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MINERAL EXPLORATION IN THE TWENTIETH CENTURY

S.K. Mukerjee
Former Director General,
Geological Survey of India,
Flat No. 6B, 315/B, UN Banerjee Road
Calcutta - 700 050

The Indian scenario of the pre-industrial era brings out a glorious past of utilisation of mineral resources. Recovery of diamond and gold by mining and simple processing for separation can be traced back to very ancient times. Extraction of base metals was a flourishing industry, as evidenced by extensive slag heaps in the mineralised belts all over the country. Indian steel earned its fame throughout the world. But earth science investigations in the modern sense were initiated in India only in the 1850s with the organising of the Geological Survey of India. The Survey functioned as a small unit concerned primarily with systematic geological mapping and examination of reported mineral occurrences. After independence, the role of earth sciences in development was recognised and the Geological Survey of India was expanded and it developed a number of disciplines. As a discipline attained a certain status, it was separated from the Survey and made into an independent organisation. Petroleum Geology Wing of Oil and Natural Gas Commission, Central Ground Water Board, Atomic Minerals Division of the Atomic Energy Commission, and Mineral Exploration Corporation are some of the organisations and units which had their beginning in Geological Survey of India. The role of geophysics has been appreciated in the country and all the major organisations have developed strong geophysics units. Analytical chemistry and geochemistry have received considerable importance and facilities have been built up for precise chemical determinations of rock forming minerals together with X-ray diffraction study facilities. The role of airborne survey has been recognised and complete aerial photocoverage of the country is available together with airborne geophysical coverage of parts of the country. Regional computer centres are being established for processing and interpreting the data provided by the Indian Remote Sensing Satellite. Core drilling capacity has been developed and depth range up to 1000 m is being probed for solid minerals. Marine geological survey is receiving attention and a number of Indian research vessels are operating in the coastal waters and EEZ. India is keeping pace with the advances in earth science and the latest concepts and technology are being utilised for better interpretation of the geological frame.

Brginning of Metal Age

The first metal to be discovered by man is nuggets of gold, in the stony shoals of the river, while in search of flint. Copper came next. He may have been attracted by the spongy lumps of the red metal covered by a brilliant green film of oxide. But copper is too soft. Bronze, the alloy of copper and tin, was the first alloy to serve man faithfully. It was the first metal to toil and battle and to give its name to a whole period of human history. But bronze lost its place to the stronger metal iron. Iron was first collected from meteorites. More than 6000 years ago in Egypt, iron ornaments were costlier than those of gold. About 4000 years ago, man first learnt to recover the metal from its ores and since then iron and its alloys have dominated the human destiny. Technology is self-propelling and demands continuously improved tools and the nations which have failed to move with the time have lost in the struggle for existence. The native of America who knew only stone and bronze, was a poor match for the conquerors clad in iron armour. The Africans who could not go further than primitive forge, fell under the attack of cast iron tools of the Europeans.

Impact of Industrial Revolution

The recognition of properties and the development of technology to utilise the possibilities inherent in minerals is a continuous human endeavour. However, industrial revolution, which represents a great leap forward, came with the development of technology for harnessing the energy of fossil fuels. Coal was first used as a commercial fuel sometimes in the thirteenth century. The Industrial Revolution was, however, started in the eighteenth century after the recognition of the tremendous implication of steam energy by James Watt in 1782 and the development of better iron-making technology to withstand the energy. In 1716, Britain brought first consignment of 35 tons of Russian iron, which built the foundation of Industrial Revolution. The real breakthrough came on 14 July 1830, when Stevenson's Locomotive 'Rocket' made 20 miles an hour to win the competition of speed. The impact of the development can be appreciated from the fact that while it took thousands of years to achieve that speed, in the next 150 years, man-made rocket has attained the speed of about 25000 miles per hour to break away from the gravitational pull.

Discovery of New Metals

Minerals played a vital role in bringing about this technological breakthrough. The ancient Romans knew about eight metals only. Towards the end of the eighteenth century, chemists had identified 20 metals and today about 80 metals are known. Since the middle of the nineteenth century, a number of new metals came up for human use or many new usages were discovered for old metals. A large number of metals like manganese, chromite, vanadium and tungsten became very important, as they added 'vitamin' to steel. With the invention of electric generator, copper became a major industrial mineral. Commercial extraction of aluminium was made possible due to electric power and it became a major metal of the twentieth century. A large number of metals came into use in the space age and the nuclear age. However, even today iron accounts for 94% of all metal production.

Mineral Development Scenario in Twentieth Century

The rising demand for minerals which came as 'breeze' in the later part of the nineteenth century, developed into a 'storm' in the twentieth century. The major changes which shaped the mineral development scenario in the twentieth century can be summarised as follows:

a) Demands for minerals and fuels are increasing at an unprecedented scale. Coal production in the country, which was about 1 lakh tons in 1850 and six million tons in 1900, rose to 130 million tonnes in 1984 and is projected to rise to 387 million tonnes by 2000 AD. Iron ore production has gone up from 66000 tons in 1900 to 41 million tonnes during 1980. The progressive increase in coal demand between 1850 and 2000 AD will illustrate the point (Table 1).

b) Development in science and technology has helped in detection and extraction of valuable minerals/metals from lower and lower grade ores and from greater depths. In late eighteenth century, copper ore with grade as high as 10-20% was usable, but in 1980s, grade as low as 0.5% Cu and less was being worked in large prophyry deposit.

c) It is realised that minerals are non-renewable wasting assets. Resources, though vast, are not unlimited. In spite of tremendous technological advance, only a small part of the planetary resources can be usefully exploited. Beyond a certain point, the cost of extraction in terms of money, energy and environmental degradation becomes prohibitive, compared to the benefits that accrue.

Table 1. Progressive increase in coal demand in India

Period	Production/Demand (in million tonnes)
1850-1900	43
1901-1947	858
1948-1950	90
1901-1950	948
1951-1984	2387
1985-2000 (Projected)	4045
1951-2000 (Projected)	6432

It will be seen from Table 2 that presently usable grade remains much above the background value of the elements in the earth's crust (known as Clarke value). It will be seen from Table 3 that in the case of many metals, maximum recoverable tonnage is not very large. The situation may not, however, be as gloomy as projected earlier by Club of Rome in their treatise designated 'Limits to Growth'.

(d) Mining has become a massive high risk capital intensive venture and necessitates large pre-investment exploration to minimise the risk.

(e) Identification of vast potentiality of sea bed.

Beginning of Systematic Mineral Search in Nineteenth Century

Since the middle of the nineteenth century, with increase in the demand for minerals and metals, mineral prospecting and mining no longer remained in the hands

Table 2. Concentration Clarkes for ore bodies of the common metals

Metal	Clarke (elemental distribution in crust)	Minimum percentage profitably extracted	Concentration Clarke necessary for an ore body
	(1)	(2)	(2)/(1)
Al	8.13	30	4
Fe	5.00	30	6
Mn	0.10	35	350
Cr	0.02	30	1500
Cu	0.007	1	140
Ni	0.008	15	175
Zn	0.013	4	300
Sn	0.004	1	250
Pb	0.0016	4	2500
U	0.0002	0.1	500

Table 3. Possible 'life' of net available resources on continental crust

Metal	Known reserves and conditional resource (million tonnes)	Duration of reserves +conditional resource with a stable consumption in years	Maximum recoverable tonnage (million tonnes) assuring 0.01% figure (B.J. Skinner 1976)
Ni	100	150	1,200
Cu	350	46	1,000
Pb	150	43	170
U	1.5	–	27
Sn	20	95	25
W	1.5	38	17

Note: The net available resources usable in conceivable future form only a small fraction of the total available planetary resources. This will be obvious from a comparison of the maximum recoverable resources (Reserve + Conditional Resources). The maximum quantity of copper in the continental crust, which may be concentrated in deposits (with at least a 0.1% Cu grade), would range between 0.01% and 0.001%. Keeping the 0.01% figure for all metals and applying a 10 km crust, the estimates have been made (Ref. B.J. Skinner, 1976).

of traditional local prospectors and corporate bodies took over from skilled artisans. Mineral prospecting, prior to that period, depended on certain 'thumb rules' developed by the traditional prospectors. In certain fields, they had attained remarkable success. It is difficult to name any base metal mineralised belt in India without old workings. With opening up of virgin areas due to spread of communication network, huge mineral deposits were located in areas earlier considered as *terra incognita*. Mining became a high risk capital intensive venture and the sub-discipline of mineral exploration developed as a part of the discipline of economic geology. Well-trained geologists who brought in an understanding of the genesis of mineral deposits could identify features and predict occurrence, which were not possible for the adventurous prospector. From the middle of nineteenth century, geologists started preparing systematic geological maps, which became invaluable aids to the later prospectors. In the search for gold and base metals, the 'old favourites' of ancient people, the ancient workings and slag heaps, mining implements, etc. proved to be invaluable guides. But though science improved, exploration tools remained primitive. The success of the geologists of the nineteenth century was very much dependent on improved communication and the assistance of the trained villager. W.H. Hughes, one of the greatest Indian geologists of the nineteenth century, used to pay to the guide Re 1 for the *Khabar* of coal outcrop and Rs 2 for *Khabar* about tiger.

Mineral Exploration in Twentieth Century

In the face of ever-rising demand for minerals in the twentieth century, new resources are to be identified to increase the inventory position continuously. The days of locating easily identifiable surface deposits by ancient workings or through surface geological mapping are nearing an end and the stress in this century is shifting to ore bodies which have poor surface shows. Mineral deposit is an anomaly and hence rare. For example, most of the chromite resource in India is concentrated in 1 sq km area in Sukinda, Orissa; most of the baryte reserve in 0.25 sq km area in Mangampeta, Andhra Pradesh; 60% of zinc reserves in 1 sq km area in Agucha, Rajasthan. Only a small part of the economic mineral occurrences is exposed on the present-day 'change erosion surface'. Many more Sukindas, Mangampetas or Aguchas may have remained buried. Search for such 'buried' deposits is a challenging job, but a proper understanding of the various parameters of a 'known deposit' leads to a new discovery. Simple thumb rules have yielded place to deposit modelling. Improved geological concepts for modelling by dynamic evaluation of the earth's crust have been possible through an enlarged database with inputs from satellite imagery, aerial photography and airborne geophysics coupled with more intensive ground coverage and petrological studies. These conceptual models are establishing the physico-chemical environment of geological formations. Chemical determination of a wide spectrum of rock forming elements is helping in visualising partitioning of constituents within the geological units, suggesting possible loci of mineralisation within the favoured geological frame. Better drilling techniques are providing reliable sub-surface samples from desired depth. Computer analysis of the mass of data generated is helping in reaching firm conclusions. Search for minerals is being extended from on-shore to off-shore areas and research ships equipped with sophisticated geophysical instruments and capabilities of sampling the seabed are being deployed for locating minerals on the sea floor.

Changing Concepts

Geological concepts have undergone major changes since the days of Hutton, particularly with the fundamental discoveries in the allied physical sciences in the present century. It is now possible to simulate to a large extent the natural processes in the laboratory, which has improved our understanding of the process of ore genesis and localisation. According to the magmatic school fashionable in early part of the century, many of the mineral deposits were ascribed to magmatic origin. In the middle of the century, irrefutable evidences were available to postulate the sedimentary origin of some of the massive sulphide deposits. Geosynclinal concepts on the origin and development of crustal mobile belts have helped to build up a coherent framework of correlating ore mineralisation with the different stages of the evaluation of geosyncline. The global plate tectonics concept propounded in the sixties laid focus on accretive and destructive plate margins and their spatial relationship with the prophyry copper and massive sulphide deposits. It has also been possible to arrive at a broad generalisation on the nature and distribution of different metals/minerals in different geological times, as for example, gold, iron ore, nickel have better concentration in the older geological set-up, while prophyry copper, tin, tungsten, phosphorite, etc. show better concentration in relatively younger environment.

Exploration Techniques Based on Remote Sensing

The technological development since the second quarter of the present century has made more significant contributions in improving the mineral exploration capability. Though the first air photo was taken in France as early as 1858 from balloons, large scale black and white and colour air photography were introduced since World War II. The satellite age started when NASA sent up the Earth Resource Satellite (ERTS-1) in 1972. Visual and multi-spectral scanning are now widely applied in geological sciences. These developments have helped in understanding global geological and tectonic features, as well as the geological truths of inaccessible terrains.

Geophysics

Airborne and ground geophysical survey is one of the most important tools for understanding sub-surface geology that was introduced extensively in mineral exploration in the twentieth century. Magnetic surveying is the oldest geophysical prospecting technique and is reputed to have been used in prospecting for iron in Sweden in the seventeenth century. By the nineteenth century, magnetic survey using dip needles was extensively used for iron prospecting. However, it was not until the early part of the present century, when the first precision magnetometer was designed, that magnetic prospecting as we know today really began. Magnetic surveying is the most widely used airborne geophysical survey and aero-magnetic map has come to be regarded as of fundamental importance in interpreting the geological map of the country. Electromagnetic survey, which is a useful tool for locating sulphide minerals, was developed in 1920s and many refinements have been made in recent years, including the airborne EM Survey technique. Induced Polarisation Survey was used experimentally in 1940s, but after 1960s, it has become a popular prospecting tool. Gravity and seismic surveys, originally introduced in the nineteenth century, have become useful for understanding the sub-surface geology and structure. These methods play an important role in delineating possible oil-bearing structures, and locating massive buried deposits of coal, baryte, evaporites, chromite, volcanic plug (host rock for diamond), etc., However, except gravity and seismic surveys, which have deep penetration, other geophysical methods have effective penetration of only 150-200 metres depth. Borehole geophysics to a large extent has filled the gap. Multisensor geophysical logging like electrical, gamma and neutron logging are now in extensive use.

Geochemistry

The science of geochemistry has largely developed during the present century, though the term geochemistry was introduced by the Swiss chemist Schonbein in 1838. F.W. Clarke of United States Geological Survey made monumental contributions in the development of geochemistry between 1833 and 1925 by projecting data available through the analysis of available rocks. Further development had to await the development of the fundamental sciences. In 1912, Von Laue showed that the regular arrangement of atoms in crystals acts as diffraction grating towards X-rays, which helped the determination of atomic structure of minerals. The work of the Geophysical Laboratory of Carnegie Institution of Washington since 1904, oriented towards laboratory experimentation under controlled condition to study the geological process, was a great step forward. At the same time, Scandenavian School of Geochemistry started developing under the leadership of Goldschmidt. The School of Geochemistry was developed in Russia since 1917, under the leadership of V.I. Vernadsky and A.E. Fersman. Geochemistry in Russia has been particularly directed towards the search for the exploration of mineral raw materials, evidently with considerable success.

Development in geochemistry in the twentieth century helped in determining elemental distribution in the earth's crust (Clarke value), the tendency of different elements to adjust themselves in different crystal structures, the effect of temperature, absolute and partial pressure in formation of mineral phases, the dispersal of elements by different geological processes and the interrelationship of different elements, etc. Geochemistry has also been greatly helped by the development of sophisticated instruments like emission spectrograph, atomic absorption spectrophotometer, flame photometer, X-ray fluoresence spectrometer, etc., which enabled quick analysis of a large number of elements occurring even at ppb level. The instrumental analytical facilities have revolutionised fundamental and applied geochemistry.

Drilling

Drilling is at present the most useful and direct tool for mineral exploration and the technology of faster and deeper drilling has developed tremendously in the present century. In the nineteenth century, only percussion drilling technique was used, which was a very slow method with limited depth penetrability. The development of rotary drilling technique in the first quarter of the present century had made a tremendous impact on geological studies and mineral exploration. In the present century, it has been possible to drill even up to Mohorovicic discontinuity up to 20 km depth or to drill in the sea bed from floating platforms.

Marine Geology

Earlier, search for minerals was restricted to land, but since 1960s, development of marine geology has opened up vast areas for mineral search. The discovery of manganese nodules in the sea bed, containing good concentration of important metals like Cu, Ni, Co, etc., is a tremendous contribution and has far-reaching implications for future resource supply and global politics. The deep sea resources are recognised as 'common heritage of mankind', but international community is yet to work out the modality of resource sharing.

Deposit Modelling

The present century is experiencing an 'information explosion' and geological sciences are no exception. Large amount of data are being generated every day and for processing the data to arrive at a useful conclusion, mathematics and statistics and computers have made deep inroads in all branches of geology and mineral exploration. Deposit modelling based on study of multiple parameters of the known deposits helps in prediction of favourable geological melieu for mineral search.

Indian Scenario: A Glorious Past

The Indian scenario of the pre-industrial era brings out a glorious past of utilisation of mineral resources. In the pre-Vedic period (4000-1600 BC), mining and use of metals, specially gold, silver and gemstone, were common. Chemical and metallurgical processes of making copper alloy were known to the highly skilled artisans of pre-Harappan (4000-3000 BC) and Harappan civilization (3000-1500 BC). The *Yajurveda* (1100-1000 BC) mentions the use of copper, silver, gold, lead, tin and iron. India was a major producer of diamond. Later historical treatises of Greek and Roman historians like Megathenese (300 BC) and Pliny (70 AD) abound in records of great development of mineral industry in India. The 250 ft deep workings in Singhbhum copper mine, 600 ft deep vertical shaft in Hutti gold mine indicate a high degree of technical competence of ancient miners. The wootz, an Indian steel, was probably exported to western lands before the Christian era to be worked into the Damascus swords of medieval time. The famous pillar, now located at Kutub, which bears the epitaph of King Chandragupta, composed in or about 415 AD, still remains a unique example of high level of competence of Indian metallurgists.

Establishment of Geological Survey of India

The demand for coal for steamers and railways led to the development of modern mining industry. The first attempt at coal mining was made in 1774, but coal mining industry flourished in the middle of the nineteenth century only after the coalfields were linked with Howrah with a 190 km long railway line. In 1840, a nucleus of economic geology museum was established in the Asiatic Society. In 1846, at the recommendation of the Coal Committee, D.H. Williams of Great Britain was sent to map the coal-bearing districts. However, earth science investigation in the modern sense was initiated in 1851, when Tomas Oldham organised the Geological Survey of India.

In the first hundred years, the Survey functioned as a small unit concerned primarily with systematic geological mapping and examination of reported mineral occurrences. The objective of Geological Survey of India was spelt out by Dr Oldham in his memorandum to the Secretary to the Government of Bengal in 1852:

> "There appear to me two distinct plans which might be adopted. One in which the progress of the Geological Survey would successfully and continuously embrace the whole of the country, so that after a time a general Geological map could be published. And another, on which detached districts should be examined, to which attention might be directed by any special discoveries, or for any special object and thus a series of isolated maps, and reports on detached districts be prepared. Undoubtedly, the former plan by which a steady continuous and systematic examination of the whole country would be undertaken, is the one most likely to lead to sound practical results (although in some cases not so immediately as the other system) and by which the most valuable additions to geological science would be obtained".

Taking the cue from Oldham, emphasis on systematic survey became the guiding principle for the department. In the first hundred years, many of the fundamental geological ideas and a sound knowledge of Indian geology developed through the contributions made by the geologists of GSI, which is the third oldest survey in the world. Preliminary mapping of most of the major coalfields was done in the second part of the nineteenth century. The goldfields of Southern India, the copper belt in Singhbhum, the manganese belts in Central India, mica field of Bihar, were mostly delineated in the nineteenth century. Drilling for oil was started in Upper Assam in 1866 by the Assam Oil Company. The discovery of iron ore in Mayurbhanj in 1904 by P.N. Bose and in Singhbhum by R. Soulballe in 1907 heralded the beginning of modern iron age in India. The geologists at that time worked under most adverse conditions. The mortality rate of staff and officers of GSI was so high that the insurance companies refused to insure their lives as 'no premium whatever can cover the risk' reported Oldham in 1864. It was only after the progressive opening of the country from the late nineteenth century by the extension of roads, introduction of railways and communication network and controlling of disease like malaria (by discovery of Ronald Ross in 1894) that the mineral search got new impetus. Many of the Indian states had also established their own Geological Surveys like Mysore in 1894, Kashmir in 1917, organised by officers retired from GSI, namely R. Bruce Foote and C.S. Middlemiss respectively.

First Half of Twentieth Century

In India, however, in the first half of the twentieth century, there was no significant change in the technique of mineral exploration. In their review of economic geology

(1905-1955), two great geologists, J.A. Dunn and A.K. Dey (1956) acknowledged that many of the good discoveries are due to keen sense of the villagers, trained under the guidance of the geologists. Regarding the role of geological knowledge they mentioned:

> "The real foundation of economic geology in India has been the steady regional mapping over the past century by geologists of GSI and others. The value of this regional mapping cannot be too strongly stressed; again and again, problems which may appear in the study of individual mineral deposits are solved when the regional context is understood."

Regarding their achievements, they wrote "in 1905 there were but 16 official geologists and two mining specialists to work over the whole vast territory of former Indian Empire, and indeed, often deputed to investigate mineral deposits far beyond its territories. Over the great part of the period under review, the total strength of the field geologists remained much the same and when it is remembered that economic geology formed but a part of their duties, the wonder is that so much was accomplished by so few."

Development after Independence

The industrial situation started changing the world over after the First World War, but the wind of change started blowing in India only since the Second World War. Before that, except for coal, mineral industry was mainly export-oriented. The industry as a whole was in private hands. The war need prompted the British Government to involve GSI directly in mineral development and the Strategic Minerals Division was set up. However, the real change took place after independence. The need for conservation was given due recognition and the Industrial Policy Resolution 1956 expressed the government's commitment to take over the responsibility of development of major minerals. The progressive establishment of social control was culminated with the nationalisation of coal industry in early 1970s. Major industrial development took place after independence, which brought about tremendous development in mineral industry. The role of earth sciences in development was recognised and the Geological Survey of India was expanded during the last 37 years. The number of geoscientists in GSI itself has increased from 150 in 1950 to about 2000 at present. In response to developments in science and technology, a number of disciplines developed. As a discipline attained a certain status, it was separated from the Survey and made into an independent organisation. Petroleum Geology Wing of Oil and Natural Gas Commission, Atomic Minerals Division of Atomic Energy Commission, National Coal Development Corporation (now forming a part of Coal India), Mineral Exploration Corporation and Central Ground Water Board are some of the organisations and units which had their beginning in Geological Survey of India. A number of public sector organisations came into existence to develop the mineral deposits explored after independence. Important among them are: Coal India Limited, National Mineral Development Corporation, Hindustan Copper Limited, Hindustan Zinc Limited, Bharat Aluminium Corporation, National Aluminium

Corporation, etc. Indian Bureau of Mines was set up just after independence to supervise the conservation and development aspects. To supplement the efforts of GSI, the state governments opened up their own prospecting wings and an apex body called Central Geological Programming Board has been set up to coordinate the activities of the different prospecting wings. In the post-independence period, a large number of research organisations were set up to assist the mineral development activities, like the Ore Beneficiation Wings of IBM, National Metallurgical Laboratory, Central Fuel Research Institute, Central Mines Planning Development Institute, Central Mining Research Institute, National Geophysical Research Institute, National Remote Sensing Agency, Central Glass and Ceramic Research Institute, etc.

Adoption of New Techniques

In response to international developments, major changes have taken place in exploration strategy and technique. Airborne and ground geophysics, geochemistry, remote sensing and drilling are now used extensively by all the major organisations. Use of deep needles for manganese exploration by Fermor, at the turn of the century, was the first application of geophysics in the country. A gravity survey in the Indus Valley in 1923-24 was among the earliest applications of geophysical methods in the search for oil. The Assam gravity survey began only two years later. Geophysical survey for metallic minerals was first made at Mosabani, Singhbhum district and for gold in South India in 1933 by Elbof Geophysical Prospecting Company of Germany. Geophysical Division was opened in Geological Survey of India in 1945 and this marked the beginning of systematic geophysical survey. Early significant magnetic survey carried out by GSI was for iron deposits near Daltonganj in Bihar in 1946-47. Magnetic survey was also helpful in locating the kimberlite pipe in Hinota, Madhya Pradesh, which was later proved to be diamondiferous. Later, other geophysical survey methods were gradually adopted in the country and stress was laid on the search for base metals. In oil exploration, seismic survey was rewarded with the finding of a new oil-field in Naharkotiya in 1953 by the Assam Oil Company. Search for oil-bearing structures was carried out by the GSI in Gujarat (before the formation of ONGC) and Standard Vacuum Oil Company in the deltaic region of Bengal. Gravity survey led to the establishment of world's largest baryte deposit at Mangampeta, and for the first time an attempt was made to hypothicate the resources on the basis of gravity survey. The National Geophysical Research Institute made significant contributions in the development of geophysics in the country. NGRI for the first time undertook deep seismic survey, which provided a large volume of data on deep seated geology and structure. Aeromagnetic surveys over parts of Meghalaya, Assam and Arunachal Pradesh were carried out by Assam Oil Company in 1954, over Indo-Gangetic alluvial country and parts of Rajasthan desert by ONGC in 1956 and over parts of Gangetic delta area by Standard Vacuum Oil Co. in 1956. Airborne aeromagnetic and electromagnetic surveys for the soiled minerals were started in GSI in 1967 under operation Hard Rock Project and later continued under BRGM programme. Later, GSI toop up a 15 years programme of aeromagnetic survey with the help of facilities available with NGRI and the National Remote Sensing Agency, which is well equipped for airborne survey. GSI will shortly procure its own aircraft equipped with an on-board sensor system for aeromagnetic survey. A large number of EM anomalies generated during 'Operation Hard Rock' and 'BRGM' flights are being tested and a few mineral occurrences of economic significance have been located.

Geochemical Survey

Geochemical prospecting for minerals was first introduced in GSI in 1960s. The first chemical laboratory was set up in GSI as early as 1906, but the instrumental analytical facilities like emission spectrograph were first introduced in 1954, which helped the development of geochemical prospecting. In the first stage, only the distribution pattern of 'target' elements like Cu, Pb and Zn in the soil used to be tested to identify the 'anomaly' leading to the location of mineral deposits. With the development of applied geochemistry in the world, the significance of other factors like distribution of associated elements, which are more mobile and easily detectable; the ratios of different elements; vapour phase geochemistry, etc. has been realised. These help in locating buried deposits. Integrated geological, geochemical and geophysical surveys have led to identification of a number of base metal, gold, tin and tungsten deposits in the country. From early 1970s, regional integrated surveys have been initiated in the major mineralised belts.

Remote Sensing

Use of airphotos for preparing regional maps was introduced in 1960s, but remote sensing as a discipline was developed only in 1970s, when the data of the ERTS satellite were available in the country. The satellite data in visual and multi-spectral bands help in identifying regional tectonic structures like lineaments. Now India is entering the satellite age and Indian Earth Resource Satellite is expected to be launched shortly. GSI is collaborating with ISRO in the satellite project and as a part of the National Resource Management System (NRMS), a number of centres are being developed for the processing and application of data to be generated by the Indian satellite.

Drilling

In the nineteenth century, drilling was first undertaken for coal in Wardha Valley coalfield and for oil in Upper Assam. Only percussion drilling technique was available at that time. A great advance was the introduction of rotary drilling, which was used in Digboi as far back as 1912, long before its regular deployment in Burma. In 1906-8, GSI undertook a diamond drilling campaign along the Singhbhum copper belt under the geological supervision of K.A.K. Hallows. A regular drilling section was started in GSI in 1946, while a full-fledged drilling division was started only in the year 1955 with the procurement of 6 rigs. By 1980, the annual drilling capacity (except oil) in GSI and other organisations had gone up to about 7 lakh metres and it was expected that by the end of the seventh plan, the annual capacity would go up to 10 lakh metres. For increasing the rate of drilling, drilling with wire-line attachments was introduced towards the end of 1960s. At present, capability exists in the country for drilling to 1000 m depth for solid minerals and rigs with deeper capacity are under procurement. Considerable work has also been done in mud chemistry for producing suitable drilling mud. The modernisation that was implemented or conceived during the seventh plan included non-coring drilling with multi-sensor loggers, faster vacuum/ reserves circulation drilling, direct motorised auger drills for shadow cappings, increased use of wire line drilling, warman type drilling machine with in-built sampling facility, etc.

Standardization of Resource Classification

The ultimate objective of mineral exploration is to estimate reserves and resources and their physical and economic parameters. These aspects have received attention in this century because of high investment required for mineral development. Besides, knowledge of national and international inventories is required for realistic perspective planning. Method of exploration, exploration density and sampling methods need to be adequate, so that the tonnage, grades and geometry of the ore body can be projected with the desired level of assurance. Various attempts have been made worldwide for standardization of ore reserve classification based on physical parameters. The concept of 'Reserve' as a dynamic phenomenon varying with techno-economic changes (as the exposed height of iceberg changes as the density of water varies) evolved gradually. In 1956, the concept of 'Mineral Resources' consisting of presently exploitable 'Reserve' and 'Potential Ores' developed. In 1974-75, USGS and USBM jointly finalised a resource classification system based on techno-economic factors and degrees of geological assurance, which is graphically represented as 'Mc Kelvey Box'. A similar type of system was also evolved in Russia. An international system was also evolved by the United Nations in 1979. Various documents have been published to standardize Indian system of exploration and resources classification like Manual of Mineral Technology and Classification of Mineral Resources (1981). A diagrammatic representation of the present system, which is a modified version of the Mc Kelvey Box, is given in Appendix I.

Marine Geological Survey

The Exclusive Economic Zone (EEZ) of India covers an approximate area of 1.86 million sq km of sea bed, which is equal to about 60% of the land area. This vast area offers a challenging target for mineral search. The discovery of oil in Bombay High has brought about a major change in the oil scenario. Placers of valuable minerals occurring in land areas are expected to be concentrated in the off-shore areas. Besides, there are possibilities of locating concentration of chemical precipitates (like phosphatic nodules) in the EEZ area. The prospect of manganese nodules with the associated valuable metals in sea bed beyond EEZ is vast.

The first attempt for sea bed survey was made in 1964, when some scientists from GSI participated in the cruise organised under the International Indian Ocean Expedition. The systematic marine geological activity was started at a low key in GSI in 1971. The work in the country was intensified in 1976, when the National Institute of Oceanography initiated geological and geophysical explorations in off-shore areas. Off-shore exploration was carried out with the help of a smaller craft (M.V. Tarini) in shallow water and large ocean going vessels (R.V. Gaveshani and O.R.V. Sagar Kanya). Scientists of GSI also took advantage of these vessels or other chartered vessels for near-shore and off-shore surveys till 1983, when the department procured a well equipped Research Vessel 'Samudra Manthan'. Recently, two coastal launches have been procured to survey in the territorial water. NIO is also undertaking cruises in the international sea to assess the potentiality of manganese nodules. India has been recognised as one of the leading countries in Marine Geological Survey.

Present-day Mineral Outlook

The achievement in mineral exploration in the post-independence period is reflected in augmentation of the reserve, which is given in Table 4. The present-day resource scenario can be summarised as follows:

Self-sufficient Group — Iron ore, power, coal, bauxite, baryte, mica, chromite, china clay, cement grade limestone, dolomite.

Marginal — Base metals, metallurgical coal, manganese, kyanite, sillimanite, magnesite (low silica), fireclay (high P.C. E., non-plastic), flux grade limestone (low silica).

Deficit — Phosphorite

Poor or non-existent — Potash, tungsten, tin, platinum, molybdenum, nickel, cobalt.

Table 4. Increase in mineral reserves in three decades (Reserve in million tonnes)

Ore/Mineral	1950	1955	1960	1965	1970	1975	1980	1983	Resource adequacy
1. Barytes	–	–	–	–	2.54	8.08	73.39	75.17	Adequate
2. Bauxite	–	254	276	–	227	425	2489	(2697)	Adequate for long-term planning
3. Chromite	1.3	3.40	4.86	–	13.86	17.27	111	135.3	Satisfactory
4. Coal	40285 (1932: 20, 320)	25000+	NA	NA	74254	85773	111000	127240	Adequate for long-term planning
5. Copper ore	–	3.4	40	70	244	400	455	566	Marginal
				Metal:	3.50	5.02	5.66	6.30	
6. Dolomite	–	–	–	–	–	4065	5085	5086	Adequate for long-term planning
7. Gold ore	–	–	4.11 (9.14 ppm)	–	–	4.47 (6.5-14 ppm)	8.70 85 tonnes metals 65 tonnes	60.8	Crucial
8. Iron ore (Haematitic)	–	5000+	788.5	–	8183+	9711	11470	11485	Adequate for long-term planning
9. Lead-zinc ore	–	4.87	28.45	33	107	212	350	360	Satisfactory for zinc, marginal for lead
			Metal:	Lead:	3.12	4.38	4.01	5.83	
				Zinc:	3.81	7.59	12.21	17.96	

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Appendix 1. Diagrammatic representation of suggested national ore/mineral resources classification

<table>
<tr><td colspan="2">Mining
Phase</td><td colspan="3">Detailed Exploration
Phase</td><td colspan="2">Reconnaissance &
Prospecting Phase</td></tr>
<tr><td colspan="5">Identified Resources</td><td colspan="2" rowspan="4">Undiscovered
Resources (Tonnes)
(Based on Surmises)</td></tr>
<tr><td colspan="2">Ore Reserves</td><td colspan="3">(Tonnage and Grade)</td></tr>
<tr><td colspan="2" rowspan="2">Developed Ore
(Mining Reserves
with Design, Dulution
& Extraction Factor)</td><td colspan="3">Undeveloped Ore
(in situ Reserves)</td></tr>
<tr><td colspan="3">Demonstrated</td></tr>
<tr><td>Fully</td><td>Partly</td><td>Proved</td><td>Probable</td><td>Possible</td><td>Prospective
(in known
area)</td><td>Prognostic
(in unknown
areas)</td></tr>
<tr><td colspan="5">E
C
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C</td><td colspan="2"></td></tr>
<tr><td>Sub-
economic</td><td>Sub
Para</td><td colspan="3">Conditional Resources
Marginal ____________
Marginal ____________</td><td colspan="2"></td></tr>
</table>