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Assessment of Mining Lease Adequacy and Land Use Dynamics in Manganese Deposits of Vizianagaram District, South India

Ahmed K. S. Dalbon[1,2*], E. N. Dhanamjaya Rao[1], A. Santha Ram[1]

[1] *Department of Geology, College of Science and Technology, Andhra University, Visakhapatnam 530003, AP, India.*
[2] *Department of Geology, Sudan University of Science and Technology, Al-Mogran, Khartoum, Sudan.*

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Abstract

The study investigates the relationships among orebody geometry, stripping intensity, and adequate areal leasing in three open-cast manganese mines (A, B, and C) in the Eastern Ghats Mobile Belt of India. The deposits are hosted in high-grade metamorphic Khondalite–Charnockite assemblages and exhibit variable structural continuity, dip, and lens-shaped formation. An integrated geological–spatial assessment framework is applied, combining orebody characterization from approved mining plans with GIS-based land-use analysis and normalized efficiency metrics (stripping ratio, waste area per unit of extractable ore, ratio of undisturbed/inactive land). The results reveal that stripping intensity and surface occupation are notably near the boundaries of structural complexity and orebody discontinuity. High stripping ratios and waste intensity in Mines A and B (which exhibit irregular, pinching–swelling geometries with increased dip angles) progressively saturate their lease areas. Mine B is a spatially constrained system in which high stripping burden intersects with limited lease extent. Conversely, Mine C shows relatively high geological continuity and large untouched territory, leading to lower stripping intensity and greater operational flexibility. Rather than relying solely on regulatory limits, this analysis shows that lease adequacy is a function of coupled orebody geometry and surface land availability. Normalized spatial efficiency metrics provide a functional foundation for assessing extractability risk in structurally complex manganese deposits. Land-use assessment to create continuity in the geological picture is a key part of lease planning. This facilitates long-term material recovery and minimizes the risk of premature sterilization, particularly in high-grade metamorphic terrains.

Keywords: Stripping ratio; Ore geometry; Waste-to-one ratio; Mining sustainability; Open-pit mining.

Introduction

Manganese deposits in the Vizianagaram district, Andhra Pradesh, are part of the Khondalite belt in the Eastern Ghats, from which manganese ores have been exploited for the past four decades. The deposits exhibit prominent pinch-and-swell behaviour, lensoid shapes, and significant grade variability, which pose challenges for long-term mine planning, pit development, and land-use allocation. In India, open-cast manganese ore mines

[1] Corresponding Author: Tel: +919100624310 & +249961860711; Email: ibndalbo.rs@andhrauniversity.edu.in

face challenges such as shrinking lease areas, high stripping ratios, and environmental compliance requirements, especially when ore lenses are discontinuous and surrounded by highly weathered host rocks. The three investigated manganese mines, A (56.837 ha), B (13.868 ha), and C (41.054 ha), are characteristic of Eastern Ghats deposits but differ in geological continuity, excavation trends, and land-use limitations, as recorded in their approved mining plans and statutory reports. Mine A contains a 900 m long ore zone with variable width, high susceptibility to friability generation, and overburden production. Mine B hosts a more restricted 410 m strike-length body with sharp thickness variations and sub-horizontal pockets, resulting in local high stripping requirements. Mine C is characterized by a more continuous lens within the calc-granulite, leading to considerable unworked areas between the lease boundary that affect land flexibility for dump extension and subsequent extraction.

However, no previous comparative study has evaluated the combined impact of ore geometry and structural controls on land-use allocation, lease adequacy, waste generation potential, and extractable resource volumes in these deposits. This gap is significant because lease conditions tend to influence the economics of Eastern Ghats manganese mines more than ore tonnage alone. In India, human-driven re-vegetation in post-mining sites is often strongly influenced by anthropogenic factors in modern landscapes; proximity to settlements, infrastructure, and roads may still hinder natural revegetation even when formal reclamation processes are followed (1). Additionally, dramatic vegetation loss was observed between 2019 and 2023 in mining areas, with large open pits and alterations to river courses, indicating that land-use changes due to mining involve not only surface loss but also hydrological re-engineering (2). The main aim of this study is to examine the leased areas of three manganese mines, namely Mines A, B, and C, in Vizianagaram district, Andhra Pradesh, India (Figure 1), and to clarify land use within the leased zones. The study also determines whether the areas designated for lease are sufficient to support sustainable,

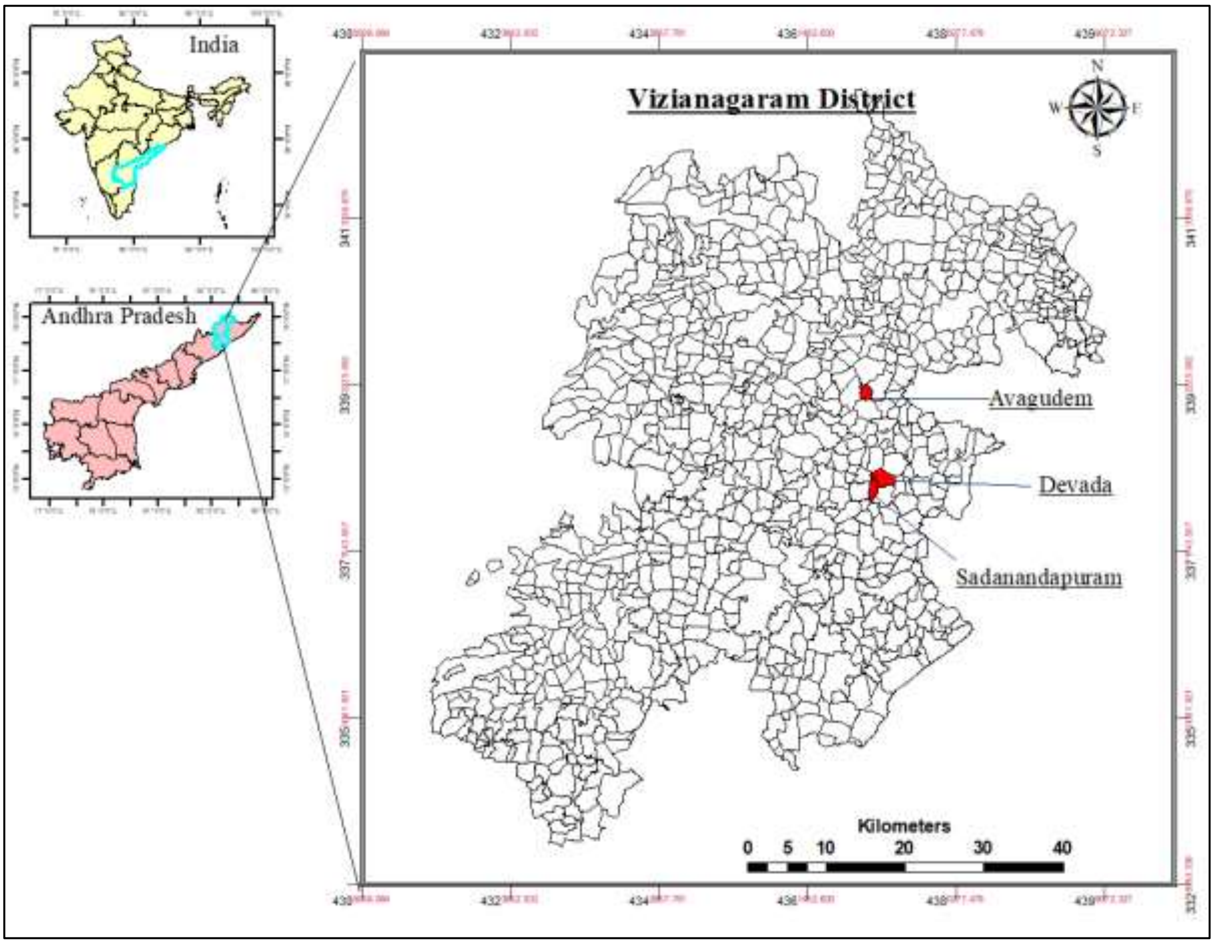

Figure 1. The map of the study area displays the manganese mines A, B, and C in Vizianagaram District.

long-term mining and environmental management. This method provides a comparative understanding of land-use patterns related to mineral occurrences and operational needs. Thus, the following are the research questions for this study: (1) How does the shape of an orebody impact stripping ratios, and how saturated is the land within mining leases? (2) How much do the size and shape of a lease limit the long-term extractability of manganese resources? (3) Can geological-spatial comparison analysis reveal thresholds beyond which lease areas become operationally inadequate?

The importance of this study lies in its contribution to sustainable mining practices and environmental management in India by analysing granted lease areas. The findings guide stakeholders in responsibly using the land before operations begin, providing valuable information for regulators, mining proponents, and environmental planners. It also fills a gap in the literature by linking the mineral mode of occurrence to land-use trends. Furthermore, the results provide preliminary guidance for lease planning evaluation for future lease grants: leased land must be demonstrated not only to contain ore deposits but also to be extractable in a manner that minimizes its impact on nature and society. However, existing open-pit optimization research relied mainly on economic pit limits or focused on land-use impact assessments. Yet few studies quantitatively related orebody morphology to spatial lease adequacy under regulatory constraints. Using a comparative approach to three structurally complex manganese deposits in the same tectonic setting, the study develops a potentially adaptable approach to assess long-term recoverability and land-use efficiency in high-grade metamorphic terrains.

The traditional open-pit optimization studies, which are mainly concerned with depicting an economic pit-shell design, present a geological–spatial lease adequacy model that considers orebody shape complexity, stripping ratio impact efficiency, and land-space saturation in a comparative evaluation framework. The new aspects include (1) the normalization of stripping load on strike length, (2) the development of a spatial sufficiency index linking undisturbed land to waste disposal demands, and (3) the cross-mine geological–spatial comparability in a single tectonic environment.

Materials and Methods

In this study, an integrated geological-spatial-operational assessment approach is used to examine how orebody shape, land use, and waste generation interact to influence mine-planning efficiency at three manganese mines (A, B, and C) (Figure 1). The methodological approach is structured around four interconnected activities: (1) geological data compilation and orebody characterization; (2) spatial and land-use analysis; (3) computational evaluation of overburden stripping ratios, waste–ore ratios, and lease adequacy; and (4) integrated synthesis across the three mines. All modules employ repeatable analytical processes to promote transparency and reproducibility.

Geological data compilation and orebody modelling

Geological data were obtained from the statutory mining plans (2022 - 2026), field-based geological sections, lithological descriptions, and structural measurements in the authorized mining documents for Mines A, B, and C. These datasets were complemented by established regional geological and metamorphic models of the Eastern Ghats Mobile Belt (3, 4).

Lithological contacts, ore-waste boundaries, structural trends, and their association with supergene alteration were subsequently interpreted using a systematic approach to develop an integrated geological model for each mine. Orebody geometry was described in terms of strike length, changes in width, dip direction and angle, persistence with depth, and morphological features such as pitching, dying, swelling, and lensoid continuity.

Spatial and Land-Use Analysis

A spatial analysis was conducted to estimate the proportion of land use within each lease boundary. The digitization of lease polygons, pit outlines, waste dump footprints, stockyard areas, and undisturbed zones was carried out from mining plan maps and spatial annotations. Since no original GIS shapefiles were provided, georeferenced mine plan plates were interpreted to estimate surface-area distributions, following best practices in mining land-use studies (5) (based on control points from mine plan grids; georeferencing accuracy was ±3 m). Land-use units included: (1) active extraction areas, (2) overburden and waste dumps, (3) infrastructure and haul roads, (4) mineral stockpile zones, (5) greenbelt or reclamation zones, and unmanaged natural terrain. The area for each category was calculated, enabling comparisons between mines with different lease areas. The adequacy of leases was assessed using a spatial sufficiency index (SSI), defined as the ratio of undisturbed area to the estimated surface area required for waste deposition.

$$SSI = \frac{Au}{Aw}$$

Where:

- A_u = Undisturbed land area (ha)
- A_w = Required waste dump area (ha)
- SSI > 1 = spatially flexible lease, SSI ≈ 1 marginal adequacy, SSI < 1 spatial deficiency

Comparative distribution across the three mines and thresholds from the literature for sustainable surface mining: a lease was defined as spatially stressed when undisturbed land accounted for < 20% of the lease area, waste area/Mt > 8 ha/Mt, and the stripping ratio > 4.

Stripping Ratio, Waste Volume, and Lease Adequacy Analysis

To evaluate mine-planning efficiency, stripping ratios were calculated as the total overburden/waste volume divided by the extractable ore volume for each mine.

$$SR = \frac{Vw}{Vo}$$

Where:

- Vw is the total waste volume (m3), and
- Vo is the extractable ore volume (m3)

For example, in Mine A:

Assuming the total amount of waste = 6.59 Mm^3

Volume of extractable ore = 1.83Mt (volumetric conversion at density of 3.5 t/m^3),

Calculated stripping ratio = 3.6 (waste: ore).

Waste production rates were obtained from mine plan outputs, haulage data, and forecast excavation profiles. When explicit volume information was unavailable, waste volumes were estimated from known pit geometry (bench and slope), following the approach used for volumetric estimation in open-cast mine optimization (6).

The suitability of leases was evaluated by comparing the availability of space within a lease for (1) proposed extensions to the pit, (2) essential waste dump capacity, and (3) adequate safety buffer zones. Mines with large areas of undisturbed land were seen as more adaptable in the long run. In contrast, those with highly saturated land-use patterns or high waste-to-footprint ratios were considered limited. The study also considered geological features that increase stripping requirements (e.g., steep orebody, irregular shape, grade discontinuity) and the additional land they require.

Comparison of the Three Mines

Geological, spatial, and operational analysis results were combined to identify cross-mine patterns and explanatory relationships. Measures included (1) orebody continuity in relation to stripping intensity; (2) the shape of an orebody in relation to land-use efficiency; and (3) the fraction of undisturbed land affecting extractable reserve potential and the surface area: waste dump ratio per unit of mined ore. This multi-criteria comparison aligns with recent approaches in mine optimization research that evaluate the interaction between orebody geometry and land-use constraints (7, 8).

Resource quantities were based on approved statutory mining plans and reported under UNFC Category 222 (probable reserves) based on known geological continuity and exploration density. No distinction is made between the proved and probable categories in the study but reported extractable reserve values are used for comparison purposes. In this study, where direct volumetric data were absent, estimates were obtained from pit geometry using conservative assumptions; these address uncertainties that are qualitatively discussed in the Discussion section.

Geology and Deposit Description

Manganese deposits A, B, and C are hosted by the Eastern Ghats Mobile Belt (EGMB), characterized by high-grade metamorphism of Khondalite–Charnockite litho-assemblages, developed through multiple deformation and granulite-facies metamorphic phases. This belt is known for its complex tectono-thermal evolution and strategically important manganese occurrences (3, 9). The deposits are associated with the Khondalite Group, mainly composed of garnet–sillimanite gneiss, feldspathic quartzite, calc-granulite, and interbedded meta-sedimentary units regionally. Foliations are predominantly oriented N–S or NE–SW, with dips ranging from 30° to 80°, indicating the polyphase structural features reported in other studies of EGMB (Eastern Ghats Mobile Belt) (10). Though similar models for Precambrian manganese deposits elsewhere in India (4) suggest that sedimentary, hydrothermal, metamorphic, and supergene processes account for the diversity of manganese mineralization represented at the three mines.

The ore bodies are not only of different shapes and distributions but also occur under specific geological conditions (rock types) – there is a similar host-rock structure across the three mines at the SZV study site. Stratigraphically, Mine-A consists of garnet-sillimanite gneiss, feldspathic quartzite, calc-granulite, and a broad zone of kaolinized lithomarge, with manganese ore occurring as brownish-black, friable lenses closely associated with zones of kaolinization and monetization. Mine-B displays similar lithologies, although the host contacts are sharper and structurally controlled, and ore is hosted in feldspathic quartzite and garnet–sillimanite gneiss with occasional sulfide dissemination. Mine-C is associated with manganese mineralization that follows closely on calc-granulite horizons, with the mineralized zone laterally constrained by garnet–sillimanite gneiss. At the same time, extensive kaolinization defines the alteration halo. This lithological association is also consistent with recent regional work describing mineralization in the EGMB (Eastern Ghats Mobile Belt) as structurally conformable bands within quartzite–gneiss sequences enriched by lateritic supergene oxidation (11).

The orebodies have different structures, which significantly impact mine design. Mine A has the most extended continuous strike length at 900 m and ranges from 30 to 60 m in width, with a depth continuity of 20 to 40 m. The 199 orebody plunges to the north-northwest along a linear trend, with dips toward the east, exhibiting lens-shaped topologies, paleo-deposition-driven deep pinching and swelling, and steep grade variability, like structurally disrupted Precambrian Mn-ore lenses (12).

Mine B features a shorter strike length of 410 m and a steep WNW–ESE-trending orebody dipping approximately 80° south. The shallow discontinuous linear structure suggests several structural failures prior to the independent extension. The narrow size, along with sporadic ore pockets between its limbs, suggests significant structural dissection of oxide mineralization formed under local conditions; this resembles recently documented structure-dissected oxide deposits in metamorphic terrains (13). Mine C exhibits greater continuity than A and B, with a relatively flat-dipping, lens-shaped ore zone and a less complex structural configuration of the lenses, suggesting it is a more intact section of the mineralized horizon. The high variability over short distances is typical of Khondalite-hosted manganese systems overprinted by a Proterozoic metamorphic event (3).

Petrographic and mineralogical features in the mines are characterized by an assemblage dominated by psilomelane, pyrolusite, and cryptomelane, with wad and hausmannite as accessories, alongside quartz, feldspar, garnet, and kaolinite. Textural features such as radiating or acicular psilomelane, anisotropic pyrolusite, banding, and fracture-filling oxides resemble those described by Roy (2020) for supergene enrichment and metasomatic replacement, based on extensive data from other modern manganese geochemistry literature (14). Oxidation has significantly enhanced the mineral fraction, destroyed many primary components, and increased friability. This weathering-induced enrichment is characterized by the leaching of Mg, Ca, and Na, along with elevated levels of Mn, Fe, Al, and Ti, consistent with findings from a recent geochemical study of manganese oxide systems in weathered Archean terrains (15).

The manganese in Mines A-C consists primarily of friable, lenticular, and discontinuous occurrences, with a steep but irregular ore-waste contact. Variography at the meter scale reveals grade variability within the intervals, and combined with high structural complexity, it led to classifying the deposit under UNFC in Category II due to uncertain predictability and geological continuity. Relatively speaking, Mine A represents the most structurally deviating and pinching-and-swelling-oriented orebody; Mine B displays the steepest orientation and has the fragmentized ore-pocket trend, while Mine C offers the highest geological continuity (Table 1). These differences highlight the importance of integrating geological modeling with land-use planning, given the close connections among orebody geometry, stripping requirements, pit growth options, and ultimate resource extraction plans.

Results

The results combine geology, land use, and overburden-ore relationships across Mines A, B, and C to highlight significant differences in ore-body shape, waste-ratio distributions, and spatial constraints, affecting long-term reserve extraction and mine-planning flexibility.

1. Orebody Geometry and Continuity

The three ore bodies have different shapes and features that directly impact mining effectiveness. Mine A has the widest lateral coverage (30–60 m) and the most extended strike length (~900 m). Despite this size, the geometry varies significantly, with many areas showing noticeable pinching and swelling. Valid flow continuity assessments indicate thicknesses ranging from 20 to 40 m, with the structural dip from 45° to 60° east, leading to significant lateral waste stripping, especially where ore pinches along the axis. In contrast, Mine B has a

Table 1. Geological features of the three manganese mines, A, B, and C

Feature	Mine A	Mine B	Mine C
Strike length	~900 m	~410 m	Moderate–continuous
Geometry	Highly irregular, intense swelling	Narrow, steep, pocketed	Moderate continuity
Dip	45–60° E	~80° S	Moderate, consistent

relatively short (410 m), narrow (20–45 m) and steep-dipping ore body (80° S), with low continuity, pocketed geometries and varying lens orientations that increase internal dilution and extremely variable ore exposure. This steep geometry, however, complicates stable benching further despite the smaller footprint. The deposit at Mine C has the most uniform geological parameters, characterized by a continuous, lenticular ore

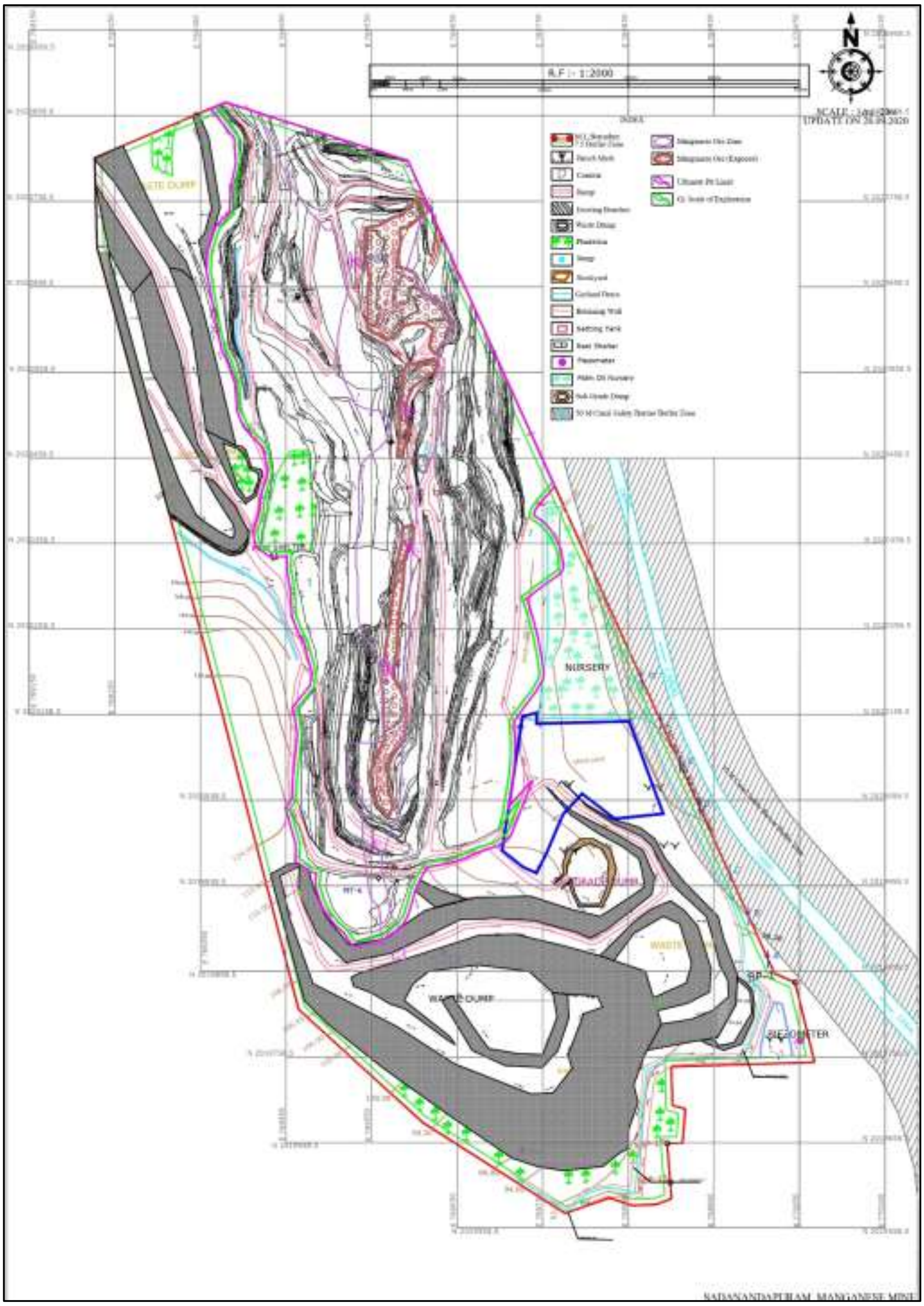

Figure 2. Surface land-use map of Mine A (WGS84 coordinate system; scale 1:5000; source: Approved Mining Plan 2022).

body that schematically dips slightly into calc-granulite units. Predictability still beats Mines A and B in terms of geological risk for pit advancement, though pinching and swelling do occur.

Allocation of Use of Land within Lease Sites

Based on land-use classification, the three mines show causal differences in space utilization and operational flexibility.

Mine A (lease area: 56.837 ha) is characterized by saturated heavy land use. The area under the lease is approximately square, and there are waste dumps influencing most of that block. Constraints for future pits, limited space for haul roads. The 'pit' zone is high because of the extended strike length, with small patches of virgin land left suggests little room for more dumps or buffer zones. As illustrated in Figure 2, there's a concentration of waste dumps along the northern and western margins of the lease, which restricts future pit pushback into those areas. The pit footprint covers around 40% of the lease, thereby decreasing spatial redundancy. Mine B has the most intensive land use (13.868 ha). Its narrow, mineralized footprint, small lease area, and the need for steep-sided-wall stripping result in a much larger waste-dump area per hectare than the total leased area. Nearly no virgin land remains, making expansion of dumping and future ore recovery complicated (Figure 3). Mine C, covering 41.054 ha (Figure 4), retains a sizable portion of undisturbed land (Table 2). The availability of waste land allows for greater flexibility in selecting dump locations, redesigning haul roads, and expanding open pits as needed. The canal crossing the lease poses a local constraint, but overall capacity is higher than in Mines A and B.

Land-use saturation is closely related to the orebody's complexity and the total stripping required across all mines. Mines with predictable ore geometries (C) also show better land–use efficiency compared to those with irregular, multi-lensed systems of ore zones (A, B).

2. Stripping Ratios and Waste Production

An examination of operating projections reveals significant variations in stripping requirements across the mines, primarily driven by differences in ore geometry and host-rock arrangements.

Inconsistent ore thicknesses and dipping geometry result in high strip ratios at Mine A. Limestone alteration

Figure 3. Surface land-use map of mine B (WGS84 coordinate system; scale 1:5000; source: Approved mining Plan 2021)

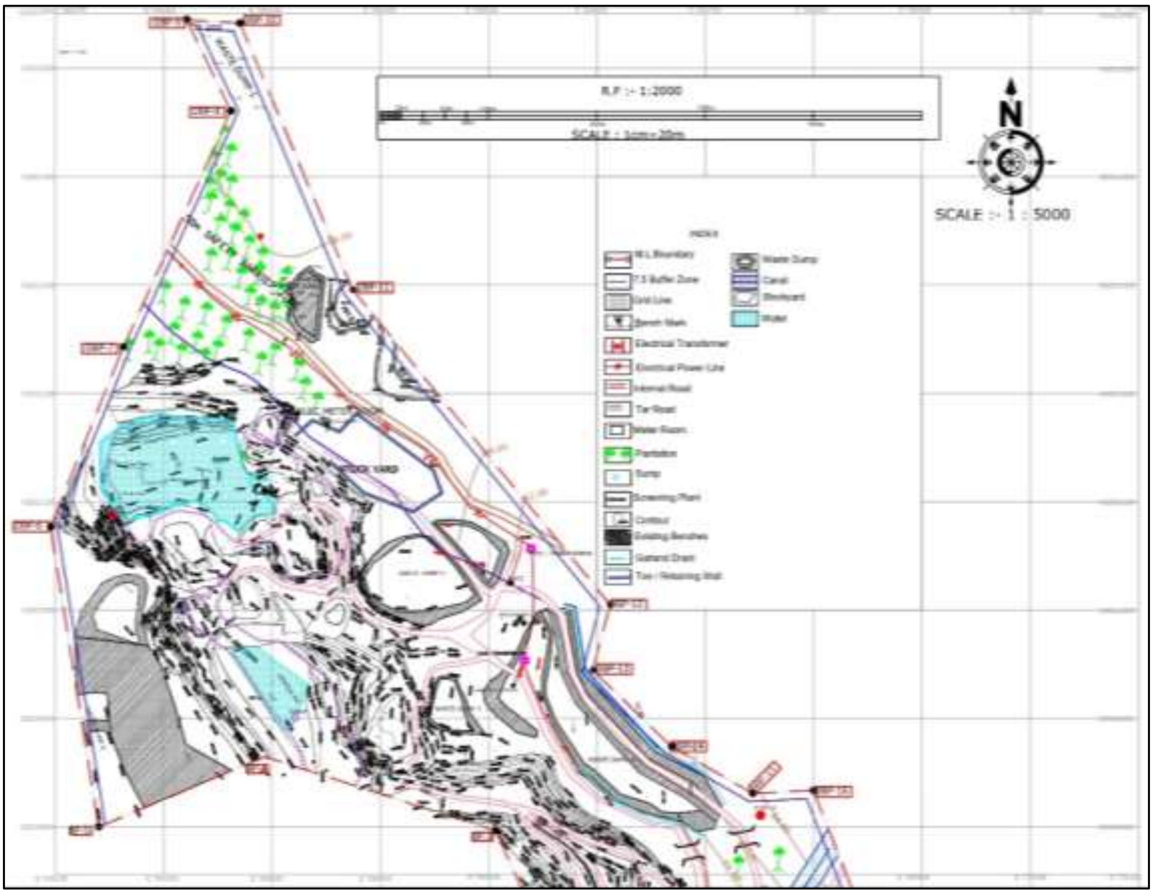

Figure 4. Surface land-use map of mine C (WGS84 coordinate system; scale 1:5000; source: Approved Mining Plan 2022).

Table 2. Land use patterns in manganese mines

No.	Activities	Area in %		
		Mine A	Mine B	Mine C
1	Excavation area	40.60%	56.00%	29.68%
2	Waste dumps	30.60%	24.70%	13.41%
3	Minerals storage	4.10%	2.80%	2.89%
4	Green belt	12.50%	1.59%	0.26%
5	Nursery	3.30%		

products (barren lithomarge and kaolinized zones) also considerably increase waste volumes. Documentation indicated a large amount of waste to be removed during previous plan periods, with upward trends and a continuous increase in waste as it moves up narrow segments of the ore body. Mine B has the most significant stripping burden relative to lease size. The steep dip (~80°S) demands significant sidewall buffering and contributes to more rapid waste build-up than ore generation. To accommodate the required pit-slope geometry, this entails gradually increasing the size of a pit – an exercise in waste economics with considerable implications. The orebody is relatively uniform and gently dips in Mine C, hence its efficient stripping ratio is lower. Host rocks modified by supergene processes still require removal, but (with more consistent ore shapes) dilution and other costs are minimized.

Stripping ratios for the three mines rank in descending order: B > A > C

Table 3. Normalized land-use and geological efficiency metrics for Mines A, B, and C.

Parameters	Mine A	Mine B	Mine C
Lease Area (ha)	56.84	13.87	41.05
Orebody strike length (m)	900	410	420
Waste dump area (ha)	17.40	6.10	9.20
Undisturbed land	11.60	1.90	21.60
Extractable ore (Mt)	1.83	0.62	2.45
[illegible]	[illegible]	[illegible]	[illegible]

Normalized measures indicate that Mine B has the highest surface and stripping burdens per unit of resource, despite its smaller lease size. The stripping ratios of both Mine C and Mine A are heavier than those of Mine B because of relatively steep dips, short strike lengths, and discontinuous ore lenses, which present a major influence on the development of these open pits. Mine C has the lowest waste intensity (3.76 ha/Mt) and the highest spatial flexibility index (0.53), indicating good or better geological continuity and lease suitability. The stripping ratio per unit strike length also suggests the asymmetrical stripping requirements, as increased geological complexity adds to land-use stress for each unit of ore continuity (Table 3).

3. *Lease Adequacy Evaluation*

Sufficient leases were assessed based on space availability for dumping and exploitation, as well as meeting buffer zones. Mine A: The lease boundaries restrict any additional pit extension at both ends of the strike. Waste dumps, which have covered even larger areas of hillsides, have left less area available for future mining. Some ore could not be developed due to space constraints. Mine B: The lease seems spatially constrained. These factors, along with a small lease area, a steep ore body, and significant waste volume, preclude any expansion of the dump. Without having land beyond the working surface, other shafts would not be mined. Mine C: The lease is sufficient to continue operations. Over 50% of the area is unexploited, creating opportunities for selective dumps and advanced pit sites. Lease sufficiency aligns well with the in-situ ore geometry, with minimal potential for sterilization given spatial constraints. An analysis indicates that lease coverage is primarily determined by orebody geometry (Mine B → exceeds all thresholds, Mine A → borderline, Mine C → below critical values).

4. *Comparative Synthesis*

Regardless of the parameter(s) considered, geometry, land-use saturation ratio, waste burden, and lease adequacy, the mines follow a common trend. Mine C suggests the optimal combination of geological continuity and space availability. Mine A has moderate potential and is a large but spatially constrained lease. B: The most adverse conditions occur at mine B in a limited space and with high structural complexity. These results demonstrate the dependence of operating outcomes on geology and how land use restrictions can compound those imposed by orebody geometry.

- Dip vs stripping ratio → positive correlation
- Undisturbed land % vs waste area Mt → negative correlation

Discussion

Geological Control on Stripping Intensity

The comparative analysis with Mines A, B, and C shows that orebody geometry is a key factor in determining stripping intensity and excavation efficiency. Despite the three deposits being related by their occurrence in the same tectono-metamorphic settings of the Eastern Ghats Mobile Belt (EGMB), local structural preparations lead to varying operational characteristics. Mine A and B have discontinuous, lensoid orebodies with distinct pinching–swelling behavior and structural segmentation. These morphologies are characteristic of manganese deposits with polyphase strain and weathering in high-grade terrains (4, 12). These geometrical indices reduce the predictability of pit progress (more sidewall stripping) when ore thickness changes rapidly along strike or down dip. The extreme slope of Mine B (~80° S) also contributes to waste removal, as stable slopes are required, which aligns with previous open-pit design principles stating that steeply dipping resources require greater waste rock-to-ore ratios (6). Mine C, in contrast, shows better lateral continuity and a moderate dip. Likewise, the high level of geometric coherence reduces the need for repeated pit reconfiguration and lowers stripping intensity. The stripping ratio order observed (B > A > C) is thus a function of structural geometry, rather than ore grade or host lithology. Similar relationships between orebody continuity and volumetric efficiency have been observed in open-pit optimization studies (7), further supporting the interpretation that excavation performance is enhanced by geometric regularity.

Spatial Saturation and Lease Adequacy

It is not just the intensity of stripping that determines operational sustainability; it also interacts with the availability of surface land. Spatial saturation differs notably across the three leases according to land-use analysis. Mine B occupies the least favorable spatial position, with no surplus land and a high waste-to-recoverable-ore ratio. Mine A also has moderate spatial occupation sensation (despite undisturbed land), and Mine C maintains significant undisturbed territory within its lease. Leases with less than 20% undisturbed land remaining and waste intensity greater than 8 ha/Mt can be classified as being spatially stressed for comparison in this geological context. According to these indicative benchmarks, Mine B is clearly constrained, Mine A borders this situation, while Mine C remains comparatively unconstrained. However, they are relative and context-specific thresholds that can help inform a quantitative basis for assessing lease adequacy. Previous research on land-use assessments of mining sustainability has focused on spatial allocation (5); however, the linkages between stripping burden and lease saturation in structurally complex manganese deposits have been less clearly explored. This analysis shows that spatial redundancy is vital when ore geometry requires significant waste removal. Limited opportunities for pit expansion, dump relocation, and buffer-zone maintenance arise due to elevated stripping within a limited lease area.

Geological–Spatial Interdependence

This functional relationship among structural complexity, stripping intensity, and spatial occupation indicates a coupled geological–operational system. This waste generation satisfies the appetite that promotes land saturation, reinforced by steep dips and sporadic lenses. The feedback loop is clearest in Mine B, where steep dips and broken ore pockets require significant sidewall extraction, which soon depletes the surface area. Mine A demonstrates a key characteristic: historical waste placement, along with irregular geometry, restricts future pit pushback, even though the lease area is relatively more robust. Thus, lease size alone does not guarantee adequacy; similarly, internal spatial configuration and geological continuity must also be considered. Mine C, with its container openings and limited space, maintains sufficient structural continuity to enable collective action based on spatial surpluses, thereby enhancing operational flexibility. The presence of unperturbed land allows flexible scheduling of pits and dumps, thereby preventing sterilization before it is necessary. This degree of flexibility aligns with multi-criteria mine planning methods that consider spatial efficiency in their sustainability evaluation (8).

Regional Significance of EGMB Manganese Deposits

While the study is operationally focused, our findings represent a broader metallogenic variability across the EGMB. The structural segmentation observed in Mines A and B could thus reflect localized shear-controlled remobilization from a common high-grade metamorphic background (3, 9). Similar granulite-facies terrains have shown structural control over manganese mineralization (10, 11), and deformation-related discontinuities are almost certainly responsible for both ore continuity and stripping requirements. At mine scale, geometric irregularity is also contributed by processes such as supergene enrichment and weathering, which further modify ore morphology and friability (14, 15). As a result, variations in stripping burden between the three deposits may indicate differences in both structural preservation and alteration intensity rather than simply lithological differences. Incorporating structural interpretation into lease planning, using spatial analysis for extractability forecasting, may thus improve forecasts in other Precambrian manganese provinces.

Lease Sufficiency and Long-Term Extractability

The discussion shows that lease sufficiency must be considered a geological–spatial parameter rather than merely a binary regulatory boundary. More specifically, extreme stripping intensity, combined with spatial constraints, may result in sterilization of the remaining ore during closure in Mines A and B. Similar limitations were found worldwide, where land-use constraints lower extractable tonnage, although reserves persist (15). Mine C exemplifies how geological uncertainty is mitigated through spatial flexibility. Abundant, undisturbed land allows for adaptive waste management, staged pit development, and better coordination of extraction with reclamation. This flexibility enables longer-term planning capabilities and reduces operational inflexibility.

Implications for Integrated Mine Planning

The comparative framework shows that orebody geometry, stripping ratio, and lease saturation are interdependent variables. A steep dip increases stripping intensity, and an irregular morphology increases the density of occupied allopatric space (e.g., sinkholes), thereby limiting adaptive capacity. Less waste burden, more planning flexibility, coproducts of continuous geometries. It provides a strong case for incorporating geological continuity parameters from spatial land-use evaluation into early-stage mine design. Although open-pit optimization primarily focuses on economic pit limits in the traditional sense (7), adding spatial sufficiency metrics enhances sustainability-oriented planning (5, 8).

In geologically complex manganese lands, the extractability of the mineral is based equally on ore grade and tonnage, as well as on the geometric configuration with respect to available land for surface mining.

There is a positive correlation between orebody dip angle and stripping ratio intensity across the three mines. On the contrary, there is a pronounced negative association between the proportion of undisturbed land and waste-area intensity. Based on the comparative analysis of the three mines, leases with SSI < 0.5 and undisturbed land proportion < 15% appear constrained in operation. Contrarily, leases with SSI >1 show spatial flexibility for sustainability. Although thresholds vary across datasets, they serve as initial standards for evaluating lease adequacy. The varying performance of Mines A–C reflects not just operational variability but metallogenic heterogeneity characterizing the Eastern Ghats Mobile Belt. The strong pinching–swelling morphology in Mines A and B is attributed to localized shear-controlled remobilization during phases of late Proterozoic deformation.

Conclusion

Orebody geometry and structural configuration are implicated as primary controls on stripping intensity, land-use saturation, and lease adequacy within manganese deposits of the Eastern Ghats Mobile Belt, as demonstrated by this study. Despite occurring in a similar lithological and metamorphic context, significant variation in orebody continuity, dip, and structural segmentation leads to substantially different operational and spatial outcomes for Mines A, B, & C.

Mines A and B, with more discontinuous lensoid geometries and greater structural complexity, can have higher stripping ratios and higher waste tonnage per tonne of extractable ore. And together with limited spatial redundancy, this raises the risk of operational constraints and possible partial resource sterilization. Specifically, Mine B is a spatially stressed system, for which steep dips and limited lease area increase waste burden and decrease adaptive planning capacity. Mine A is moderately simple at the spatial level, which integrates historical land occupation and non-standard geometry.

Mine C, which has relatively higher orebody continuity and a moderate dip, shows results with a low stripping intensity (stripping ratio) and less disturbed land within the lease area. Spatial flexibility improves long-term extractability by allowing adaptive pit development and waste management.

The results suggest that lease adequacy must be assessed as a geological–spatial parameter rather than merely a regulatory boundary condition. Normalized efficiency indicators, such as waste area per ton of ore or proportion of undisturbed soil, can be useful metrics of spatial stress in these structurally heterogeneous deposits. Thus, integrating geological continuity analysis with land-use evaluation during lease planning can enhance predictions of extractability and minimize the risk of premature sterilization.

In high-grade metamorphic manganese terrains, sustainable mine planning relies on resources' tonnage and grade as well as mineralization's geometric configuration with respect to the surface land available. Here, we provide an integrated geological–spatial framework that serves as a transferable methodology for evaluating lease suitability in Precambrian manganese systems elsewhere.

Recommendations

1. Incorporate 3D geological modelling to improve predictability: The unrealistic shapes of Mines A and B also justify developing higher-resolution 3D models to forecast ore continuity better, reduce dilution, and optimize pit design. Advanced modelling would also enable more accurate resource characterization and reduce uncertainty in potential extraction plans.
2. Re-evaluate the Design and Site Selection of Waste Dumps: Review waste dumps from a geotechnical and spatial-optimization perspective in Mines A and B, where high stripping ratios and limited land are present. Moving or redesigning dumps where possible could improve strip ratio for pit expansion and boost haulage productivity.
3. Implement zoning for geological constraints land-use: Future mine planning should define functional zones (e.g., considering pit advance corridors, waste dump areas, infrastructure zones) based on orebody shapes and the expected stripping profile.
4. Sector C has a lot of undeveloped land, which lends itself to zoning that will keep it sustainable for the long haul. Apply if possible: Progressive Backfilling: Sequential backfilling of unspent pit sections significantly reduces a mine's overall waste footprint, environmental impact, and frees land to some extent.
5. Apparently, geotechnical stability is not well monitored: the failure of these steeply dipping, wide and tight ore lenses in Mine B carries a high level of risk. Safe operations and pit integrity will be maintained through regular stability-monitoring techniques (e.g., drone photogrammetry and radar slope monitoring).
6. Explore Availability of Strategic Lease Modification or Land Acquisition: If operational constraints potentially lead to resource sterilization, particularly at Mine B, the results indicate that regulatory options to allow alteration of lease boundaries may be worth pursuing if spatial limitations threaten resource

sterilization. Such moves might add to ore stockpiles and lengthen the mine's lifespan.

7. Enhance resource recovery through beneficiation: Given the observed variability in grade and fines production patterns, especially at Mines A and B, the use of beneficiation techniques (such as gravity concentration, scrubbing, or sensor-based sorting) may improve yields from lower-grade or friable material.

Validity of Research, Assumptions, and Limitations

For methodological rigor, only outputs based on reported values in the mine plans were considered. When numerical data were unavailable, estimates were made using defensible engineering assumptions, which are cited in the Results section of the paper. The analysis lacks real-time satellite imagery, remote sensing data, or 3D block models because they are not currently available, but it suggests potential future improvements. Instead, the focus is on internal consistency, comparative logic, and transparency of assumptions, which can only increase confidence in the findings, given that they are all based within the limitations imposed by the available datasets.

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