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A Geology-Based Assessment of Mining Lease Adequacy and Land-Use Efficiency: A 3D Geological Modeling Case Study of a Manganese Deposit in the Eastern Ghats Mobile Belt, India

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Abstract

Mining lease boundaries are often set by administrative considerations, with little regard for the orebody's geometry and the spatial requirements of mineral extraction. This can be particularly problematic in structurally complex manganese deposits, where variable orebody geometry and significant waste generation affect both mine development and land requirements. A geology-based approach has been developed and applied to assess the suitability of mining leases and support sustainable mine planning for the Sadanandapuram manganese deposit in the Eastern Ghats Mobile Belt, India. The methodology comprises borehole data, geological interpretation, 3D implicit modeling, geostatistical analysis, resource estimation, waste assessment, and mining land-use analysis. The geological model presents a discontinuous, lensoidal mineralized system with variable thickness and strong directional continuity. Declustering reduced the arithmetic mean Mn grade from ~26.9% to 23.7%. Variography showed anisotropic continuity of ~320 m in the major direction and 180-200 m across it. The modeled mineralized volume is approximately 17.078 million m³, with approximately 11.122 million m³ of modeled waste. Operational records also show large quantities of waste relative to ROM ore, emphasizing the importance of orebody geometry for stripping and land requirements. The lease area is 56.837 ha. Of this area, about 47.772 ha is under mining-related activities, and 9.065 ha is nominally unused. The results suggest that the adequacy of a lease should be viewed as a geological-operational property rather than a cadastral property. The proposed framework provides a practical foundation for incorporating orebody geometry, waste generation, land-use requirements, and mineral conservation for sustainable mine planning.

Keywords: Manganese deposits; 3D geological modeling; geostatistics; stripping ratio; mine waste; lease adequacy; mineral conservation; sustainable mining.

1. Introduction

The global economy depends on mining for minerals used in infrastructure, manufacturing, renewable energy technologies, and industrial development. Yet as pressure has grown to reduce environmental impacts and extract the maximum value from resources, mine planning has become more sustainable and scientifically rigorous. Sustainable mining integrates geological, economic, engineering, and

environmental factors over the life cycle to optimize resource recovery and minimize land use [1-5].

Recent advances in three-dimensional (3D) geological modeling and geostatistics have greatly improved the characterization of complex orebodies, enabling more realistic representations of lithologic contacts, mineralized domains, and grade variability [6-8]. These methods are now widely used in mineral resource estimation and mine design to reduce geologic uncertainty and improve decision-making at both the exploration and production stages. Despite these advances, delineation of mining lease boundaries in many mining jurisdictions remains largely unaffected by geological modeling. Lease areas are often defined by administrative or cadastral boundaries that meet legal and regulatory requirements but do not reflect the spatial characteristics of mineralization, waste-disposal requirements, or long-term mine development [9-11]. Thus, lease boundaries may limit the extent of economic orebodies, constrain pit expansion, increase waste-handling costs, and restrict efficient mine scheduling and progressive rehabilitation. These limitations reduce operational efficiency and increase environmental and economic risks.

This problem is especially acute in deposits with complex structures, where mineralization occurs in discrete, irregular, or lenticular bodies that vary considerably in thickness, continuity, and orientation [12-14]. In such cases, the adequacy of the lease cannot be determined by the mere presence of mineral resources within a legally defined area. Rather, it must show whether the lease provides sufficient area to accommodate the full geological extent of the orebody, as well as waste dumps, haul roads, infrastructure, and safety and future mine-expansion buffers. Failure to account for these geological constraints risks resource sterilization, inefficient land use, and increased environmental disturbance over the life of the mine [11,15].

Although extensive work has been done in 3D geological modeling, geostatistical resource estimation, pit optimization, and mine waste management, these topics have largely evolved in isolation [6,8,16,17]. Mine planning studies primarily focus on operational optimization and economic performance. Studies on waste generation usually include environmental management but do not link waste requirements to lease boundary design [17,18]. Consequently, there is no widely accepted geological framework that integrates orebody geometry, grade distribution, stripping ratio, waste generation, and land-use requirements to assess the adequacy of a mining lease. This disconnect represents a major gap in more sustainable mine planning because lease boundaries directly affect mineral recovery, land use, environmental management, and the long-term conservation of resources [10,11,19]. The manganese deposits of the Eastern Ghats Mobile Belt (EGMB), India, provide an ideal setting to address this problem.

Thus, the aim of this study is to evaluate the adequacy of mining leases from geological and operational perspectives by integrating 3D geological modeling, geostatistical analysis, orebody geometry, stripping ratio, waste generation, and land-use information. Using the Sadanandapuram manganese deposit in the Vizianagaram District of the Eastern Ghats Mobile Belt, India, as an example, the relationships among mineralization geometry, grade continuity, waste generation, and the spatial requirements of mining within the existing lease are examined. The analyses lead to a proposal for a geology-based lease adequacy assessment framework that provides a scientific basis for evaluating an existing lease's capacity to accommodate systematic mineral development, waste management, and associated land-use

requirements, and for identifying potential mineral conservation and boundary-related risks. The approach extends the utility of 3D geological modeling beyond conventional resource characterization by linking geological information with mine-planning and land-use considerations, and offers a transferable platform for evaluating lease adequacy in other structurally complex mineral deposits.

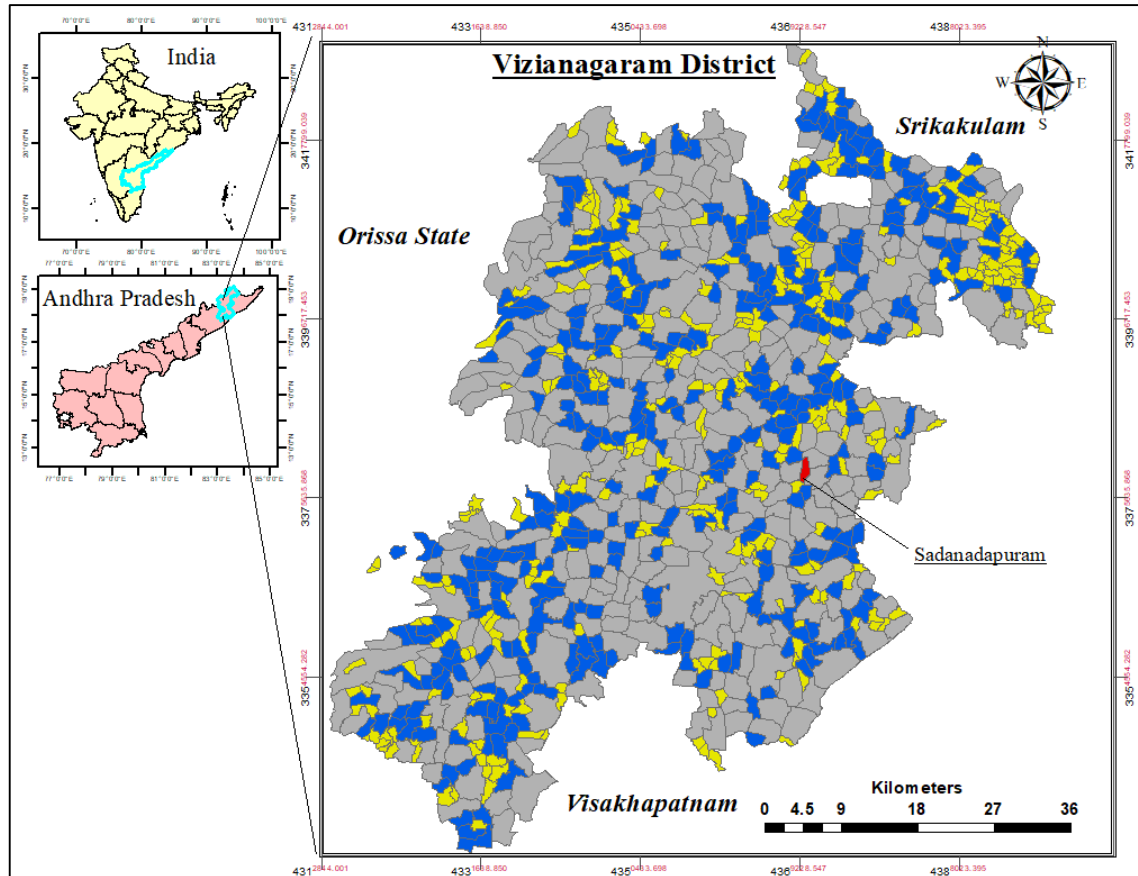


Fig. 1 Location map of the study area within the Eastern Ghats Mobile Belt, India

2. Geology and orebody characteristics

The study area is in Vizianagaram, a manganese-bearing region of the Eastern Ghats Mobile Belt (EGMB), India (Fig. 1), where manganese mineralization occurs in high-grade metamorphic rocks of the Precambrian Khondalite Group [20-22]. The ore is hosted by Khondalite, with minor weathered Khondalite, quartzite, and calc-granulite, and is covered by a thin layer of lateritic and unconsolidated surficial material. Among these lithologic units, Khondalite is the primary host rock, and quartzite and calc-granulite are important lithologic markers that locally control ore continuity and geological interpretation.

The manganese mineralization is interpreted to have originated from sedimentary, manganese-rich protoliths, which were later subjected to regional granulite-facies metamorphism [12,13,23,24] and subsequent supergene enrichment [13,14]. Thus, the deposit is structurally modified stratiform, with manganese ore occurring as discontinuous but laterally persistent lensoidal bodies within the Khondalite sequence [12-14]. Weathering has also enhanced near-surface enrichment and contributed to local variations in ore thickness and grade.

The 3D geological model indicates that the orebody is not a continuous horizon but a series of interconnected mineralized lenses. Individual ore lenses vary widely in thickness, strike length, and depth continuity, exhibiting characteristic pinch-and-swell structures, local bifurcation, and irregular lensoidal geometries. The ore zones are primarily hosted in Khondalite and weathered Khondalite, with quartzite locally separating adjacent mineralized lenses and calc-granulite forming relatively continuous horizons beneath parts of the orebody, providing important stratigraphic control in geological modeling.

The mineralization is strongly controlled by lithologic contacts and regional structural features [13,21,22]. Geological modeling and borehole interpretation indicate that mineralized horizons follow the regional structural trend and maintain consistent dip continuity across the deposit. Ore thickness varies locally but is strongly correlated with structural deformation, leading to localized thickening, segmentation, and displacement of mineralized horizons. These structural controls largely govern the distribution of economically recoverable ore and the heterogeneous geometry observed throughout the deposit. The mineralized lenses are irregularly shaped, which has a considerable impact on stripping ratios, waste generation, pit design, and the location of mine infrastructure [8,16,25]. Thus, defining lithologic boundaries and structural continuity through 3D geological modeling provides an important geological basis for resource estimation, waste assessment, and evaluation of mining land requirements.

3. Materials and Methods

3.1. Geological database construction and study workflow

The research employed an integrated workflow that combined geological interpretation, 3D geological modeling, geostatistical analysis, resource estimation, waste assessment, and lease adequacy assessment. The workflow was based on six sequential steps, i.e., (1) Data Acquisition and Validation, (2) Implicit Geological Modeling, (3) Geostatistical Analysis, (4) Block Modeling and Resource Estimation, (5) Waste Generation and Stripping Ratio Assessment, and (6) Geology-Based Lease Adequacy Evaluation. This integrated approach has enabled the direct incorporation of the deposit's geological characteristics into mine planning and lease adequacy.

The geological database comprised exploration borehole logs, collar coordinates, lithologic records, downhole survey data, manganese assay results, topographic survey data, production records, and approved mining lease plans for the study area. The mineralized horizons were characterized in terms of geometry and continuity using data from 28 exploration boreholes over a strike length of approximately 900 m (Table 1). The average borehole spacing within the central mineralized zone was 40–50 m, increasing toward the deposit margins.

Prior to modeling, all datasets were quality-controlled to ensure consistency and reliability. Borehole collar coordinates were compared with the mine survey database, lithologic coding was standardized to a uniform lithologic classification, and assay intervals were checked for overlaps, missing values, and duplicate records. Prior to geologic interpretation, downhole survey data were verified to confirm the suitability of

the borehole trajectories. These procedures reduced errors in data integration and produced a consistent database for geological modeling.

Table 1 Geological and mining dataset used in the study

Dataset	Information	Application
Boreholes	28	Geological modelling
Lithology	Geological intervals	Domain construction
Assays	Mn grades	Geostatistics/resource estimation
Downhole surveys	Borehole trajectories	3D positioning
Topography	Surface elevation	Geological model
Production records	Ore/waste	Operational assessment waste
Mining plan	Lease/land use	Lease assessment

3.2. 3D Geological Modeling

3D geological modeling was performed using Leapfrog Geo (Seequent Ltd., Version 5.1). The software's implicit modeling algorithm generates geological surfaces from scattered drill-hole data by interpolating geological boundaries with radial basis functions. The major lithological domains modeled were Manganese ore, Khondalite, Weathered Khondalite, Quartzite, and Calc-granulite. Lithological contacts were interpreted from borehole logs and surface geological mapping. Observed stratigraphic relationships were used to iteratively update geological surfaces while minimizing unrealistic surface intersections. The final geologic model was compared with geologic cross-sections and borehole intercepts to validate that the interpreted surfaces were consistent with observed geologic data.

3.3. Geostatistical Approach

Prior to geostatistical analysis, assay intervals were composited to a constant length of 1.5 m to match the average sampling interval in the exploration database. Compositing removed bias from variable sample lengths and gave equal weight to all samples in variogram modeling and grade estimation. Exploration drilling on the deposit is concentrated in known mineralized zones, resulting in spatial clustering that may bias global grade statistics [7,8]. Declustering cell sizes were varied to determine the optimal cell size for producing a stable declustered mean grade. Small changes in the estimated global mean grade were due to small increases in cell dimensions, which were then declustered from the mean.

Experimental variograms were computed along the main geological directions to quantify the spatial continuity of manganese grades [7,8]. Directional variograms were fitted along the major, semi-major, and minor directions. The fitted theoretical variograms provided estimates of the nugget effect, sill, range, and anisotropy ratio. These parameters were then used to define the search ellipsoid for ordinary kriging.

Interpolation used a search neighborhood aligned with the primary anisotropy directions, derived from variogram analysis. The search ellipsoid was constructed using the fitted variogram ranges:

- Major axis $\approx$ 320 m/ Semi-major axis $\sim$ 190 m/ Minor axis $\approx$ 120 m

The search was oriented along the strike and dip of the mineralized horizons.

3.4. Building and Validation of the Block Model

A 3D block model was constructed within the geological domains derived from the implicit geological model (1295 m by 308 m by 115 m). Grade estimation was performed using the Ordinary Kriging (OK) method, which provides unbiased estimates with minimum estimation variance for spatially correlated regionalized variables [7,8]. Interpolation was restricted to individual geological domains to prevent grade smearing across lithologic boundaries. Several validation procedures were used to assess the estimated block model. Validation included: comparison of estimated and composite grade distributions, visual cross-checks of block grades against drill hole assays, and statistical comparison of global mean grades. The comparison between estimated and observed grades indicates that the model reasonably reproduces both geological continuity and grade variability.

3.5. Waste Generation and Stripping Ratio Evaluation

Waste generation was determined using annual mine production records, excavation volumes, and waste disposal data. The calculated stripping ratio (SR) was:

$$SR = W/O$$

Where SR = stripping ratio, W = waste tonnage, and O = run-of-mine ore tonnage (Hartman & Mutmanský, 2002; Hustrulid & Kuchta, 2006).

The relationship between orebody geometry and waste generation during the mining period was evaluated by analyzing annual waste volumes, waste dump capacities, mineral rejects, and recovery rates.

3.6. Geology-Based Approach to Evaluating Lease Adequacy

A mining lease is typically defined by legal and administrative boundaries rather than by the geological characteristics of a mineral deposit [9,10]. These methods can lead to incomplete recovery of economically viable resources, inadequate space for waste disposal, limited mine expansion, and inefficient land use [10,11,17]. To address these limitations, this study proposes a Geology-Based Lease Adequacy Assessment Framework (GLAF) that quantitatively integrates geological, operational, and environmental considerations into lease assessment. The framework was motivated by a simple question: Is the current mining lease adequate to enable efficient orebody recovery, with space for waste disposal, infrastructure, and long-term mine development? The framework assesses lease adequacy using land-use allocation analysis and complementary geological land-use efficiency (GLUE) indices.

Geological Land-Use Efficiency (GLUE)

Sustainable mining aims to maximize mineral recovery while minimizing land use. Geological Land-Use Efficiency quantifies the amount of modeled mineralized material per hectare of land used for mining-related activities.

$$GLUE = \frac{Mr}{Ad}$$

Where: Mr = modeled mineralized material (t), Ad = disturbed land (ha)

Higher values indicate more efficient land use.

4. Results

4.1. Geological Modeling

The deposit was explored by drilling twenty-eight boreholes along a 900 m strike length. The average borehole spacing is 40–50 m in the central mineralized zone and increases toward the deposit margins. The drill-hole density is sufficient for geological modeling, variography, and resource estimation. The 3D geological model of the Sadanandapuram manganese deposit was developed by integrating borehole lithologic data, surface geological observations, and interpreted lithologic contacts. The model defines the spatial relationships among the main lithologic units, including manganese ore, Khondalite, weathered Khondalite, calc-granulite, and quartzite.

The model suggests that manganese mineralization occurs in a discontinuous yet laterally continuous lenticular horizon, primarily hosted within the Khondalite Group. The presence of a manganese-bearing zone within the Khondalite and weathered Khondalite units indicates that the mineralization is lithologically controlled. The ore horizon varies considerably in thickness along strike and dip, exhibiting the pinching-and-swelling pattern typical of manganese deposits in the Eastern Ghats Mobile Belt.

The 3D visualization shows that the manganese orebody is heterogeneous, occurring as a succession of interconnected lenses and elongated pods. These ore lenses exhibit moderate strike continuity and locally thicken within structurally favorable zones. The observed geometry aligns with earlier geological interpretations of a vein-like to lenticular mineralized body formed by combined sedimentary, metamorphic, and supergene enrichment processes [12-14,23]. The orebody has an irregular shape due to post-depositional deformation and weathering, which have modified the original mineralized horizons.

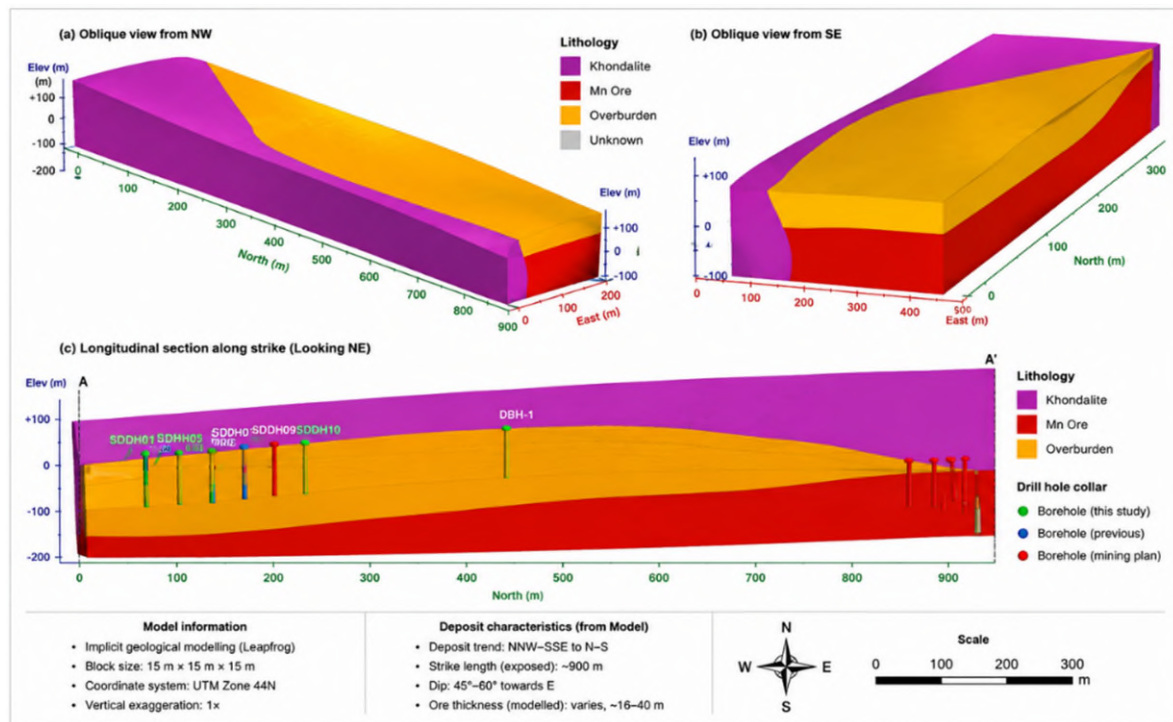


Fig. 2 3D geological model of the Sadanandapuram manganese deposit, (a) oblique view from the northwest, (b) oblique view from the southeast, and (c) longitudinal section along strike (NE) showing the spatial relationships among Khondalite host rock, manganese ore, and overburden, with drill-hole collar locations

The 3D geological model shows an NNW-SSE- to N-S-trending, east-dipping manganese-mineralized system hosted primarily in Khondalite and covered by variable overburden. The oblique views demonstrate that the Mn ore is a laterally continuous but geometrically variable body, with thickness variations and localized irregularities along strike and down-dip. The longitudinal section further indicates that the mineralized horizon is approximately 900 m long along strike, dips 45–60° to the east, and varies in thickness, consistent with the interpreted lensoidal and pinch-and-swell geometry of the deposit. The spatial distribution of boreholes provides reasonable geological control over the modeled mineralized domain, although drilling density varies along the deposit and is comparatively limited toward some margins. The model reveals that manganese mineralization is strongly controlled by the regional lithologic and structural framework and provides an appropriate 3D basis for subsequent grade estimation, waste assessment, and evaluation of mining land requirements (Fig. 2).

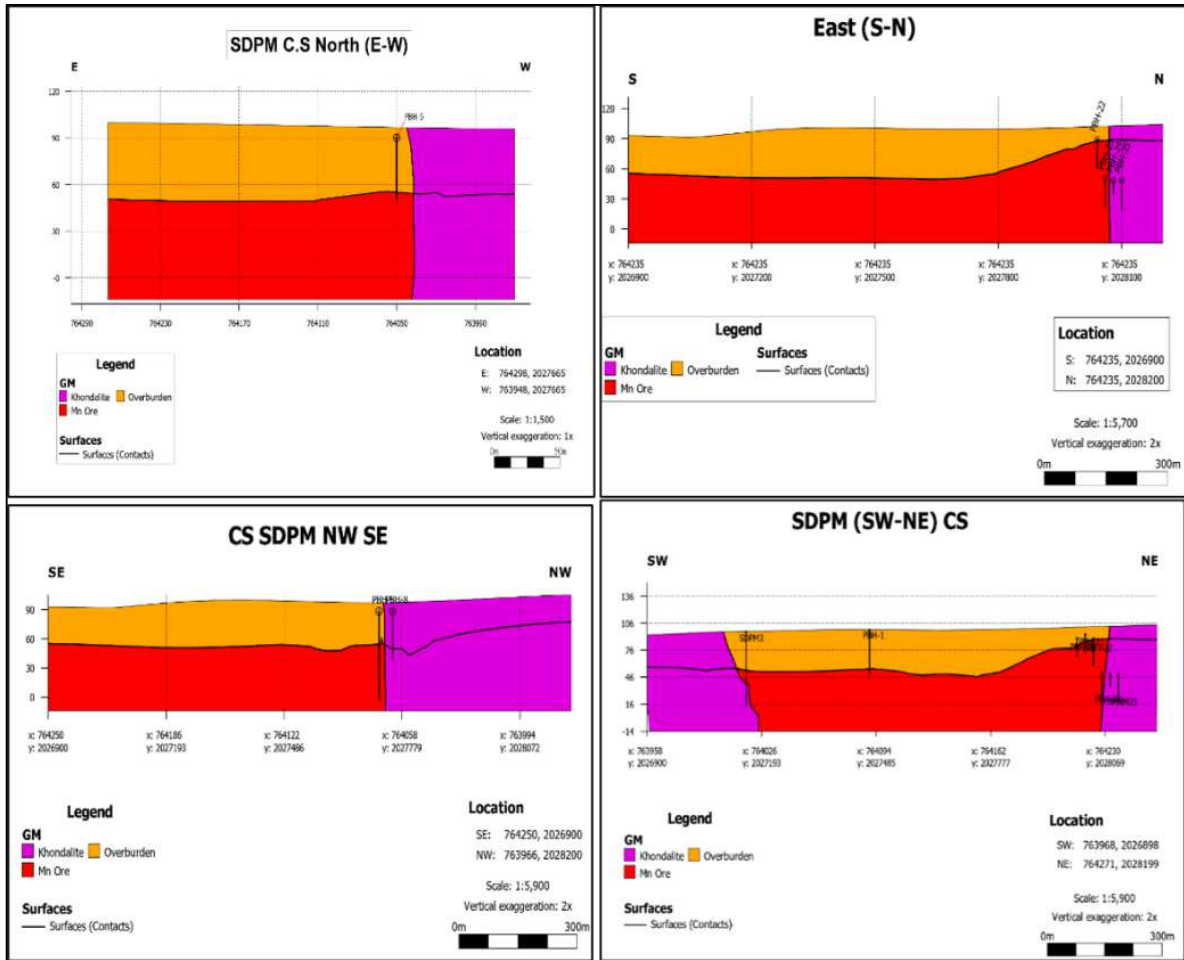


Fig. 3 Geological cross-sections of Sadanandapuram manganese deposit

4.2. Geostatistical Results and Grade Tonnage

Exploration drilling at the Sadanandapuram manganese deposit is spatially clustered, particularly in areas of known mineralization, which may bias global grade statistics. Before variogram modeling and resource estimation, cell declustering was performed to assess and correct for this bias. The aim was to evaluate the impact of preferential sampling and to obtain a representative estimate of the deposit-wide manganese grade.

The declustering results indicate that the concentration of samples in higher-grade parts of the deposit influences the arithmetic mean manganese grade, which is 26.87% Mn. As the declustering cell size increased, the declustered mean grade decreased progressively and stabilized at approximately 23.6%-23.8% Mn, indicating effective mitigation of the clustered sampling effect (Fig. 4, Fig. 5). The stabilization of the declustered mean values at cell sizes of about 120 m and 180 m shows that the selected declustering parameters are sufficient to account for the non-uniform distribution of drill holes.

The ~3.0–3.3% difference in Mn between the arithmetic and declustered means indicates a positive sampling bias due to preferential drilling in mineralized zones. Furthermore, the declustered mean was quite stable at declustering cell sizes above

the optimum, suggesting that it was relatively stable beyond the selected cell size range.

The convergence of the minimum, average, and maximum declustered mean curves demonstrates the robustness of the declustering procedure and supports the reliability of the corrected dataset. Therefore, the declustered mean of ~23.7% Mn was used as the representative global grade for further variogram analysis, block model validation, and resource estimation. The results show that declustering successfully removed sampling bias and produced a statistically representative database for geostatistical modeling and mineral resource assessment.

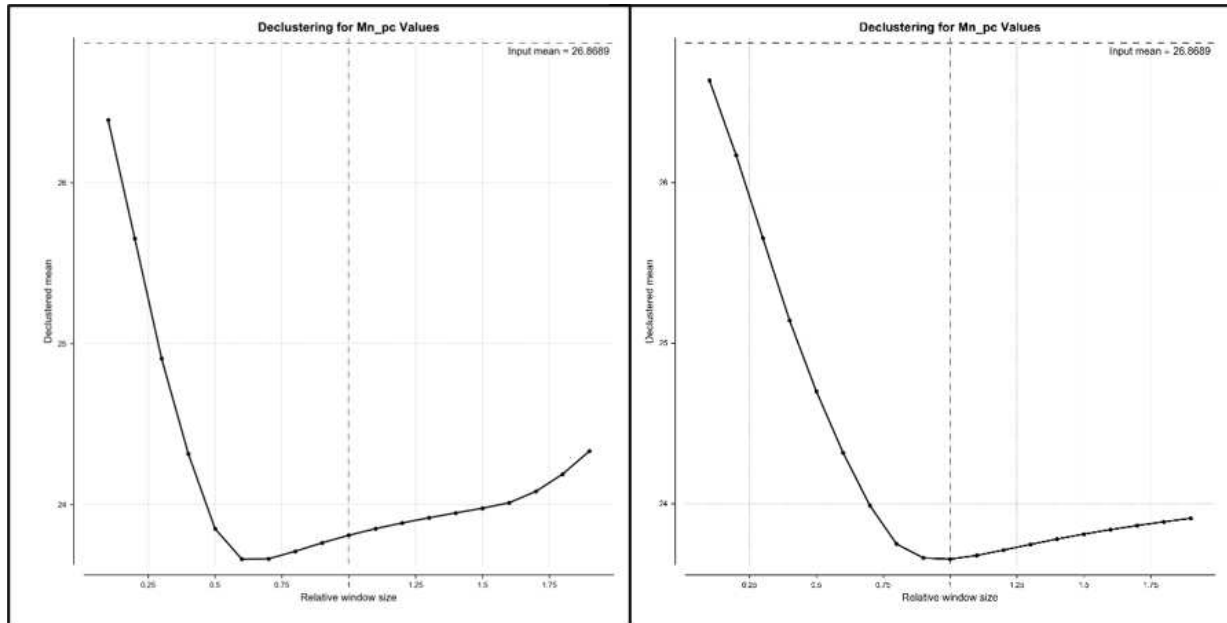


Fig. 4 Cell declustering optimization using relative window size

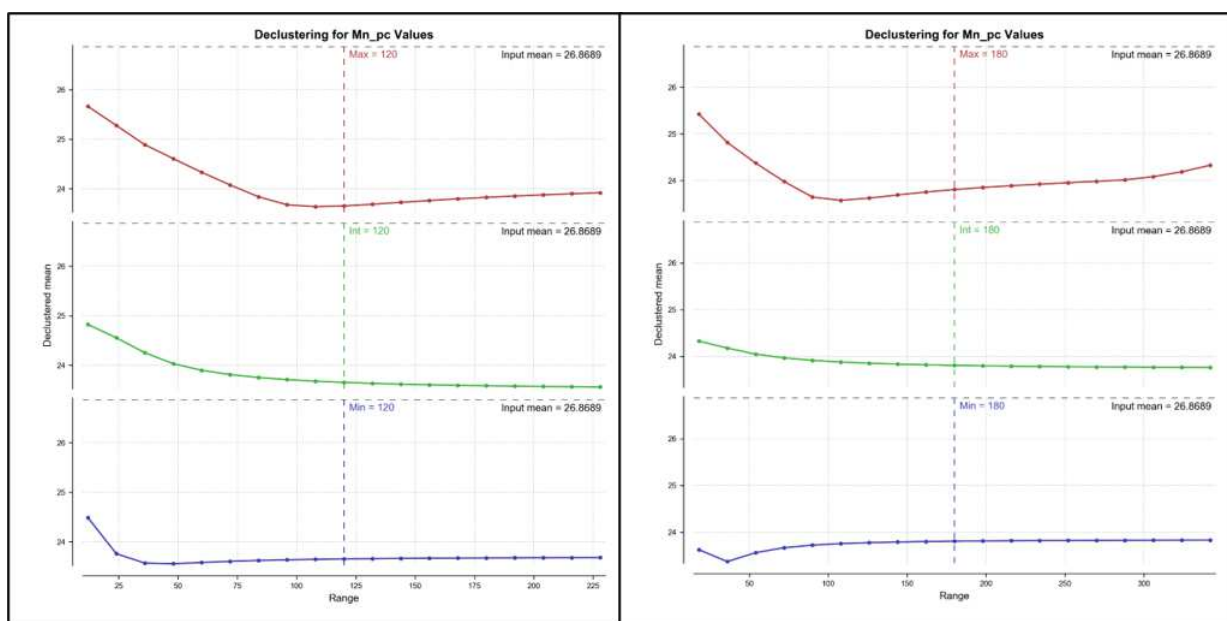


Fig. 5 Range-based declustering analysis showing stabilization of the declustered mean at the optimum cell sizes

4.2.1. Variography and Analysis of Spatial Continuity

Experimental variogram analysis of Mn grades was conducted to quantify the spatial continuity and anisotropy of mineralization in the Sadanandapuram deposit. The downhole variogram approaches zero and shows little variability across the sampled interval, indicating extremely high-grade continuity along individual drill holes and confirming that the selected compositing length is appropriate for characterizing local grade variations without excessive smoothing. Directional variograms along the main directions of horizontal continuity show a clear anisotropic spatial structure. The major-axis variogram (direction 180°) reaches the modeled sill of about 1.0 at a range of approximately 320 m, indicating that Mn grades are spatially correlated over relatively long distances along the principal geological trend. The semi-major-axis variogram in the 090° direction (Fig. 6, Table 2) reaches the sill at a shorter range of approximately 180–200 m, indicating less continuity perpendicular to the main trend of mineralization. The major direction at longer range is consistent with the elongate geometry of the manganese-bearing horizon and indicates preferential continuity in the strike direction. The nugget effect in both directional variograms is low, indicating little short-scale randomness and good geological continuity between sample locations. The anisotropic ratio derived from the major and semi-major ranges indicates that the mineralization is much more continuous along the principal structural trend than across it. This agrees with the lensoidal and stratiform geometry observed in the geological model and cross sections (Fig. 3). For ordinary kriging, the fitted variogram models reproduce the experimental data and provide a good statistical basis for the search ellipsoids and interpolation parameters.

Table 2 Key variogram parameters for Sadanandapuram

Parameter	Downhole	Major Axis (180°)	Semi-Major Axis (090°)
Nugget Effect	Near zero	Very low	Very low
Sill	~0	1.0	1.0
Range	Very short	~320 m	~180–200 m
Continuity	Very high	High	Moderate to High
Anisotropy	Not applicable	Principal continuity direction	Secondary continuity direction
Geological Interpretation	Excellent grade continuity within drill holes	Strong continuity along strike	Reduced continuity across the strike

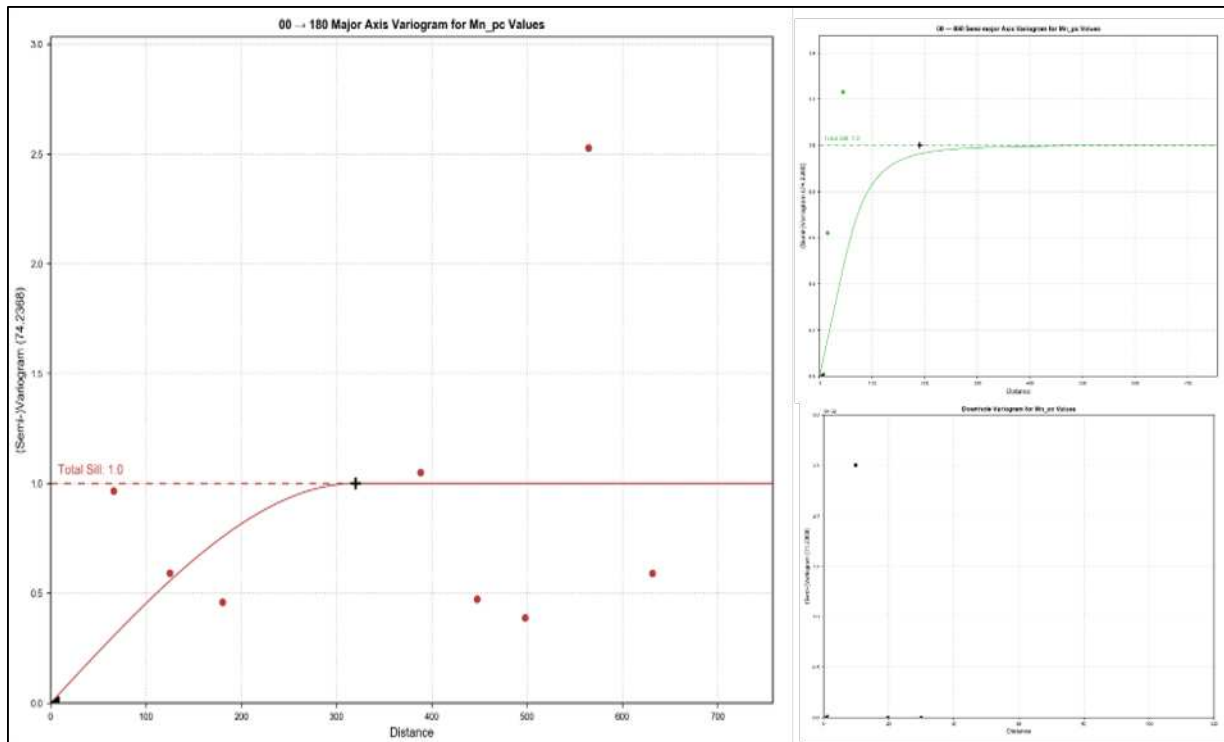


Fig. 6 Experimental variograms (Downhole, Major Axis, Semi-major Axis) for manganese grades

4.2.2. 3D Grade Distribution

The 3D grade shell model of the Sadanandapuram manganese deposit clearly illustrates the spatial distribution and continuity of manganese mineralization across grade ranges. The model also divides the mineralized domain into grade populations, i.e., low-grade (<12.38% Mn), medium-grade (12.38–17% Mn), high-grade (17–25% Mn), and very high-grade (>25% Mn). The grade shells are zoned, indicating that manganese mineralization is not uniform throughout the deposit but is concentrated in discrete ore shoots and enrichment domains controlled by lithology and structure. The grade shells are generally elongated and ellipsoidal, with high continuity along the main trend of mineralization, consistent with the anisotropic behavior shown in the variogram analysis and structural modeling. The low-grade shell (<12.38% Mn) is the largest, most laterally extensive domain, forming the outer mineralized envelope around higher-grade cores. The low-grade zone outlines the general shape of the deposit and comprises the outer parts of the mineralized system, where manganese enrichment was less intense. The large spatial extent of this shell indicates that manganese-bearing processes affected a large volume of host rock, but economic concentrations were confined to local areas (Fig. 7).

The moderate-grade shell (12.38–17% Mn) forms discontinuous lenses within the low-grade envelope and shows greater spatial continuity along the main ore trend. These zones are likely transitional mineralization, with manganese enrichment enhanced by favorable lithologic conditions, fluid pathways, or localized supergene concentration. Their intermediate grade suggests progressive grade upgrading toward the central parts of the orebody.

The high-grade shells (17 to 25% Mn) are much smaller in volume but have much higher manganese concentrations. These domains appear as strongly continuous, elongated, lensoidal bodies spatially associated with the central portions of the mineralized horizon. The geometry of these shells implies that manganese enrichment was localized within structurally or stratigraphically favorable zones, leading to the development of economically important ore shoots. The presence of these high-grade bodies indicates a stable mineralizing environment and reinforces confidence in resource estimation within these domains.

The spatial distribution of these high-grade domains is consistent with localized enrichment, although the grade model alone does not uniquely constrain the underlying enrichment mechanism. The presence of these high-grade cores within large, low-grade envelopes argues for a combination of primary depositional control and subsequent upgrading via weathering and remobilization. The spatial distribution of grade shells is nested, with successively lower-grade mineralization surrounding higher-grade domains. This is a typical grade zonation for many stratiform manganese deposits, showing a gradual decline in manganese concentration as one moves away from the ore centers. The orientation of the grade shells is consistent with the modeled plunge and anisotropy directions, suggesting that the mineralization is structurally controlled and shows preferential continuity parallel to the main geological trend. The strong correlation among grade shell geometry, lithologic boundaries, and variogram anisotropy supports the geological interpretation and bolsters confidence in the resource estimation methodology.

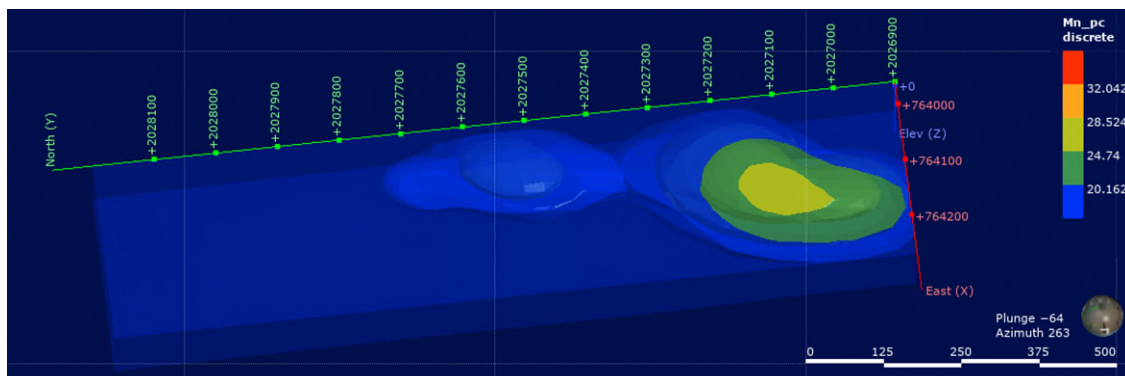


Fig. 7 3D Mn grade model (Mn%) derived from numerical interpolation of assay data, constrained by the deposit's geological framework. The color scale ranges from ~20.16% Mn to 32.04% Mn, showing the spatial variability of manganese concentration in the modeled orebody.

From a mining and resource evaluation perspective, the grade shell model defines the economically feasible ore zones and high-grade targets for selective extraction. The interlocked geometry of the grade shells provides a strong framework for pit optimization, grade control, and resource classification. Furthermore, very high-grade manganese in discrete ore shoots suggests that future exploration should focus on extending these high-grade zones along the interpreted plunge direction.

4.2.3. Geological Validation

The Sadanandapuram manganese deposit shows strong geostatistical continuity and a predictable grade distribution. Declustering mitigated the effects of clustered drilling

and yielded a representative average grade of about 23.7% Mn. Variography revealed significant anisotropy, with major continuity of ~320 m, semi-major continuity of 190 m, and minor continuity of 120 m. The kriging search ellipsoid was defined, and Mn block models were built using these parameters. Validation results indicate that the estimated grades are consistent with the statistical and geological properties of the original data and provide a solid basis for resource estimation and reserve evaluation. This integrated modeling workflow increases confidence in the reported resource estimates for the Sadanandapuram manganese deposit and will support further mine planning and economic assessment.

4.3. Geometry of the orebody and generation of waste

The 3D geological model illustrates the detailed spatial geometry of the manganese mineralization and its relationship to the surrounding lithologic units. The model indicates that the Sadanandapuram deposit is not a single homogeneous orebody but a discontinuous, lensoidal mineralized system with variable thickness and continuity along strike and dip. The host rocks of the manganese mineralization are predominantly khondalite and weathered khondalite, while quartzite and calc-granulite locally define lithologic contacts and control the distribution of individual mineralized lenses.

The reconstructed orebody exhibits a general NNW-SSE to N-S structural trend and an eastward dip of about 45-60°. The mining plan's geological investigation reports an exposed strike length of approximately 900 m. Orebody thickness varies from approximately 16 to 40 m and displays characteristic pinch-and-swell geometry. These observations are consistent with the 3D model, which shows localized thickening and thinning of the mineralized horizon. Spatial continuity is more evident along the main geological trend than perpendicular to it, consistent with the anisotropic behavior inferred from variography, where the major continuity is around 320 m, compared with around 180–200 m along the secondary horizontal direction. The modeled ore volume is approximately 17.078 million cubic meters. This equates to approximately 45.09 Mt of modeled mineralized material at the representative ore density used for the geological model (2.64 t/m³). This volume represents the geological model domain and should thus be distinguished from the operational ROM production reported in the mining plan. The latter reflects the material mined during the production period under study, whereas the 3D model is a spatial reconstruction of the mineralized system.

The geological model also includes approximately 11.122 million m³ of associated waste material within the modeled mining domain. This corresponds to approximately 25.58 Mt of waste, based on the adopted waste density of 2.30 t/m³. The resulting waste:ore ratio from the model is approximately:

$$\text{Model-based volumetric stripping ratio (SRv)} = \frac{\text{waste volume}}{\text{ore volume}}$$

$$\text{SRv} = \frac{11,122,000}{17,078,000} = 0.651$$

$$\text{SRv} = 0.65:1$$

Model-based tonnage stripping ratio (SRt) = 0.568:1

This value represents the volume ratio from the geological model and should not be considered the operational stripping ratio. Orebody Coverage Index and production records provide a second measure of waste generation. The mine is expected to mill approximately 4.70 Mt of material from 2021-22 to 2024-25, including 3.44 Mt of waste and 1.26 Mt of ROM ore. Waste-to-ROM ratios ranged from 3.76:1 to 5.14:1, with an average of about 4.3:1. In 2023-2024, the stripping ratio was 5.14:1, and the lowest stripping ratio was in 2022-2023, at 3.76:1. The variation is due to changes in the waste-to-ROM ore ratio across different stages of mine development.

The operational ratio (4.3:1) differs significantly from the model-based ratio (0.65:1), which represents the relative volumes of ore and waste in the geological model. The operational ratio is calculated based on actual waste mined and ROM production. Thus, these metrics measure different aspects of the mining system and should not be directly substituted for one another. The operational ratio depends on the geometry of the active excavation, mining sequence, bench development, dilution, and material handling. The geological model describes the reconstructed spatial distribution of ore and associated waste. Therefore, a key conclusion of this study is the spatial relationship between orebody geometry and waste generation. The mineralized horizon has an irregular, lensoidal geometry, variable thickness, and variable depth, resulting in heterogeneous excavation requirements. In areas of the orebody where the mineralization is relatively shallow and thick, it is possible to access ore with relatively less waste removal. In other areas, where the mineralization is thinner or deeper, more excavation is required to expose sufficient ROM ore. The strong anisotropy and geological continuity indicated by the 3D model and variography also suggest that mine development should follow the main geological direction, rather than treating the mineralized zone as a geometrically uniform body.

The results of these studies indicate that waste generation is inherent to the deposit's 3D geologic setting. Hence, waste requirements should be integrated with orebody geometry in mine planning and in assessing the adequacy of land set aside for mining and waste management.

4.4. Sufficiency of the Mining Land Use and Lease

The Sadanandapuram mining lease area covers 56.837 ha and is an existing non-forest mining lease operated using open-cast methods. Land use records show a continuous increase in the proportion of the leased area dedicated to mining-related activities over the planning period. By 2024–25, the approved land-use allocation was 23.052 ha for mining, 17.403 ha for overburden/waste dumping, and 2.340 ha for mineral storage. Another 4.977 ha was allocated to other specified uses. Thus, the total area used was 47.772 ha, leaving about 9.065 ha nominally unused within the 56.837-ha lease (Table 3).

Table 3 Summarizes main elements of land use.

Land-use category	Area (ha)	Proportion of lease (%)
Mining area	23.052	40.56
Waste dumping	17.403	30.62
Mineral storage	2.340	4.12
Other specified uses	4.977	8.76
Total area used	47.772	84.04
Remaining nominally unused area	9.065	15.96
Total lease area	56.837	100.00

The results suggest that approximately 84.0% of the lease area is already committed to identified mining-related uses, leaving only about 16.0% nominally unused. This represents a substantial reduction in spatial flexibility relative to the original lease area. The land-use pattern is critical. Two major components, mining and waste dumping, together occupy 40.455 ha, about 71.18% of the total lease area. Waste disposal alone uses 17.403 ha, or about 30.62% of the total lease area. This demonstrates that waste management is a major land-use requirement, not a minor aspect of the mining operation. This requirement is as important as the production record, which shows that about 3.44 Mt of waste was produced during the four-year operating period, compared with 1.26 Mt of ROM ore.

The spatial distribution of the lease suggests a strong relationship between geological characteristics and land requirements. The 3D model shows that the mineralized system is laterally persistent yet geometrically irregular. Operational data indicate that large volumes of waste are generated during mining. Consequently, the land area required for mine development cannot be derived from the orebody footprint alone. Space is also needed for waste disposal, mineral stockpiling, access, environmental management, and other mining-related activities. Thus, the remaining 9.065 ha should not be treated as excess land. Its practical availability depends on its location relative to the active pit, waste dumps, mineralized zones, infrastructure, safety requirements, drainage, and other spatial constraints. However, the reduction in the proportion of land nominally unused provides a useful indicator of the extent to which the existing lease was already committed to mining-related activities.

The results support a geology-based interpretation of lease adequacy rather than a definitive determination of whether the existing lease is adequate or inadequate. The current data set lacks sufficient spatial information to quantify mineralization volume outside the lease boundary or to define the land requirements for a detailed future mine plan. The risk of resource sterilization and the flexibility of future mine development cannot be directly quantified in the present study. Instead, the evidence suggests that lease adequacy should be determined by the relationship among the 3D orebody, waste generation requirements, and the spatial allocation of mining land.

This is particularly important for deposits with irregular lensoidal geometries. A constant cadastral area can contain a significant volume of mineralization, yet it becomes increasingly constrained by waste dumps and other mining-related land uses. Thus, the Sadanandapuram case underscores the need to incorporate

geological information into future lease planning and review, even if a quantitative boundary-optimization exercise is not feasible.

4.5. Efficiency of land use

Land-use efficiency was assessed by comparing the modeled mineral inventory with the area committed to mining-related activities. The analysis indicates the proportion of mineralized material in the geological model relative to the land area allocated to mining, waste management, mineral storage, and other related uses. The 3D geological model contains approximately 17,078,000 m³ of manganese-mineralized material. The corresponding modeled mineralized tonnage, based on an ore density of 2.64 t/m³, is approximately:

$$17,078,000 \times 2.64 = 45,085,920 \text{ t or approximately } 45.09 \text{ Mt.}$$

The Mining Plan provides for a total working area of 47.772 ha during 2024-25. The modeled mineral inventory per unit of land use is as follows:

$$GLUE = \frac{45,085,920}{47.772}$$

$$GLUE_{\text{geo}} = 943,773 \text{ t/ha}$$

or approximately: 0.944 Mt/ha

This value indicates that approximately 0.944 Mt of modeled mineralized material is represented per hectare of land used for mining-related purposes. However, this measure should be considered an indicator of geological land-use efficiency rather than a measure of actual mine productivity. The denominator includes the total area placed in use, including mining, waste disposal, mineral storage, and other specified uses, while the numerator is the geological mineralized volume converted to tonnage. It thus provides a spatial metric for the association between the mineral inventory and the land requirements of the current mining configuration. For comparison, the corresponding geological mineral inventory density, considering only the 23.052-ha mining footprint, is approximately:

$$\frac{45,085,920}{23.052} = 1,956,000 \text{ t/ha}$$

or about 1.96 Mt/ha. This latter value should not be used as the primary indicator of land-use efficiency, as it does not account for the substantial land required for waste disposal and other mining-related activities. The waste dumps alone cover about 17.403 ha (30.62 % of the total lease area), and the mine footprint is 23.052 ha (40.56 %). Therefore, a substantial portion of the land used in mineral extraction is for purposes other than direct ore mining.

The land-use efficiency evaluation reinforces the general conclusion that mineral recovery and land use should be integrated into sustainable mine planning. A larger mineralized inventory within a lease does not necessarily translate to more efficient land use if a disproportionate share is used for waste disposal or other mining

activities. In contrast, orebody geometry can be ignored to reduce the disturbed area, thereby increasing resource recovery. The optimal trade-off depends on the deposit's geological structure and the spatial requirements of extraction.

For Sadanandapuram, the geological land-use indicator of 0.944 Mt/ha, combined with a high operational waste-to-ROM ratio of nearly 4.3:1, indicates that the mining operation's spatial efficiency cannot be determined solely from the orebody. This finding strengthens the case for integrating geological modeling with land-use and waste-management information when assessing the sustainability of mineral development. It is important to note that this analysis is not a definitive measure of the environmental footprint of mining, as the available data do not differentiate among temporary, permanent, rehabilitated, or indirectly affected land. It should therefore be interpreted specifically as a measure of geology-to-land-use efficiency for the present planning configuration.

5. Discussion

5.1. Geological Controls on Orebody Geometry & Resource Distribution

The geological architecture of the Sadanandapuram manganese deposit is the primary control on mineability and, consequently, on the space requirements for mining. The mineralization occurs within a metamorphosed sedimentary sequence of the Eastern Ghats Mobile Belt and is strongly controlled by lithologic contacts and structural trends that govern manganese distribution. The occurrence of mineralization within Khondalite and other metasedimentary units, with quartzite and calc-granulite as bounding or intervening lithologies, suggests that ore formation and preservation were strongly controlled by the pre-existing geological framework. This interpretation is consistent with the geological characteristics of metamorphosed sedimentary Mn systems reported from other parts of the Eastern Ghats Mobile Belt and other Precambrian Mn provinces [13,14].

The irregular lensoidal morphology has implications beyond geological interpretation. In a geometrically uniform deposit, mine boundaries and extraction sequences can be designed efficiently because ore thickness and continuity are predictable. In contrast, the pinch-and-swell character observed at Sadanandapuram introduces considerable spatial variability in the relationship between ore and surrounding waste. Local thickening can improve mining efficiency, whereas zones of attenuation may require more excavation than the ore recovered. Thus, geological complexity translates directly into operational variability [8,16,25].

In this context, the 3D modeling approach is particularly useful because it treats mineralization geometry as a continuous spatial system rather than as isolated intersections on two-dimensional sections. This distinction is important for mine planning, as the economic value of an ore intersection depends not only on its grade but also on its continuity, thickness, depth, orientation, and relationship to adjacent waste units. This model thus provides a more relevant geological basis for defining mining domains and anticipating areas where excavation needs may increase.

The implications extend beyond lease planning. A lease boundary designed without regard for the 3-D configuration of the mineralized horizon may capture only part of the economically relevant geologic system. This is especially important for elongated deposits, where the direction of geological continuity may differ significantly from the

shape or orientation of cadastral boundaries. In such cases, administrative boundaries may become a constraint on geological development rather than a neutral spatial framework.

The results are consistent with the principle that mining leases should be evaluated based on the geometry and continuity of the mineral system rather than by simply comparing the total lease area with the apparent surface expression of mineralization. Geological modeling should therefore be an early part of mine planning and, as appropriate, of lease allocation or review.

5.2. Geostatistical Implications on Resource Confidence and Mine Planning

The geostatistical analysis serves as an important bridge between geological interpretation and quantitative resource evaluation. The disparity between the arithmetic and declustered grade distributions shows that preferential sampling in mineralized areas can affect estimates of the deposit-wide grade population. This is especially true for structurally heterogeneous deposits, where drilling is often limited to areas known or suspected to be mineralized.

The greater continuity along the main trend of mineralization than across it implies that grade information should not be treated as spatially isotropic. Rather, the orientation of the search neighborhood and the interpolation parameters need to align with the geological controls on mineralization. This correspondence between geological and statistical anisotropy increases confidence that the interpolation process is geologically meaningful rather than driven solely by mathematical proximity.

The relatively low nugget effect and well-defined continuity indicate that the grade distribution has sufficient spatial structure to support interpolation within the investigated domain. However, strong continuity does not imply the absence of geological uncertainty. Uncertainties include lensoidal geometry, variable thickness, and localized enrichment, particularly near domain boundaries and in areas with decreasing well density. Resource confidence should not be uniform across the deposit but should be spatially differentiated.

These results have direct implications for mine planning and lease evaluation. Geological and geostatistical uncertainty should be considered when making decisions about future pit extensions, exploration requirements, and the potential extension of mineralization beyond currently developed areas. Thus, a geology-based lease assessment should consider not only the estimated quantity of mineralization but also its confidence, continuity, and spatial uncertainty.

The integration of geological constraints, declustering, and anisotropic interpolation is more than an improvement in resource estimation. It provides a way to translate geologic uncertainty into mine planning decisions. Higher-confidence regions can form the basis for short-term planning, while lower-confidence regions may require further drilling before they can be included in long-term mine development. This approach reduces the likelihood that lease decisions or infrastructure placement will be based on overly simplified representations of the deposit.

5.3. Orebody Geometry, Waste Production and Mining Efficiency

The sustainability of the Sadanandapuram mining operation hinges on the relationship between orebody geometry and waste generation. The key point is not that substantial quantities of waste are created, but that the magnitude and spatial distribution of waste are a consequence of the 3D geometry of the mineralized system. The variable thickness and depth of the ore horizon suggest that the amount of waste accompanying a given amount of ore cannot be assumed to be constant throughout the deposit. If the orebody is thicker or closer to the surface, the ratio of material excavated to ore recovered can be higher. By contrast, where the orebody is thinner, deeper, or structurally displaced, a greater volume of surrounding material must be removed to maintain access to the mineralized horizon. Therefore, stripping requirements may vary greatly between stages or parts of the same deposit.

This interpretation is relevant because the stripping ratio is often treated primarily as an economic or engineering parameter, yet it is also a geological parameter. An orebody's geometry, attitude, thickness, and depth set the fundamental conditions under which waste must be removed. Mine design and scheduling define how those geological conditions translate into annual excavation requirements, but do not eliminate geological control. This relationship is important, as the operational data highlight. ROM production is significantly less than waste generation over the period studied, indicating that the physical footprint of extraction is dominated by material of no immediate economic value. This means that mine planning based solely on production targets may underestimate the land and infrastructure requirements for waste management.

A more sustainable approach would therefore combine the geological block model with staged pit design and waste scheduling. It is best to forecast the extraction sequence and waste volumes as an integrated step rather than as a downstream activity. This would allow high-waste parts of the deposit to be identified in advance and would assist in selecting suitable dump locations, haulage routes, and rehabilitation schedules. The geological model may also be used to support selective extraction strategies. Where ore thickness and grade show predictable spatial variation, mine development may be preferentially directed to areas that offer a better compromise between ore recovery and waste removal. Such planning does not necessarily mean avoiding all high-stripping areas; rather, it allows them to be deliberately incorporated into the mine schedule according to economic, environmental, and operational constraints. Thus, the main implication for sustainability is that waste minimization begins with geological understanding. Dump design improvements cannot fully address excessive waste generation if the underlying extraction sequence does not account for orebody geometry.

5.4. The implication of land-use and waste management

The presence of waste management in the mining operation has implications for the lease's overall land-use structure and production efficiency. Waste storage entails a considerable, often long-term, occupation of space, since waste is not merely a transitory flow of materials. Once deposited, dumps take up land, affect surface drainage and slope stability, and may remain part of the mine landscape for many years. This creates a strong connection between the stripping ratio and the lease's sufficiency. A lease that appears adequate based on the orebody footprint may be spatially constrained when the cumulative needs for waste storage, mineral stockpiling, pit expansion, access, and rehabilitation are considered. This means that

the land required for an open pit mine is essentially greater than the area under active excavation.

The mining plan information indicates that waste dumping is a dominant land-use category. This points to the large volume of waste produced during operations and indicates that waste storage is the primary driver of the mine's spatial requirements. This implication is particularly important for long-lived operations, because dump capacity must be assessed against projected waste generation over the life of the mine rather than against current needs alone. Environmental management includes important elements such as engineered dump development and stabilization practices for existing waste management. However, physical stabilization must be accompanied by forward-looking spatial planning. Progressive rehabilitation can reduce the time that disturbed land is exposed to the environment, but it cannot eliminate the need for sufficient land during active mining.

Waste management must therefore be integrated into the initial spatial design of a mining lease. Potential dump sites should be evaluated with respect to orebody extensions, drainage, haulage distance, slope stability, and future pit expansion. When requirements compete for the same land, mine planning should favor configurations that minimize unnecessary rehandling and avoid sterilizing potentially recoverable resources. This perspective places waste management on the same footing as mine design, rather than treating it as an afterthought. This integration is particularly applicable to manganese deposits with appreciable intercalation and variable overburden conditions, where the volume of non-economic material may be large relative to the volume of saleable product.

5.5. Adequacy of Mining Lease and Conservation of Minerals

The findings have broader implications for how adequacy is defined in mining leases. An adequate lease should not be deemed adequate merely because it contains a known mineral occurrence or because its total area is sufficient for the current mining footprint. Adequacy is fundamentally a functional, dynamic property that depends on whether the available land can meet the geological, operational, and environmental requirements for systematic mineral development. This distinction is illustrated by the Sadanandapuram case. The mineralized system has a geometry that extends beyond individual mining blocks and requires significant waste management. The relevant question, therefore, is not merely whether mineralization exists on the lease, but whether the available spatial envelope can accommodate the entire mining system throughout its developmental sequence.

This distinction is important for mineral conservation. If a lease boundary cuts through a continuous or potentially economic mineralized zone, the portion of the zone outside the boundary may be difficult or impossible to recover independently. The loss of resource sterilization is not automatically visible in traditional production statistics. It can occur even when the existing operation is technically feasible. However, the present study should be careful to state that a certain quantity of resource was sterilized at Sadanandapuram. The available data show the importance of this risk but do not provide sufficient boundary-intersection analysis to quantify the volume of economically recoverable mineralization outside the lease. Therefore, resource sterilization is identified as a planning risk in the integrated geological assessment, rather than as a quantified loss in the present study.

The same principle applies to waste storage. A lease may contain sufficient ore but may not support efficient mine development if the land for waste storage, pit expansion, and associated infrastructure is unavailable. Mineral conservation and land-use efficiency are therefore inseparable. Accordingly, the notion of lease adequacy developed here must include at least four interrelated dimensions: geological coverage, waste accommodation, mine development flexibility, and resource conservation risk. Land-use efficiency is another indicator of how effectively the available spatial envelope is converted into mineral value. This multidimensional interpretation is preferred over a simple area-based assessment because two leases of the same size may have completely different development potential, depending on orebody geometry, waste generation, topography, and surrounding constraints.

5.6. Geological Land-Use Efficiency and Sustainable Mineral Development

The land-use analysis offers a different perspective on sustainability by linking the mineral inventory to the land used for mining. Its main value is conceptual, as it allows land-use efficiency to be considered alongside conventional measures such as grade, recovery, and stripping ratio. Sustainable mining is not defined by the amount of minerals per unit of land used. Land-use efficiency should be measured by waste production, waste recovery, rehabilitation, and the duration of disturbance. For example, focusing extraction on a relatively small area may increase spatial efficiency of extraction, but it may also lead to large volumes of waste or intensive localized environmental impacts. While an increased mining footprint may improve ore access, it will also increase the total area to be rehabilitated.

This is especially important for lease adequacy. When two alternative mine plans can recover similar quantities of ore, the plan with less permanent disturbance and fewer waste-handling requirements would generally yield a more favorable sustainability outcome. If, in contrast, a larger lease can provide access to a larger, more continuous portion of the orebody while reducing waste generation or resource sterilization, it may be the better overall outcome, or a coordinated development arrangement may be preferable. Therefore, sustainable land management should not be equated with simply minimizing the physical area disturbed. Rather, the objective should be to maximize the value of useful minerals per unit of land, with minimal unnecessary disturbance and the possibility of progressive rehabilitation of disturbed areas.

5.7. Geology-Based Lease Planning to Administrative Lease Boundaries

The integrated interpretation of the Sadanandapuram case signals a paradigm shift from traditional area-based assessment to geology-based lease planning. For legal and regulatory purposes, administrative boundaries are still necessary but do not need to match the spatial extent of the geological deposit. The proposed framework addresses this shortcoming by integrating geological modeling, resource confidence, waste forecasting, mine planning, and land-use requirements. Its main strength is that these elements are treated as connected rather than separate. The geological model describes the location and orientation of the mineralization; geostatistics provides confidence and continuity to the interpretation; waste forecasting translates the orebody geometry into material-handling requirements; and land-use analysis

assesses the spatial envelope available to meet those requirements. Hence, the framework provides a logical sequence for assessing lease adequacy by:

- I. Describing the geological system and defining the 3D extent of mineralization.
- II. Quantifying geological confidence and identifying areas that need further exploration.
- III. Developing alternative mine development scenarios based on orebody geometry and mining constraints.
- IV. Estimating waste generation and disposal requirements for each scenario.
- V. Determining the existing lease's spatial capacity for extraction, waste, infrastructure, and rehabilitation.
- VI. Identifying potential land-use conflicts and resource sterilization.
- VII. Amending lease boundaries or coordinated development arrangements when the spatial configuration of leases is demonstrably restrictive.

The framework's key contribution is not merely proposing to expand each mining lease. Instead, it provides a scientific basis for determining when an existing boundary is adequate, when it is limiting, and when coordinated development of adjacent areas may yield a superior mineral-conservation outcome. This is particularly important where mineralized horizons cross cadastral boundaries. Independent development of adjacent leases can lead to duplicated infrastructure, inefficient waste disposal, fragmented mine planning, and partial extraction of continuous mineralization.

5.8. Implications for Sustainable Mine Planning and Regulatory Decision Making

The findings have implications for both operations and regulation. At the mine-planning level, geological models should be used continuously rather than developed only for initial resource estimation. Access to drilling and production information enables geological interpretations to be updated and used to refine pit sequencing, waste forecasting, and land requirements. At the regulatory level, lease evaluation could be improved by requiring geological evidence that the proposed lease configuration is consistent with the known geometry of the deposit and its expected waste management requirements. This would be an addition to the existing cadastral and legal criteria, not a replacement.

The proposed methodology also applies to lease renewals, expansions, relinquishments, or consolidations. For an existing lease, the assessment can determine whether additional land is needed for planned future development or whether parts of the lease are unlikely to contribute to mineral recovery. It could provide a technical basis for evaluating improvements in resource conservation during the coordinated development of neighboring deposits. Crucially, the framework should be applied in proportion to the level of geological confidence and the stage of mine development. In the early stages of exploration, only a preliminary spatial assessment may be possible. A drilled deposit can be optimized in 3D. This prevents premature precision in the presence of high geological uncertainty.

This approach is also consistent with broader principles of sustainable mineral development by linking mineral conservation to environmental land management. Efficient resource recovery should be integrated with waste minimization, rehabilitation, and land-use planning. Instead, these objectives must be pursued in parallel throughout the mine's life.

5.9. Limitations and Future Directions

Several limitations should be acknowledged when interpreting this study's implications. First, the assessment is based on a single manganese deposit and is therefore a detailed case study rather than a statistical assessment of manganese leases across the Eastern Ghats Mobile Belt. The proposed framework should therefore be tested at additional deposits with different geometries, mining methods, and waste characteristics.

Secondly, while the geological model provides a solid framework for interpreting mineralization, the current analysis does not quantitatively determine the recoverable volume of mineralization at an economic level beyond the current lease boundary. Therefore, the potential sterilization of resources is illustrated conceptually rather than in quantified tons.

Thirdly, the land-disturbance efficiency indicator depends on the definition of “land put to use” and the categories available in the mining plan. Therefore, it should not be considered a holistic indicator of the environmental footprint. Future studies should differentiate between temporary and permanent disturbance, as well as the timing and success of progressive rehabilitation.

Fourth, the geological model describes the waste relationship, whereas the operational stripping ratio captures a different aspect of the mining system. Future work should integrate the block model directly into pit optimization, phase design, and production scheduling to generate spatially explicit stripping ratios for alternative mine plans.

Future studies should examine multiple contiguous leases and assess whether coordinated development, shared infrastructure, or integrated waste-management strategies can improve mineral recovery and reduce cumulative land use. Such analysis would provide a stronger basis for translating the proposed geology-based approach into practical regulatory guidance.

5.10. Summary Implications

The main implication of this study is that the adequacy of a mining lease is primarily a geological-operational issue, not a simple cadastral-area issue. The geometry and continuity of the orebody determine how the deposit can be accessed, and these geological characteristics affect waste generation and stripping requirements. Waste generation accounts for a substantial share of the land requirement, and the resulting spatial demands determine whether the existing lease can accommodate systematic and sustainable mine development.

The focus of lease planning should therefore shift from the question “How big is the lease?” to the more meaningful question: “Is the available land spatially configured and sufficiently large to enable efficient mineral resource recovery while accommodating waste management, mine development, and rehabilitation?”

The Sadanandapuram case study underscores the importance of addressing this question through integrated geological modeling, geostatistics, waste assessment, and land-use analysis. This combination provides a more robust scientific basis for mineral conservation and a practical pathway to geology-based lease adequacy for manganese deposits and other structurally complex mineral systems.

6. Conclusion

The results of this study show that neither the lease area nor the administrative boundaries of a mining lease can reliably indicate adequacy. In structurally complex manganese deposits, the spatial arrangement of mineralization, geological continuity, waste generation characteristics, and land requirements for mine development are interrelated. Hence, the Sadanandapuram case provides a strong foundation for geological understanding in lease evaluation and for more sustainable mine planning. The integrated 3D geological and geostatistical approach provides a more robust foundation for understanding the spatial behavior of manganese mineralization and for translating geological variability into mine-planning requirements. In particular, the relationship between orebody geometry and stripping behavior means that waste generation should be viewed as a geological and spatial planning problem, rather than a purely operational or economic parameter. The mine's high waste-to-ore ratio reinforces the need for sufficient land to accommodate not only mineral extraction but also waste disposal, infrastructure, pit development, environmental protection, and progressive rehabilitation.

The paper also demonstrates that lease adequacy is a dynamic and multidimensional attribute. It depends on the size and persistence of the mineralized system, the capacity for planned waste within the lease, the flexibility for mine development, the potential for resource sterilization, and the efficiency of land disruption. This provides a more meaningful basis for judging whether an existing lease would support systematic mineral development throughout the mine life. On this basis, a geology-based framework is proposed to assess lease adequacy and inform future lease planning by linking geological modeling and resource evaluation to waste forecasting, mine development, land-use planning, and environmental considerations. The framework shifts lease planning from a largely administrative process to an evidence-based approach in which lease boundaries are assessed against the spatial needs of the mineral deposit and its associated mining system. When geological continuity intersects existing boundaries, coordinated development or boundary optimization may be a more effective way to enhance mineral recovery and reduce the risk of resource sterilization.

The study's major contribution is therefore methodological: geological information can be transformed into a practical decision-support framework for assessing mining land requirements and mineral conservation risks. Although demonstrated for a manganese deposit in the Eastern Ghats Mobile Belt, the approach can be applied to other complex mineral systems where orebody geometry, waste generation, and fragmented land allocation are the dominant factors affecting mine development. Further application to multiple deposits and contiguous lease systems will refine the framework and establish quantitative thresholds for lease adequacy under different geological and mining conditions.

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Data availability

The datasets generated and/or analyzed in this study are not publicly available because they were obtained from project and mining plan records that are subject to access restrictions. Relevant data may be available from the corresponding author upon reasonable request and subject to applicable permissions.

Declarations

Ethics approval and consent to participate

Not applicable. This study used data on wells and mining plans and did not involve human participants, animals, or biological materials.

Consent of publication

Not applicable. This manuscript does not contain any individual person's data, images, or other materials that require consent for publication.

Competing interests:

The authors declare no competing interests.

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