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Factors for Successful Critical Mineral Beneficiation:

Andhra Pradesh and Jharkhand

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in collaboration with the Meridian Collective

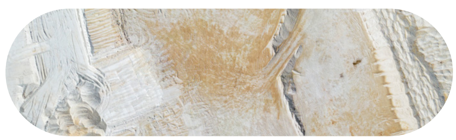
Executive Summary

As India strives to expand manufacturing in advanced technology sectors, drive economic growth and development, transition towards a lower-emissions economy, and reduce vulnerability to supply chain disruptions, advancement of domestic critical minerals projects has gained increased policy importance. However, successful execution of the National Critical Mineral Mission will manifest not only through national and international initiatives but also through sub-national strategies to map and develop resources within one or several states.

This collaborative brief developed by the Breakthrough Institute in partnership with the Meridian Collective presents an overview of key geologic, techno-economic, environmental, and policy considerations for critical mineral development in the states of Andhra Pradesh and Jharkhand. These two states both possess considerable critical minerals sector potential while also embodying a wide range of resource types and possible mineral production routes. As such, this analysis captures key principles generally applicable to state-level critical minerals strategies.

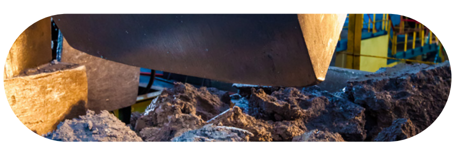
Key highlights

Andhra Pradesh's heavy mineral sand resources offer high grades of titanium and rare earth elements. Jharkhand could leverage byproduct critical mineral production from existing alumina, coal, and iron industries, and potential phosphate production, while pursuing hard rock lithium deposits.



Many high-profile critical minerals like lithium and especially rare earth elements, titanium, or germanium require high upfront capital expenditures for processing plants, challenging beneficiation economics in the absence of policy support.

When certain minerals like rare earths can be produced via multiple routes (heavy mineral sands, hard rock deposits, byproduct recovery), projects must consider competitiveness against alternative deposit types.



Many beneficiation processes, such as titanium sponge production or rare earth element refining, require not only substantial energy inputs but also other key chemical and critical mineral feedstocks.

Market uncertainty and high initial costs of sectoral development emphasize the importance of coordination within national minerals security strategy and project alignment with firm offtakers.

Titanium and Rare Earth Elements from Heavy Mineral Sands in Andhra Pradesh

Background

Andhra Pradesh possesses vast heavy mineral sand resources containing high-value critical minerals essential for defense technologies, aerospace applications, electric vehicles, and wind power. Such deposits occur as an assemblage of minerals along coastal beaches and rivers that bear titanium and rare earth elements in addition to zirconium, hafnium, thorium, and industrial materials.

Production of titanium and rare earth elements from heavy mineral sands is a well-established practice dating back to the early 20th century. In fact, heavy mineral sands served as the original primary source of rare earth elements before development of hard rock and ionic adsorption clay deposits in the 1950s and 1970s.

Andhra Pradesh can draw on its expertise from historical mining and separation operations that produced the titanium minerals ilmenite and rutile. The upcoming IREL Ltd. monazite processing facility in Gudur also positions Andhra Pradesh well for expanding into rare earth element production when restarting heavy mineral sand mining operations.

Shown above are stockpiles of heavy mineral sands waiting to undergo separation at the historical Trimex Sands facility in Andhra Pradesh.

Mineral resource quality and exploration

Historical mining, exploration programs, and academic studies have generated a robust understanding of the heavy mineral sand resources in Andhra Pradesh.

Collectively, these indicate that the volume of heavy mineral sand deposits can support a significant expansion of titanium production beyond Andhra Pradesh's historical output and could sustain monazite production at the Gudur facility for decades.

Heavy mineral sand resources in Andhra Pradesh also benefit from competitive deposit quality. Some locations across Andhra Pradesh may exhibit titanium and rare earth element concentrations below global averages, or high iron and fine particle content which may raise processing costs. But in many locations, such as deposits near Nellore, total heavy mineral grades in Andhra Pradesh are twice as high as typical commercial deposits.

Notably, limited studies have identified xenotime in heavy mineral sands near Narasapur. Further assessments here could prove valuable as xenotime offers higher grades of heavy rare earth elements and lower thorium content than monazite.

Andhra Pradesh also possesses hard rock deposits in the districts of Prakasam and Anantpur that could produce rare earth elements. Compared to heavy mineral sands, hard rock deposits benefit from higher grades, often smaller environmental footprints, and easier processing least of all due to lower amounts of uranium and thorium. However, hard rock deposits require higher mining costs and do not bear the variety of marketable products that heavy mineral sand operations enjoy.

India currently mines minimal quantities of rare earth oxides with limited domestic processing at commercial scale. However, an established industry for ilmenite mineral sands already exists, supporting titanium compounds production rather than titanium metal. At the national level, Kerala Minerals and Metals Limited leads some pilot-scale titanium sponge output (~300 tons annually), with PTC Industries in Lucknow, India conducting some downstream ingot and powder production.

Mine and processing facility requirements

Both rare earth elements and titanium require separate facilities to process and refine, each with extremely high plant capital expenditures (CAPEX). Processing pathways for both titanium and rare earths are complex, with some equipment and technical knowledge locked behind IP and national security barriers. Relative even to other critical metals, titanium and rare earths fall into a "high difficulty" category, with high CAPEX increasing project risks and depressing return on investment.

Table 1: Capital costs of rare earths and titanium processing plants per ton of annual output (tpy), relative to zinc refining and steelmaking facilities.

Production Capability	CAPEX (USD / tpy)
REE oxides	$95,000 to $180,000
REE magnets	$120,000 or higher
Titanium sponge	$45,000 to $65,300
Titanium melting & milling	$25,000 to $34,000
Zinc refining	$3,100 to $6,200
Blast furnace & basic oxygen furnace steel	$682 to $936

Values adjusted for inflation.

Energy input and operational requirements

- Titanium metal production is highly electricity-intensive (77,550 kWh of electricity per ton of titanium metal for the Kroll process step alone).
- As a batch technique requiring 4 days of process time, the Kroll process demands baseload, uninterrupted power.
- Magnesium metal, another critical metal, is a key Kroll process input.
- 8,000 tons of titanium sponge production annually requires 620.4 GWh of electricity, translating to around 71 MW of baseload electricity capacity. If generated with solar and battery storage, such power needs would require, optimistically, over 370 MW solar and 1.35 GWh of battery storage, likely with other backup power.
- REE separation and reduction can require over 17,000 kWh of electricity per ton of REE metal.
- Extraction of one REE may take 50+ chemical stages. Producing multiple REEs requires hundreds of linked stages, introducing significant operational complexity.
- Standard solvent extraction methods of REE separation use a substantial quantity of kerosene (~7 tons kerosene per ton of REE). 9,000 tons of REE in one year would require over 480,000 barrels of kerosene. Recycling can reduce total kerosene consumption.

National and global market outlook

The principal global markets for titanium metal are civil aerospace and industrial equipment, followed by defense applications comprising ~10% of world consumption. With major aerospace and defense sector actors seeking to de-risk titanium sponge sourcing, global appetite for alternative supply from India may be high. India meanwhile currently relies on imports to supply most of its domestic titanium metal consumption. Global markets are likewise keen to diversify rare earths production, particularly for heavy rare earth elements key for high-performance permanent magnets. However, markets for both titanium and rare earths may be sensitive to new shifts in Chinese trade policies or production levels, introducing risks

Subnational policy considerations

- Heavy mineral sand projects should secure strong community social license policies in advance, as mining can affect coastlines with sentimental and economic value, such as for tourism or fishing.
- With the high CAPEX of titanium and rare earth refining, low-cost debt financing can greatly improve project economics and crowd in added private capital, though state fiscal capacity may practically limit public sector support.
- Heavy mineral sands processing may generate some radioactive uranium and thorium materials, requiring dedicated handling best practices and cooperation with nuclear regulatory offices.
- Rather than selling titanium and rare earths into open global markets, government or defense sector offtake may ensure greater security for both OEMs and producers.

Table 2: Advantages and disadvantages of processes for titanium metal refining.

Kroll process	Hydrogen assisted metallothermic reduction, Armstrong, or other alternative process
Known technology, commercialized in India	Emerging technology
Highly energy intensive, capital intensive	Improved energy efficiency, lower costs
Well suited for ingot and sheet production	Potentially suited for powder applications only

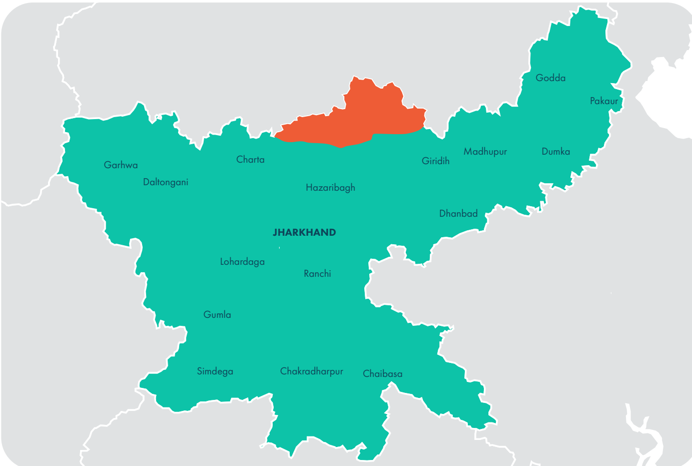
Avenues for Jharkhand: byproduct rare earths, byproduct gallium, lithium, and more.

Background

Jharkhand boasts a robust mineral industry and ranks as one of India' top producers of coal, gold, graphite, bauxite, iron ore & limestone.

Policy ambitions by the Jharkhand State Mineral Development Corporation demonstrate continued interest in expanding mineral production by expediting leases, facilitating exploration, and encouraging private sector investment.

These factors position Jharkhand well for expanding critical mineral production through a combination of recovering byproducts from existing facilities and tapping into new resources indicated by exploration efforts.



Shown in the shaded area above, Jharkhand possesses pegmatites that may be suitable for lithium mining.

Mineral resource quality and exploration

Jharkhand's bauxite, coal, iron, and phosphate resources present a valuable set of opportunities to expand critical mineral production through byproduct recovery.

Bauxite, for example, often contains the critical mineral gallium which alumina refineries can extract when processing raw ore, representing the primary route for gallium production globally. Exploration results indicate that Jharkhand bauxite contains gallium content amenable for byproduct recovery.

Potential exists to extract rare earth elements as a byproduct of mining Jharkhand's coal, iron, and phosphate resources. Commercial rare earth recovery from iron resources is currently limited to China and does not yet exist for coal and phosphate. However, Jharkhand could benefit from the considerable amount of ongoing investment in developing novel processing techniques.

Byproduct recovery offers the environmental and social license advantages of producing increased critical minerals with no additional landscape footprint since extraction utilizes ore already being mined. Byproducts can also bolster project economics by adding an additional marketable product, potentially incentivizing development of Jharkhand's undeveloped phosphate resources.

Additionally, recent exploration efforts indicate the potential to produce lithium from spodumene and lepidolite in pegmatites found in the Bihar-Jharkhand Mica Belt.

Pegmatite development may face challenges should Jharkhand resources principally contain lepidolite due to limited processing expertise outside of China. Lepidolite processing also generates fluoride compounds which require emissions scrubbing to prevent toxicity in local plant and animal life.

Overall however, pegmatite mining offers the environmental advantages of low acid mine waste risks while recent advances in spodumene processing indicate potential for lithium refining without using strong acids.

Mine and processing facility requirements

Existing processing plants in Jharkhand provide a foundation for brownfield installation of byproduct recovery capabilities at reduced capital cost. An upgrade program could install gallium recovery circuits at the Hindalco Muri alumina plant in Ranchi. Similarly numerous local steel plants could be candidates for an iron ore rare earth recovery pilot plant. Coal processing infrastructure in Jharkhand is well-developed. Multiple alumina producers globally are now pursuing gallium recovery upgrades, opening potential technology partnerships. However, pathways for rare earth byproduct recovery from iron, coal, and phosphates remain nascent, imposing significant technological risks. Downstream rare earth separation and reduction facilities remain complex and capital-intensive as noted above (see Table 1).

Lithium production would require the construction of new mines and refineries. Mining may proceed either as open pit or underground operations, and would require milling on site which involves crushing, magnetic separation, and flotation of ore to produce a mineral concentrate. Refining would require separate infrastructure that roasts the concentrate in acid then leaches it in water to form a pregnant solution. The addition of precipitants can yield either lithium carbonate or lithium hydroxide. Lithium refineries pose higher capital costs than base metal smelters or steel plants, but exhibit lower capital intensity than rare earth or titanium midstream processing plants (Table 3). Based on overseas project estimates, the capital costs of gallium byproduct recovery equipment at alumina plants may be substantial.

Table 3: Capital costs of hard rock lithium mines and refineries per ton of annual output of lithium carbonate equivalent, and capital costs of gallium extraction capabilities at alumina refineries per ton of annual output

Operation	CAPEX (USD / tpy)
Lithium mine	$5,000 to $25,000
Lithium refinery	$20,000 to $40,000
Gallium extraction	$3 million to $7 million

Values adjusted for inflation.

Energy input and operational requirements

- A sustainability challenge posed by the installation of byproduct recovery capabilities at existing alumina, coal, or steel facilities is that such recovery circuits' use of onsite coal boilers and generation for input energy needs would maximize cost efficiency, but impose higher carbon intensity of production.
- Hard rock lithium mining boasts environmental advantages over production from brines since it avoids water table drawdown and potential ground subsidence. Hard rock lithium mines - especially underground operations - can also bear smaller footprints than brine operations which require expansive evaporation ponds.

National and global market outlook

- Recovery of REEs as byproducts of other mining activities has some techno-economic advantages, but must also compete against the economics of alternative domestic production routes leveraging hardrock and mineral sand REE resources.
- Efforts by overseas producers to expand gallium recovery may furthermore induce some long-term gallium price uncertainty. From an Indian mineral strategy perspective, the Muri plant may compete with other alumina plants elsewhere in India as a candidate for an initial development of gallium recovery potential. Gallium extraction at Muri (450,000 tpy alumina) may yield 10 to 40 tpy gallium, with a value of USD $6M/yr to $23M/yr.
- The global lithium market has faced low price pressures in recent years, with the potential for oversupply and price wars likely persisting even as global consumption continues to increase. Lithium prospects in Jharkhand should carefully consider global production cost competitiveness and work proactively to secure long-term offtake.

Subnational policy considerations

- Given high project capital costs and likely increases in future global gallium output, Jharkhand-based gallium recovery should be understood as a national security investment with local economic co-benefits, rather than a resource revenue strategy.
- Global lithium market economics remain relatively illiquid and non-transparent, with lithium pricing highly sensitive to the production behavior of major market players enjoying subsidy-based advantages. An Indian lithium strategy should consider domestic policies to align projects with offtakers and support a more independent, stable market.
- Economic and competitive commercialization of REE recovery from iron, coal, and phosphate resources possesses broad national implications, with research and processing efforts thus benefiting from closer subnational and national stakeholder collaboration.
- Further local value addition for bauxite mined in Jharkhand may be limited by established aluminum smelter capacity in neighboring states. Local and neighboring steel plant capacity may also already be closely matched with existing volumes of iron mining.
- Advances in copper processing techniques now enable direct leaching and refining of lower-grade chalcopyrite ores into copper metal, dramatically reducing capital costs, energy, and emissions intensity while facilitating local value addition.

Conclusion

India's critical minerals strategy will necessarily leverage multiple production routes over the long term, ranging from primary extraction to byproduct recovery to post-consumer recycling. Differing mining and beneficiation routes pose a wide range of market, financing, technical, geographic, energy, and policy questions. In many cases, particular minerals like rare earth elements or lithium can be potentially produced from multiple different deposit types, each with their own techno-economic considerations.

More efficient coordination between state officials and private market actors depends crucially on a firm foundation of shared understanding regarding the basic factors involved in establishing a robust and profitable industry from the mine mouth to the factory gate. This assessment provides initial clarity on the technical and market considerations necessary to bring state and private actors together and progress projects towards realization. Future work can similarly expand upon needs specific to other individual commodity chains, weighing local resource potential against national strategy and global market dynamics.

Assessment of the core physical infrastructure necessary for value-added beneficiation is a key first step in catalyzing more informed consideration of public-private partnerships. Such analysis can then be compared against state technical capacities, highlighting where industry familiarity and process knowledge from existing mineral production could apply to new ventures and where workforce development may be required, potentially through partnerships with other states or national-level programs.

In the end, industry actors possess the freedom to pursue natural resource projects and to site beneficiation plants across any number of geographies globally. As outlined here, key benchmarks industry will judge in weighing investment decisions will include mineral resource quality, environmental and labor standards, plant infrastructure considerations, local operational and energy costs, and more. A credible state-level strategy for fostering sectoral development must surgically consider how to maximize comparative advantages that ensure local conditions for success.