The Prospects for Expansion and Cost-Effective Development of Mineral Resources in the Mining and Industrial Areas of India

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Abstract: Exploitation of different kinds of mineral deposits is currently addressed to recover mostly the main product from an ore, with little effort either for its co-/by-products or for *value-addition* and *creation of wealth from waste*. Presently, mineral industry is facing many problems that make it less attractive for old and new entrepreneurs. To overcome them, there is a need for 'Mega-, Micro- and Nano (10^{-9})-Scale' (MMNS) investigations on both working and potential ore deposits. Salient aspects of these multi-disciplinary and multi-faceted, both field- and laboratory-based, investigations, together with their main objectives, during different stages of 'Mineral Exploration and Exploitation' (MEE) are presented. Brief description of some major explored and exploited ore deposits in India, along with their possible, high-value by-products, and waste from a few mining industries, both recommended for research, are listed. Nano-scale mineral technology, presently in its initial stage, may be effectively used to isolate valuable elements or molecules from ore and gangue minerals as well as has the potentiality for 'Recycling and Reusing' (R & R) of waste material, thereby serving the twin concept of *value-addition* and *creation of wealth from waste*. Some pertinent problems of mineral industry, which can be tackled by comprehensive MMNS studies, and some requiring future Research and Development (R & D), as well as expected results of such research are given. The objectives of these studies on ore deposits are (i) maximum recovery of both the main and valuable co-/by-products from ores for *value-addition*, (ii) utilization of their waste material for *creation of wealth from waste* and (iii) expansion and cost-effective development of mineral resources in mining and industrial areas of India.

Keywords: Ore deposits, mineral industry problems, mega-micro-nano-scale investigations, value-addition, creation of wealth from waste, recycling and reusing, India.

1. INTRODUCTION

Among the three major natural resources blessed by the Mother Earth, *viz.,* land, water and minerals, the first two are renewable and in a sense inexhaustible, whereas mineral resources are non-renewable and get progressively depleted as they are mined and removed from the Earth. Mineral- or ore-deposits constitute the backbone for development of any country, since they are the sources from which metals and non-metals are to be obtained for meeting many societal needs, like numerous basic and high-tech industries, development of infrastructure, production of fertilizers and pesticides for use in agriculture, production of diverse chemicals, fulfilling health- and medicinal-requirements, generation of various modes of both renewable and non-renewable energy, and defence needs. Exploitation of the mineral deposits is currently addressed to recover mostly the main product from an ore, with little effort either for its co-/by-products or for *value-addition* and *waste-utilisation*. Furthermore, mineral industry is presently facing many problems, like (i) fast depletion of surface and near-surface deposits thereby necessitating deeper level exploration - drilling - extraction leading to high-costs in 'Mineral Exploration – Exploitation' (MEE); (ii) refusal for selective resource assessment/extraction of the main components only, i.e., the transfer of deposits to the category of poly-component (complex) ones by additional study of ore deposits in order to identify and quantify the accumulation of valuable components like precious metals, rare metals and rare earth elements in the form of micro-/nano-minerals and organo-metallic clusters, using enrichment techniques; (iii) volatile market with decreasing values for minerals; (iv) pressure to contain costs, including work related to Corporate Social Responsibility (CSR); (v) uncertainty and tough operating climate due to issues like Brexit, some critical policies of Mr. Donald Trump as US President, increasing economic strength of P.R. China and conflict of interests of USA and North Korea; (vi) environmental and ecological problems for mining as in forest areas and animal-sanctuaries; and (vii) increasing cost of land, required for mining, ore processing and stocking of mineral products. To overcome these major negative aspects of mineral industry, a need arises for comprehensive studies by mega-, micro- and nano (10^{-9})-scale investigations on both the working and potential ore deposits for full-utilisation of their ores in order to have holistic, sustainable and profitable mineral development. In this, mega-scale, multi-disciplinary and field - laboratory investigations for MEE [1] are aimed at to (a) discover, delineate (in 3 dimensions) and characterize ore bodies; (b) compute

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the range of and average grade of ores; (c) probe their possible lateral and vertical extensions (in 3 dimensions) by drilling; (d) estimate total and exploitable statistically-computed ore reserves in a deposit; (e) cost-effective mechanized and digital mining; and (f) undertake their mineral-processing, at both laboratory- and pilot plant-scale, so as to establish a plausible flow-sheet for industrial-scale, cost-effective recovery of products from ores. Micro-scale investigations in MEE are intended for (a) comprehensive characterization of ores by detailed transmitted- and reflected-light microscopy so as to identify ore and gangue minerals as also their textural and morphological features, which have critical bearing in ore processing, besides characterization of waste, generated during mining and after extraction of ore minerals [2]; and (b) on-site, non-destructive 'Electron Probe Micro Analysis' (EPMA) of ore/gangue minerals and waste material to know their respective quantitative data of major, minor and trace elements [3]. The data and information from these micro-scale investigations will form the basis for follow-up nano (10^{-9})-scale geologic investigations so as to generate value-added products, by establishing feasibility for extraction of high-value and strategic metals, both from ore minerals and some gangue minerals. *Nanotechnology*, with Physicist, Richard Feynman being its father, is the engineering of functional systems at the molecular levels and is the manipulation of matter on atomic, molecular and supra-molecular scales. For example, the scientists of the North Western University, USA have discovered an inexpensive and environmentally benign green method that uses simple, cheap and biologically friendly material of cornstarch, instead of cyanide, to extract Au from crude sources [4]. This process also can be used to extract Au from consumer electronic waste. Furthermore, nanotechnology may be effectively used to isolate valuable elements from ore and gangue minerals as well as has the potential of 'Recycling and Reusing' (R & R) waste material, thereby serving the twin concept of *value-addition* and *creation of wealth from waste*. Indeed, R & R techniques are being adopted in South Africa to treat mine-waste to recover precious metals of Au and PGE [5]. In fact, nano-mineral technology, like nano-medicine and nano-surgery, is quite recent and much of it is expected by new R & D work in the near future. In this, it needs to break chemical bonds in minerals of different ores at atomic and molecular levels of crystals, since the crystal-dimensions are in a few angstrom (Å)–units (10^{-10} m) and investigations at nano-level (10 Å = 1 nm) may provide the best ways for such study. This should be followed by enrichment and purification of released, atomic- and molecular-scale valuable metals in different ore- and gangue-minerals, using concentration methods like solvent extraction, ion-exchange separation, fire assay, selective sample dissolution, sorption on activated carbon and clays, and bio-leaching. The ultimate aim of the above proposed comprehensive studies on ore deposits, including placer mineral sands, is to increase the profitability and ecological safety in the development of mineral resources in India and elsewhere, which should be based on the use of present and new technologies to extract the highest possible quantity of dominant and concomitant components during operating mineral deposits, including their mountain dumps, tailings and other types of waste material, and the same is dealt with in this paper.

2. BRIEF DESCRIPTION OF THE EXPLORED AND EXPLOITED ORE DEPOSITS IN INDIA, RECOMMENDED FOR RESEARCH

There are many industrial-genetic diverse types of both explored and exploited ore deposits in India, containing basic ore elements and main components as well as potential, derivable and perspective ore elements and components. Important ones of these are listed in Table **1**. These are recommended for research on the lines, given above under 'Introduction'.

An examination of Table **1** demonstrates that in different ore deposits, there are numerous, high-value/-utility ore elements and components as possible by-products, and intensive research is needed to extract them, which will substantially enhance the total value and utility of each deposit.

3. WASTE FROM MINING INDUSTRY, RECOMMENDED FOR RESEARCH

Waste material, produced during mining and processing of different ores in mineral deposits can be made into a good resource for valuable and useful products, and this leads to *'Creation of Wealth from Waste'.* A few examples under this, recommended for research, are listed below:

1. Separation and enrichment of P_2O_5 in huge mine-waste of Tummalapalle U-deposit in Andhra Pradesh from ~ 4 - 8 % to commercial grade of ~ 18 - 30 %, so as to utilize the treated waste as a low-cost substitute of phosphate fertilizer in place of high-cost chemical fertilizer, for use in agriculture, thereby addressing the

Table 1: Industrial-Genetic Types of some Indian Ore Deposits, their Basic Ore Elements and Possible Derivable and Perspective (In parentheses) By-Products

S. No.	Industrial-genetic types of Indian ore deposits	Basic ore elements and components	Possible By-products: derivable and perspective ( ) ore elements and components
1.	Gold deposits and mine dumps in Karnataka	Au, Ag	Sulphides of Cu, Ni, Co (Hg from Au-Hg amalgam), Cd, Ni, Bi and Te
2	Chromite and PGE in ultramafic-mafic rocks in Sukinda in Odisha, Kondapalli (layered complex) in AP, Karnataka and ophiolite belts in Manipur-Nagaland and Andaman & Nicobar islands	Cr_2O_3, PGE	Al, Mg, Fe, Ni-Co, Cu sulphides - pyrrhotite and pentlandite, spinel, magnetite
3.	Diamonds in kimberlites and lamproites in parts of AP and MP	Diamonds	Au, Pd, Ir (Mineral Carbonation: CO_2 - sequestration)
4.	Banded Iron Formations in parts of Chhattisgarh, Odisha, Karnataka, AP, etc.	Magnetite, hematite	Ti, Ni, V, Cu, limonite, Fe-laterite, siderite, chert, (Au, Ag in sulphide-bearing horizons)
5.	Manganese ores of Sausar Group in MP and in Mn-granulites of AP	Mn-minerals: pyrolusite, haussmannite, bixbyite, cryptomelane	Fe, Ba, Ni, Co, Cr, V, Cu, Zn, Ga, Pb
6.	Copper: (a) Khetri belt, Rajasthan (stratabound); (b) Malanjkhand, MP	Cu Cu	Pyrrhotite, tourmaline, Mo, Au, Ag and Hg
7.	Lead – Zinc: Polymetallic Dariba - Rajpura, Rajasthan (Sedex type; stratiform, zoned)	Lead (Galena), Zinc (Sphalerite)	Ni, Cu, As (several sulphides, sulphosalt minerals, inter-metallic compounds of Ag, Au, Hg)
8.	Rare Metal Pegmatites in parts of Chhatisgarh, Odisha, Jharkhand	Li, Cs, Be, Nb-Ta	Sn
9.	Mica Pegmatite belts of Nellore in AP, Jharkhand and Rajasthan	Muscovite	U-HREE-minerals in mine dumps
10.	Uranium (different types): (a) Hydrothermal: SSZ, Gogi (Karnataka) (b) Carbonate-hosted: Tummalapalle (AP) and Gogi (Karnataka) (c) Unconformity-proximal: Telangana (d) Sandstone-type: Meghalaya (e) Albitite-type: Rajasthan (f) QPC-type: Karnataka	Uraninite (Ur), brannerite (br.) Pitchblende (pit), coffinite Uraninite, pit., coffinite Coffinite, pitchblende Ur., davidite, brannerite Th-Ur., br., pit.	Fe/Ti-oxides, Cu-Mo sulphides Chalcopyrite, C-matter, (P_2O_5) anatase, Ag, Au Chalcopyrite, ilmenite Cu, Pb, selenides, C-matter Th, Ti, Zr, Cu, Fe Ti, Zr, REE, Y, Ni, Cr, Cu, Zn, Au
11.	Placer Mineral Sands (E & W Coasts) in Odisha, AP, Tamil Nadu & Kerala	Ilmenite, Rutile, Zircon, Sillimanite, Garnet	Monazite (LREE & Th)
12.	Carbonatites in parts of Gujarat, Rajasthan, Tamil Nadu & Meghalaya	Nb > Ta, REEs, igneous phosphate	Strontianite, Ti-mag., vermiculite, barite, fluorite, Zr, U, Th
13.	Bauxite in E-(Odisha, AP) & W-Ghats, (Maharashtra); Chhattisgarh, Jharkhand	Gibbsite (for Al)	Red Mud (as additive in cement industry), Ga
14.	Barytes near Mangampeta, AP	Barytes	Overburdern grey shale for ceramics
15.	Ball-/fire-clay in Rajasthan, W. Bengal, Odisha, Gujarat, MP, Telangana etc.	Kaolinite	Smectite, illite, goethite, Ba
16.	Coal-lignite in Jharkhand, MP, Odisha Telangana, Meghalaya and Tamil Nadu	Non-coking and coking coals, lignite	Rutile, Fe-oxies, sulphides, diaspore, Ge, Ba, Sr, Zr

AP: Andhra Pradesh; MP: Madhya Pradesh.

needs of farmers as also creating wealth from waste [6];

2. Plans to recover gold in residual dumps by re-opening the colonial-era gold mines in the Kolar belt (started by John Taylor & Co., in 1880 and closed 15 y ago) [7];

3. The diatremes of kimberlites and lamproites in places like Vajrakarur, Lattavaram (Andhra

Pradesh) and Majgavan; manganese deposits of the Sausar Group and Khondalite Supergroup; stratified poly-metallic deposits of Dariba – Rajpura in Rajasthan; Rare Metal Pegmatites and their derived alluvium and soil in the pegmatite belts of Bastar – Malkangiri in parts of Chhattisgarh and Odisha, Marlagalla in Karnataka and Nellore – Bihar – Rajsthan mica pegmatite belts; and bauxite laterite deposits in the Eastern Ghats in parts of Odisha and Andhra Pradesh could be the resources for precious metals (Au, Ag), rare metals (Li, Cs, Be, Nb-Ta, Sn-W) and Ga (Table **1**).

4. Characterization of waste-rock material (~ 80%), generated in dimensional stone industry in terms of its morphology, petrography, alterations, weak zones and geochemistry, for its R & R as saleable products, like floor- and wall-tiles, tumbled- and textured-pavers for use in walkways, porches, pool patios, barn and shed flooring, artefacts, garden-scaping, stone-seats, etc. [8];

5. R & R of carbonate-rock waste at cement plants to use it, in powder form, for treating dreaded fluorosis by putting it in direct contact with high fluoride (> 1 ppm) water for 24 h and draining and cleaning the water to use as drinking water [9] in many fluoride-rich areas, as in parts of Andhra Pradesh and Telangana States; and

6. R & R of kimberlite tailings for 'Mineral Carbonation' and 'Carbon-neutral Mining'. Diamond miner De Beers Group is leading this groundbreaking research project, in close collaboration with a team of internationally renowned scientists to investigate the potential to store large volumes of carbon at its diamond mines worldwide in waste kimberlite tailings, the material that remains after diamonds have been removed from the ore. Mineral carbonation is a natural or artificial process, in which rocks on the Earth's surface react with CO_2 (a major greenhouse gas) sources from atmosphere and lock it away in safe, nontoxic and solid carbonate materials. This project will assess the carbonation potential of kimberlite, which has been found to offer suitable properties for storing carbon through mineral carbonation technologies [10]. This will help in carbon sequestration, thereby lowering global warming to some extent.

7. Fly ash (waste product from coal-fired power plants), to use as (i) 'self-cementing' Fly Ash Brick (FAB) that costs < 20% than traditional clay-brick; and (ii)'Supplementary Cementitious Material' (SCM) in production of portland cement concrete.

4. PRIORITY MINERAL INDUSTRY PROBLEMS, PROPOSED FOR VALUE-ADDITION, USING MAINLY NANO-TECHNOLOGY AND A FEW OTHERS

A few problems of mineral industry that may be tackled by the earlier given MMNS investigations, mainly for *value-addition*, are listed in the following:

1) Molecular-level separation of Al_2O_3 from Sillimanite ($Al_2O_3.SiO_2$) in unconsolidated, coastal placer mineral sand in countries like India, Brazil and Australia to serve as new, high-value Alumina resource;

2) Atomic-scale extraction and purification of much sought after HREEs from garnet in mineral sands (0.1-0.5 %) of East Coast, India [11] and from refractory granitic and pegmatitic minerals, like betafite, fergusonite, samarskite and euxenite, which usually occur in A-type granitoids and related pegmatites in the Kullampatti [12] and Kanigiri [13] areas, as also in the mine-dumps of the pegmatititc mica deposits of the Nellore in Andhra Pradesh [14], Jharkahnd and Rajasthan mica belts;

3) Enrichment of TiO_2 to > 95 wt. % (as synthetic rutile) in ilmenite (~ 50 wt. %) of mineral sands, present in countries like India, Australia and Brazil, in a manner similar to the one developed and patented by Argex Titanium Inc., Canada, using the method of solvent extraction at low-temperature (~ 70°C) and atmospheric-pressure, in place of costly, high temperature, toxic and environmentally problematic chloride and sulphate methods [15];

4) Atomic- and molecular-scale extraction of 1-2% LREE from apatite, as reported from the apatite-magnetite veins in the Khondalite Supergroup of rocks in the Kasipatnam area, Visakhapatnam district, Andhra Pradesh [16];

5) Atomic-scale extraction and purification of Rare Metals like Li, Cs, Be, Nb-Ta and Sn from minerals like lepidolite, amblygonite and

spodumene (Li, also in brines), pollucite (Cs), columbite-tantalite (Nb-Ta), beryl (Be) and cassiterite (Sn), present in the pegmatitic belts of countries like India and Canada;

6) Extraction of Mo (~ 0.02%), V (~ 0.02%), Au (18-105 ppb, av. 56 ppb) [17] and U (~ 20% present in collophane) from U-ore and gangue minerals of low-grade (av. grade: 0.045% U_3O_8) but large-tonnage (> 1,00,000 t) Uraniferous Phosphatic Siliceous Dolostone (UPSD) ore deposit in the Tummalapalle area, Andhra Pradesh [6];

7) Extraction of Ag, Au, Co and Ni from medium-grade (~ 0.15% U_3O_8) granite- and limestone-hosted U-deposit in the Gogi area, Karnataka [18];

8) Extraction of PGE from chromite ores and ultramafic-mafic rocks, present in different countries like India and South Africa;

9) Adoption of mechanized- and digital-mining to increase life of a mine, e.g., Au in South Africa with ~ 400 Mt in ground and 160 Mt, locked in underground support-pillars [19];

10) Conversion of non-coking (thermal) coal to coking (metallurgical) coal grade by removing (or minimising to tolerable levels) the impurities in the former, like phosphate, sulphur, nitrogen and ash comprising mainly siliceous, ferrous, aluminous and other inflammable ones.

11) Hydrogen-powered fuel cells, with platinum-catalyst, for electric vehicles and future clean energy needs, with only discharge of water, unlike polluted coal-based energy [20]; and

12) Bacteria-powered fuel cell that can convert methane into electricity [21].

5. EXPECTED RESULTS OF RESEARCH

Comprehensive characterization of ore deposits by meg-, micro- and nano-scale investigations, as indicated in the earlier sections, is to be carried out. In this, importance in the mega-scale operations is to be given for mechanized-/digital-mining, use of machine vision cameras and machine assistance with optional loading, driver assistance, which reduces hauling and driver fatigue, real-time surveying and geological model updating, improved dispatch system and digitally enabling the frontline workforce and operations through ‘Inference and Communication Technologies’ (ICTs). Furthermore, the asset health of mining equipment will also to be increasingly monitored, predicted and automatically responded [22]. Such mining will lead to fast, ore-band specific, cost-effective and much-reduced generation of waste in mining. During the micro-scale operations, comprehensive characterization of both ore-/gangue-minerals in different ores by transmitted- and reflected-microscopic study, followed by quantitative mineral analysis by EPMA will help in knowing the potential of high-value metals, both in space and quantity, in different ores. Nano-scale operations are intended to liberate, at atomic- and molecular-scales, high-value and strategic metal products by treating ore-/gangue-minerals and mine waste with nano-scale mineral processing techniques, much of which is to be developed by future R & D investigations. The liberated products should be further enriched and purified by adopting concentration methods like solvent extraction (e.g., enrichment of TiO_2 in ilmenite (~ 45-50%) to synthetic rutile-grade (> 95%) by Argex Titanium Inc., [15]), ion exchange, selective sample dissolution, fire-assay, sorption and bio-leaching. All this will result in (i) generation of co-/by-products together with main product, (ii) *value-addition* and (iii) *creation of wealth from mine-waste.* Such processing of mine-waste will drastically reduce the requirement of large space for storing as well as effectively tackle environmental and ecological problems, which otherwise would have posed them due to accumulation of large quantity of waste, near to mines. For example, the mine-waste of the Kolar gold deposit in Karnataka can be a resource of such ore elements like Cd, Ni, Bi and Te, and probably also PGE. Similarly, (i) the kimberlites of Vajrakarur and Lattavaram in Andhra Pradesh and of Majgavan in Madhya Pradesh are promising for Au, Pd and Ir; (ii) poly-metallic sulphide deposits in parts of Rajasthan are promising for Au, Ag and Hg; (iii) U-deposits in parts of the states of Andhra Pradesh, Telangana, Jharkhand and Rajasthan for Mo, V, Au, Ag and Cu; and (iv) chromite deposits in parts of Odisha and Andhra Pradesh, and occurrences in ultramafic rocks in parts of Karnataka and in the ophiolite suites of the NE states of Manipur - Nagaland and of the Andaman and Nicobar Islands are potential for PGE, Ni and Co. It may be added that research on similar lines is being carried out in Russia and a few other countries.

It appears that to carry out all the above, the following may be necessary: (i) Problem-Identification by Industries; (ii) Collaborative R & D among Mineral

Industries, National Science Laboratories and Academia in Universities; (iii) Multi-Disciplinary Intra- and Inter-Departmental focused work in Universities and National Geo-science Laboratories on Problem-Solving; (iv) Selection of Topics, having Relevance for Industry and Society, by dedicated, determined and disciplined Students and Researchers; and (v) resultant Resource-Generation. Thus, mega-micro-nano-scale investigations on ores will lead to better utilization of their many constituents present in ore- and gangue-minerals as co-/by-products together with main product, besides *value-addition* and *creation of wealth from waste*. All these make MEE as a comprehensive, cost-effective, holistic and sustainable development of mineral industry, thereby making it a more profitable business that will attract more entrepreneurs.

6. CONCLUSIONS

'Minerals' are essential and play a critical role in meeting the needs of both industry and society. Present scenario of 'Mineral Exploration and Exploitation' (MEE) is presented, which is currently operated mainly for recovery of main product (s) from different ores. Numerous problems faced currently by the mineral industry are given. To overcome such problems and make mineral industry profitable, a need arises for listed 'Mega-, Minor- and Nano (10^{-9})-Scale' (MMNS) investigations on both working and potential ore deposits by *recovery of co-/bi-products*, apart main product (s) of ore deposits as well as by *value-addition* and *creation of wealth from mine-waste*. Many problems in mineral industry, requiring such MMNS investigations are listed like digital mining and nano-scale geo-techniques, which require much 'Research and Development' (R & D) in the near future. The main objective of these proposed studies is to fully utilise ores for profitable, comprehensive and sustainable exploitation of mineral deposits, besides taking care of environment and ecology.

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