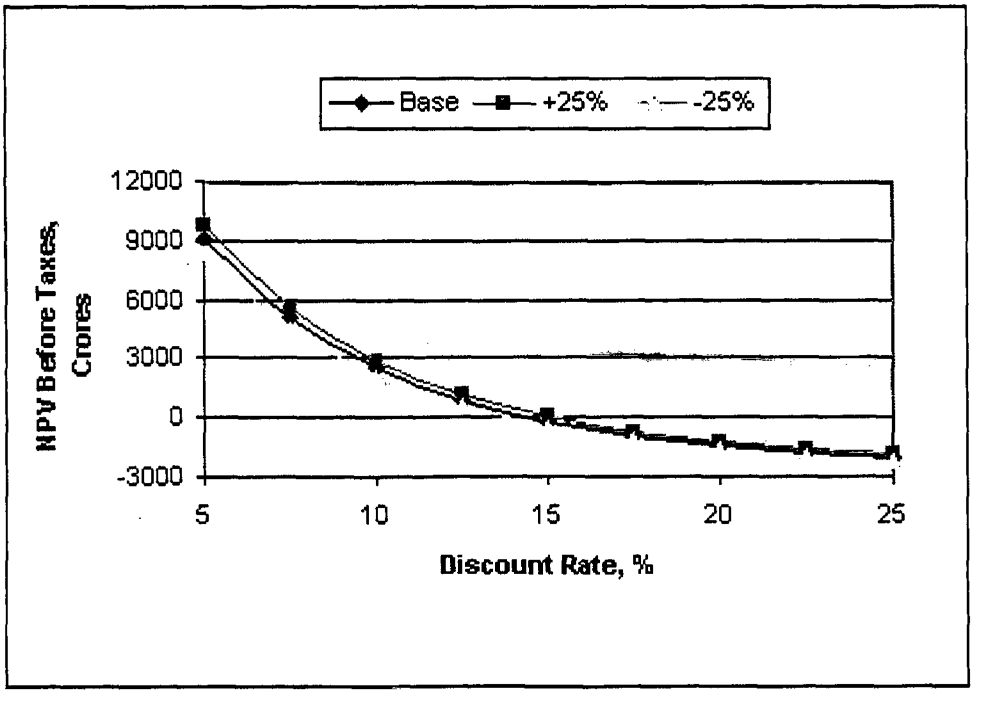


Fig. 8.10: Impact of variation of cobalt prices on profitability

Table 8.14 Impact of 25% upward and downward shifts in cobalt prices on NPV

Discount rate	Base	+25%	-25%
5	9087	9860	8314
7.5	5083	5653	4514
10	2553	2986	2120
12.5	914	1252	576
15	-170	100	-440
17.5	-900	-681	-1120
20	-1399	-1217	-1580
22.5	-1741	-1589	-1894
25	-1978	-1848	-2107
IRR-B Tax	14.50%	15.30%	13.80%
IRR-A Tax	10.70%	11.30%	10.10%

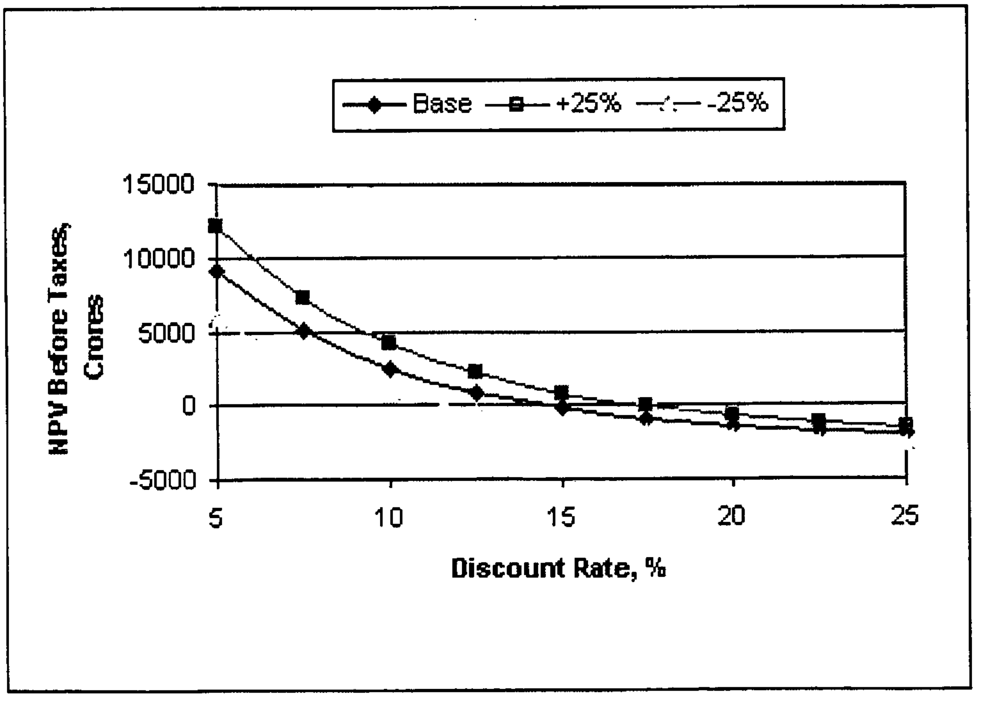


Fig. 8.11: Impact of variation in nickel prices on profitability

Table 8.15: Impact of 25% upward and downward shifts in manganese prices on NPV

Discount rate	Base	+25%	-25%
5	9087	13269	4905
7.5	5083	8166	2001
10	2553	4896	211
12.5	914	2743	-914
15	-170	1290	-1630
17.5	-900	288	-2089
20	-1399	-415	-2382
22.5	-1741	-916	-2567
25	-1978	-1277	-2679
IRR-B Tax	14.50%	18.40%	10.40%
IRR-A Tax	10.70%	13.80%	7.40%

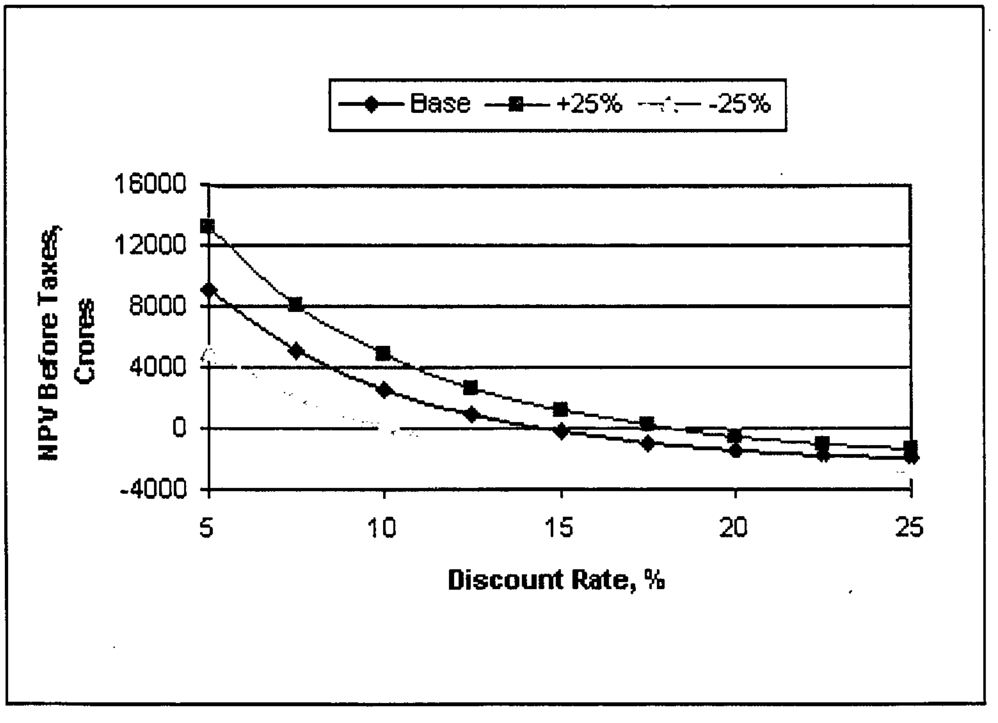


Fig. 8.12: Impact of variation in manganese prices on profitability

8.7.2 Summary of the sensitivity analysis

Sensitivity analysis carried out by considering various options are summarized below in table 8.16.

Table: - 8.16: Summary of the sensitivity analysis

Variables	IRR – Before Tax(BT)
a) Capital cost – base	14.50 %
Increase by 25 %	10.8 %
decrease by 25 %	20.4 %
b) Operating cost – base	14.5 %
Increase by 25 %	10.4 %
decrease by 25 %	18.4 %
c) Revenue – base	14.5 %
Increase by 25 %	22.4 %
decrease by 25 %	5.4 %
d) grade (cu + Ni + Co)	
base - 2.45 %	14.5 %
decrease by 2 %	11.3 %
e) Metal Price	
Cu – base	14.5 %
Increase by 25 %	15.2 %
decrease by 25 %	13.9 %
Ni – base	14.5 %
Increase by 25 %	17.5 %
decrease by 25 %	11.5 %
Co – base	14.5 %
Increase by 25 %	15.3 %
decrease by 25 %	13.8 %
Mn – base	14.5 %
Increase by 25 %	18.4 %
decrease by 25 %	10.4 %

It is clear from the trend of metal prices, particularly that of Mn and Ni, both for upward trend as well as downward trend would be main contributor to the economics of the project, and, the prices of these metals (Mn and Ni) would play an important role in the viability of project and the market price is not in the hand of entrepreneur. Most important factor is the supply of these metals in the world market. So far as economics of the project due to changes in the operating cost of the project is concerned, it would also play an important role. If the operating cost is reduced, the project would be very promising.

8.7.3 Comparison with studies already carried out

A number of studies carried out by various agencies over the years starting from 1978 and their target output for mining and the capacity for refining are different. A brief outline of the same is presented below.

Sl. No.	Agencies	Process Route	Throughput Capacity (Dry)/ year
1.	Andrews 1983	Reduction and HCL leach process	1.5 M tonnes
2.	Hillman and Gosling 1985	Cuprion ammoniacal leach process	3.0 M tones
3.	Lenoble 1988	Smelting process H_2SO_4 leaching	1.5 M tones
4.	Charles 1990	Reduction and HCL leach process route	1.5 M tones
5.	KORDI 1994	Chloride leach	3.0 M tones
6.	Sorcide 2001	High Pr. and high temperature, H_2SO_4 leach	0.7 M tonnes

The details of their capital cost and operating costs are given in table 8.17 to 8.22. As these studies were carried out in different time, inflation factor has been computed and all the estimates have been adjusted to 2003 US $ (Table 8.23 and figure 8.13).

The comparative picture of economic studies carried out by various agencies in respect of PMN without adjusting and after adjusting the prices up to 2003 US $ are given in table 8.24 and table 8.25.

Table - 8.17: Andrews, 1983 (reduction and HCl leach process)

	Mining (Wet)	**Transportation (Dry)**	**Process (Dry)**
Production- tpy	2.3 M 300 dpy	1.5 M 300 dpy	1.5 M 330 dpy
Capital cost	180 M US$	176 M US$	513 M US$
Capital cost ratio	21%	20%	59%
Operating cost	45 M US$	25 M US$	165 M US$
Operating cost ratio	19%	11%	70%
Metal	**Price**	**Recovery**	**Product**
Cobalt	$ 5.5/lb	85%	3375 tpy
Nickel	$ 3.75/lb	95%	18525 tpy
Copper	$ 1.25/lb	95%	15675 tpy
Manganese	$ 0.4/lb	93%	404550 tpy
Taxes	46%		
NPV			
IRR	6.4%		

Table - 8.18: Hillman and Gosling, 1985 (cuprion ammonical leach process)

	Mining (Wet)	**Transportation (Dry)**	**Process (Dry)**
Production- tpy	4.2 M 300 dpy	3.0 M 300 dpy	3.0 M 330 dpy
Capital cost	590 M US$	310 M US$	727 M US$
Capital cost ratio	36%	19%	45%
Operating cost	77 M US$	37.0 M US$	111.0 M US$
Operating cost ratio	34%	16%	50%
Metal	**Price**	**Recovery**	**Product**
Cobalt	$ 8.53/lb	65%	5070 tpy
Nickel	$ 3.62/lb	92%	36708 tpy
Copper	$ 1.17/lb	92%	28704 tpy
Manganese	**	**	
Taxes	29%		
NPV			
IRR	7.4%		

Table - 8.19: Capital cost estimates – M US $ plant capacity – 1.5 M tpy

	Smelting	**Sulphuric Acid Leaching**
Mining system		
Surface platform	123	123
Lifting system	38	38
Collector	59	59
Control	18	18
Exploration and supply vessel	26	26
Total mining system	264 (27%)	264 (28%)
Transport		
Conversion of 9 ore carriers	202	202
Total transport	202 (21%)	202 (22%)
Metallurgical processing		
Concentration plant	226	104
Refining plant	130	95
Silico manganese plant	146	269
Total metallurgy	502 (52%)	468 (50%)
Total capital cost	968	934
Operating cost estimates (1.5 MTPY) – M US$		
	Smelting	Sulphuric acid leaching
Mining system		
Personnel	13.4	13.4
Fuel	6.9	6.9
Maintenance	13.4	13.4
Exploration and supply vessel	5.3	5.3
Overheads	15.9	15.9
Total mining system	54.9 (23%)	54.9 (22%)
Personnel	5.3	5.3
Fuel	7.9	7.9
Panama canal	5.3	5.3
Unloading	4.7	4.7
Overheads	10.0	10.0
Total transport	33.2 (14%)	33.2 (14%)
Metallurgical processing		
Concentration plant	55.1	39.7
Refining plant	24.4	19.7
Silico manganese plant	73.4	97.6
Total metallurgy	152.9 (63%)	157.0 (64%)
Total operating cost	241.0	245.1

Table 8.19: (contd) Metal recovery and revenues (1.5 MTPY)

	Smelting	**Sulphuric Acid Leaching**
Metal recovery	%	%
Manganese	87	85
Nickel	95	96
Copper	86	95
Cobalt	83	94
Revenue	$/kg	$/kg
Nickel	8	8
Copper	2.1	2.1
Cobalt	15	15
Manganese	0.65 as Fe-Si-Mn	0.65 as Fe-Si-Mn
Gross/annum	491.2 M $	496.7 M $
Revenue ratio		
Manganese	50	
Nickel	32	
Cobalt	10.5	
Copper	7.5	
IRR	15.4	15.7

Table 8.20: Charles, 1990 (reduction and HCl leach process)

	Mining (Wet)	**Transportation (Dry)**	**Process (Dry)**
Production- tpy	2.3 M 250 dpy	1.5 M	1.5 M
Capital cost	282 M US$	188 M US$	470 M US$
Capital cost ratio	30%	20%	50%
Operating cost	48 M US$	36 M US$	156 M US$
Operating cost ratio	20%	15%	65%
Metal	**Price**	**Recovery**	**Product**
Cobalt	$ 6.8/lb	85%	3525 tpy
Nickel	$ 3.6/lb	95%	19730 tpy
Copper	$ 0.95/lb	95%	17810 tpy
Manganese	$ 0.3/lb	93%	382500 tpy
Taxes			
NPV			
IRR	12%		

Table - 8.21: KORDI-(1994 prices M US $) Capital cost estimates- 3 M dry tonnes nodules/year

Sector	Capital expenditure	%
R and D and exploration	401.74	16.46
Mining	290.80	11.91
Ocean transportation	202.80	08.31
Nodule offloading terminal	24.80	01.02
Land transportation	23.50	0.96
Processing	1,315.04	53.88
General and administration	22.90	0.94
Working capital	159.12	06.52
Grand total	2,440.70	100.00

KORDI-1994 prices M US $ Operating cost estimates-3 M dry tonnes nodules/yr

Sector	Operating expenditure	%
Mining	79.92	14.24
Ocean transportation	34.50	06.15
Nodule offloading terminal	3.32	0.59
Land transportation	6.20	01.10
Processing	433.26	77.17
General and administration	4.20	0.75
Grand total	561.40	100.00

KORDI-(1994 prices M US $) Annual revenues-3 M dry tonnes nodules/yr

	Recovery %	Price $/ton	Production tonnes	Annual revenue
Manganese	85	758.39	842,400	638.9(55.98%)
Nickel	90	10,115.30	32,400	327.8(28.72%)
Cobalt	90	25,728.85	3,900	100.4(8.80%)
Copper	65	2,665.04	27,810	74.1(6.49%)
Total				1141.2(100%)
IRR	11.93% (When R and D expenses born by private companies)			

Table 8.22: Soreide, 2001 (High Pr. and high temp. H2SO4 leach process)

	Mining (Wet)	**Transportation (Dry)**	**Process (Dry)**
Production- tpy	1.1M	0.7M	0.7M
Capital cost	127 M US$	93 M US$	271 M US$
Capital cost ratio	26%	19%	55%
Operating cost	21.8M US$	13.5 M US$	22.9 M US$
Operating cost ratio	38%	23%	39%
Metal	**Price**	**Recovery**	**Product**
Cobalt	$ 20/lb	83%	
Nickel	$ 3.33/lb	98%	2548 tpy
Copper	$ 1/lb	97%	1890 tpy
Manganese	**	**	
Taxes	10%		
NPV	-81 M		
IRR	9.6%		

Table - 8.23: Inflation factor adjusted to 2003 US$

Year	**Inflation factor compared to 2003**
1980	2.4173
1983	1.8192
1985	1.6892
1988	1.5445
1990	1.4157
1994	1.2150
1998	1.1029
2000	1.0570
2001	1.0323
2003	1.0000

(Source:westegg.com/inflation)

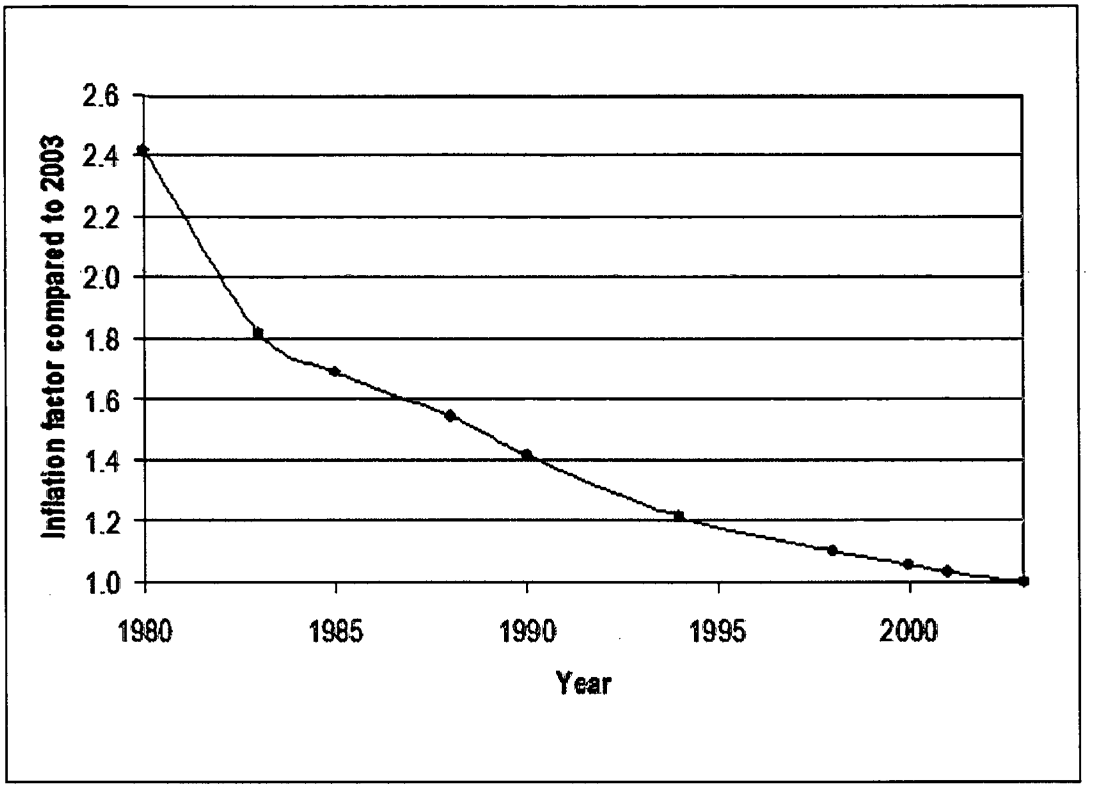


Fig. 8.13: Inflation profile adjusted at 2003

Table - 8.24: PMN economic studies (Mining+Processing)

	Year	Plant capacity	Capital cost		Operating cost	
		Mtpa	M US \$	US \$/t	M US \$	US \$/t
Andrews	1983	1.5	869	579	235	157
Hillman	1985	3.0	1617	542	225	75 (3-metal)
Lenoble	1988	1.5	950	633	243	162
Charles	1990	1.5	940	627	240	160
KORDI	1994	3.0	2440.7	814	561.4	187
Soreide	2001	0.7	491	700	58	83 (3-metal)

Table - 8.25: PMN economic studies (Mining+Processing) capital and operating cost adjusted to 2003 US $

	Year	Plant Capacity	Capital cost		Operating cost	
		Mtpa	M US $	US $/t	M US $	US $/t
Andrews	2003	1.5	1581	1054	428	285
Hillman	2003	3.0	2731	910	380	127 (3-metal)
Lenoble	2003	1.5	1467	978	375	250
Charles	2003	1.5	1331	887	340	227
KORDI	2003	3.0	2965	988	682	227
Soreide	2003	0.7	507	724	60	86 (3-metal)

8.7.4 Comparison of capital cost ratio and operating cost ratio

Agency - wise details of capital cost ratio and operating cost ratio is shown in table 8.26 and 8.27. From the point of view of the analysis carried out in the present cost model, operating cost in respect of processing component, mining component and transportation component are about 85.57 %, 8.28 %, 6.13 % respectively. The summarized picture of the capital cost and operating cost (Table 8.3 and 8.4) indicates a clear picture of the cost model presented in the exercise is comparable with studies made by different agencies earlier. It shows the nodule mining is a promising area for meeting the demand of the country in the years to come. In the present cost model presented more realistic picture has emerged, as the costing of processing sector which is the most capital intensive, is on the basis of latest state-of-the-art facility created by India. The operating cost towards processing component is also calculated on the basis of consumption pattern of all consumables/ reagents achieved in the pilot plant for recovery of four metals (Cu, Ni, Co and Mn).

Table - 8.26: Capital cost ratios

	Plant capacity Mtpa	Mining %	Transportation %	Processing %
Soreide	0.7	26	19	55
Andrews	1.5	21	20	59
Charles	1.5	30	20	50
Lenoble	1.5	27	21	52
Hillman	3.0	36	19	45
Average		28	20	52

Table - 8.27: Operating cost ratios

	Plant capacity Mtpa	Mining %	Transportation %	Processing %
Soreide	0.7	38	23	39
Andrews	1.5	19	11	70
Charles	1.5	20	15	65
Lenoble	1.5	23	14	63
Hillman	3.0	34	16	50
Average		27	16	57

8.8 Observations / Conclusions

Any entrepreneur venturing into deep seabed mining has to face high risk but the field of competition is at present quite small. India has a technical potential for commercial development of deep seabed mining within the next two decades. At this point of time, we have to consider the following important aspects:

- Predictable rules of the game
- Mechanism to protect investment

- Favourable economics (bottom line rate of investment and rate of return on investment)
- Risk sharing
- Cooperative environment

This deep sea venture can be divided into two stages upstream (exploration, transportation and mining) and downstream (processing and marketing) operations. In the upstream, only mining we are lacking; we have to speed up our activity to demonstrate the commercially flexible system. In the other component, India is already in the forefront starting from exploration to processing and capable of taking up the challenge.

The deep sea mining policies will be a bargainer or trade-off process in two distinct senses. The first trade-off will have to be made between objectives, often short-term, economic, social or political exigencies, and second, the favoured prime objective, at any point of time, will be determined by the balance of power between group having different economic interest and holding to different value systems. As the immergence of stable rising market for the metals to be exploited from the deep seabed is anticipated from around 2020, India will have sufficient expertise to master its technology for exploitation of nodule from the deep sea. The study made here clearly shows the techno--economic feasibility of deep seabed mining. A variety of sensitivity analysis have been made to know the impact on economic return by changing discount rate, capital cost, operating cost, grade and metal praises etc.. on the base line cost model. The study made us to believe and confident, that it has provided, reasonably detailed and accurate estimates. This can stand as a basis for assessing the comparative impacts, a broad range of policy and regulatory options on a typical deep sea bed mining operations. It would be possible to capture the market and to take advantage of the immergence of stable rising market by entering into deep sea bed nodule mining venture as a first country / enterpriser.

CONCLUSIONS AND RECOMMENDATIONS

For nearly two and half decades the nodule deposits in the Indian Ocean have attracted the attention of scientists from this country both for resource potential and basic science of formation of these deposits.

The polymetallic nodules in the CIB have been extensively studied on various aspects and studies include mineralogy, morphology, chemistry and other related aspects such the environment, topography of the region, sediment characteristics, sea bed conditions, nodule potential and distribution.

Although the technology, economic viability and environmental aspects of deep-sea mining of nodules has been under discussion for the last two decades by various Consortia, Countries etc., no concrete results have come out of these discussions and many gray areas do still exist.

There is no systematic documentation on the economic, environmental and feasibility of mining aspects in Indian Ocean.

This work incorporates the results of the studies/ analysis carried out on polymetallic nodules of Indian Ocean with particular reference to the Central Indian Basin (CIB) nodule deposits.

A large exploratory dataset available for the Indian Ocean site was used to arrive at a comprehensive analysis of polymetallic nodules with an emphasis on economic, environmental and mining aspects. This is a first attempt to collate various datasets and develop suitable models for selection of potential sites, and evaluate various mining systems/ technologies, the impact of mining on the environment and understand the demand and supply of the metals that form a resource from nodules.

A large number of stations ($n = 435$) computed for nodule abundance and grade (Co+Ni+Cu) suggests an inverse relation ($r = -0.52$) between the two variables.

These results corroborates the earlier findings of inverse relationship between nodule abundance and grade.

The two sets of values considered for the present study include the stationwise values and the blockwise kriged values, and they reflect the difference in the results due to different support and areal extent. Moreover, the stationwise values represent direct measurements, whereas the blockwise values are approximated by a model used for estimation of a variable. Therefore, the stationwise values provide an idea on the distribution of values on a point scale with a limited areal extent (area of influence), and the statistics of blockwise kriged values reflect the distribution of estimated values on a much larger areal scale.

It is observed that the mean values based on stationwise measurements compare reasonably well with the mean values based on blockwise estimates, and the variability of blockwise estimates are considerably reduced when compare to the stationwise measurements. Therefore, the blockwise kriged values have greater reliability due to the optimizing techniques than the direct measurements based on stationwise values.

A model developed based on frequency distribution studies of stationwise and blockwise kriged values suggest using a transformation, $Z = \log x$ or $Z = \log (a+x)$, and the variables such as abundance, grade, Co, Ni, Cu and Mn considered in this study respond to log distribution models. It is therefore approximated by a 2-parameter log normal distribution model. Thus, the frequency distribution models so developed are used for arriving at a suitable selection criteria at block level, for identification of potential areas as well as to demarcate a mine-site in the CIB.

If the selection blocks/areas are based on abundance, then 50% of the samples/ area provide an estimated abundance of 9 kg/sq.m. Whereas the selection of area based on grade results in 50% of the samples/ area to provide an estimated grade of 2.9%.

The experimental grade-tonnage curves based on stationwise and blockwise values suggest the dependence of the curve on block size. The resultant curve based on stationwise values may be too optimistic and not realizable in mining practices. However, the curve based on blockwise values relate to a larger block size to be considered for acceptance or rejection. The smaller block sizes may provide the desired resultant abundance and grade values of selected blocks and may be reliable and more realizable while mining the nodules.

Based on the analyses of various available technologies for mining and the Indian efforts to develop a reliable mining system, an environmentally safe mining system has been proposed in this study.

The compounded demand growth rate of various metals have been analyzed both for globally and in Indian context. An analysis has also been made on the trends and prices of these metals (Co, Ni and Cu) for the last century. Considering the growth in demand supply and metal prices , the expected level of demand-supply of Co, Ni, Cu and Mn for the year 2020 has been projected.

A cost model has been developed based on ta suggested mining technology and process package already developed by India. The cost model finally suggests that the polymetallic nodule mining would be economical by 2015 considering the present price trends of Co, Ni, Cu and Mn .

It is suggested that detailed studies on economics of mining, transportation of nodules from the site in Indian Ocean, and extraction of metals be taken up by researchers based on the demand-supply scenario and prevailing market trends of metal prices.

REFERENCES

1. Aitchison, J., and Brown, J. A. C., 1957. The lognormal distribution with special reference to its uses in economics. Cambridge university press, Cambridge, 176 p.

2. Amann, H., 1991. Soft ocean mining. Offshore technology conference, May, 1991, Houston, Texas, USA (abstract).

3. Amann, H., 1994. Basic engineering and new technologies for an environmentally acceptable deep seabed collector. International Conference on deep seabed mining policy, September 5-6, Seoul, Korea. (abstract).

4. Andrews, B, V., 1977. A report on waste disposal system for manganese nodule processing, U.S. Department of commerce, pp. 3-8.

5. Andrews, B. V., 1983. Economic viability of a four-metal pioneer deep ocean mining venture. US dept. of commerce, PB84-122563, 201p.

6. Archer, A. A., 1979. Resources and potential reserves of nickel and copper in manganese nodule. In: United Nations ocean economics and technology office(ed), Manganese Nodules: Dimensions and Perspectives. Reidel, Dordrecht, pp. 71-82.

7. Archer, A. A., 1985. The metal resources of manganese nodules. In: Marine mining a new beginning-conference proceedings, July 18-21,1982. Hawaii department of planning and economic development, University of Hawaii, Seagrant program. pp. 13-22.

8. Backhurst, J. R., and Harker, J. H., 1973. Process plant design. pp. 300-301.

9. Banakar,V.K., Gupta S.M., and Padmavathi, V.K., 1991. Abyssal sediment erosion in the Central Indian Basin – evidence from radiochemical and radiolarian studies. Mar. Geol., v. 96, 169 p.

10. Barkenbus, J. N., 1979. Deep seabed resources. The free press, London, 191 p.

11. Bath, A. R., 1989. Deep sea mining technology: Recent developments and future Prospects. OTC 5998, pp. 339-340.

12. Blais, R. A., and Carlier, P. A., 1967. Application of geostatistics in ore evaluation. Ore resource estimation and grade control, v. 9; pp. 41-68.

13. Brockett, F. H., 1999. Nodule collector sub-systems. Proceedings ISBA workshop Aug. 3-6, (abstract).

14. Brockett, F. H., and Kollwentz, W. M., 1977. An international project – nodule collector. Proceedings offshore tech. conf. OTC 2777, pp. 413-418.

15. Brockett, F. H., Petters, R. A. and White, G. M., 1979. Designing an ocean mining collector system. Proceedings of offshore tech. conf, OTC 3368, pp. 95-98.

16. Bruland, K.W., 1983. Trace elements in sea-water. In Chemical Oceanography. J.P Riley & R. Chester (ed) Academic Press, London, 2nd edition v. 8; pp. 157-220.

17. Burns, V. M., and Burns, R. G., 1977. Mineralogy in marine manganese deposits. Glasby, G. P., (ed) Elsevier. 185 p.

18. Charles, C., 1990. "Views on future nodule technologies based on IFREMER-GEMMOND Studies". Materials and Society, v.14; pp. 299-326.

19. Chung, J. S., and Tsurusaki, K., 1994. Advance in deep – ocean mining system research. Proceeding in offshore and polar engineering conference, ISOPE, Osaka, v.1; pp. 18-31.

20. Cronan, D. S., 1977. Deep sea nodules: distribution and geochemistry, In: Marine Manganese Deposits. Glasby, G., P. (ed) Elsevier, pp. 11-44.

21. Cronan, D. S., 1980. Underwater Minerals. Academic press, London, pp. 121-195.

22. Cronan, D. S., and Moorby, S. A., 1981. Manganese and other ferromanganese oxide deposits from the Indian Ocean. Jour. Geol. Soc. , London, v. 138; pp. 527-539.

23. David, M., 1972, Grade tonnage curve: use and misuse in ore reserve estimation. Transactions of the institution for mining and metallurgy. v. 81; pp. 129-132.

24. David, M., 1977, Geostatistical ore reserve estimation. Elsevier, Amsterdam.

25. Flipse, J. E., 1973 Mineral resources of the deep seabed. p. 12 and p. 607.

26. Frankel, E. G., and Marcus. 1973. Ocean transportation. pp. 328-378.

27. Fraze, J. Z., and Wilson, L. L., 1980. Manganese nodule resources in the Indian ocean. Marine Mining, v. 2; pp 257-292.

28. Glasby, G. P., and Hubred, G. L., 1976. Comprehensive bibiolography of marine manganese nodules. NewZealand Oceanographic Institute Memoir. v. 71; 55 p.

29. Gross,G.A., and McLeod, C.R.,1987. Metallic minerals on the deep seabed. Geol. Surv. Canada. 14, 65p.

30. Haynes, B., Barron, D., Kramer, G., maeda, .R., and Magyar, M., 1985. Laboratory processing and characterization of waste materials from manganese nodules. Bureau of mines report of investigations, 893 p.

31. Herrouin, 1999. Scientific and technology R and D related to deep seabed mining. Proceedings of ISBA workshop Aug 3-6, (abstract).

32. Herrouin, G., Germonod, J-P Lenoble, Charles, C and F. Mauviel, F. 1989. A Manganese Nodule Industrial Venture would be profitabile: Summary of a 4-year study in France. Paper presented in 21st annual OTC in Houston, Texas.

33. Heye, and Marching. 1977. Relationship between the growth rate of manganese nodules from the central Pacific and their chemical constitution. Mar. Geol. v. 23; pp. M19-M25.

34. Hillman, CT and Gosling, B. B., 1985. Mining deep ocean manganese nodules: description and economic analysis of a potential venture, US Bureau of mines, IC 9015, 19 p.

35. Hong, S. 1995. Three dimensional analyses on behavior of mining pipe of deep seabed mineral resources. Proceedings of 1st ISOPE ocean mining symposium, Tsukuba, Nov 21-22, 69-74.

36. Iyer, S.D. and Sudhakar, M., 1993. Coexistence of pumice and manganese nodule fields-evidence for submarine silicic volcanism in the Central Indian Basin. Deep Sea Research-I, v. 40(5), 1123-1129.

37. Inokuma, A., 1995. Current status of deep sea mineral resources development in Japan. Proceedings of 1st ISOPE ocean mining symposium, Tsukuba, pp. 9-13.

38. Kamesh Raju, K., Ramprasad, T., Kodagali, V. N., and Nair, R. R., 1993. Multibeam bathymetry, gravity and magnetic studies over 79° E fracture zone, Central Indian basin, Jour. Geophy. Res, 98, 9605-9618.

39. Khadge, N.H., 2000. Geotechnical properties of surface sediments in the INDEX area. Marine Georesources and Geotechnology. V.18(3); pp.251-258.

40. Koch, G. S. Jr., and Link, R. F., 1971. Statistical analysis of geological data. John Wiley, Newyork , Vol-II.. 438 p.

41. Kodagali, V. N., 1989. Morphology of an uncharted seamount from Central Indian basin. Mar. Geodesy, v.13, pp.83-90.

42. Krige, D. G., 1960. On the departure of ore value distributions from the lognormal model in South African gold mines. Jour. South African Inst. Mining Metal., v. 61; pp. 231-244.

43. Lasky, S. G., 1950. How tonnage and grade relations help predict ore reserves. Eng. Mining Jour. V. 151(4); pp. 81-85.

44. Lenoble, J.P., Herrouin, G., Charles, C., Mauviel, F., Bernard, J., and Taine, B., 1989, A manganese nodule industrial venture would be profitable. Summary of study in France, Proc. 21st Annual OTC in Houston, Texas, May 1-4. OTC 5997, pp. 321-327.

45. Liu, F., 1995. China's programme in marine resources development. Proc 27th . Offshore Technology Conference, Houston, Texas, May 1-4, OTC 6003, pp.315-322.

46. Liu, F., 1997. Navaba - a new initiative of COMRA's Environmental programme'. Proceedings of international symposium on environmental studies for deep sea mining, November 20-21, Tokyo, Japan.

47. Liu, F., and Ning Y., 1999. Environmentally friendly deep sea mining system. Proceedings of ISBA workshop on technologies for mining deep seabed polymetallic nodules, 3-6 August, Kingston, Jamaica, (abstract).

48. Masuda, Y., Mero, J. L., and Cruickshank, M. J., 1971. Continuous line bucket (clb) line dredging at 12000 ft. Offshore Technology Conference 1410 (abstract).

49. Masuda, Y., and Cruickshank, M. J., 1994. Progress in development of a continuous line bucket (clb) mining system. Proceedings MTS93, Long Beach Proceedings – ISOPE 194, Osaka, Japan, (abstract).

50. Matheron, G., 1963. Principles of geostatistics. Economic geology, v. 58; pp. 1246-1266.

51. Matheron, G., 1967. Kriging of polynomial interpolation procedures. Canadian Inst.of Mining Bull, v. 60; pp. 1041-1045.

52. Mero, J. L., 1965. The mineral resources of the sea. Elsevier Amsterdam. 312 p.

53. Middelhaufe, A., 1979. Deep sea mining system, 2nd WEGMENT. Technical University Aachen and NSMB, Wageningen, March 5 -16, (abstract).

54. Moore, J. R., and Cruickshank, M. J., 1973.Identification of technological gaps in exploration of marine ferromanganese deposits. In: Inter-university program of research on ferromanganese deposits of ocean floor. Phase I report, Seabed assessment program IDOE, NSF, Washington, pp. 279-335.

55. Moore, J. W., and Ramamoorty, 1984. Heavy metals in natural waters. Springer Verlag, N.Y. 286p.

56. Mukhopadhyay, R., and Khadge, N. H., 1990. Seamounts in the Central Indian ocean basin: Indicators of the Indian plate movement. Proc. Indian, Acad. Sci. (Earth planet sci.) v. 99 (3), 357 P.

57. Murray, J., and Renard, A. F., 1891. Report on deep sea deposits. Report on the scientific results of the voyage of H. M. S. Challenger, deep sea deposits, 525 p.

58. Nyhart, J. D., Antrim, L., Capstaff, A. E., Kohler, A. D., and Leshaw, D., 1978. A cost model of deep ocean mining and associated regulatory issues. In: MIT seagrant program, dept. NO.HITSG 78-4. Cambridge, Mass. MIT seagrant information centre.

59. Oebius, H. U., 1993. Enfevicktung eines Umwelt schonendew manganese knollewabbaus and gewinnungs verfahrens. Report No: 1228/93, VWS, (abstract).

60. Oebius, H. U., 1997. Deep sea mining and its environmental consequences. Publication of technical university, Berlin, Germany.

61. Ogley, R.C.,1984. Internationalizing the seabed, Gower. In: inter-university program of research on ferromanganese deposits, Aedershot 234 p.

62. Pardo, A., 1967. Who will control the sea bed? Foreign affairs. v. 47; pp. 123-137.

63. Pasho, D. W., 1979. Determining deep seabed mine site area requirements- a discussion. In: United Nations ocean economics and technology office (ed), Manganese Nodules: Dimensions and Perspectives. Reidel, Dordrecht, pp. 83-112.

64. Schlich, R., 1982. The Indian Ocean: aseismic ridges, spreading centres and ocean basins, In Ocean basins and Margins, v. 6, Indian Ocean pp. 51-147 (Ed. Nairn and Stehly, NY).

65. Schmidt, M. G., 1989. Common heritages or common burden?. Oxford, NewYork., 251 p.

66. Sharma, R., 2001. Indian deep sea environment experiment (INDEX): An appraisal. Deep Sea Research v. II, 48, pp. 3295-3307.

67. Sichel, H. S., 1966. The estimation of means and associated confidence limits for small samples from lognormal populations. Symposium on mathematical statistics and computer applications in ore evaluation. South African Inst. Mining and Metal, v. pp. 106-122.

68. Soreide F., 2001. Deep ocean mining reconsidered a study of the Manganese Nodule Deposits in Cook Island". Proc. 4th ISOPE ocean mining symp., pp. 88-93.

69. Stermole, F. A., 1974. Economic evaluation and investment decision methods. 165 p.

70. Sudhakar, M., 1989a. Ore grade manganese nodules from the central Indian basin:an evaluation. Marine mining, v. 8; pp. 201-214.

71. Sudhakar, M., 1989b. Grade distribution in manganese nodules of central Indian basin. Current science, v. 58; pp. 277-247.

72. Sudhakar, M., 1993. Geostatistical analysis of polymetallic nodule data from Indian ocean and a comparative study with Pacific ocean deposits. Ph.D. Thesis (unpublished), Indian School of Mines, Dhanabad. p. 274.

73. Sudhakar, M., Kodagali, V.N. and Jaisankar, S., 1996. A model for relative ranking of blocks and selection of candidate mine sites for manganese nodule mining: a case study of the Indian Ocean. 28th Annual Offshore Technology Conference Proceedings, Texas 0810, 475 – 483.

74. Thiel, H., Schriever, G., Bussau, C., and Borowski, C., and 1993. Manganese nodule crevice fauna. Deep Sea Research, v.4; 2 p. and 49 p.

75. Thiel, H., and Forschungsverbund. 1995. The German environmental impact research for manganese nodule mining in the SE Pacific Ocean. Proceedings of the ISOPE – Ocean mining symposium, Tsukuba, Japan.

76. Valsangkar, A.B., and Ambre, N.V., 2000. Distribution of grain size and clay minerals in the sediments from INDEX area, Central Indian Basin. . Marine Georesources and Geotechnology. V.18(3); pp.189-200.

77. Vinogradov, A.P., 1967. Introduction to geochemistry of the ocean.Nauka, Moscow.215p.

78. Welling, C. G., 1976. "Mining congress journal" pp. 46-47.

79. Zuleta, B., 1982. The law of the sea: myths and realities. Oceanus v. 25; pp. 28-30.