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GUEST EDITORIAL

India's mineral exploration requirements in the twenty-first century*

A crystal ball gazing allows us to imagine a twenty-first century India having a secure, sustainable, resilient and modern infrastructure. This infrastructure would include smart cities and villages, high-speed trains, inter-city expressways, coastal infrastructure and ports, inland waterways, high-speed telecom networks, modern airports, power grids, etc. Engineering all these would require using special metals, like lithium, niobium, tantalum, rare earth, vanadium, zircon, tin, tungsten, elements of platinum group, nickel, cobalt, cadmium, scandium, molybdenum, rhenium, etc. Mineral commodities for most of these metals have significant exploration potential in India's fascinatingly diverse geological set-up, but are yet to be explored!

India, with a mining pedigree of over 3000 years today produces about 5 billion tonnes of ore minerals annually, in a portfolio of approximately 90 different commodities including coal, lignite, industrial minerals and aggregates. We are also bestowed with multiple geotectonic domains of all ages ranging from the Early Archean granites and gneisses in various cratonic nuclei in the Peninsular Shield, to Recent age rocks. There are corresponding metallogenic epochs and metallotects. India, until recently, appeared self-sufficient in bulk mineable commodities required for the nation's infrastructure development, e.g. iron ore, bauxite, limestone, coal, manganese and chromite. Among the non-bulk mineable commodities, India is among the largest producers of zinc and chromium ores in the world, and is self-sufficient in silver.

However, there are concerns related to the nation's mineral resource inventory! The (mineable) reserve to geological resource ratio of India's bulk mineable mineral commodities has been dwindling. Also, the established resources for most bulk commodities have either stagnated or continually depleted in the last three decades; and would urgently require replenishment with new finds. India continues to import many ore minerals where large internal demands exist, including metallurgical grade coal, gold, copper, diamond, platinum group elements (PGE), coloured gemstones, fertilizer commodities like potash, phosphates and others.

With its large market, the twenty-first century India would have to embrace the entire value chain of minerals – from exploration for discoveries to establishing resources to mines to metal extraction and product development. The globally ongoing developments in the field of material science are leading to innovative uses of different metals and mineral commodities. India would aspire to be a leader in product development as well, and correspondingly must explore self-sufficiency in the ore resources and reserves of new age strategic commodities too.

What does this imply for India's mineral exploration strategy in the twenty-first century?

Since independence, India has focused on finding extensions of stratiform bulk commodities like iron ore, bauxite, coal, manganese and limestone; or brownfield exploration of operating mines and old workings; or on establishing the geological resources of discrete chance discoveries like Sukinda chromite and Malanjkhand porphyry copper deposits. The investors, mine owners and explorers have banked on cheaply available drilling rigs and the labour arbitrage, complemented by high-level geological maps to establish the geological resource of mineral assets. India has largely ignored modern geochemistry and geophysics tools in its exploration process. While our successes helped us to meet the infrastructure sector commodity demands in the first few decades of India's development after independence, we are now facing progressive mineral supply crunch and increased mineral imports, straining our balance of payments. For bulk commodities too, India has lagged behind while countries like Australia and Brazil with similar mineral potential as ours have been continually adding to their resource base through modern exploration.

Geologists around the world, who have been closely watching India's exploration progress, are unanimous in that India is one of the last bastions on the planet with high Greenfield Exploration potential, having remained severely under-explored with modern exploration tools and technologies. Thus, Australia's greenstone belts with thick laterite capping in the Yilgarn Craton had numerous large gold, nickel and PGE discoveries in recent decades contrast with India, which has not been able to find another Kolar or Hutti-like gold deposit and no nickel, PGE or chromite deposits in the known ultramafics in its Archean greenstone belts. While most of the Alpine-Himalayan Mobile Belt from Portugal to Pakistan/Afghanistan in India's west and from Myanmar to Papua New Guinea to our southeast have demonstrated enormous

*The opinions expressed in this article are entirely that of the author, which has evolved through many rounds of brainstorming with his colleagues in the Geovale Services.

potential for base metal and other minerals, India has only a few base metal in the entire Himalayan region. Similarly, while large flood basalt provinces of Siberia and Greenland have some spectacular nickel, copper and PGE deposits, India's Deccan Trap is yet largely unexplored! It would be quite a geological quirk to explain a lone, isolated discrete porphyry copper deposit at Malanjkhand, had we not left the extensions of Malanjkhand batholith and its other analogues in the Kotri Lineament Zone of the Bastar Craton unexplored for copper systems! During the last 75 years, we have focused on drilling in the vicinity of the old workings for gold, copper, lead and zinc in the states of Karnataka, Andhra Pradesh, Rajasthan and Jharkhand. We have never systematically looked at the potential for other metals in the larger hydrothermally altered zones in our gold and base metal belts.

India has the potential to be self-sufficient in the entire value chain of the mineral commodities required for the new age technologies. Our 2 million square kilometers of 'Obvious Geological (mineralization) Potential (OGP)' area has many reported occurrences of alkaline igneous rocks, phosphates, ultramafic rocks, evolved granites, heavy mineral-bearing beach sands, black shale, kimberlitic rocks, and favourable geotectonic milieu, where mineral deposit potentials need assessment. However, as these mineral commodities do not have 'old workings' as exploration vectors, we must focus on conceptual targeting in the right geological domains to discriminate the mineral fertile regions under a framework of Mineral Systems Analysis (MSA). This would require developing an understanding of the fundamental geology of the OGP areas in terms of potential metal sources, metal transport conduits and deposit-forming traps to zoom on to the deposit through a process of predictive mineral exploration. Our metals exploration programmes for discovery must prioritize the fertile segments of the OGP areas.

India is fortunate to have near complete coverage of the entire country with 1 : 50,000 scale geological maps prepared by the Geological Survey of India (GSI). Various geotectonic domains have been further analysed into mineral-based OGP areas. GSI is also about to conclude its National Geochemical Mapping (NGCM) programme and has embarked on National Aero-geophysical Mapping Program (NAGMP) in the OGP areas. To facilitate India's next-generation exploration, GSI must now identify the mineral fertile districts within the OGP areas. The fertility assessment would require use of specialized tools like geological and structural mapping, petrological studies, detailed rock and mineral geochemistry including isotopic (O, S) geochemistry, extensive geochronological studies, sequence stratigraphy and regional and mineral district level geophysical studies. GSI may also consider launching a country-wide geochronology-based mineralization event mapping programme, deep lithosphere mapping programme, regolith mapping programme, regional scale alteration mapping programme using tools like hyperspectral surveys and other baseline geochemical data collection and analysis. High-resolution electro-magnetic and gravity surveys can be adopted as follow-up tools before testing the deposit potential anomalies. The MSA-based fertile OGP blocks at both district (regional) and camp (target) scales could then be explored in detail economic deposits.

India must reboot its mineral exploration strategy for twenty-first century with a new mission to discover Greenfield deposits for all the commodities critical for the country. An ideal mining sector ecosystem would require all stakeholders to act in tandem for success. Our regulatory framework should transition from the current 'revenue maximization' regime into a globally competitive 'exploration incentivization' regime. This would require investors to have freedom of exploration area selection from anywhere within the country's mineral fertility map. A flexible mineral asset auction regime would allow even a single concession application from a specialized exploration or mining agency to be accepted without having to conduct rebids. India's entire vibrant capital market could be available for investments in the high-risk–high return exploration to mining projects, however, in a strict regulatory and transparent reporting regime. A security of title and tenure of the allotted concession from early exploration to mining would have to be ensured.

India's academia too would have to play its role in the nation's mineral security needs. It has to pitch its intellectual prowess for solution-oriented fundamental research to innovate exploration concepts and tools. The analogues for India's academia would be organizations like the CSIRO or research incubation platforms like AMIRA in countries like Australia, funded both by the industry and the government. India's research would contribute to developing better understanding of the mineral systems, while developing new tools in exploration, mining and beneficiation. Investors and entrepreneurs in India's mineral sector would have to trust and invest in the science of geology for innovations and solutions to increase the asset value and optimize mining processes and costs.

Twenty-first century will see enormous advances in the applications of science, technology, and communication tools. India's exploration sector would adopt sensor-based real-time and dynamic data collection processes (IOT), large data analytics, artificial intelligence, augmented reality and virtual reality for visualization, application of nano-sciences and others to keep innovating exploration tools for data acquisition, processing, and analysis. Exploration in the twenty-first century India would also reach deep ocean for mineral resources. By the middle of the century, India could join those who are planning to dock on interplanetary space for mineral exploration and exploitation.

India's mineral exploration is now poised to take a leap of faith into the future.

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