



Technical Report Summary

Serra Norte Complex
Brazil

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1. Executive Summary

1.1. Introduction

The purpose of this Technical Report Summary is to state the mineral resources and mineral reserves for the mines of the Serra Norte Complex to comply with the ownership disclosure requirements of the US Securities and Exchange Commission (SEC). This is required for mining registrants as described in Subpart 229 of Regulation S-K 1300 and disclosed by those involved in mining operations (S-K 1300) and item 601 (b) (96) Technical Report Summary.

VALE is one of the largest mining companies in the world, a large Brazilian exporter and one of the main private companies in Brazil. With operations on the five continents, the company has a global and diversified shareholder base and its shares are traded on the main stock exchanges in the world. World leader in the production of iron ore, pellets and nickel, VALE also produces manganese, ferroalloys, coal, copper, gold, silver, cobalt and metals from the platinum group. Its ores are of high quality and produced to meet the needs of the customers in the steelwork industry worldwide competitively. To deliver products quickly, the mining company operates an integrated and efficient logistics chain globally, which includes railways, maritime terminals and ports, in addition to floating transfer stations and distribution centers.

Serra Norte Complex is part of Vale's Northern System in the southeast of the Pará state in Northern Brazil. Various geological processes in this region also formed large deposits of manganese, gold, copper, palladium, platinum, and nickel. This mineral wealth makes the Carajás region the most geologically important and well-studied area in Northern Brazil.

1.2. Property description

The Serra Norte Complex is included in mining process 813.682/1969 and is in the mining concession phase. All mineral deposits are within the Carajás National Forest and do not interfere with third-party properties.

The Serra Norte Complex corresponds to deposits called N1, N2, N3, N4 and N5. The mines in operation are N4E, N4W and N5. There are four processing plants: Plant I (capacity of 85Mt/year), Plant II (capacity of 40Mt/year), Plant III (capacity of 18Mt/year) and Plant IV (capacity 3Mt/year).

Projects N1 and N2 are expected to start up in 2026 and project N3 is expected to start up in 2023. These projects will not require implementation of new structures for mineral processing, support, temporary or permanent. These needs will be met by structures already in operation at the Carajás Iron Mining Complex. All existing structures are properly licensed.

The Serra Norte complex has four mining easements which are contiguous and form a unique contour that circumscribes all current and future industrial facilities in the Serra Norte complex. Two of the easements are authorized and two are in the approval stage.

1.3. History

The geological surveys in Serra dos Carajás began in 1922, but the first citations on the occurrence of iron formations date back to 1933. In Carta do Brasil ao Milionésimo, published by IBGE in 1960, in the aerial photograph, orebodies C and D of Serra Sul can be seen, which were initially misinterpreted as "limestone plateaus with elevated lakes in the south of Pará". From 1967 onwards, several detailed works began to be carried out on the different targets that compose the areas known as Serra Norte, Serra Sul and Serra Leste.

In 1977, VALE (at the time Companhia Vale do Rio Doce – CVRD) acquired the shareholding in United States Steel (USS), being solely responsible for conducting the project. In 1979, the construction of the complex, integrating the mine, railroad, and port, of the Carajás Iron Project began. In February 1985, the São Luiz – Carajás railroad was completed. Iron ore production began in 1984, the N4E deposit and the N4W deposit came into operation in 1994. Serra Sul operations started in 2016.

1.4. Geology and mineralization

The main Carajás iron ore deposits are associated with flat-topped elevated plateaus, in general, elevated areas, between 650-800 meters, defined along two main morphological alignments corresponding to Serra Norte and Serra Sul. These alignments materialize the limbs of the Carajás Syncline.

The Serra Norte Complex corresponds to the inverted limb geological domain of the Carajás Syncline. The high deformation pattern of this domain is reflected in the geometry and the distribution of the iron formations, whose segmentation by faults and folds of different orientations and scales, individualizes plateaus from N1 to N9.

The plateaus of the Serra Norte Complex are limited to the north by the domain of volcanic rocks of the Parauapebas Formation, and to the south, by the domain of terrigenous sediments of the Águas Claras Formation.

At plateaus N4 and N5, where there are mine pits, the geological information was obtained by mapping on a 1:2000 scale, diamond drilling, trenches and channels. Therefore, at N1, N2 and N3, most of the geological information was obtained from diamond drill cores and surface mapping of alteration materials due to the strong/deep weathering and the absence of cuts and excavations, making the outcrops scarce.

The mineralization at The Serra Norte Complex is mainly formed from supergenic alteration of jaspilite, which constitutes the Carajás protolith. The high-grade ore is mainly represented by friable hematite, the structured canga is also considered as a mineralized lithotype.

Deposit N1 is in the extreme west of Serra Norte and corresponds to part of the homonymous plateau. This plateau has an elongated shape in the NW-SE direction. It is predominantly composed of rocks from the Carajás and Igarapé Cigarra formations. In general, the layers show medium to high angle dips to the northeast, configuring an inverted stratigraphic stack. The thickness of the layer varies between 250-600 m and is strongly controlled by folds and faults.

Deposits N2 and N3 are located on the homonymous plateaus, with an elongated shape in the E-W direction, in the central portion of the Serra Norte. The rocks of the Igarapé Cigarra Formation are predominant in these plateaus. In general, the layers show a medium to high angle dip to the north, configuring an inverted stratigraphic stacking.

Most of the iron formations of plateaus N2 and N3 were attributed to the Igarapé Cigarra Formation, they do not stand out in the relief due to the low thickness. Structural controls and their relative chronological ordering are like those described for N1, differing by the low continuity of iron formations, which reflects the importance of the faults for the local geological framework.

Plateau N4 is in the central-east portion of Serra Norte, where there are several mine pits, distributed along the homonymous plateau. The dimensions of N4 are big and it is composed of rocks from the Carajás, Parauapebas, and Igarapé Cigarra formations, with tabular shape and general dip to the west configuring a normal stratigraphic stacking. Prior to the start of mining, the plateau was already divided into the east and west portions by a drainage that separates the two main bodies of iron formations.

The Carajás Formation occurs continuously in the central portion of the plateaus and corresponds to the domain with the highest thickness of iron formations, which are strongly controlled by strike-slip faults and present thickness between 200-500 meters.

On the N4 plateau, the Carajás Formation assumes a strong N-S trend and defines two occurrence belts called N4W and N4E, with a distinct structural pattern, separated by an eastward verging thrust fault. The N4W region is relatively simpler and behaves like a homocline, the N4E region is more complex, given the rotation of the banding, folding in southern portion and drag along the large dextral strike-slip faults.

The N5 plateau is in the extreme east of Serra Norte, where there are five mine pits called N5W, N5N, N5E, N5S, and M1, distributed along the homonymous plateau. This plateau has elongated geometry at the NNW-SSE direction, suffering a strong curvature in the north-central portion as a reflection of interference by folding. The iron formations occupy the central portion of the plateau layers and show general dip to the west direction, configured at a normal stratigraphic stacking. At

N5, the Carajás Formation behaves like a homocline, with a trend varying from NW-SE to N-S and dips to the SE and E. The sinuous character in the northern portion of the plateau is given as a function of a syncline, which, associated with the fault system, verified throughout the plateau, controls the geometry of the iron formation.

1.5. Exploration, drilling, and sampling

1.5.1. Exploration

Exploration work is initially based on highlights of regional mapping on a scale of 1:100 000 produced by Geological Survey of Brazil (CPRM). Detailed work is developed with mapping at different scales and drilling carried out by Vale's team.

In and around the mine areas, geophysical anomalies are detailed with mapping and drilling. The geological mapping at a 1:2,000 scale is performed by the short-term geology team, updated monthly in N4 e N5 mines. The work is done using GPS precision and the mapped lithologies are classified according to visual classification and compactness.

1.5.2. Drilling

The exploration work carried out in Carajás began in the late 1960s and early 1970s, covering areas of Serra Norte, Serra Sul, Serra Leste and São Félix do Xingu, all with great potential for geological resources of iron ore.

Long-term drilling campaigns were carried out in spaced grids of 200x200m in all Serra Norte deposits and closures of 100x100m, 100x50m, up to 50x50m, mainly in the mining areas. A summary of drilling per area is presented in Table 1-1.

Table 1-1 – Summary of drilling

Deposit	Total Drilling (m)
N1	56,783.26
N2	9,401.03
N3	33,968.70
N4	385,436.50
N5	250,947.80

1.5.3. Hydrology

Groundwater models were prepared using industry-standard water modelling software to support permits for dewatering. Hydrogeological models are tools used to represent the dynamics of groundwater in a simplified way and enable the simulation of different scenarios.

The numerical modelling software FEFLOW and MODFLOW were used by Hidrovia in 2020 and MDGEO in 2020 and 2021 for the simulations of water table drawdown for N1, N2, N3, N4 and N5 open pits. The simulated outflow will be of about 5,530 m³/h, 670 m³/h of which in the N1 pit (FEFLOW / Hidrovia, 2020), 164 m³/h for N2 (FEFLOW / Hidrovia, 2020), 570 m³/h for N3 (MODFLOW / MDGEO, 2021), 2,636 m³/h for N4 (MODFLOW / MDGEO, 2020) and 1,490 m³/h for N5 (MODFLOW / MDGEO, 2020). To calibrate the models, 78 instruments were used.

The database used was considered satisfactory to achieve the main objective, which consists of building, calibrating and simulating future mining scenarios in a groundwater numerical model to provide water level data which will be used as input to geotechnical stability analysis and guarantee dry mining operation and depressurized slopes.

1.5.4. Geotechnical

Core logging, surface mapping, and laboratory tests are the main source of geotechnical information. For core logging and mapping, the collected data follows tables proposed by International Society for Rock Mechanics and Rock Engineering (1997), Bieniawski (1989) and Martin & Stacey (2018) adjusted by Vale (2019) to fit the iron formation deposits. These characterization parameters are applied to define different rock mass classification systems and to build the geomechanical model.

A combination of historical closer sites and current geotechnical data, with the mining site experience of internal teams supported by national and international consultants, are used to establish internal guidelines and procedures in the slope stability design and operation for pits N1, N2, N3, N4 and N5.

1.5.5. Sampling

The core sampling is performed according to corporate governance procedures and follow mining industry standards. The efficiency of the sampling and the laboratory analysis processes applied in the Serra Norte Complex operations are ensured by periodic reviews and/or audits.

1.5.6. Density determinations

The density database is composed of samples collected by conventional methods, such as volume displacement, volume filling, sand flask and hydrostatic weighing, as well as geophysical survey data (gamma-gamma). These data is combined with normative mineralogical calculation techniques to assign the final density values in the geological model.

The tonnage reported in the Serra Norte Complex mines corresponds to the natural base, and therefore, it is very important to determine the average moisture values for each lithology. Such values are obtained by testes, drying an aliquot of the sample and comparing the dry and wet mass of the sample.

1.5.7. Sample preparation and analysis

The physical preparation and chemical assays of the drill hole cores in the Serra Norte deposits were performed following procedures that varied over time. During the different drilling campaigns carried out, the samples were assayed in different analytical flowcharts and later grouped into five flowcharts. The main differences between them are the number of particle size fractions, the number of size fractions with chemical analysis, and the analytes measured, in addition to the type of sieving (dry or wet).

For the geological modeling the samples were grouped in the following particle size ranges: G1: +8 mm; G2: -8+0.15 mm and G3: -0.15 mm, with G1 and G2, subdivided into G1A: +19 mm, G1B: -19+8 mm, G2A: -8+1 mm and G2B: -1+0.15 mm. The long-term geological model database contains analytical results for Fe, SiO₂, P, Al₂O₃, Mn, LOI, CaO, MgO, TiO₂, FeO, K₂O, and Cu. The short-term database contains the analytes Fe, SiO₂, P, Al₂O₃, Mn, LOI, CaO, MgO, and TiO₂.

1.5.8. Quality assurance and quality control

The treatment and the evaluation of historical QA/QC data (prior 2012) related to control samples, twin samples, field duplicates, crushed material duplicates, pulverized material duplicates, external duplicates and standards did not reveal points of attention (in frequency and/or magnitude) regarding precision and accuracy (of sampling and chemical assays) which compromise the databases used for geological modeling and resource estimation purposes, resources and reserves classification of areas and mines in the Serra Norte and Serra Sul Complexes of the Carajás Mineral Province.

Upon evaluation of the results of QA/QC data for the period from 2012 to 2019, in most cases, the sampling/chemical assays accuracies are good and analytical biases/flaws are small or insignificant compared to the grade ranges involved. The investigation of the most relevant points of attention has already been requested from the responsible people (geology teams and laboratories involved).

QAQC data revealed general indicators of non-compliance, precision and accuracy considered satisfactory, not compromising the database related thereto.

1.6. Data verification

Vale had data collection procedures in place which included several verification steps designed to ensure the database integrity. Vale staff also conducted regular logging, sampling, laboratory and database reviews. All technical records related to the borehole, spatial and geophysical trajectory logs, photographs of core boxes, description, density tests, samples, petrography, physical and chemical results, among others, are kept in repository(ies) and/or information technology system(s) adequate and accessible for check and/or investigation, whenever necessary.

Mineral resources and mineral reserves are estimated in accordance with Global and Vale Ferrous Guidelines and Standards for Mineral Resource and Mineral Reserve Reporting protocols. Consequently, each topic is handled by the qualified person/competent persons from the respective department: resources, reserves, mineral processing, geotechnics (pit, project and dam), hydrogeology, production, strategy, environmental, speleology, finance, mining rights, mining future use and engineering.

Alongside the mining operation activities, periodic reconciliations are performed in each site. Annual consolidated result report comparing short term model, mineral resource, and reserves model, in addition to production grades and tons, are discussed in annual technical meeting to promote continuous improvement among all involved areas.

1.7. Mineral resource estimate

1.7.1. Estimation methodology

Vale has a set of protocols and guidelines in place to support the estimation process, which the estimators must follow. These include: comprehensive lithological and mineralization domain characterization; selection of all representative samples inside the domain(s); compositing of drill hole information on a consistent support size (length, density, recovery), validation through statistics on lengths and variables before and after compositing; comprehensive understanding of the statistical characters of the variables; in each estimation domain and at the contacts between domains; characterization of the spatial continuity of each variable to be modelled (variograms); understanding of the influence of outliers and variables with highly skewed distributions and selection of an appropriate handling strategy (restricted neighborhood); spatial distribution of drillhole and sample data, mining method and production rates under consideration; selection of an appropriate modelling technique and definition of proper parameters and options to be used (e.g., kriging plan, search strategy, variogram models to be used, post-processing methods); validation of the estimates (visual inspection, checks for global and local bias, confirmation of the kriging plan, and a check on the degree of grade smoothing resulting from the interpolation); and confidence classification.

Estimation was made by Vale personnel. The mineral resource estimate is supported by core drilling. Software used for estimation includes Vulcan, Leapfrog Geo and Isatis.

Block grades were estimated using Ordinary Kriging (OK) in Vulcan software whilst the variography is performed in Isatis software. Blocks were estimated in a single run with some post-processing corrections. Block estimation was completed on a 25 m x 25 m x 15 m block model, exception made for SN3 block model with blocks of 12.5 m x 12.5 m x 15 m. Classification of blocks was assigned according to Risk Index methodology which combines orebody continuity and estimation error. Measured blocks estimated using only one drillhole were downgraded to the indicated blocks. Subsequently, this automated classification was compared with regular geometric classification method to assess the classification better.

Mineral resources were confined within an optimized conceptual pit shell. The resulting pit extents were considered for reasonableness, such as any potential impact on planned mine infrastructure (processing facilities), suitability of the current waste projected piles capacities. Pit inter-ramp slope angles vary according to lithology and range from 22-48°.

The commodity pricing forecasts were established using a consensus approach based on long-term analysis and bank forecasts, supplemented with research by Vale's internal specialists. This approach is considered reasonable to support the mineral resource estimates.

1.7.2. Mineral resource statement

Mineral resources are reported using the mineral resource definitions set out in S-K1300 and are reported exclusive of those mineral resources converted into mineral reserves. A summary of the mineral resource estimates exclusive of reserves is provided in Table 1.2 and in Table 1.3. Mineral resource estimates stated as metric million tonnes including moisture and dry %Fe grade.

Table 1-2 Measured and indicated mineral resources exclusive of mineral reserves

Complex / Deposit	Measured		Indicated	
	Tonnage (Mt)	Grade (%Fe)	Tonnage (Mt)	Grade (%Fe)
N1	128.1	66.5	133.4	66.2
N2	1.8	66.1	18.2	65.3
N3	7.5	66.1	21.1	65.7
N4	190.0	65.7	138.3	65.6
N5	265.2	66.9	180.5	66.4
Total	592.7	66.4	491.5	66.1

Notes to accompany mineral resources tables:

1. The effective date of the estimate is 2021/Dec/31.
2. The mineral resource prospects of economic extraction were determined based on a long-term price of US\$78/dmt for 62% iron grade.
3. Tonnage stated as metric million tons inclusive of 6.51% of moisture content and dry %Fe grade. The point of reference used is in situ tons.
4. Numbers have been rounded.

Table 1-3 Inferred mineral resources exclusive of mineral reserves

Complex / Deposit	Inferred	
	Tonnage (Mt)	Grade (%Fe)
N1	52.8	66.3
N2	13.2	65.2
N3	24.0	66.1
N4	73.1	65.7
N5	130.3	66.2
Total	293.4	66.0

Notes to accompany mineral resources tables:

1. The effective date of the estimate is 2021/Dec/31.
2. Tonnage stated as metric million tons inclusive of 6.51% of moisture content and dry %Fe grade. The point of reference used is in situ tons.
3. The mineral resource prospects of economic extraction were determined based on a long-term price of US\$78/dmt for 62% iron grade.
4. Numbers have been rounded.

Areas of uncertainty that may impact the mineral resource estimates materially include: changes to long-term metal price and exchange rate assumptions; changes in local interpretations of mineralization geometry, structures, and continuity of mineralized zones; changes to geological and grade shape and geological and grade continuity assumptions; changes to the input assumptions

used to derive the conceptual optimized open pit shell used to constrain the estimates; changes to the forecast dilution and mining recovery assumptions; variations in geotechnical slope angles, hydrogeological and mining assumptions; and changes to environmental, permit and social license assumptions.

1.8. Mineral reserve estimates

The Serra Norte reserves were based on the measured and indicated resources of the deposits and N1, N2, N3 and N4, respectively, which were used as input and converted into proved and probable after estimating the reserves. More details about the features can be seen in chapters 12 and 13.

The optimized pit considered environmental and some structure restrictions, process and mine costs were also used, which consider additional deepening cost, sales costs, commodity price curve and geotechnical parameters. Mining recovery and dilution factors were also considered.

Based on these parameters, a family of pits is generated, and the choice is made based on economic criteria. This pit undergoes first geotechnical evaluation, and then, it is optimized again, where corrections of some geotechnical parameters are made. After this second round, the pit goes to operationalization and a final geotechnical analysis for final corrections in the operationalized geometry to ensure safety and stability of the slopes. Table 1-4 shows the reserve statement results.

Table 1-4 - Proven and Probable Mineral Reserve Statement 2020

Pit/Operation	Classification	Tonnage (Mt)	Fe (%)
N1	Proven		
	Probable	323.6	66.1
	Subtotal Proven + Probable	323.6	66.1
N2	Proven		
	Probable	42.9	66.3
	Subtotal Proven + Probable	42.9	66.3
N3	Proven		
	Probable	91.8	65.3
	Subtotal Proven + Probable	91.8	65.3
N4	Proven	337.7	66.5
	Probable	295.1	66.3
	Subtotal Proven + Probable	632.8	66.3
N5	Proven	126.6	65.0
	Probable	372.5	64.9
	Subtotal Proven + Probable	499.1	64.9
Total	Proven	464.3	66.1
	Probable	1,125.9	65.7
	Total Proven + Probable	1,590.2	65.8

Notes to accompany mineral reserves table:

1. The estimate has an effective date 31/Dec/2021.
2. Tonnage stated as metric million tons inclusive of 6.41% of moisture content and dry %Fe grade. The point of reference used is in situ metric tons.
3. The mineral reserve economic viability was determined based price curve with the long-term price being US\$70/dmt for 62% iron grade
4. Numbers have been rounded.

The following factors can affect the mineral reserve estimate: commodity prices; US dollar exchange rate; Brazilian inflation rate; geotechnical (including seismicity) and hydrogeological parameters; changes in capital inflows and operating cost estimates; changes in pit designs compared to the currently planned; inventory assumptions; ability of the mining operation to meet the annual production rate; process plant recoveries and the ability to control levels of deleterious elements within the expectations of the LOM plan; assumption plants 1 and 2 will perform as expected; ability to meet and maintain environmental permits and licenses; and ability to maintain social license to operate.

1.9. Mining methods

Conventional open-pit mining methods are used in Serra Norte mines based on in-house equipment and labor. All engineering studies are minimum level FEL2.

The production plans aim at average annual production of around 100 Mt. There may be small variation depending on the company's strategy throughout the life of the mine.

Geotechnical parameters are provided for each pit. Periodic inspection procedures are followed to verify the stability of slopes, sterile piles, dams, dikes and drainages in order to guarantee the operation safety and continuity.

In the operations, mainly big hydraulic and cable excavators are used to produce ore and waste rock. Loaders are also used to ensure greater flexibility in mining, as well as different cleaning and back-up jobs for the excavators, when necessary. A fleet of off-road haul trucks is used to transport material to waste dumps and primary crushers. Crawler tractors are planned to maintain production and bench cleaning areas. Wheel tractors, motor graders and water trucks complete the rest of the auxiliary equipment fleet.

1.10. Processing and recovery methods

The Serra Norte complex is of great importance to Vale's production system both in terms of volume and in terms of quality. This installed capacity of this complex is 145 Mty where part of ROM is processed using natural moisture, and part is wet.

The deposits that constitute this complex enable the generation of products with iron content of around 65% with low variability. In plants that process ROM with natural moisture, there are only crushing and screening steps and only the Sinter Feed product is generated. In the plant that processes wet ROM, in addition to the crushing and screening operations, there is a magnetic concentration step for the fines processing. This plant generates Lump, Sinter Feed and Pellet Feed products.

The product Pellet Feed is destined to the pelletizing plant in São Luis. Magnetic concentration was installed to improve the quality of the Pellet Feed product; thus, making the pellet generated at the São Luis pelletizing plant more competitive. Magnetic concentration is in ramp up and to support the definition of this process route, pilot scale magnetic concentration tests were carried out, which indicated that this route allows to increase the iron content and reduce the content of contaminants with satisfactory mass recovery.

1.11. Infrastructure

Most of the infrastructure to support mining operations is in place. There is an urban center close to the Carajás operations that absorbs part of the workforce, and another part lives in the city of Parauapebas and the region.

Water may be captured from selected watercourses and drawdown wells under granted licenses. The replacement water for the process comes from the Gelado and Pera dams. Drinking water is also from wells located in the mine. This water is treated in Water Treatment Plant. Serra Norte Operations monitor water levels, flows and balances regularly.

Electricity is supplied by the National Interconnected System and is connected to 230 KV voltage.

The internal distribution system is carried out through Vale's own electrical networks of 34.5 kV. The consumption in 2020 was around 468,794.24 MWh, 68.87% of which fed the mineral processing plants, 27.57% was distributed to the N4/N5 mines, and the remaining 3.56% was consumed by the Urban Center and other support structures.

1.12. Environmental studies, permits and plans, negotiations, or agreements with local individuals or groups

Vale's operations in Carajás started in the 1980s with the opening of the N4 Mine, at a time when the environmental legislation in Brazil was starting to emerge and the need for baseline environmental studies was not rigorously applied compared to today.

In the 2000s, after the creation of the Carajás National Forest, Vale started a licensing process with the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA), presenting updated environmental studies, creating a new baseline in accordance with the legislation at the time regarding land use, topography, regional geology, geology site and mineralogy, soil, climate hydrology, hydrogeology, biotic environment, socioeconomic and mine closure plan.

As mines and plant sites continue to expand, supportive environmental studies were conducted to assess environmental conditions and support IBAMA to decide on environmental permit, highlighting the study called Global, carried out in 2010, which created a new environmental baseline in Serra Norte (N4 and N5).

Characterization studies have been completed for all environmental media including soil, water, waste, air, noise and closure. Plans and Programs were developed and implemented for all locations in Mines N4 and N5, now in operation.

The current operating license is in the process of analysis by IBAMA, for the 10th renewal.

Additionally, processes are underway to obtain a preliminary permit to open pits and processing facilities for N1, N2 and N3, which will support the replacement of production volume in the Serra Norte mining complex and other studies to support the discussion with the licensing agency to reduce the cavity radius and modify the Carajás National Forest Management Plan to release areas to be mined.

1.13. Market studies

Iron ore is one of the core products that Vale commercialize globally. Its price and premiums can fluctuate along the year according to changes in the balance between its supply and demand and short-term trends on market's sentiment.

The global iron ore and iron ore pellet markets are highly competitive. The main factors affecting competition are price, quality and range of products offered, reliability, operating costs and shipping costs.

The commodity pricing forecasts were established using a consensus approach based on long-term analyst and bank forecasts. The sole purpose of the presented figures is to demonstrate the economic viability of the mineral reserve, therefore it can differ from other information we publish and should not be considered as a guidance.

By the time this report was prepared, the price consensus for iron ore prices at 62% Fe in 2022 of the analysts was USD112/t, with a downward trend going forward until prices reach the long-term level of around USD 70/t and the price consensus for iron ore prices at 65% Fe in 2022 of the analysts was USD 127/t with a downward trend going forward until prices reach the long-term level of around USD 84/t. Additionally, we believe that the expected future production, relative to our iron ore reserves, can be absorbed by the market in the long term given the expected demand by market analysts.

1.14. Capital costs estimates

Economic valuations consider the sustaining CAPEX in cash flows, necessary for the maintenance of existing assets / operations, and capital projects which aim to maintain and/or increase the productive capacity. Sustaining CAPEX can be classified into routine and non-routine.

Routine refers to projects aimed to maintain the operational capacity of the assets, including acquisition and replacement of equipment and readjustment of operating structures. They are estimated based on a diagnosis made by the Engineering area on the asset base, a maintenance backlog and the investment, target defined by the company for future years.

Non-routine refers to projects that support the business strategy, ensuring compliance with the production plan, but which do not occur frequently. Included in this list: expansion of pits, waste and tailings disposal projects, changes in processes and technologies in the plants, among others. They are estimated based on the expected needs of each operation or production complex over the evaluated horizon. Based on these needs, Vale's multidisciplinary teams estimate the values of the investments considered in the cash flows of the economic evaluations.

The sole purpose of the presented figure is to demonstrate the economic viability of the mineral reserve, therefore it can differ from other information Vale publishes and should not be considered as a guidance.

Additionally, economic assessments of reserves consider capital projects that aim to maintain and/or increase the productive capacity. The overall capital cost estimate for the LOM or evaluation period is US\$ 6,202 million as shown in Table 1-5.

Table 1-5 – LOM Capital Cost Estimate

Capital Cost Type	Unit	Value
Sustaining CAPEX	US\$ M	5,026
Non-routine	US\$ M	1,126
Mine and plant	US\$ M	794
Waste and tailings piles	US\$ M	332
Routine	US\$ M	3,900
Capital projects CAPEX	US\$ M	1,176
Mine and plant	US\$ M	119
Logistics and Other	US\$ M	1,056
TOTAL	US\$ M	6,202

Note: numbers have been rounded

1.15. Operating cost estimates

Operating costs and expenses are grouped as follows:

- Mine and plant Opex: mine and plant costs includes mining, processing, storage, and shipping from the ore to the loading points;
- Logistics and distribution costs: logistics and distribution costs include railroad, ports, maritime freight, and distribution centers;
- Sales, R&D and pre-operational expenses: sales, R&D and pre-operational expenses are related to teams expenses with sales and offices, expenses on research and development of solutions for projects and/or the maintenance of operations, and pre-operational expenses, when there are projects under implementation.

In summary, the mining Opex is forecast considering the costs of the operation or similar operations in previous years and their respective operational indicators as a reference. Thus, future operational indicators are estimated based on long-term mine planning. This way, the estimated costs are projected considering the future changes in the operational indicators of the operations.

Total average unit operating costs and expenses are 33.0 US\$/ton of product. LOM average unit operating cost and expenses are composed of:

- Mine and plant: 11.0 US\$/ton of product
- Logistics and Distribution: 19.3 US\$/ton of product
- Royalties: 2.5 US\$/ton of product
- Sales expenses, R&D, others: 0.1 US\$/ton of product

The sole purpose of the presented figure is to demonstrate the economic viability of the mineral reserve, therefore it can differ from other information Vale publishes and should not be considered as a guidance.

The overall costs and expenses estimate for LOM or evaluation period is US\$ 51,872 million as shown in Table 1-6.

Table 1-6 – Operating Costs and Expenses

Type of costs and expenses	Unit	Value
Mine and plant	US\$ M	17,264
Logistics and Distribution	US\$ M	30,378
Royalties	US\$ M	3,999
Sales expenses, R&D, others	US\$ M	232
TOTAL costs and expenses	US\$ M	51,872

Note: numbers have been rounded

1.16. Economic analysis

1.16.1. Introduction

The aim of the economic evaluation presented in this chapter is to demonstrate the economic viability of the mineral reserve, therefore the production rates, operating efficiencies, costs and expenditures, taxes and other information presented can differ from other information we publish and should not be considered as a guidance. Note that our planned production extraction may vary due to continuous mineral exploration and technical studies to add new mineral reserves.

1.16.2. Methodology and assumptions

The economic evaluation methodology used was the Discounted Cash Flow (DCF), the main methodology used to value companies, projects, operations, etc., and widely used by companies, investment banks and consulting companies.

The forecast cash flow is composed of cash inflows (revenues) minus cash outflows (costs, expenses, taxes and capital expenses/costs) of an enterprise in given period. This period may vary according to the Mineral Reserve size associated with the asset (mine, operation and logistics). When the forecast cash flow brought to present value is positive (greater than or equal to zero), it means that the enterprise is economically viable.

For the valuation of reserves, the cash flows given mass of product can generate were projected. To estimate the potential annual revenues from the mining of this resource, the annual processed tonnages and grades, the associated process recovery and the metal prices were taken into account. The operating costs, logistics costs, royalties, taxes, and capital expenditures necessary for its economic use were also estimated. If the forecast cash flow, brought to present value through the discount rate, is positive, it means that the Mineral Resource is economically mineable, and can be classified as Mineral Reserve. The currency used to document the cash flow is US\$ and all costs and prices are in unescalated “real” dollars. The forecast long term (LT) exchange rate is shown in Table 1-7.

Table 1-7 – Exchange rate

Exchange rate – real terms	2022	LT
R\$ / US\$	5.25	5.00

The cash flows period of the economic evaluations is the shortest period between 30 years and the end of reserves of the operation or project analyzed. The economic valuations of the reserves assume 100% equity, so there are no interest and debt amortization expenses in the cash flows. Revenues from economic evaluations of iron ore reserves are based on projections of international market price indicators, as follows:

- Platts IODEX 62% Fe CFR China
- 65% Fe Index CFR China for the mass that will generate the IOCJ product.
- VIU per additional percentage point of Fe CFR China

It is assumed in the evaluations of operations and projects that produce pellet feed (PF) for supply our own pellet plants, that the product is sold to third parties at market price, without considering the pelletizing process, that is, without considering the costs of pellet processing and the pellet premiums in revenue.

1.16.3. Economic analysis

The economic valuation model of reserves considered the discounted cash flow method and it took into account annual processed tonnages and grades. The associated process recovery, metal prices, operating costs, logistics costs, royalties, and capital expenditures were also considered. The economic analysis confirmed that Serra Norte are economically viable. The after-tax NPV at 7.5% discount rate and following a mid-year convention is US\$ 26,215 M. The summary of the results of the cash flow analysis is presented in Table 1-8.

Table 1-8 – Economic Evaluation

Net present value of overall cash flow	Unit	Value
Total revenue	US\$ M	70,616
Total costs and expenses	US\$ M	-31,163
Mine and plant	US\$ M	-10,343
Logistics and Distribution	US\$ M	-18,150
Royalties	US\$ M	-2,459
Sales expenses, R&D, others	US\$ M	-142
Closure costs	US\$ M	-70
Income Tax and working capital change	US\$ M	-9,134
Operational Cash Flow	US\$ M	30,319
Total CAPEX	US\$ M	-4,104
Free Cash Flow	US\$ M	26,215

Sensitivity analysis

The biggest impact in the sensitivity analysis is the price and VIU, followed by opex mine, plant, logistics and distribution, exchange rate and the total capex.

Upon application of the sensitivity analysis in the main variables, NPV remains positive, confirming the robustness of the mineral reserves.

2. Introduction

2.1. Term of reference and purpose

The purpose of this Technical Report Summary is to state the mineral resources and mineral reserves for the mines of the Serra Norte Complex to comply with the ownership disclosure requirements of the US Securities and Exchange Commission (SEC). This is required for mining registrants as described in Subpart 229 of Regulation S-K 1300 and disclosed by the involved in mining operations (S-K 1300) and item 601 (b) (96) Technical Report Summary.

The new SEC rules align the disclosure requirements with global regulatory practices and standards, as incorporated in the standards developed by the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) which VALE is accustomed to using. As this is the first Technical Report Summary issued by VALE for the Serra Norte complex, previously filed reports of this nature will not be mentioned.

The effective date of this Technical Report Summary is 31st December 2021.

The assumptions adopted in the preparation of this report involve inherent uncertainties and risks, and the information in this report is not a guarantee of future performance. This report contains estimates, forecasts, and forward-looking statements, which can be identified using words related to future projections, such as “anticipate,” “believe,” “may,” “expect,” “should,” “plan,” “intend,” “estimate,” “will be,” and “potential,” among others. These estimates, forecast, and statements involve several known and unknown risks and uncertainties. Vale and its QPs cannot guarantee that such forward-looking statements will prove to be accurate. The risks and uncertainties related to our estimates and forecasts include, among others, factors related to (a) economic, political and social issues in the countries where we operate, including factors related to the coronavirus pandemic; (b) the global economy; (c) the financial and capital markets; (d) the mining and metals businesses, which are cyclical, and their reliance on global industrial production, which is also cyclical; (e) mining, environmental and health and safety regulations, including regulations relating to climate change; (f) operational incidents or accidents, (g) the high degree of global competition in the markets where Vale operates, (h) information available at the time of preparation of the forward-looking statements and (j) data provided by external sources.

Vale and its QPs emphasize that the actual results referring to Vale's mineral resources and reserves may materially differ from the plans, objectives, expectations, estimates, and forecasts expressed herein. Vale does not undertake any obligation to update or revise any forward-looking statement publicly, whether because of new information or future events or for any other reason.

2.2. The company

VALE is one of the largest mining companies in the world, a large Brazilian exporter and one of the main private companies in Brazil. With operations on the five continents, the company has a global and diversified shareholder base and its shares are traded on the main stock exchanges in the world. World leader in the production of iron ore, pellets and nickel, VALE also produces manganese, ferroalloys, coal, copper, gold, silver, cobalt and metals from the platinum group. Its ores are of high quality and produced to meet the needs of the customers in the steelwork industry worldwide competitively. To deliver products quickly, the mining company operates an integrated and efficient logistics chain globally, which includes railways, maritime terminals and ports, in addition to floating transfer stations and distribution centers.

VALE is publicly traded on the New York Stock Exchange (NYSE) and in Brazil on the B3. Figure 2-1 shows the location of VALE's business segments in the world.

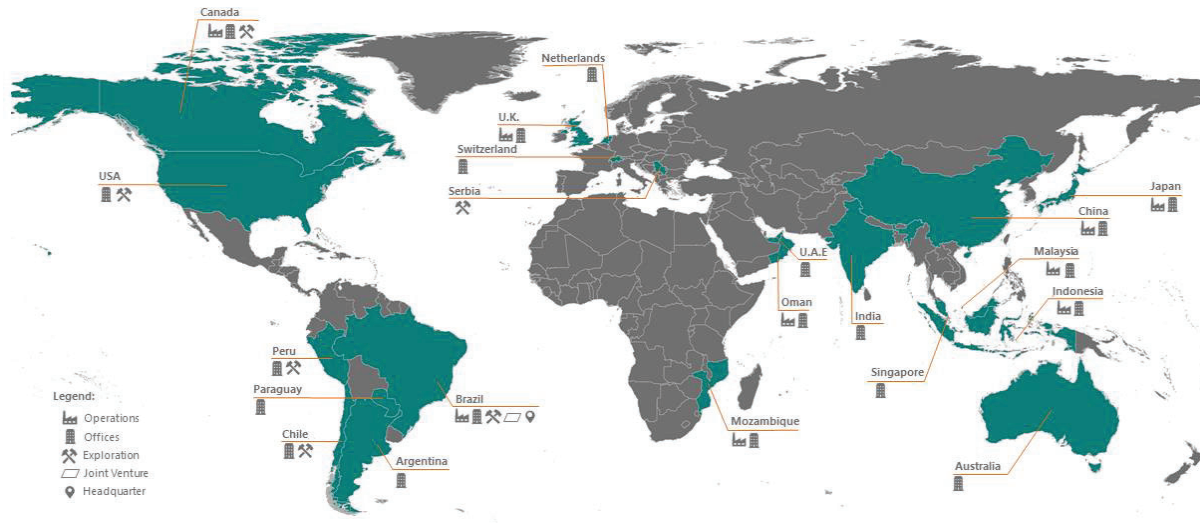


Figure 2-1 - Location of VALE's business segments.

2.3. Site visits

Qualified persons (QPs) involved in the estimation of mineral resources and reserves at Serra Norte are professionals with extensive experience in their areas of operation who pay repeated visits to the respective sites described in this report. Due to the COVID 19 epidemic, these visits were impaired. Table 2-1 shows the latest visits and future schedule.

Table 2-1 - QPs site visits

QP	Visit period	Visits scheduled
Arnor Barbosa de Couto Junior (Mineral Reserves)	March/2021	First half/2022
Guilherme Paiva da Silva (Mineral Reserves)	March/2021	First half/2022
Carlos Eduardo Reinaldo Delgado (Geology)	March/2021	First half/2022
Evandro Machado da Cunha Filho (Mineral Resource)	November/2018	First half/2022

2.4. Qualified Persons

The following Vale employees serve as Qualified Persons (QPs):

Table 2–2 - QPs list

Qualified Persons (QPs)	Role	Sections of responsibility
Alessandro Resende, PQR CBRR	Engineer Specialist	1; 2; 3; 20; 21; 22; 23; 24 and 25
Arnor B. Couto Jr., PQR CBRR	Mineral Reserves Technical Specialist	1; 2; 4; 12; 13; 15; 16; 17; 18; 19; 20; 21; 22; 23; 24 and 25
Carlos E. R. Delgado, PQR CBRR	Master Geologist	1; 2; 5; 6; 7; 8; 9; 20; 21; 22; 23; 24 and 25
Evandro M. Cunha Filho, MAusIMM	Specialist Geologist	1; 2; 5; 6; 8; 9; 11; 20; 21; 22; 23; 24 and 25
Guilherme Paiva da Silva, PQR CBRR	Specialist Mining Engineer	1; 2; 12; 13; 15; 20; 21; 22; 23; 24 and 25
Helder Reis, PQR CBRR	Mineral Reserves Engineer Specialist	1; 2; 12; 13; 15; 20; 21; 22; 23; 24 and 25
Hely Simões, PQR CBRR	Process Development Specialist Engineer	1; 2; 10; 14; 20; 21; 22; 23; 24 and 25
Teófilo Costa, PQR CBRR	Senior Geotechnical Technical Specialist	1; 2; 7; 13; 20; 21; 22; 23; 24 and 25

2.5. Terms, units and abbreviations

VALE based all measurements on the metric system and identified exceptions thereto, mainly when listing the English and the metric standards. The currencies are generally based on US Dollars (US\$), converted into Brazilian Real per US Dollar. The exchange rate used to convert amounts in Brazilian reais into US dollars is BRL: US\$ = 5.25 for 2022, and then long term mean of 5.00 BRL: US\$. Unless indicated otherwise, Dollars are US Dollars and the weights are in metric tons of 1,000 kilograms (2,204.62 pounds). Table 2-3 shows the units used in this report. Table 2- shows the abbreviations used in this report, and Table 2-5 shows the chemical symbols used in this report.

Table 2-3 - Units of measure used in this report

Unit	Abbreviation
American Dollar	USD
GigaYears	Ga/Gy
Million Years	Ma
Hectahá	ha
Bond Ball Mill Work Index (metric)	kWh/t
Brazil Real	R\$ or BRL
Centigrade	°X
Cubic centimetre	cm ³
Centimetre	cm
Cubic metre	m ³
Cubic metres per second	m ³ /s
Day	d
Dead weight ton (imperial ton – long	Dwt
Dry metric tonne	dmt
Gram	g
Gram/litre	g/L
Gram/tonne	g/t
Hour	h
Hours per Year	h/yr
Kilogram	kg
Kilogram per tonne	kg/t
Kilometre	km
Kilopascal	kPa
Kilovolt	kV
Kilovolt amp	kVA
Kilowatt	kW
Kilowatt hour	kWh
Litre	T
Litre per second	L/s
Megawatt	MW
Metre	m
Metre per hour	m/h
Metre per second	m/s
Metric tonne	t
Metric tonnes per hour	t/h
Metric tonnes per day	t/d
Metric tonnes per Annum	t/a
Minute	min
Micron	Mm
Milligram	mg
Milligram per litre	mg/L
Millimetre	mm

Million	M
Million short ton	MT
Million short ton per annum	MT/a
Parts per billion	ppb
Parts per million	ppm
Percent	%
Second	s
Short ton	T
Square metres	m ²
Tonnes per Day	t/d
Troy ounce	Oz.
Wet metric tonne	wmt
Work index	WI
Year	yr

Table 2-4 - List of abbreviations used in this report

Abbreviation	Acronym
ANM	National Mining Agency
BRBF	Brazilian Blend Fines
BSM	Semi-Mobile Crusher
CAPEX	Capital Expenditure
CD	Consolidated Drained Triaxial Shear Test
CDM	Mineral Development Center
CNM	Mineralogical Normative Calculation
CE	Structural canga
CFEM	Financial Compensation for the Exploitation of Mineral Resources
CFR	Cost and Freight
CKS	Carajás Mineral Province
CKS	Carajás Mineral Province
CLI	Interpreted Classification
CLM	Mathematical Classification Key
CLV	Variable of Visual Classification
CPRM	Geological Survey of Brazil
CPT	Technological Research Center
CQ	Chemical canga
CRIRSCO	Committee for Mineral Reserves International Reporting Standards
CS	Social Contribution
CU	Consolidated Undrained Triaxial Shear Test
DCF	Discounted Cash Flow
DCF	Discounted Cash Flow

DNPM	National Department of Mining Production
EBIT	Earnings Before Interest and Taxes
EFC	Carajás Railroad
EL	Environmental License
ELM	Equilibrium Limit Method
WTP	Water Treatment Plant
FAI	Investment Amount
FEGL	Distribution of Global Iron
FLONACA	National Forest of Carajás
FMN	Manganiferous Iron
FOB	Free on Board
FoS	Sa29aspiactor
GDMS	Geological Database Management System
GM	Mining Group
HC	Compact hematite
HF	Friable hematite
HMN	Manganiferous hematite
HMN	Manganiferous hematite
IBAMA	Brazilian Institute for the Environment and Renewable Natural Resources
IBRAM	Brazilian Mining Inst'tute's Mine Closure Planning Guide
ICM	Intrinsic Correlation Models
ICMBio	Chico Mendes Institute for Biodiversity Conservation
ICMM	International Council on Mining and Metals
IK	Indicator Kriging
IOCJ	Iron Ore Carajás
IR	Risk Index
IR	Income Tax
IRR	Internal Rate of Return
JCS	Joint Compressive Strength
JP	Jaspilite
JRC	Joint Roughness Coefficient
LI	Installation Permit
LO	Operation Permit
LOI	Loss on ignition
LP	Preliminary Permit
LT	Long Term
MD	Decomposed mafic
MS	Fresh mafic
MSD	Semi-decomposed mafic

NN	Nearest Neighbor
NPV	Net Present Value
nRMS	Normalized Root Mean Squared
NYSE	New York Stock Exchange
OK	Ordinary Kriging
OL	Operation License
OL	Operation License
Operation License	Exploratory Data Analysis
OPEX	Operational Expenditure
PAE	Economic Exploitation Plan
PF	Pellet Feed
PI	Inhalable Particles
PT	Suspended Particles
QA/QC	Quality Assurance/Quality Control
QPs	Qualified persons
RAL	An30aspilitert of Mining
RFP	Exploration Technical Report
ROL	Rolled
ROM	Run-of-mine
RPM	Runge Pincock Minarco
RQD	Rock Quality Designation
SEC	Securities and Exchange Commission
SIN	National Interconnected System
SNUC	National System of Conservation Units
TFRM	Mineral Resources Inspection Fee
TMPM	Ponta da Madeira Maritime Terminal
TTG	Tonalite-trondhjemite-granodiorite
UC	Conservation Units
UCS	Unconfined Compressive Strength
USS	United States Steel
VALE	Formerly known as CVRD
VIU	Value-in-use
WSA	World Steel Association
YoY	Year on Year

Table 2-5- List of chemical symbols used in this report

Element	Symbol
Aluminum	Al
Iron	Fe
Magnesium	Mg
Manganese	Mn
Oxygen	O ₂
Phosphorus	P
Potassium	K
Calcium	Ca
Silica	Si
Titanium	Ti
Potassium	K

3. Property description

3.1. Brazilian mining code

Under the Brazilian laws, the Federal Government owns all mineral resources. Under Article 176 of the Brazilian Constitution, all mineral deposits belong to the Federal Government, whether or not the deposits are in active production. Mineral rights are distinct from surface rights.

Mining is regulated by Decree-Law 227, 1967 (the Mining Code), Mining Regulations that came into force in December 2017, and other regulations issued by the National Mining Agency (ANM), formerly known as National Department of Mining Production (DNPM), which controls the mining activities in Brazil.

Regarding the mining authorization and concession regimes, the objective is to obtain the mining title document that allows exploitation of the mineral resource, which in this case, is administrative rule granted by the Minister of Mines and Energy, commonly known as Mining Concession. There is an intermediate title, an exploration permit granted by ANM General Director, which authorizes the interested party to prospect certain mineral substance, in order to define its quantity, quality and spatial distribution.

The mining cycle begins with the Application for Exploration Permit, followed by the publication of the Exploration Permit (*Alvará de Pesquisa*) in the Federal Gazette – DOU. Its holder is authorized to carry out the research work within a period of 3 to 6 years, the goal of which is to define a deposit, that is, to qualify, quantify and spatially locate the mineral substance of interest.

At the end of the exploration stage, the holder must submit an Exploration Technical Report (*Relatório Final de Pesquisa*) to ANM, according to the presented results. After analysis by ANM, and considering the approval of the document, the mining company will have 1 year to apply for mining concession. This application is based on the presentation of an Economic Exploitation Plan (*Plano de Aproveitamento Econômico* or PAE), which must be prepared by a legally qualified professional.

Once PAE is presented, ANM will demand presentation of the installation license (LI – Licença de Instalação), granted by an environmental licensing agency, and the mining company shall carry out due diligence with this agency every 180 days, to prove the progress in the environmental licensing process to ANM.

After obtaining the environmental license (LI), the mining company will be able to obtain the Mining Concession in the Federal Gazette – DOU. Figure 3-1 shows the flowchart of the Brazilian mineral licensing process.

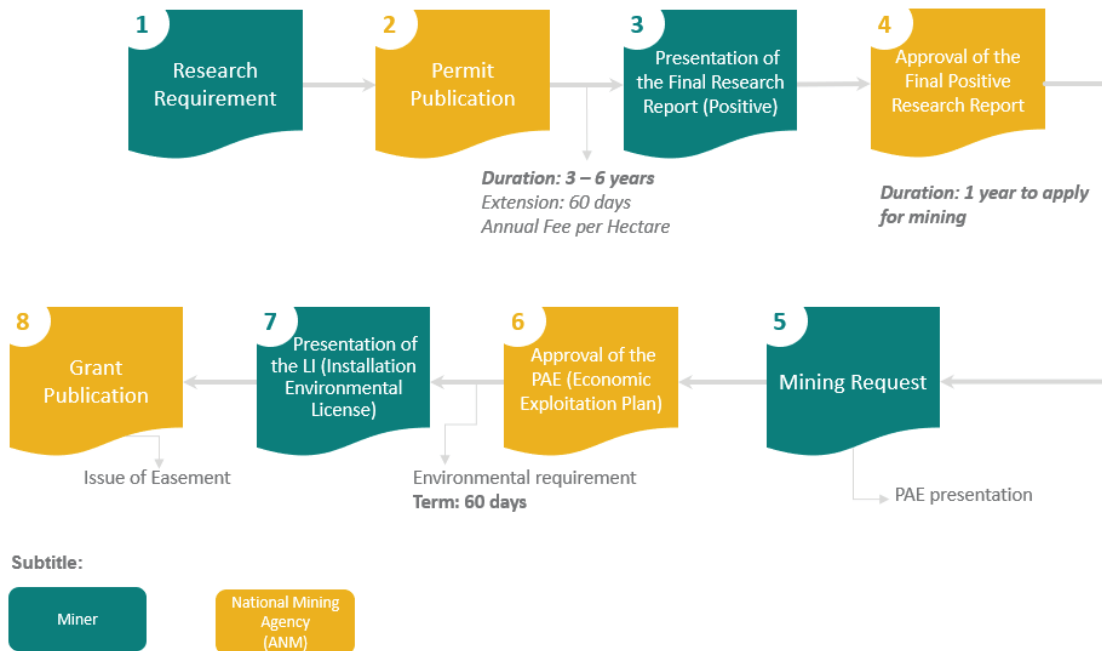


Figure 3-1: License process flowchart

The mining activities must start up to six months from the mining concession grant. Annual production reports must be filed. Assuming all other conditions are met, the mining concessions remain valid until the deposit is depleted.

The mining company can conduct mining activities after the appropriate environmental operation license (LO - Licença de Operação) is issued. The mining operations must be in accordance with the Economic Exploitation Plan approved by ANM. If additional minerals are discovered, ANM must be notified of the discovery, and the mining concession must be amended to include the new list of minerals before those minerals can be commercially produced and sold.

3.2. Land tenure

At Serra Norte, the mining right was grouped in a permit referred to as “Mining Group” (*Grupamento Mineiro* or GM) which is concession grouping, allowing processing and approval of mining rights for a group of concessions in a single process. Figure 3-2 presents the mining right of Serra Norte (813.684/1969), which is part of a Mining Group (852.145/1976) among other operations, including Serra Sul and Serra Leste. Table 3-1 shows further information on Serra Norte mining concession.

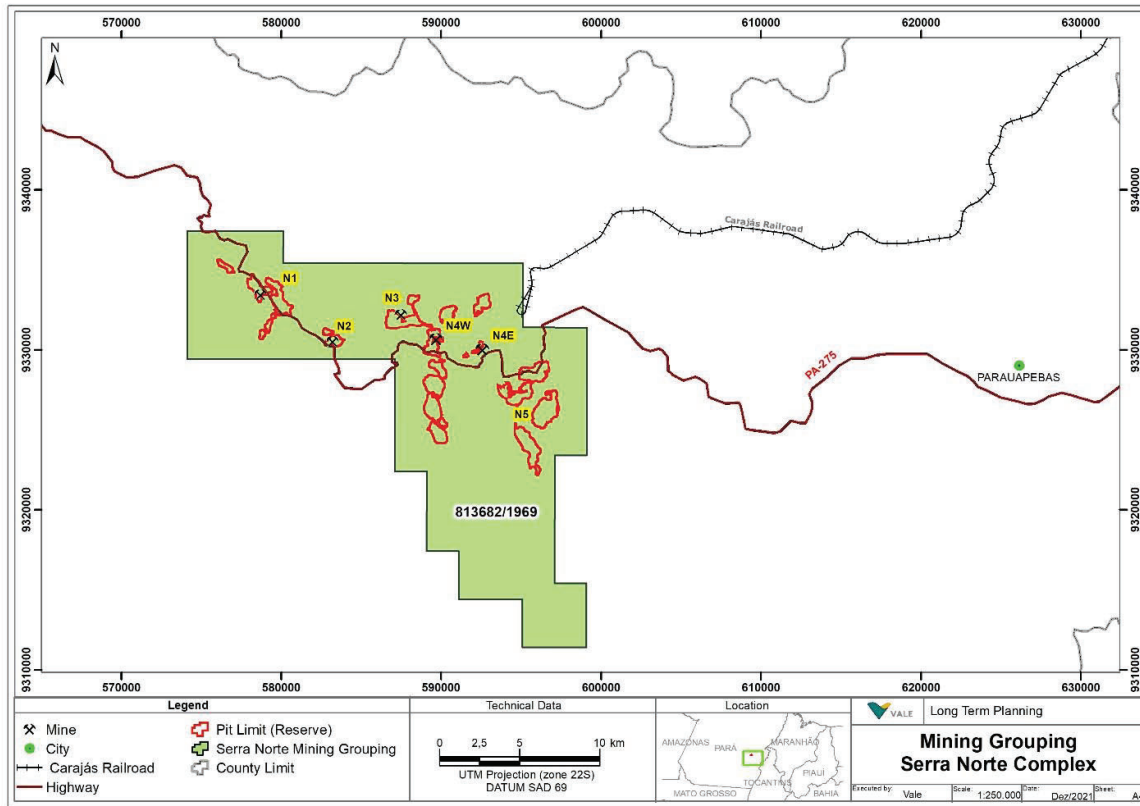


Figure 3-2 - Serra Norte Mining Concession

Table 3-1 - Serra Norte Mining Rights forming the Concession Grouping

ANM Process	City	Area (ha)	Title	Number	Issue date	Element	Mine
813.682/1969	Parauapebas	30,000	Mining right	74.508	06/09/1974	Iron	Serra Norte

Currently, the Serra Norte complex possesses four mining easements as follows.

- Easement 1, with an area of 4,052.46 ha, whose technical report was approved on 13/07/88;
- Easement 2, with an area of 8,527.54 ha, whose technical report was approved on 01/12/88;
- Easement 3, with an area of 15,565.33 ha, whose technical report approval was requested at the same time PAE was registered on 30/01/2009 and reiterated in 03/07/2013;
- Easement 4, with an area of 10,031.52 ha, was requested on 17/02/2017, which the PAE was approved on 19/04/2021.

These 4 easements are contiguous and make a unique shape that encompasses all current and future industrial installations necessary for the Serra Norte life of mine.

Vale is required to pay a monthly federal fee known as Financial Compensation for the Exploitation of Mineral Resources (“CFEM”) over the sales of iron ore, at the current rate of 3.5%. The state of Pará also imposes a tax on mineral production (“Taxa de Fiscalização de Recursos Minerais – “TFRM”), which is currently assessed at a rate of R\$ 4.1297 per metric ton of minerals produced in or transferred from the state.

An annual report (RAL - Brazilian acronym) is required to be lodged with ANM, detailing the production for the year. This reporting obligation has been met for each year since concession grant.

3.3. Surface rights and easement

According to the General Mining Law and related legislation, surface rights are independent of mineral rights. The law requires that the holder of a mineral concession either reach an agreement with the landowner before starting relevant mining activities (i.e., exploration, exploitation, etc.) or complete the administrative easement procedure, following the applicable regulation. Surface property is acquired through:

- The transfer of ownership by agreement of the parties (derivative title);
- Acquisitive prescription of the domain (original title);
- Temporary rights to use and/or enjoy derived powers from a surface property right may be obtained through usufruct (a right to temporarily use and derive revenue) and easements.

As indicated by Vale, the Serra Norte is located within the National Forest of Carajás (FLONACA), which belongs to the Federal Government and there are no interferences of the operations with third-party properties, as shown in **Erro! Fonte de referência não encontrada..**

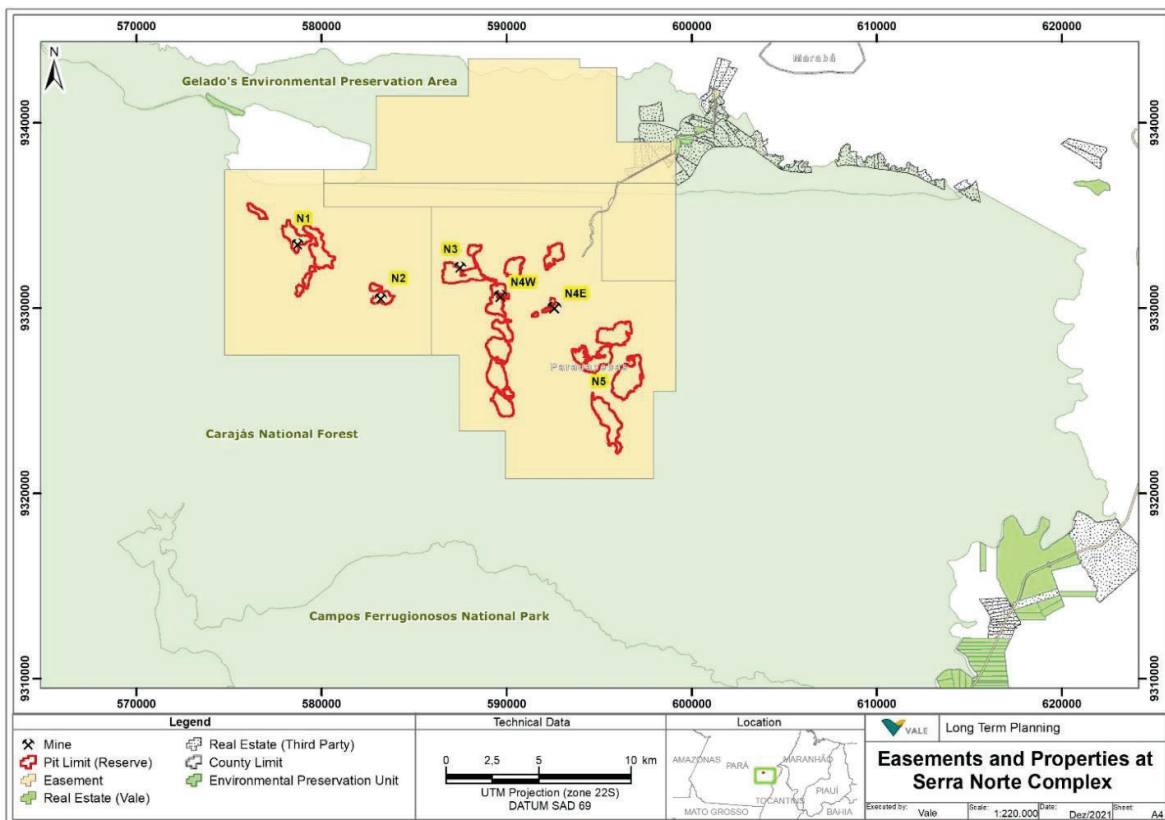


Figure 3-3 - Easements and properties at Serra Norte.

4. Accessibility, climate, local resources, infrastructure and physiography

4.1. Accessibility

Access to Parauapebas is provided via regular flights between Carajás and the cities of Marabá, Belém, Belo Horizonte and Brasília, in addition to paved roads (PA-275, PA-150 and PA-70) and a railway which connects Carajás to the city of São Luiz (Maranhão State).

To access the Serra Norte Carajás Mines departing from Marabá, take highway BR-230 east, and approximately 1 km at the junction with BR-155, head south towards the municipality of Eldorado dos Carajás, approximately 95 km away. From there, take the exit to PA-275, head west 230km towards Parauapebas, passing through the entrance of the Carajás National Forest, and continuing another 30 km to the east to arrive at the gatehouse of Mina Serra Norte Carajás.

4.2. Climate

The climate in the region is humid tropical monsoon, with dry spring, hot weather, and high average temperatures. The coldest months correspond to the period from January to March (averages 18°C to 21°C), coinciding with the highest rainfall and the greatest presence of cloudiness. From November to April, it rains 80% of the annual total. The dry season, which runs from May to October, with the driest quarter (June, July, and August), has monthly averages of just 24 mm, little rain by Amazon standards. The average annual rainfall for the region varies from 1,500 to 1,900 mm and the average annual temperature is between 23.5 and 25.5°C, with the maximum average temperature reaching 32.5°C June through August, the minimum never lower than 18°C.

The region is humid, with average humidity ranging between 70 and 85%. In the driest months, June to August, humidity is slightly reduced, reaching minimum levels of around 50% and average around 70%. During the rainy months, from October to May, the maximum average can exceed 95%. The Mine operates year-round.

4.3. Local resources

Various services, including temporary and permanent accommodations, are available in Parauapebas (population 213,576, estimated 2020), located approximately 50 km east of the Mine Complex. A greater range of general services is available at the state capital, Belem, located approximately 770 km to the northeast.

4.4. Infrastructure

The Serra Norte operational complex (Carajás) is fully provided by the Brazilian electricity production and transmission system “Sistema Interligado Nacional” (SIN) and is connected to the Basic Network (230kV). The power system is supplied through two transmission lines from the Carajás Substation owned by Eletronorte (Centrais Elétricas do Norte do Brasil S.A.) which is responsible for power generation, transmission, and distribution in the state of Pará.

The internal distribution system is carried out through Vale's electrical networks of 34.5kV. Consumption in 2020 was about 468,794.24 MWh, 68.87% of which fed the mineral processing plants, 27.57% was distributed to the N4/N5 mines and the remaining 3.56% was consumed by the Urban Center and other support structures.

The project includes complete maintenance workshop infrastructure (three units located in mines N5, N4W, and Central) equipped with bays for mobile machines, machining, subassemblies maintenance workshop, electrical workshop, electronics workshop, warehouse, and tooling.

All quality control of the ore is carried out using the structures of the Carajás Iron Mine Laboratory, where physical tests and chemical assays of the entire production chain are carried out.

The administration offices house Vale S.A. and its contractors. They are composed of offices for direction, management, coordination, meetings, technicians, files, reception, and restrooms, which serve all administrative staff.

A canteen (meal room) serves all staff, both in-house and contractors, to provide lunch, dinner, and snacks. Its operation is outsourced by Vale like that adopted in other operating units of the company.

The clinic has a small office for first aid care and a restroom. The clinic is equipped for first aid care, while the most serious cases are referred to the hospital in the urban center. Patients are transported by ambulance, which is parked at the clinic with a driver on permanent standby.

Part of the company's staff resides in the urban center of Carajás, and part, in the city of Parauapebas, with no need to build new accommodation in the industrial area.

4.5. Physiography

The physical relief of the area is composed of three geographies: plateaus formed on rocks of the jaspilites and basalt types, Vertentes (sloping areas of mountain slopes), and Fluvial Depressions (valley bottoms). The plateaus form the high reaches elevations of around 720 meters and are separated by valleys where the watercourses are located. When plateaus are situated over basalt-like rocks, their tops are flatter. These are very stable portions of land due to the low slopes, the existence of resistant and permeable rock, in addition to permeable soils (oxisols), and dense vegetation cover (forests). On the other hand, when the plateaus are situated on jaspilite-type rocks, they are undulating and may reach up to 800 meters in elevation.

The fluvial depressions constitute the areas located below 400 meters and correspond to the lower part of the slopes and the bottom of the valleys of the “igarapés” and streams that flow into the area. They usually occur on basalts, covered by forest on thick soils. In the lowered and flat portions, wet soils (gleysols) occur in marshy areas. Depressions can also occur on sandstones, covered with forests and shallower soils.

The Carajás complex is located in the domain of the Parauapebas River sub-basin, a tributary of the Itacaiúnas River that flows into the Tocantins River in the city of Marabá.

The source of the Parauapebas river is in Serra Arqueada and it is formed by the junction of the Caracol and the Onça streams. It flows to the north, receiving the following tributaries: Goiaba stream, Sossego river, Taboca stream, Jacaré stream and Gelado stream (also known as Cigano or Mombuca), on the left bank; and the Plaquê and Verde rivers, the Ilha do Côco creek and the Novo and Caracol rivers, on the right bank.

The project area is located in the basins of the Gelado, Geladinho, Taboca, and Jacaré streams. The springs of these watercourses are located in the high parts of the Serra dos Carajás plateaus.

The flow of underground water occurs from the infiltration of rainwater in the plateaus towards the bottom of the valleys where the watercourses are located. In unexplored areas, the groundwater level is on average between 10 and 70 meters below the ground surface.

Disregarding the places where the streams themselves disappeared with the deepening of the mining, studies indicate that the lowering of the water level in the mines did not cause any disappearance of big springs, as the springs are at lower altitudes, at the bottom of the valleys and slopes, and only their flow was affected.

Regarding the biotic environment, the Serra Norte unit is located in the Amazon Forest biome, in a region of relatively recent socioeconomic occupation. Serra Norte is part of a Conservation Unit managed and protected by the Chico Mendes Institute for Biodiversity Conservation (ICMBio), with support from Vale. Vegetation varies between savanna (typical vegetation of iron formations — where iron ore is present) and Amazon Forest. Due to the heterogeneity and high degree of conservation of the natural environments which still exist, this conservation unit is a valuable refuge for fauna and is very important for the conservation of biodiversity in the state of Pará.

Protected areas close to the Mining Complexes include the National Forests of Tapirapé-Aquiri, Itacaiúnas, and Carajás, the Campos Ferruginosos National Park, the Tapirapé Biological Reserve, the Xikrin Indigenous Land of the Cateté River, and the Igarapé Gelado Environmental Protection

Area. These areas add up to some 1.2 million hectares which are relatively well preserved, in contrast to the anthropized areas in the surroundings.

5. History

5.1. Exploration and development history

The first geological survey in Serra dos Carajás was carried out in 1922 by Avelino Ignácio de Oliveira, who revealed the occurrences of galena in São Félix do Xingu and carbonaceous material in the Fresco River. The first citations involving iron formations were made in 1933 when the engineer Luiz Flores de Moraes Rego referred to “flat-top hills where general fields are found” in the high region of the Itacaiúnas River. In 1951/1952, geographer Luiz Castro Soares conducted an aerial survey of the phyto-physiognomy of the region, where he observed the existence of non-forest formations with large clearings and lakes.

The first publication of Carajás can be seen in the aerial photograph of bodies C and D of Serra Sul in Carta do Brasil ao Milionésimo, published by IBGE in 1960, seven years before the discovery of the deposits (Magalhães, 1960). In this publication, the areas of elevated fields were wrongly classified by the author as “limestone plateaus with elevated lakes in the south of Pará”. As seen later, they correspond to iron plateaus and the lagoons fill sinkholes over cangas.

In 1967, the pioneering mapping “Stratigraphic, Structural and Economic Geology of the Araguaia Project Area” – DNPM/PROSPEC (1954 to 1966) was released. In this work, a complete aerial photogrammetric survey was carried out, but the occurrences of iron ore were not identified due to lack of fieldwork. Due to the presence of lakes, the land clearings were interpreted as karst relief. In the same year, the United States Steel (USS) created the Brazilian Exploration Program – BEP, to explore manganese, since it is strategic for the steel industry and for the American economy during the cold war. At the end of May 1967, reconnaissance flights were made between the Tocantins and Tapajós rivers.

In July 1967, the Brazilian Exploration Program team received the aerial photos of the Araguaia Project and verified the existence of several large land clearings in the forest, like those seen in the reconnaissance flights carried out in May 1967.

On July 31, 1967, the first helicopter landed in the Serra Arqueada hematite canga glade. In August, an overflight was made, at low altitude with a single engine plane, in the clearings of Serra Norte verifying the great similarity with the canga cover of Serra Arqueada and an aeromagnetic survey was carried out in Sereno, Serra Leste, Serra Norte, and Serra Sul. Preliminary field surveys of Serra Norte (N1, N2, N3, N4, N5) and Serra Sul were also conducted. In September 1967, potential of 2 to 35 billion tons of iron ore was communicated to the United States Steel in Pittsburgh (USA) .

Between September and October 1967, exploration requests were prepared and filed at Departamento Nacional de Produção Mineral (DNPM), covering a total of 160,000 hectares of Serra Norte, Serra Sul, Serra Leste and São Félix.

In April 1970, Amazônia Mineração S.A. was created, constituted 51% by VALE (at the time Companhia Vale do Rio Doce – CVRD) and 49% by United States Steel. The evaluation of the Carajás iron deposits began in 1970, carried out with air support, due to the lack of access by road. Between 1970 and 1972, intensive exploration work was carried out on the identified occurrences. CVRD geologists, led by engineer Aluizio Licínio de Barbosa, together with the United States Steel team, were responsible for estimating iron ore potentials in Serra dos Carajás. Total resources of about 18 billion tons of iron ore, with 66% Fe content, concentrated in four main deposits were determined: N4, N5, N1 (Serra Norte), and S11 (Serra Sul).

In 1977, VALE (CVRD) acquired the shareholding in United States Steel, being solely responsible for conducting the project. In 1979, the construction of the complex of the Carajás Iron Project started, integrating the mine, railroad, and port. In February 1985, the São Luiz – Carajás railroad was completed. Iron ore production began in 1985 in the N4E deposit, and the N4W deposit came into operation in 1994. Serra Sul operations started in 2016.

5.2. Production history

Table 5-1 shows a summary of the production history of Serra Norte Complex.

Table 5-1 - Past production of Serra Norte mines.

Years	Ore (t)	Waste (t)	Total (t)	Product (t)
2016	159,919,775	62,535,175	222,454,950	143,560,547
2017	141,690,807	63,523,090	205,213,897	142,683,237
2018	134,443,397	73,349,550	207,792,947	131,536,360
2019	117,010,321	101,548,705	218,559,026	115,277,540
2020	110,185,273	100,758,725	210,943,999	109,123,167
2021	111,857,464	109,042,539	220,900,002	109,268,321

6. Geological setting, mineralization, and deposit

6.1. Regional geology

The Carajás Mineral Province (CKS) comprises an area of approximately 30,000 km² located in the southeast of Pará state and stands out as the main operating polymetallic province in the country, hosting world-class deposits and important mines of Fe, Cu, Au, Mn, and Ni.

The province occupies the eastern portion of the Amazonian Craton (Figure 6-1) and corresponds to the oldest core, of Archean age, limited by the Geochronological Province of the Central Amazon (1.9-1.7 Ga) to the west and by the Paraguay-Araguaia mobile belt (700-450 Ma) to the east (Santos, 2000 and Santos, 2003). Although the classifications of the Amazon Craton are a matter of debate in the scientific literature, the subdivision of its southeast portion is well accepted and justified, both from the geochronological point of view and from the orientation of its main structures. In this sense, the domains Rio Maria, of Mesoproterozoic age, with preferential N-S orientation, Carajás (Neoproterozoic), with WNW-ESE orientation, and Bacajá (Paleoproterozoic), with NW-SE orientation, are recognized. The tectonic evolution of this portion of the craton is not clear, and the boundaries between these domains are fuzzy and usually transitional.

The geological framework of the southeastern portion of the Amazon Craton is widely discussed in scientific literature, with different proposals for evolution, subdivision, and nomenclature. According to the definition by Tassinari and Macambira (2004), adopted here, the Carajás Mineral Province would fit into the Maroni-Itacaiúnas Geochronological Province, limited by the Central Amazon Province to the west, the Bacajá domain to the north, and the Araguaia Belt to the east. This geochronological province would be subdivided into the Rio Maria Granite-Greenstone Terrane Meso-Archaean domain (Dall'Agnol et al., 1987; Dall'Agnol et al., 1997, 2006; Althoff et al., 2000) and the Carajás Neo-Archaean domain (Araújo and Maia, 1991; Vasquez et al., 2008).

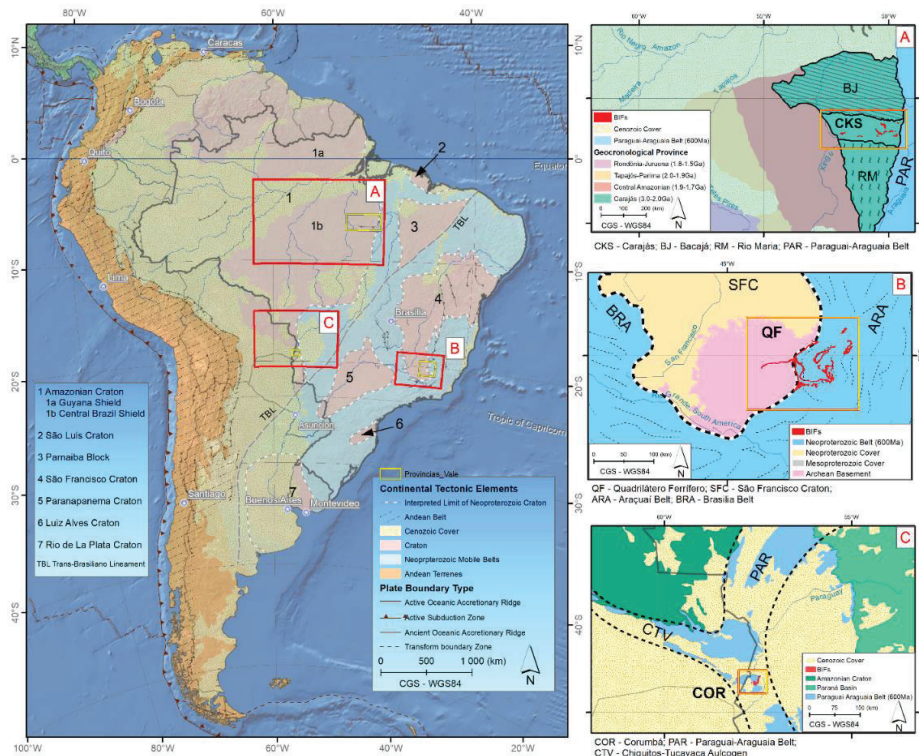


Figure 6-1 - Tectonic map of South America (Cordani et al. 2016; Gómez et al. 2019), with localization of the Brazilian mining provinces operated by Vale.

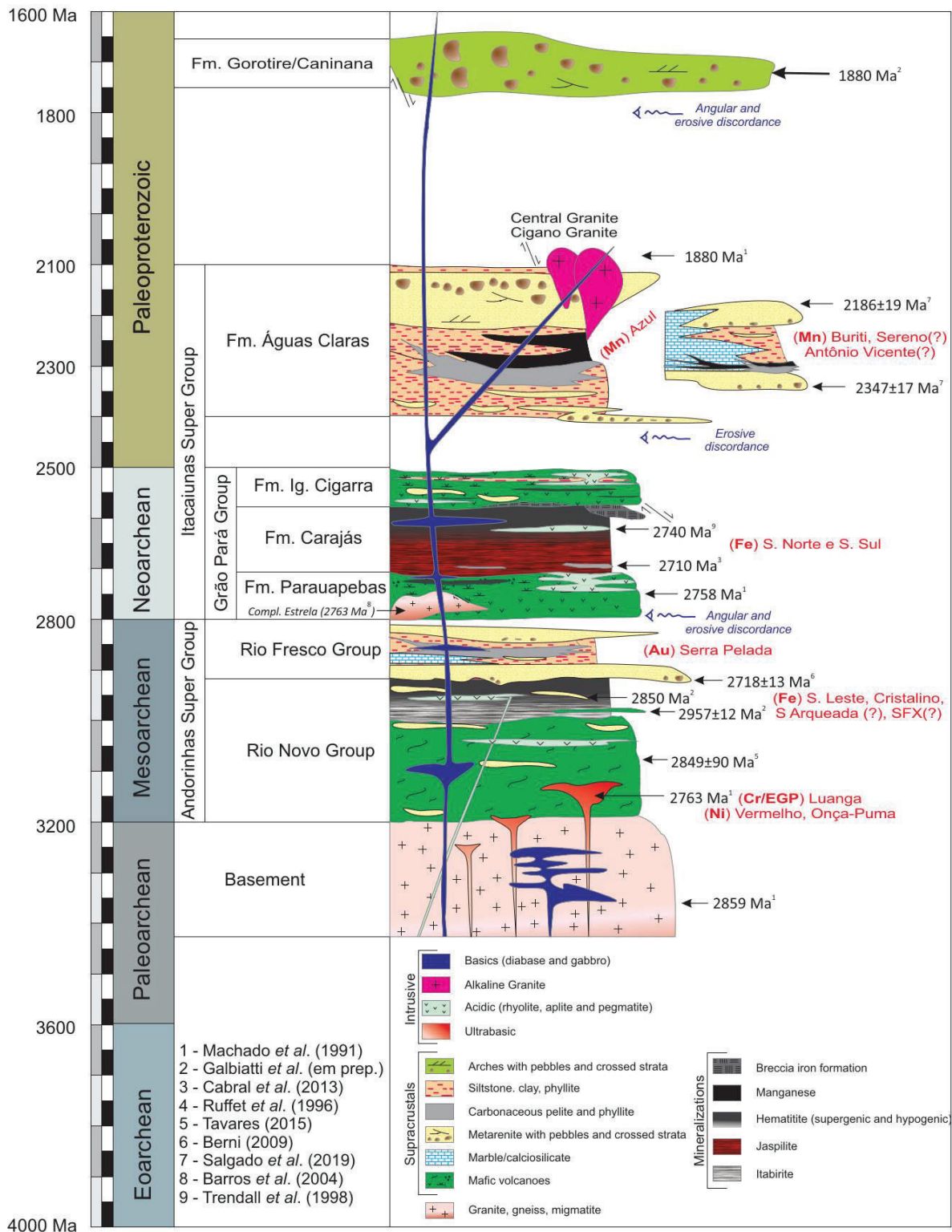


Figure 6-3 - Stratigraphic Column of the Carajás Mineral Province.

6.1.2. Granite-gneiss terrains

The granite-gneiss terrains comprise a set of Tonalite-trondhjemite-granodiorite (TTG) granites and gneisses, amphibolites, and migmatites predominant in the northern and southern limits of the Carajás Mineral Province, originally attributed to the Xingu Complex (Silva et al., 1974; Hirata et al., 1982; DOCEGEO, 1988) which, with the increase in the geological knowledge, has been reviewed and subdivided, mainly in the southern portion of the Carajás Mineral Province.

Estrela Complex: defined by Barros (1997) as a set of granites, monzonite, syenite and diorite dating from 2,760 Ma (Barros et al., 2001), which intrude the base of the Andorinhas and Itacaiúnas supergroups in the Carajás Block.

Plaquê Suite: comprises bodies with syn-collisional granitic to granodioritic composition, with calcium-alkaline to alkaline character, dated 2,736 Ma (Avelar et al., 1999) and correlated to the Planalto and Serra do Rabo granites (Santos, 2003).

6.1.3. Andorinhas Supergroup

With wide representation in the Rio Maria Domain, the Andorinhas supergroup encompasses a Meso-Archaean succession (3.0 to 2.86 Ga) of the granite-greenstone belt type. It constitutes a metamorphic succession under greenschist to amphibolite facies conditions, composed of granitoids, mafic/ultramafic intrusive, and volcanic rocks, which occur intercalated with clastic and chemical sediments (Macambira and Lafon, 1995; Althoff et al., 2000; Souza et al., 2001; Dall'Agnol et al., 2006; Oliveira et al., 2009, 2011; Almeida et al., 2011, 2013). These lithologies were grouped by Santos et al. (2000) in the groups: Babaçu, Sapucaia, Lagoa Seca, Gradaús, Tucumã and São Félix do Xingu, in addition to the TTG granitoids (Arco Verde, Caracol, Mahogany and Cumaru) and calc-alkaline granitoids (Guarantã, Rio Maria, Mata Surrão and Xinguara). In the east and south portions of the Carajás domain, there is a set of metavolcanosedimentary rocks correlated to the Andorinhas Supergroup (DOCEGEO, 1988), here subdivided into the Rio Novo and Rio Fresco groups.

Rio Novo Group: originally defined in the Serra Leste region as a greenstone belt-type sequence, metamorphosed into greenschist facies, with mafic, ultramafic, and felsic rocks and sediments (Hirata et al., 1982; Meireles et al., 1982). The base of the package is composed of shales with varying proportions of chlorite and amphibole, which are interbedded with lenses of metasediments, including amphibolite itabirite, that grades to siliceous itabirite at the top.

Rio Fresco Group: originally defined as the entire Carajás cover (Hirata et al., 1982; Meireles et al., 1982; DOCEGEO, 1988), it is now restricted to metasediments that cover the rocks of the Rio Novo Group in the Serra Leste and Serra Pelada region. This unit is composed of a succession of meta-sandstones and metapelites (locally carbonaceous), with discontinuous levels of dolomitic marble (Figure 6-1 and Figure 6-2).

6.1.4. Mafic-ultramafic complexes

They are complexes such as Luanga (Medeiros Filho and Meireles, 1985; Suita et al., 1988; Ferreira Filho et al., 2007) and related ones (Onça-Puma, Vermelho and Madeira), dated 2,763 Ma (Machado et al., 1991) that occur as intrusions in the basement and the basal portion of rocks attributed to the Rio Novo Group (Figure 6-1 and Figure 6-2). They host Ni and Cr deposits and present the same deformation pattern as the Rio Novo Group shales, indicating contemporaneity. The strong deformation and evidence of metamorphism of the Gabro Santa Inês (DOCEGEO, 1988), which occurs as an intrusive anorthositic leucogabbro body in the basement and base of the Rio Novo Group, suggest chrono-correlated placement to the ultramafic rocks.

6.1.5. Itacaiúnas Supergroup

The Itacaiúnas Supergroup (DOCEGEO, 1988; Figure 6-2 and Figure 6-3) is a Neo-Archaeon succession that encompasses the Grão Pará Group (CVRD/AMZA, 1972; Beisegel et al., 1973) and its correlated units (Igarapé Salobo, Igarapé groups Pojuca and Igarapé Bahia; DOCEGEO, 1988).

Grão Pará Group: was defined by CVRD/AMZA team (1972) and named in honor of the original name of the captaincy that currently corresponds to the state of Pará. It comprises a volcano-sedimentary sequence of neo-Archaeon age, where the mineralized layer occurs interspersed with two layers of mafic volcanic rocks, named, from bottom to top, as Parauapebas Formation, Carajás Formation, and Igarapé Cigarra Formation.

The Parauapebas Formation was originally defined by CVRD/AMZA team (1972) as the Lower Paleovolcanic Sequence and later renamed due to the occurrence of felsic volcanics (Machado et al., 1991). The age of this unit is well defined by U/Pb dating, with results around 2,750 Ma (Wirth et al., 1986; Lindenmayer et al., 1998; Tavares, 2015). The succession occurs according to a stratiform body of indeterminate thickness (>200 m), which represents the stacking of several flows in conformable transitional contact (<1 m) with the overlying sediments.

The Carajás Formation was named by CVRD/AMZA team (1972) for forming the main crests of the Serra dos Carajás. This unit consists of iron formations deposited during the Neo-Archaeon (2,740 Ma., Trendall et al., 1998) and is host to the world-class iron ore deposits of the Carajás Mineral Province. In general, it occurs as large discontinuous bodies, which define the relief in canga plateaus, which inhibit the growth of the tropical forest, typical of the surrounding region (Figure 6-4).



Figure 6-4 - Plateaus of S11D (left) and N1 (right) of Carajás Mineral Province.

The thickness of the iron formations varies between the different plateaus and is normally proportional to their area in plan, typically varying between 100-200 m, and may exceed 500 m in the main deposits (Figure 6-4). Hematites are distributed throughout the province and constitute high-grade ores (> 60% Fe). They are classified according to their compactness and contaminants (when present) and are associated with supergenic and hypogenic processes developed on jaspilite (Lobato et al., 2005; Silva et al., 2008). Friable supergenic ore is the predominant type, occurring from the surface to average depth of 150 m, exceeding 300 m in the main deposits (Figure 6-5).

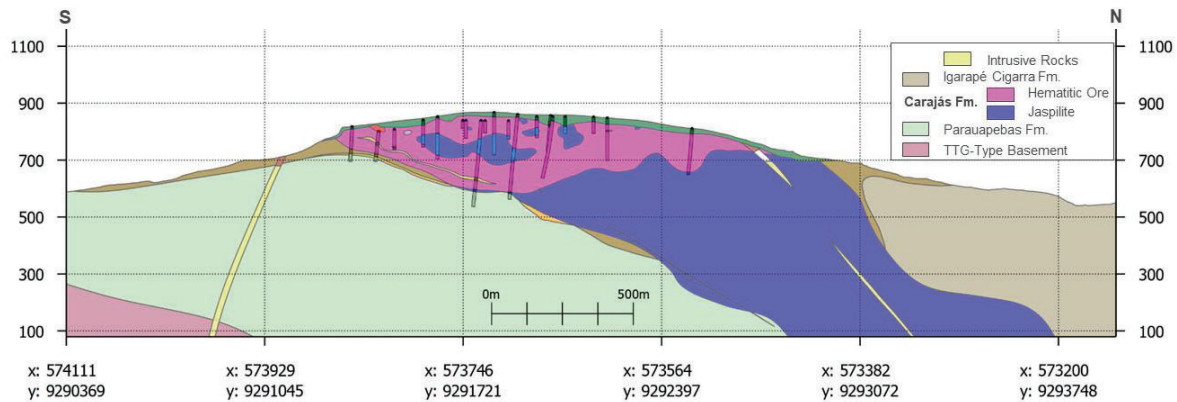


Figure 6-5 - Geological cross-section of the S11D mine, Carajás Mineral Province

The Igarapé Cigarra Formation was originally defined by CVRD/AMZA team (1972) as the Upper Paleovolcanic Sequence and later renamed due to the identification of sedimentary levels (Macambira, 2003). It occurs according to a stratiform body, in conformity with the banding of iron formations, with thickness of about 300-400 m (CVRD/AMZA, 1972). It is predominantly composed of basalts with intercalations of tufts and clastic sediments and iron formation lenses (Macambira, 2003). In Serra Sul, the contact between the Carajás Formation and the Igarapé Cigarra Formation is locally marked by a breccia horizon in the iron formation.

6.1.6. Proterozoic covers and intrusions

The Águas Claras Formation is the main sedimentary cover overlaying the Grão Pará Group in the Carajás Mineral Province. It was originally defined by CVRD/AMZA team (1972) as the Gorotire Formation, later renamed the Rio Fresco Formation (Hirata et al., 1982; DOCEGEO, 1988), receiving its current name from the works of Nogueira (1995), who characterized the sedimentation environment of this unit. It constitutes a package of pelites and sandstones about 1,500 m thick, respectively subdivided into the Lower and Upper members, which occur superimposed to the rocks of the Grão Pará Group by erosive unconformity (Figure 6-1). The age of this unit is not well defined yet, but recent studies indicate that its deposition would be younger than 2.45 Ga (Cabral et al., 2017), compatible with the age range defined for quartzites from the Buritirama Formation (2,186-2,347 Ma, Salgado, et al., 2019). The manganese ore from the Azul mine is associated with the pelites of the Lower Member of this unit, which is correlated, in terms of age and environment, with the Buritirama manganese mine and the Sereno and Antônio Vicente deposits.

Serra dos Carajás Suite comprises a set of anorogenic alkaline to calcium-alkaline granites and post-tectonic acid dikes that cut the rocks of the Xingu Complex, the Andorinhas Supergroup, the Itacaiúnas Supergroup, and the Águas Claras Formation (DOCEGEO, 1988). The Central, Cigano, Pojuca, and Musa granites are dated between 1,800-1,900 Ma (Gibbs et al., 1986; Machado et al., 1991); therefore, chronocorrelates to Uatumã Magmatism.

The Gorotire Formation also known as the Caninana Unit (Pereira, 2009; Pereira et al., 2009), constitutes a siliciclastic cover composed of conglomerates and arcosean sandstones about 300 m thick (Barbosa et al., 1966), formed in an anastomosing river environment (Oliveira and Nascimento, 2013; Nascimento and Oliveira, 2015) in a restricted basin developed during the reactivation of the Carajás Fault (Lima and Pinheiro, 2001).

Mafic Intrusives: the Rio da Onça Gabro (Tavares, 2015) and the Rio Pajeú Diabásio (Macambira et al., 2014) occur as undeformed dykes with direction close to N-S, cutting through all aforementioned units. These dikes continue for hundreds of kilometers and have a strong magnetic signature, being easily observed in aerial survey products.

6.1.7. Cenozoic units and recent coverage

Cangas: commonly formed from the weathering of iron formations or the residual concentration of iron and aluminum oxides from the host rocks. They are divided, depending on their structure, composition, and iron content, into structured (rich or ore), detrital, and chemical (or laterite) types. They usually have high concentrations of aluminum, phosphorus, and manganese, which do not favor their use as ore. However, they can make up a fraction of ROM in a diluted form, being, therefore, subject to economic use. Big part of the caves recorded in Carajás is associated with cangas domains, mainly on the edge of the plateaus.

Eluvium-colluvial deposits: form small discontinuous deposits of little economic interest at the base and the slopes of the plateaus.

Alluviums: do not form significant iron ore deposits.

6.1.8. Metamorphism and deformation

The Carajás Mineral Province registers a polyphase tectonic evolution, attested by its wide range of age distribution and by the high complexity of its structural arrangement (Figure 6-2 and Figure 6-3). The compilation of structures and geochronological data supports the interpretation of three main moments of deformation (or tectonic cycles), responsible for the architecture of the Carajás Mineral Province:

The Archean Cycle comprises the main period of crustal growth in the Carajás Mineral Province, responsible for the formation and deformation of the TTG basement (Xingu Complex and related), deposition and deformation, with low-grade metamorphism, of the rocks of the Andorinhas Supergroup, ending with the sedimentation of the Grão Pará Group. Recent studies (Ganad et al., in prep.) propose its subdivision into events: G1 (3,015-2,920 Ma), G2 (2,880-2,835 Ma), G3 (2,780-2,720 Ma) and G4 (2,590-2,530 Ma). The first two events are associated with dome-and-keel tectonics. The latest events related to the opening of the Carajás Basin and the development of the first IOCG system.

The main structures attributed to this cycle are folds with the axis around E-W, present in the basement and greenstone belt sequences of the Andorinhas Supergroup (such as the Serra Pelada synclines, Rio Maria; DOCEGEO, 1988), and the implementation of a fault system (Carajás and Gray faults), at first with sinistral trans-tensional character (Araújo and Maia, 1991; Pinheiro, 1997; Pinheiro and Holdsworth, 2000).

The Paleoproterozoic Cycle is the event responsible for the current geometry of the province. It occurred with no record of significant metamorphism and is recorded in SSW-verging regional-scale folds, such as the Carajás Syncline (CVRD/AMZA, 1972; Beisegel et al., 1973). This event is also responsible for the reactivation of faults in the dextral transcurrent regime (Araújo and Maia, 1991; Pinheiro, 1997; Pinheiro and Holdsworth, 2000) and for the placement of the first IOCG system (Ganad et al., in prep.).

Faults and folds correlated to this cycle are important from a prospective point of view, as they interfere in the thickness and the geometry of iron formations and may have been responsible for the hypogenic formation of high-grade bodies.

The Neoproterozoic/Paleozoic Cycle is equivalent to the Brasiliano orogeny (700-450 Ma), which defines the current cratonic limits of the interior of the South American Platform (Almeida et al., 1973; Almeida et al., 1981; Cordani et al., 2016; Gómez et al., 2019). This event expresses the development of a moving belt that verges westward and is characterized by a sequence of N-S direction folds and faults. It is mainly marked by the development of brittle-ductile structures, such as kink-style folds, usually with an axis around N-S that occur at various scales, in addition to the intrusion of mafic dykes with orientations similar to these fold axes.

The structures of this cycle interfere in the deposits, with variation in the thickness and the geometry of the iron formations (either by duplication of layers due to folding and faulting or omission of these layers, due to faulting), in addition to the hypogenic formation of high-grade bodies in fault zones.

6.2. Local geology

6.2.1. Physiography

The plateaus of the Serra Norte Complex generally constitute elevated areas, with elevations between 650-800 m, limited by the domain of volcanic rocks of the Parauapebas Formation to the north, which configure an extensive plain, with elevations between 200-400 m, and by the domain of terrigenous sediments of the Águas Claras Formation to the south, which present morphology of intercalated crests and valleys, aligned according to the NW-SE direction, with elevations ranging from 500-700 m (Figure 6-6).

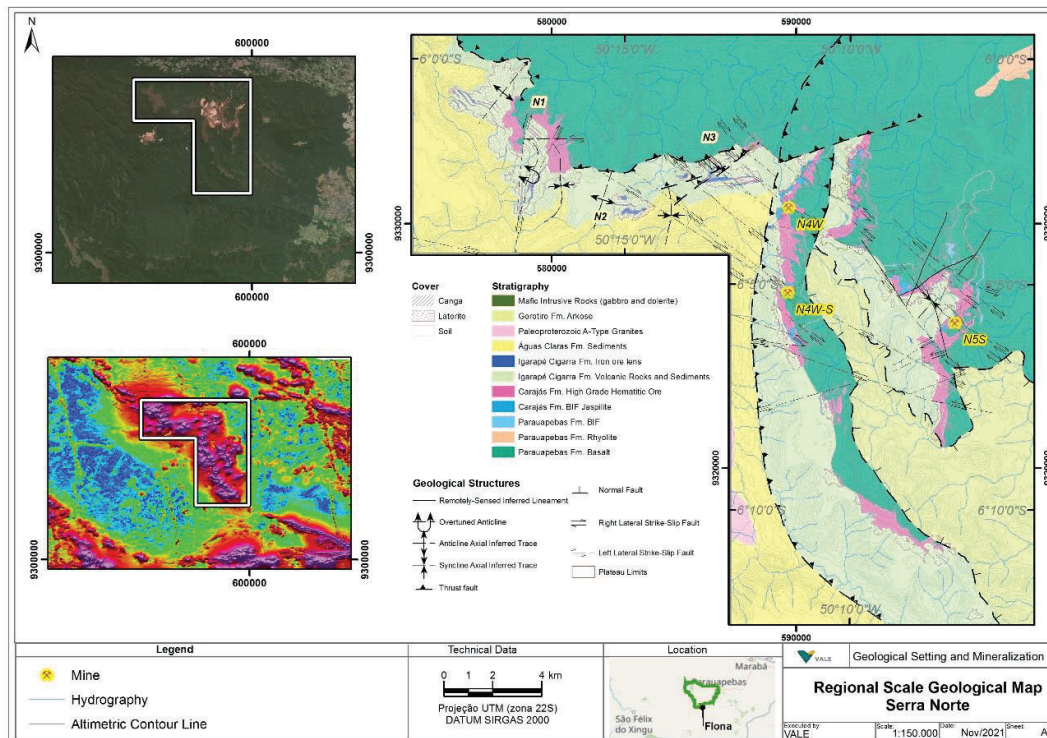


Figure 6-6 - Geology of the Serra Norte Complex (right) and satellite and aero-geophysical (MAG) images

6.2.2. Stratigraphy

The Serra Norte stratigraphic succession encompasses the entire Grão Pará Supergroup and Águas Claras Formation, in addition to the Cenozoic and recent sedimentary covers.

The main iron ore deposits are mostly hosted at Fm. Carajás, which is part of the Neo-Archaean metavolcanosedimentary sequence of Grão Pará Group (Itacaiunas Supergroup), which superimposes the crystalline basement and the Mesoproterozoic greenstone belt sequence of the Andorinhas Supergroup and are covered by the terrigenous sediments of the Águas Claras and Gorotire formations and was cut by acidic and basic intrusive rocks.

Mafic rocks are the host rocks of the iron formation, occurring both at the base and at the top of it. They are represented by the mafic rocks of the Parauapebas (bottom) and Igarapé Cigarra (top) formations, according to Macambira (2003). Mafic rocks mainly correspond to basalts. For geological modeling purposes, they were not classified in the mentioned stratigraphic units, and are considered only as mafic rocks, discriminated into decomposed mafic (MD), semi-decomposed mafic (MSD), and fresh mafic (MS). In addition to their occurrence as host rock (top and base of the iron formation), they also occur as sills and mafic dykes in iron formations.

Decomposed mafic (MD) – It presents a high degree of alteration, poorly structured, with color ranging from reddish to yellowish, clayey, with predominantly soft consistency.

Semi-decomposed mafic (MSD) – It is an intermediate-term between MS and MD, sometimes still showing relicts from the original texture of the rock, but already with deep mineralogical transformation, and consequently, in its color.

Fresh mafic (MS) – rock not affected by weathering, systematically chloritized, and corresponding to the product of the hydration of basalts and diabases. Its color is dark green, sometimes with typical volcanic structures, such as quartz amygdales. Compositional variations and even non-ferrous clastic and chemical sediments were grouped under this name to simplify the geological interpretations.

6.2.3. Mineralization

The Carajás Mineral Province hosts world-class deposits of Fe, Cu, Au, Mn, and Ni, resulting from polyphase tectonic evolution, accompanied by hypogenic and supergenic enrichment processes, developed on sedimentary and magmatic rocks of the Archean core of the Amazonian Craton.

Mineralization occurs mainly as a product of supergenic enrichment, developed on jaspilites (algoma-like BIFs interlayered with basalts) in high, flat-topped regions that make up the plateaus observable by remote sensors. The irregularity and discontinuity of the deposits along this mineral province demonstrates the existence of structures inherited from deformational events that favored the thickening of the jaspilite and the efficiency of supergenic processes through the tilting and fracturing of these rocks.

The different types of iron formation and host rocks of the Serra Norte district are described below. The mean grades mentioned refer to the average grades of the samples (weighted by length) of each lithotype modeled in this review, considering the interpreted classification (CLI).

The cangas represent a product of weathering on the rock sequences typical of the region. For modeling, they are divided into two different types: structural canga (CE) with iron contents greater than or equal to 55%, products of the weathering of iron formation, and chemical canga (CQ), which is covering the mafic rocks.

Chemical canga (CQ) – represents the iron-aluminous crusts that usually cover the decomposed mafic rocks. It has a colloform texture and high porosity. It often has a high content of Al₂O₃GL, evidenced by the light coloring of gibbsite and clay minerals. Hematite fragments are scarce or absent. In general, the iron content is under 55%, with high phosphorus and Al₂O₃GL.

Structural canga (CE) – term commonly used by Vale to designate ferruginous lateritic crusts. It is usually located over iron ore outcrops *in situ*. It also occurs as transported canga, but at short distance from the source area, being a good indicator of the location of ore bodies. The thickness is variable, reaching more than 20 meters. It has iron content above 55% and relatively low Al₂O₃GL and phosphorus grades, thus allowing its potential use as iron ore.

Jaspilite (JP) – banded iron formation, usually of the oxide facies, composed of alternating bands of opaque minerals, such as hematite (predominantly), magnetite or martite, and reddish or white bands composed of jasper and/or chert. Hematite crystals occur mainly in the form of microcrystalline and lamellar hematite, in addition to martite and magnetite, magnetite being uncommon and generally martitized, with kenomagnetite relicts (Lobato et al. 2005). The jaspilite is reddish-gray and represents the ore protolith of the Carajás iron deposits. It occurs predominantly at the base of the iron formations, in contact with mafic rocks or as lenses, immersed in a large mass of friable hematite. The thickness of the lenses is usually small (a few meters), ranging from centimeters to about 20 m. The jaspilite that occurs in the basal portion can reach up to 350 m in thickness, the continuity in-depth in some regions of the mine is unknown. In the large mass of jaspilite, which constitutes the base of the iron formation, hematite lenses, more commonly friable hematite, are observed in regions close to the jaspilite/hematite top contact.

Friable hematite (HF) – is the predominant type of ore, occurring throughout all Serra Norte mines. It is commonly banded, locally showing primary lamination planes. It consists of a gray friable hematite material with metallic luster with high porosity. It can be powdery or disaggregate into small fragments (placoid or not).

Hematite crystals occur mainly in the form of microcrystalline, lamellar, anhedral-subhedral, and euhedral-subhedral hematite, in addition to martite, as magnetite pseudomorphs (Lobato et al. 2005). It is predominantly formed by the supergenic enrichment of the ore protolith (jaspilites). It has variable thickness in the enrichment profile, reaching up to 350 m and great continuity throughout the dip.

Compact hematite (HC) – a material rich in iron and, like HFs, generated from the weathering alteration of jaspilite. Its color varies from black to reddish-brown, the latter being typical of a goethite/limonite cementation, which is deemed to be responsible for the high compactness of this lithotype. HC occurs subordinately throughout the entire deposit, like lenses inside the large friable hematite mass, usually with thicknesses around 5 to 10 m, without considerable lateral continuity (few tens of meters). Locally, it can reach thicknesses of up to 50 m. The color of HC is bluish-gray color with metallic luster. It is dense, with low porosity, and it can be banded, characterized by the original banding of the preserved jaspilite, defined by compact layers alternating with porous or brecciated layers. This lithotype can also be massive, with the original texture destroyed, composed of aggregates of hematite crystals. Fe contents are between 59 and 69%. Al₂O₃GL represents an important contaminant in this lithology.

Manganiferous hematite (HMN) – The color of manganese hematite is dull dark gray, it occurs in lenses with thicknesses ranging from 5 to 10 m, and locally, it may reach thicknesses of 60 m, without much lateral continuity, dispersed within the mass of friable hematite. HMN is a material rich in Fe and with Mn contents greater than 2% (global). It is usually positioned at the base of the hematite bodies, a probable zone of accumulation of Mn leached from the weathered horizons.

Manganiferous Iron (FMN) – It is a material which apparently represents an intermediate product of the weathering alteration of jaspilite, enriched with Mn. It occurs as small lenses (usually a few meters thick, reaching up to 30 m), with little lateral continuity, within the mass of friable hematite.

6.2.4. Structural

In general terms, the main Carajás iron ore deposits are associated with flat-topped elevated plateaus, defined along two main morphological alignments corresponding to Serra Norte and Serra Sul. These alignments materialize the limb of the structure defined as Carajás Syncline (Figure 6-2) which reaches length of about 150 km and width of 100 km (CVRD/AMZA, 1972; Beisegel et al., 1973). The Serra da Bocaina region, also known as Água Boa plateau, corresponds to the closure zone of this syncline and has a large concentration of jaspilite type ore protolith. This region must not have experienced the ideal conditions for the formation of significant iron ore deposits or even for the preservation of possible previously formed deposit.

The Serra Norte Complex corresponds to the inverted limb geological domain of the Carajás Syncline. The high deformation pattern of this domain is reflected in the geometry and distribution of the iron formations, whose segmentation by faults, such as the Carajás Fault (Pinheiro and Holdsworth, 1997), and by folds of different orientations and scales, individualize the plateaus from N1 to SN9 (Figure 6-6).

6.3. Property geology

6.3.1. N1 Plateau

The N1 deposit is located in the extreme west of Serra Norte and corresponds to part of the homonymous plateau (Figure 6-6).

6.3.1.1. Deposit dimensions

This plateau has an elongated shape in the NW-SE direction, with dimensions of about 6 km x 3 km and elevations between 650-800 m. It is predominantly composed of rocks from the Carajás and Igarapé Cigarra formations of the Grão Pará Group, which make contact with rocks of the Parauapebas Formation on the northeast edge of the plateau, and the Águas Claras Formation to the southwest. In general, the layers show medium to high angle dips to the northeast, configuring inverted stratigraphic setting. (Figure 6-7).

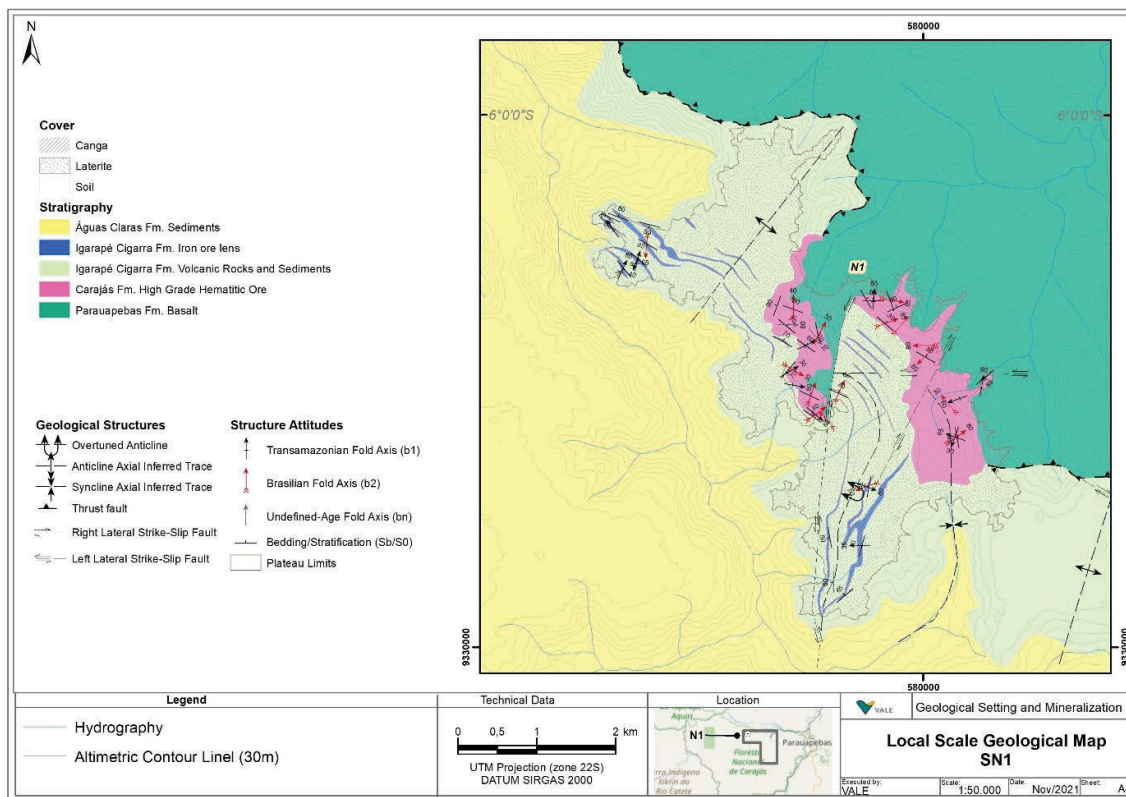


Figure 6-7 - N1 Geological map

6.3.1.2. Lithologies

The Parauapebas Formation occurs outside the plateau and marks the base of the Grão Pará Group. It is formed by a thick outflow of basalts and basaltic andesites, locally amygdaloid and vesicular, commonly hydro-thermalized, which occur underlying the rocks of the Carajás Formation, by a conformable transitional contact. In the N1 region, they are often represented by chloritites cut by carbonate and hematite veins.

The Carajás Formation comprises about 20% of the plateau area and corresponds to the thickest domain of the iron formations. It coincides with the highest elevations and occurs continuously along the northeast edge of the plateau, from the proximity of the contact with the rocks of the Parauapébas

Formation to its central portion, where it makes transitional contact with the rocks of the Igarapé Cigarra Formation (Figure 6-7).

The iron formations of the Carajás Formation domain occur according to a sub-verticalized tabular layer with a variable dip either to the northeast or southwest. Thus, its thickness in plan tends to reflect the thickness of the layer, which varies between 250-600 m and is strongly controlled by folds and faults (Figure 6-8).

The Igarapé Cigarra Formation is made up of large volumes of volcanic rocks, mainly flows and tuffs, of bimodal nature, which occur interlayered with lenses of chemical sediments and, subordinately, terrigenous. The iron formations of this unit occur beside long vertical bodies with thickness varying between 30-200 m, 50 m average, generally in pairs of parallel layers, which reflect the folding process.

It is also observed, both in drill cores and in outcrops, that the N1 iron formations, mainly in the domain of the Carajás Formation, occur intercalated with several bodies of mafic rocks, with variable orientation, generally of not of great thickness. These bodies have a basic/intermediate composition and make contacts that are conformable or non-conformable with the compositional banding of the iron formations, configuring sills and dykes (Figure 6-8).

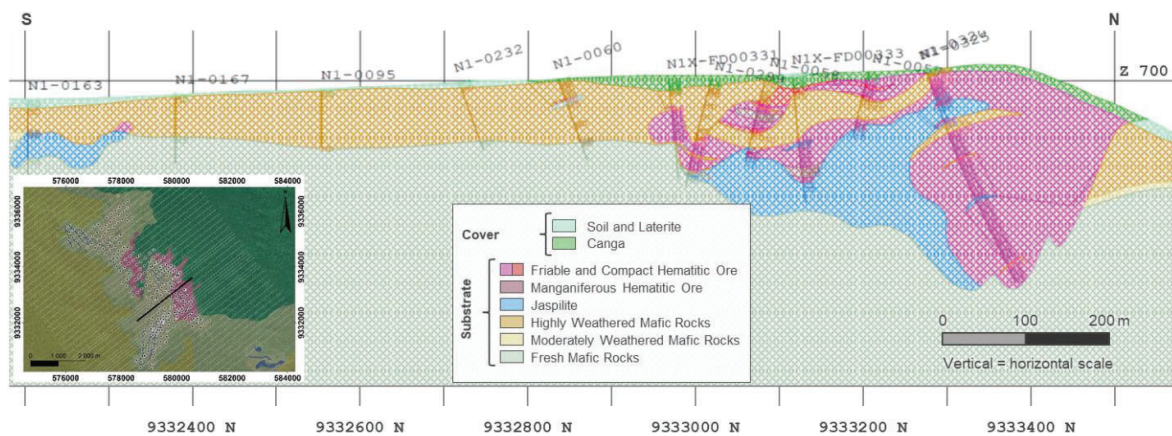


Figure 6-8 - N1 Geological section

6.3.1.3. Structures

In N1, the layers are arranged in NW-SE direction, and the outline in plan and vertical section of the N1 iron formations shows its strong structural control, in which faults and folds condition its thickness and continuity (Figure 6-7 and Figure 6-8). The main structures controlling mineralization have been recognized since the works from the 1970s (CVRD/AMZA, 1972; Beisegel et al., 1973) and will be presented below in chronological order, from the oldest to the youngest structure and related to the probable tectonic events responsible for its generation:

Structures correlated to Transamazonian tectonism:

- Thrust fault to SW, located to the north and east of the plateau, in the contact between the lithotypes of the Parauapebas Formation and the Igarapé Cigarra Formation (Figure 6-7). This fault marks the complete or partial omission of the rocks of the Carajás Formation, mainly outside the plateau domain;
- Closed fold axes to recumbent isoclinal folds, with NW-SE direction and flanks dipping to NE, traceable for 1.5 km average, in rare cases longer than 3 km (Figure 6-7 and Figure 6-8). These structures can occur rotated, due to the superposition of younger tectonic events, and are mainly observed in the iron formations of the Igarapé Cigarra Formation domain and more difficult to notice in the Carajás Formation domain, where they predominate in close contact with the rocks the Parauapebas Formation;

- Sinistral transcurrent fault of N-S direction, in the central portion of the plateau. This structure is characterized by the formation of breccias, rotation of structural elements (such as bedding and fold axes), and by the discontinuity of the main body of iron formation, which occurs in the west block with reduced thickness (Figure 6-8); and
- System of small sinistral transcurrent faults, NE-SW orientation, located in the central portion of the plateau and responsible for the extension of sections of the iron formation in the NE direction (Figure 6-8).
 - Structures correlated to Brasiliano tectonism:
 - Axes of open folds, with directions varying from NE-SW to NS, tracked over long distances, mainly observed in iron formations in the domain of the Igarapé Cigarra Formation, and in general, reflected as kink-style folds in iron formations of the Carajás Formation domain; and
 - E-W direction sinistral transcurrent fault, positioned in the central portion of the plateau and responsible for the narrowing of the north portion of the main iron formation body. This fault occurs in association with a strong magnetometric anomaly and to a fractured zone approximately 500 m thick, locally brecciated. It is common to observe part of these fractures filled by veins of compact magnetite up to two meters thick that transpose the banding, suggesting hydrothermal alteration. To the west of the large N-S transcurrent fault, the E-W direction fault takes dextral shear direction (Figure 6-7).

6.3.1.4. Mineralization

Mineralization at N1 is mainly formed from the supergenic alteration of jaspilite, which constitutes the Carajás ore protolith. The high-grade ore consists of friable hematite, compact hematite, and manganese hematite, which occur in a sub-horizontal tabular layer, which tends to follow the topographical surface, commonly covered by canga carapace, also considered as a mineralized lithotype.

The friable hematite (HF) corresponds to 80% of the mineralization, and in the area where the iron formation thickness is the greatest, the maximum thickness is 400 m, with average global iron grade of 66.677% Fe and average density of 3.03 g/cm³. It has high porosity, dark gray color, and laminated to banded texture, locally foliated or brecciated. It can be powdery or disaggregated into small plaques and fragments. It is essentially constituted by iron oxides, mainly hematite and martite, with subordinate magnetite, in addition to goethite and limonite in the shallow depth horizons. Hematite crystals are mainly microcrystalline in lamellar, granular, or pseudomorphic forms in small euhedral-subhedral magnetite crystals. In the vicinity of the contacts with mafic rocks, it is common to present contamination by manganese, aluminum and phosphorus, while silica appears as a contaminant in the vicinity of the contact with the jaspilites. HF also may contain small lenses/bands/passages of compact hematite.

Compact hematite (HC) corresponds to 7% of the mineralization and usually occurs along veins, filling fractures or associated with mafic rocks, suggestive of hypogenic origin. In general, it presents decimetric to metric thickness, maximum 70 m, average global iron grade of 66.13% Fe and average density of 3.61 g/cm³. It is a bluish-gray rock, metallic luster and massive texture, rarely foliated, which can preserve banding relicts, marked by differences in texture and size of the crystals. It has low porosity and is essentially composed of iron oxides, mainly hematite, sometimes specular, and martite.

Manganese hematite (HMN) is very subordinate, corresponding to 1% of the mineralization. It usually occurs close to contact with mafic rocks, as discontinuous lenses up to 25 m thick, with average density of 3.81 g/cm³ and about 62.12% Fe and 3.8% Mn. Its color is dark greenish gray, matte luster, with high porosity, and it is constituted by association of hematite, pyrolusite, bixbyite, ramsdellite, cryptomelane, chalcophanite, and hollandite.

The structured canga (CE) comprises 15% of the mineralization and constitutes superficial crust up to 10 m thick, formed by weathering processes directly on the mineralized types described above. It has average grade of 64.10% Fe, average density of 3.32 g/cm³, evident banding, dark gray reddish color, and is composed of variable proportions of goethite, limonite, hematite, magnetite, and martite.

Although jaspilite (JP) is not a type mineralized in Carajás, it will be described here, as it is genetically related to mineralization, with which it makes transitional and gradational contacts, due to the locally sharp increase in iron content, given by structural discontinuities. It occurs preferentially below the mineralized zone, in some cases inside it, close to the surface, raised by folds and faults, or resulting from incomplete alteration processes. It is characterized by high hardness and low porosity, with primary compositional banding and lamination of thickness ranging from 0.1-3 cm, average grade between 30-45% Fe and average density of 2.92 g/cm³. The banding is defined by the alternation of dark gray layers with metallic luster, composed of hematite, with subordinate magnetite and martite, which are intercalated with white to red and brownish siliceous layers, formed by cryptocrystalline quartz varieties. At depth, carbonate and hematite veins are commonly observed, probably associated with hypogenic processes.

6.3.2. N2 and N3 Plateaus

6.3.2.1. Deposit dimensions

The deposits of N2 and N3 are located on the homonymous plateaus, with an elongated shape in the E-W direction, in the central portion of the Serra Norte (Figure 6-6). The N2 plateau has dimensions of about 1 km x 1 km, while N3 reaches 3 km x 1.5 km, both with elevations between 650-700 m. The rocks of the Igarapé Cigarra Formation of the Grão Pará Group are predominant in these plateaus and make contacts to the north with rocks of the Parauapebas Formation and to the south with those of the Águas Claras Formation. In general, the layers show medium to high angle dip to the north, configuring inverted stratigraphic pattern (Figure 6-9).

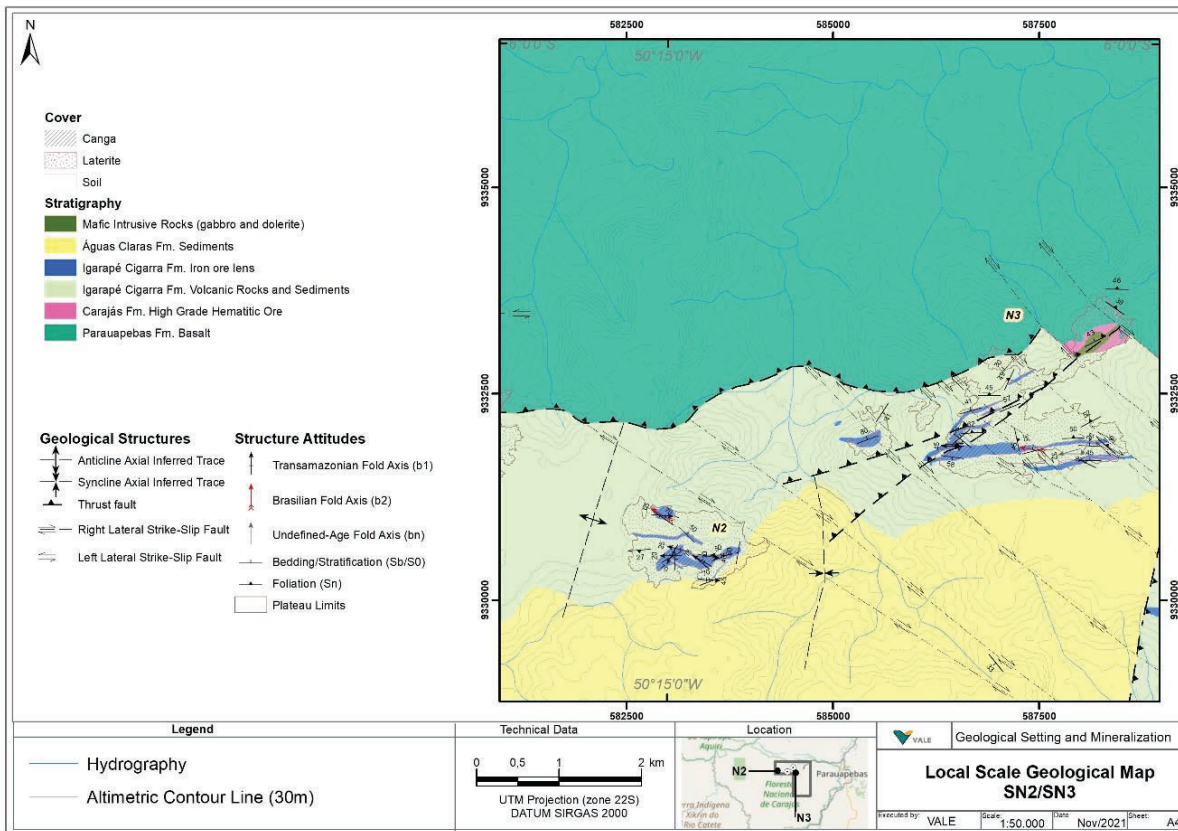


Figure 6-9 - N2 and N3 Geological map.

6.3.2.2. Lithologies

The Parauapebas Formation occurs in the low region after the northern edge of the plateau, where schist outcrops and probably represent the product of the deformation by faults on the chloritites found in the less deformed zones of the larger plateaus.

Most of the iron formations of the N2 and N3 plateaus were attributed to the Igarapé Cigarra Formation, except the extreme northeast portion of N3, which is correlated to the Carajás Formation. In general, they comprise about 20% of the area of the respective plateaus and do not stand out in the relief due to the low thickness.

The Igarapé Cigarra Formation is predominantly constituted of volcanic rocks interlayered with lenses of chemical and subordinate terrigenous sediments, identified in N2 drill cores. In this plateau, the iron formations occur according to sub-verticalized bodies, with thickness varying between 10-200 m, 100 m average, while in N3, they vary between 30-250 m, 150 m average (Figure 6-10).

The stratigraphic stacking on these plateaus is similar to that of the Igarapé Cigarra Formation on N1, as well as the main characteristics of its iron formations. These outcrops are parallel and continuous lenticular bodies, modeled as isolated layers in the stratigraphic stacking, in order not to overestimate the volume of iron formations in depth (Figure 6-9). Unlike N1, these layers occur in N2 and N3 in a segmented way, broken by several strike-slip and thrust faults, usually oblique to the main direction of the layers.

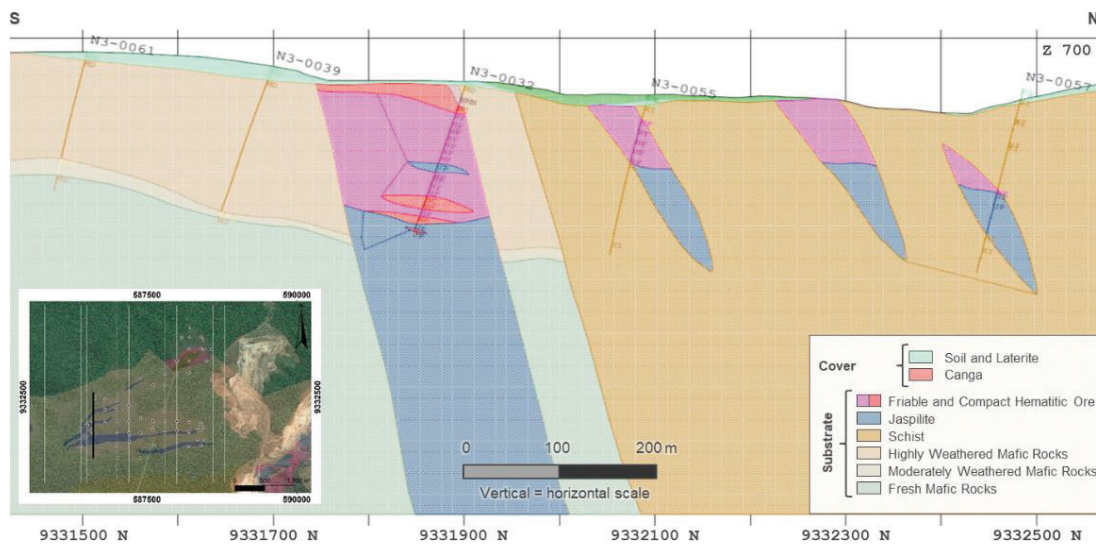


Figure 6-10 - N3 Geological map

6.3.2.3. Structures

The geological map of the N2 and N3 regions shows strong alignment of rock layers in the E-W direction (Figure 6-9). Structural controls and their relative chronological ordering are similar to those described for N1, differing by the low continuity of iron formations, which reflects the importance of faults for the local geological framework.

Structures correlated to Transamazonian tectonism:

- E-W thrust fault with vergence to the south, located in the north of the plateaus, in the contact between the rocks of the Parauapebas Formation and the Igarapé Cigarra Formation (Figure 6-9). This fault marks the omission of the rocks of the Carajás Formation, except the extreme northeast portion of N3. Thrust faults with NE-SW direction, verging to SE, derive from the large E-W fault, locally constituting a fault system;
- Although the repetition of layers has been interpreted as a result of stratigraphic stacking, this could also be explained by folding. The rheology of rocks from the domain of the Igarapé Cigarra Formation

is very favorable to this process, and in this case, it would originate closed folds to recumbent isoclines with an axis in the NE-SW direction, verging towards SE, compatible with the Transamazonian tectonism; and

- System of long dextral strike-slip faults with NW-SE orientation, located mainly in the N3 plateau, responsible for the segmentation of the iron formations, which is articulated with the small sinistral strike-slip fault system, with NE-SW orientation, in the central portion of N2, compatible with the Transamazonian tectonism (Figure 6-9).

Structures related to Brazilian tectonism:

- Axes of open folds, with direction varying from NE-SW to N-S, mainly observed outside the plateau domain and reflected as kink-style folds in the iron formations.

The iron formations of the Carajás Formation domain occur restricted to the northeast sector of N3, according to a sub-verticalized tabular layer, with northwest dip cut by a significant passage of mafic rock, associated with a thrust fault (Figure 6-9).

Basic to intermediate composition mafic sills and dykes with small thickness and variable orientation are mainly observed in drill cores intercalated with N2 and N3 iron formations.

6.3.2.4. Mineralization

The mineralization of N2 and N3 is formed through the alteration of jaspilite and has characteristics very similar to those described above for N1. For this reason, it will be addressed briefly here, emphasizing mainly its exclusive aspects in the area of plateaus under consideration (Table 6-1 and Table 6-2).

Table 6-1 - Characteristics of the mineralization in N2

Lithotype	Deposit partition (%)	Maximum section thickness (m)	Average iron content (%Fe)
Friable Hematite (HF)	84	200	66,26
Canga (CG)	12	30	63,10
Compact Hematite (HC)	4	45	65,22
Manganiferous Hematite (HMN)	< 1	5	61,19

Table 6-2 - Characteristics of the mineralization in N3

Lithotype	Deposit partition (%)	Maximum section thickness (m)	Average iron content (%Fe)
Friable Hematite (HF)	66	160	66,29
Canga (CG)	24	45	61,60
Compact Hematite (HC)	10	50	65,73
Manganiferous Hematite (HMN)	< 1	1	60,02

6.3.3. N4 Plateau

6.3.3.1. Deposit dimensions

The N4 Mine is subdivided into several pits, called N4WN, N4W, N4WC, N4WS, N4EN, and N4E, distributed along the homonymous plateau, in the central-east portion of Serra Norte (Figure 6-6). The N4 Plateau has big dimensions and is composed of rocks from the Carajás, Parauapebas, and Igarapé Cigarra formations, with a tabular shape and general dip to the west configuring a normal stratigraphic stacking. Prior to the start of mining, the plateau was already divided into the east and west portions by a drainage that separates the two main bodies of iron formations. The eastern portion has an elongated shape in the N-S direction and dimensions of about 8.5 km x 1 km, while the west is more regular, with average dimensions of 4 km x 2 km, both with elevations between 650-750 m (**Erro! Fonte de referência não encontrada.**)

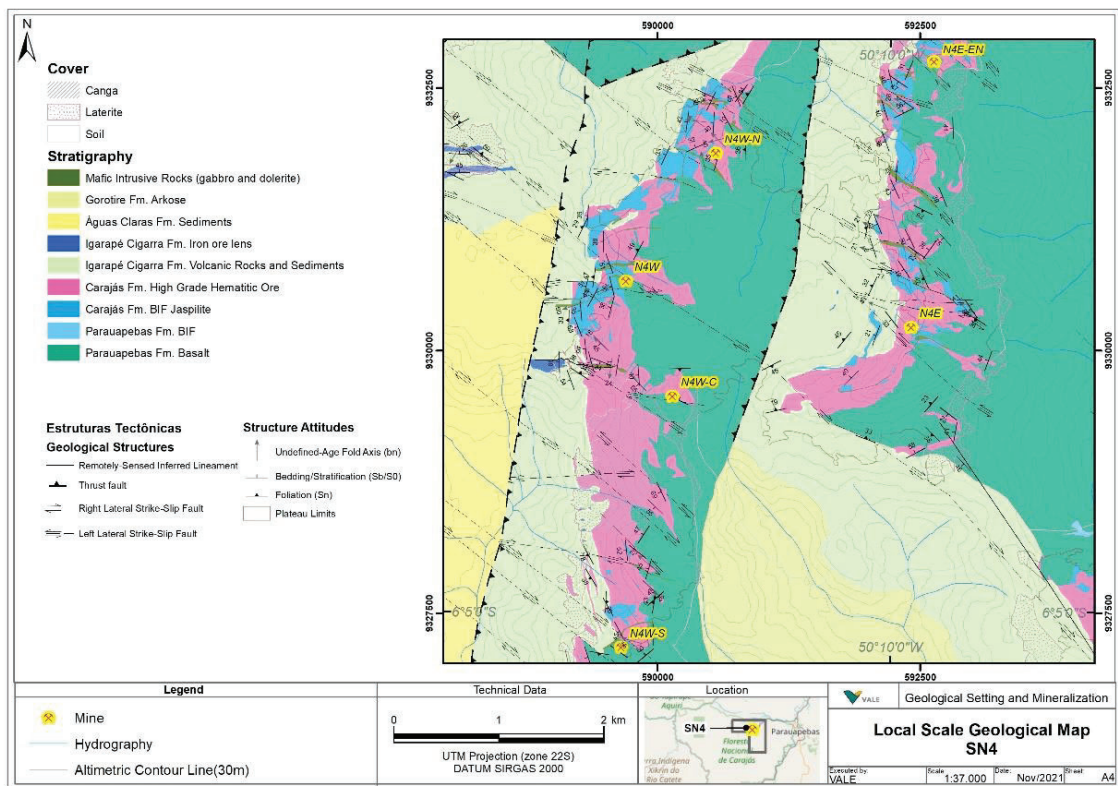


Figure 6-11 – N4 Geological map

6.3.3.2. Lithologies

The rocks of the Parauapebas Formation predominate in the eastern portion of the plateau, underlying the rocks of the Carajás Formation by a conformable transitional contact, but they also occur in the central portion, in contact by fault with the rocks of the Igarapé Cigarra Formation (**Erro! Fonte de referência não encontrada.**)

The Carajás Formation occurs continuously in the central portion of the plateau and comprises about 40% of its area (**Erro! Fonte de referência não encontrada.**). This unit coincides with the highest elevations and corresponds to the domain with the highest thickness of iron formations, which are strongly controlled by strike-slip faults and present thickness between 200-500 meters, in plan (**Erro! Fonte de referência não encontrada.**)

The Igarapé Cigarra Formation overlaps the Carajás Formation by a conformable transitional contact, outcropping to the west thereof. It consists of large volumes of bimodal volcanic rocks, interlayered with small lenses of iron formations, with thickness varying between 5-100 m (**Erro! Fonte de referência não encontrada.**)

The terrigenous sediments of the Águas Claras Formation overlap the domain of the Igarapé Cigarra Formation to the east of the plateau boundary.

Intrusive rocks define bodies of metric thickness and variable orientation that tend to follow the fault planes and cut through the entire Grão Pará Group sequence. These rocks have basic/intermediate composition, predominantly fine texture, and conformable to non-conformable contacts with the bedding and the banding, configuring families of sills and dikes (**Erro! Fonte de referência não encontrada.**)

The Gorotire Formation arkoses are considerably younger and occur limited by large normal faults, which define a graben, located in the southern portion of the plateau (**Erro! Fonte de referência não encontrada.**).

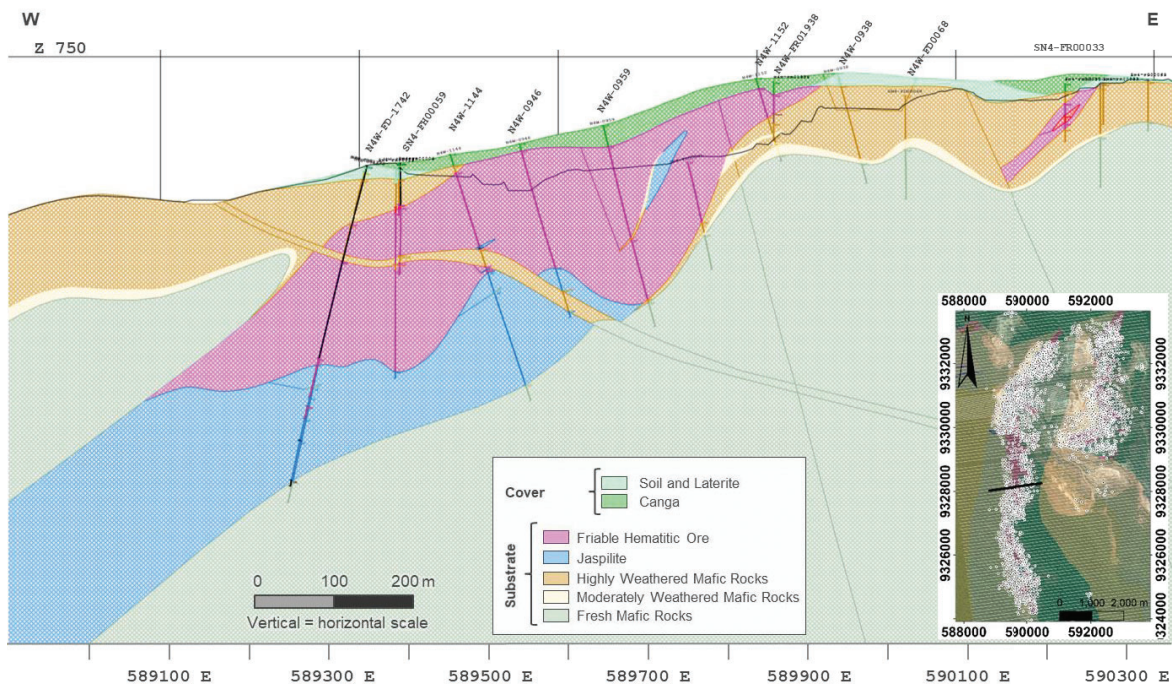


Figure 6-12 – N4W Geological map

6.3.3.3. Structures

On the N4 plateau, the Carajás Formation assumes a strong N-S trend and defines two occurrence belts called N4W and N4E, with a distinct structural pattern, separated by an eastward verging thrust fault (**Erro! Fonte de referência não encontrada.**).

The N4W region is relatively simpler and behaves like a homocline, with layers generally aligned in the N-S direction, segmented by several transcurrent faults in the NW-SE direction (**Erro! Fonte de referência não encontrada.**).

The N4E region is more complex, given the rotation of the banding, which dips to the north in the southern portion of the deposit, defining a fold that, in plant view, takes the shape of the letter "J," caused by the drag of the mineralized layer along the large dextral strike-slip faults (**Erro! Fonte de referência não encontrada.**).

Structures correlated to Transamazonian tectonism:

- ENE-WSW thrust fault, with a southern vergence, located north of the plateau, in the contact between the rocks of the Parauapebas Formation with those of the Carajás and Igarapé Cigarra Formations (Figure 6-10). This fault is compatible with the tectonic vector and necessary to justify the direct contact between the rocks of the Parauapebas and Igarapé Cigarra formations;
- System of long dextral strike-slip faults, with NW-SE orientation, which is articulated with small dextral transcurrent faults, of E-W orientation, responsible for the segmentation of the iron formations (**Erro! Fonte de referência não encontrada.**); and
- Open folds with a sub-horizontal axis in the E-W direction mainly observed in the northern portion of the plateau.

Structures correlated to Brazilian tectonism:

- Thrust faults with N-S direction, verging both east and west, which seem to be the product of the reactivation, during Brasiliano, of splays from the Carajás Fault formed in Transamazônico;
- Reactivation of faults with NW-SE orientation, giving sinistral kinematics to these, mainly in N4E (**Erro! Fonte de referência não encontrada.**); and
- Kink-style folds that form with varying scales of occurrence and axis orientations, mainly present in the iron formations.

6.3.3.4. Mineralization

As already described for the previous deposits, N4 mineralization is formed after the alteration of jaspilite and will be addressed briefly here, with emphasis mainly on the unique aspects of the area under consideration (Table 6-3).

Table 6-3 - Characteristics of the mineralization in N4

Lithotype	Deposit partition (%)	Maximum section thickness (m)	Average iron content (%Fe)
Friable Hematite (HF)	94	350	66,45
Canga (CG)	4	60	63,26
Compact Hematite (HC)	1	50	64,66
Manganiferous Hematite (HMN)	1	60	62,22

6.3.4. N5 Plateau

6.3.4.1. Deposit dimensions

The N5 Mine is subdivided into five pits called N5W, N5N, N5E, N5S, and M1, distributed along the homonymous plateau, located in the extreme east of Serra Norte (Figure 6-6). This plateau has dimensions of 7 km x 1.5 km, altitudes between 650 m and 800 m, and elongated geometry in the NNW-SSE direction. The geometry of the plateau suffers a strong curvature in the north-central portion as a reflection of interference by folding. It comprises rocks from the Parauapebas, Carajás and Igarapé Cigarra formations, of the Grão Pará Group. The iron formations occupy the central portion of the plateau and contact with the rocks of the Parauapebas Formation to the east and north, and those of the Igarapé Cigarra Formation to the west. In general, the layers show general dip to the west direction, configuring a localized normal stratigraphic stacking.

6.3.4.2. Lithologies

The Parauapebas Formation was mapped on the east and north edges of the plateau, in contact with the Carajás Formation. This corresponds to the thickest domain of the iron formations, which outcrop continuously, with thickness between 100-700 m in plan, in the central portion of the plateau, and comprises about 40% of its area, coinciding with the highest elevations and controlled by faults and folds (**Erro! Fonte de referência não encontrada.**). The Igarapé Cigarra Formation overlaps the Carajás Formation by a conformable transitional contact, outcropping to the west. It consists of large volumes of bimodal volcanic rocks, interlayered with small lenses of iron formations, with thickness varying between 10-60 m (**Erro! Fonte de referência não encontrada.**).

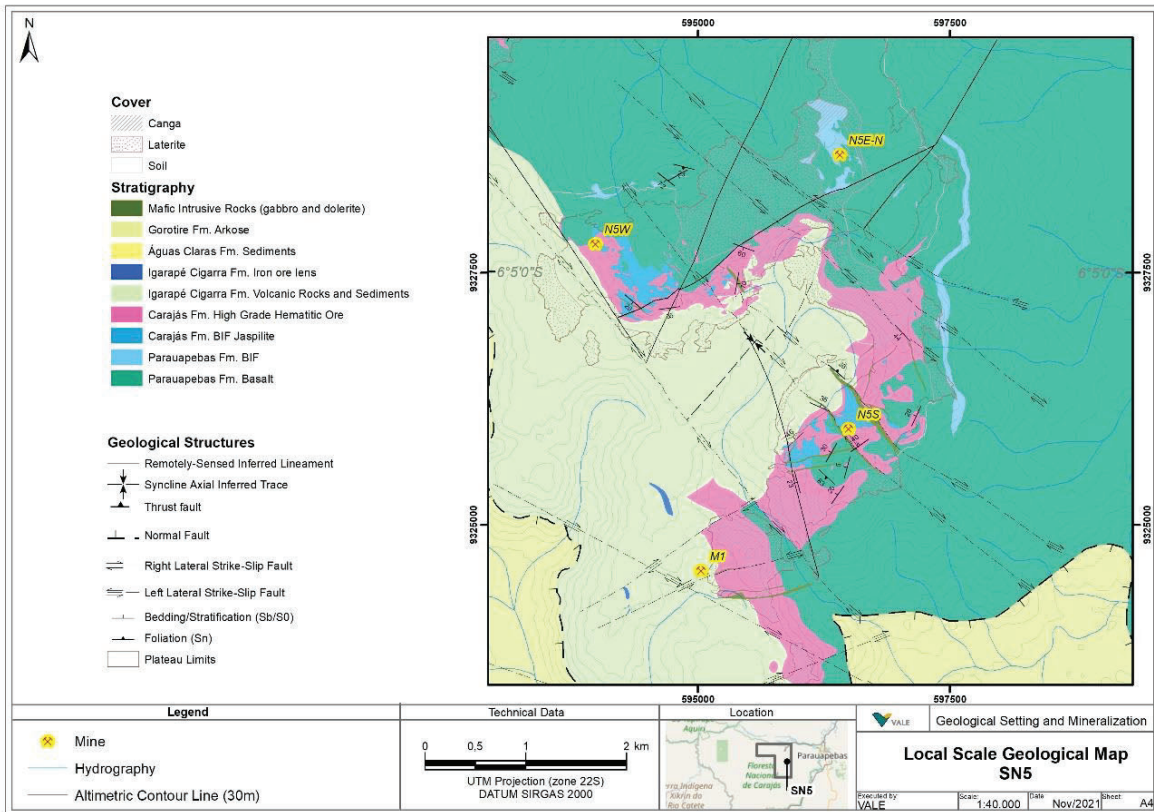


Figure 6-13 - N5 Geological map

Intrusive rocks define bodies of metric thickness and variable orientation that tend to follow the fault planes and cut through the entire Grão Pará Group sequence. These rocks have basic/intermediate composition, predominantly fine texture, and make conformable to non-conformable contacts with the bedding and the banding, configuring sill and dike families (**Erro! Fonte de referência não encontrada.**). To the west and south of the plateau, arkoses of the Gorotire Formation predominate, which constitutes a considerably younger unit occurring along a graben (Figure 6-13).

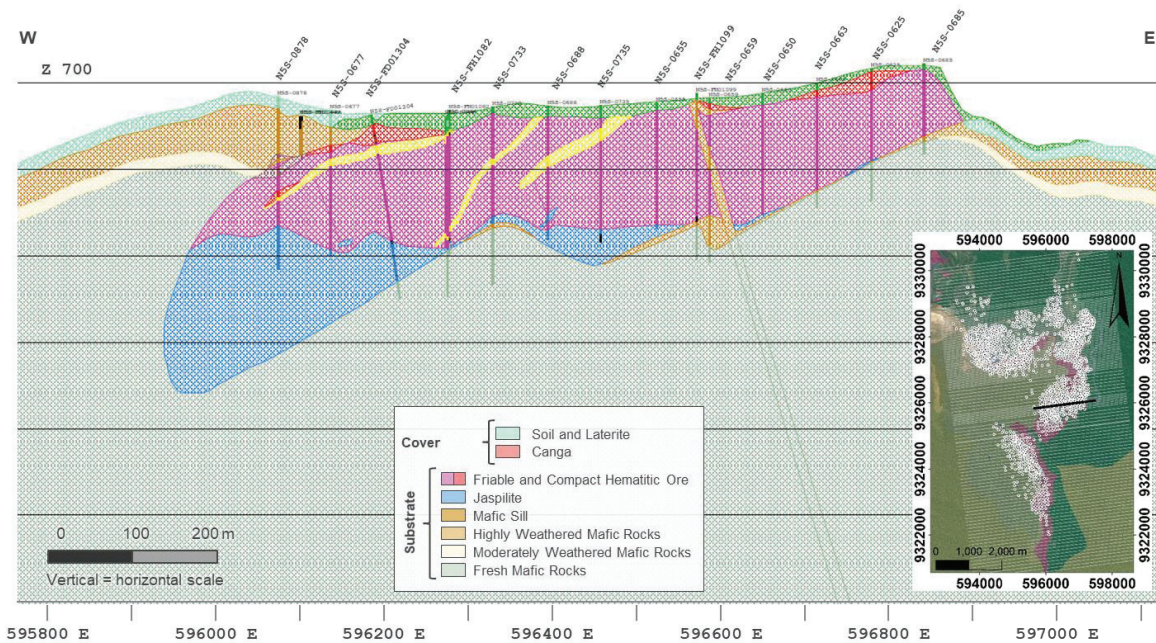


Figure 6-14 - N2 and N5 S Geological map

6.3.4.3. Structures

At N5, the Carajás Formation behaves like a homocline, with a trend varying from NW-SE to N-S and dips to SE and E. The sinuous character in the northern portion of the plateau is given as a function of a syncline, which, associated with the fault system, verified throughout the plateau, controls the geometry of the iron formation (Figure 6-13).

Structures correlated to Transamazonian tectonism:

- Dextral transcurrent fault system, with NW-SE orientation, which is articulated with small dextral transcurrent faults, with E-W orientation, responsible for the segmentation of iron formations (**Erro! Fonte de referência não encontrada.**)

Structures correlated to Brazilian tectonism:

- Reactivation of part of the faults with NW-SE orientation, giving sinistral kinematics to them (Figure 6-13);
- Kink-style folds that form with different scales of occurrence and axis orientations, mainly present in the iron formations; and
- The Buriti Syncline, with the axis falling to SW, is not compatible with the tectonic vector of either event. However, this structure is here experimentally correlated to Brasiliano, considering that the presence of the reactivated fault system may have acted as a modifier of the general field of stress on a local scale.

6.3.4.4. Mineralization

As already described for the previous deposits, N5 mineralization is formed after the alteration of jaspilite and will be addressed briefly here, with emphasis mainly on the unique aspects of the area under consideration.

In the N5 mine, the lithology known as iron-manganese (FMN) occurs as small lenses, with a thickness of up to 30 m and low lateral continuity, normally located close to the contact with sills and dikes, which suggest a hydrothermal origin. It is characterized as a hematitic material, weakly magnetic, with greenish-gray color, metallic luster, and high porosity, ranging from friable to powdery.

It has low average overall iron grade (45.03%), high Mn grade (9.28%), and contaminants, such as Al₂O₃ (3.64%), in addition to loss on ignition (LOI) of 6.267%.

Table 6-4 - Characteristics of the mineralization in N5

Lithotype	Deposit partition (%)	Maximum section thickness (m)	Average iron content (%Fe)
Friable Hematite (HF)	83	350	66,69
Canga (CG)	11	60	63,12
Compact Hematite (HC)	4	50	66,52
Manganiferous Hematite (HMN)	2	60	61,01

7. Exploration

7.1. Exploration

7.1.1. Introduction

The mineral exploration started in the '70s and is still in progress. Currently, most of the areas comprise a drilling grid of 100x100m, 100x50m or 50x50m within the mining areas, focused on detailing the ore bodies and investigation of new potential areas for reclassification of resources to measured and indicated. In the surrounding regions, the grid is generally spaced by 200x200m.

7.1.2. Topography

The topographic surveys used for modeling, resources and reserves estimation were generated by composing of detailed topographic surveys carried out by the short-term teams and LiDAR aerial surveys acquired under the supervision of Vale since 2006. The mine teams prioritize the use of information to cover all operational areas, with aerolaser being used to complements the polygonal area of interest. The topographies are available about Horizontal Datum SAD69 and Vertical Datum PD04, projected at UTM-22S.

7.1.3. Geophysics

The most used geophysical tools in ferrous mineral exploration are aeromagnetic surveys, aerial FTG gravimetry, geophysical profiling of drillholes by gamma-gamma and two-dimensional electrical imaging surveys.

Geophysical drillholes surveys have been applied systematically since 2012 in Vale's projects. Several geophysical logging tools have been used based on acoustic, electrical, nuclear and optical techniques, depending on the purpose, although the most common is the use of natural gamma radiation and gamma-gamma radiation tools. The survey is carried out by an outsourced company, supervised by Vale's team of geophysicists, who are also responsible for QA/QC of the data and the interpretation of the results.

The main geophysical anomalies detected in mine areas are handled and selected as targets of geological mapping and drilling. In addition, part of the most recent holes has been profiled by gamma-gamma method.

7.1.4. Qualified person's interpretation of the exploration information

The Serra Norte Complex has been extensively explored since '70s, and a big database has been developed as a result of both exploration and mining activities. The primary exploration method is core drilling and assay collection. However, the progress in geophysics has improved the amount and the quality of data which can be used for geological interpretations and geological modeling.

7.1.5. Exploration potential

Further work is required to determine the exploration potential below the current open-pit operations and new targets identified from mapping or geophysical anomalies, mainly associated with friable and compact hematites. However, the data available so far confirms the great continuity of the iron formation bodies both on the surface and in depth, which shows positive expectations regarding the exploratory potential of this area.

7.2. Drilling

7.2.1. Overview

The exploration of Serra Norte started in the late 60's and continued to the early 70's. At this time, a large exploration campaign was carried out, covering the entire Mineral Province of Carajás. The project included the areas of Serra Norte, Serra Sul, Serra Leste, and São Félix do Xingu, all with great potential for geological resources of iron ore. Currently, this work is coordinated by the Ferrous Geology and Drilling Management.

7.2.2. Drilling on property

Long-term drilling campaigns in Serra Norte were carried out in various periods, with the first records from the 1960s. In general, the drilling grids have spacings of 200x200 in horizontal projection in all Serra Norte deposits and closures of 100x100m, 100x50m or 50x50m in irregular grids, mainly in the mining areas of N4 and N5. Table 7-1 show a summary of the drilling campaigns carried out in the Serra Norte deposits and Figure 7-1 to Figure 7-5 presents the spatial distribution of these drilling campaigns in each deposit.

Table 7-1 - Distribution of drilling campaigns over the years in all Serra Norte deposits.

Deposit	Year	Meters
N1	1968-1971	3,760
	2001-2004	3,475
	2005	29,259
	2006-2007	13,554
	2012-2013	6,735
	Total	56,783
N2	1970	516
	2002	1,893
	2012	5,055
	2013	1,938
	Total	9,401
N3	1970	483
	2002-2009	3,861
	2010-2011	13,222
	2018	10,814
	2019	5,589
	Total	33,969
N4	1970-1979	21,271
	1991-1999	45,171
	2000-2009	191,453
	2010-2014	83,945
	2015-2018	43,597
	Total	385,437
N5	1971	5,138
	1993-1999	20,683
	2000-2009	125,271
	2010-2014	77,265

Deposit	Year	Meters
	2015-2017	22,590
	Total	250,948
TOTAL		736,537

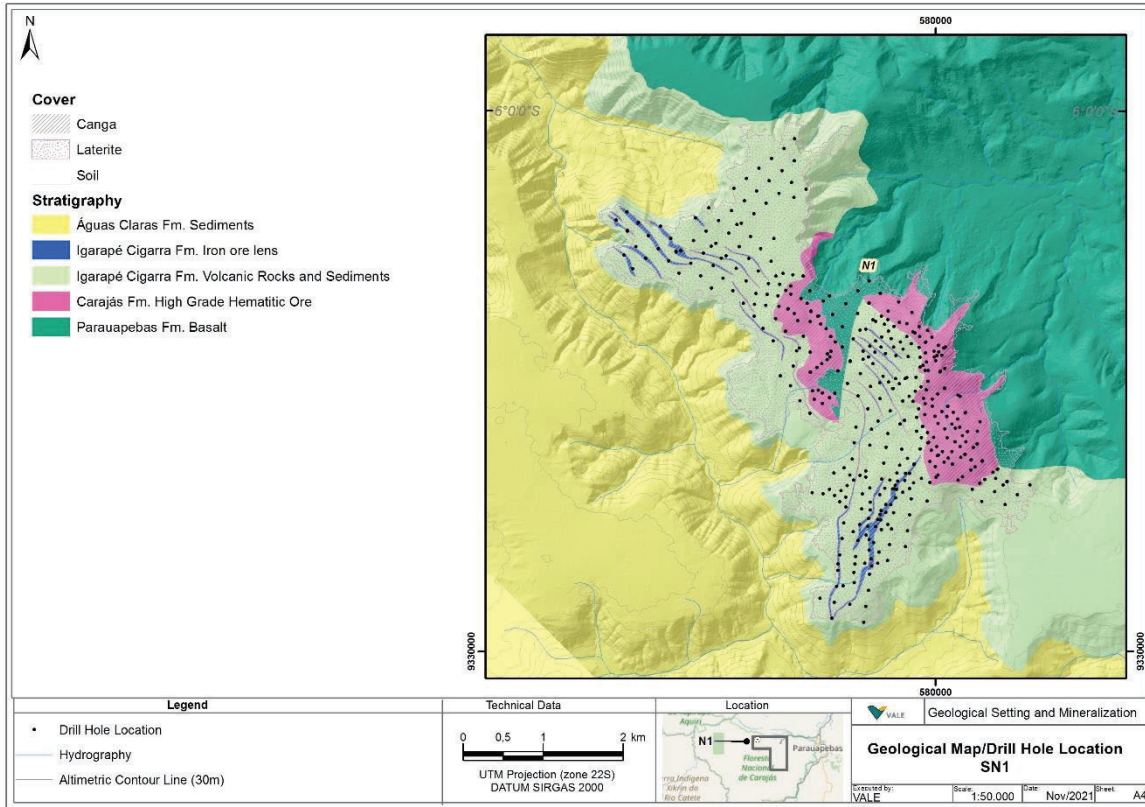


Figure 7-1 - Spatial distribution of the long-term geological drilling in the N1 deposit.

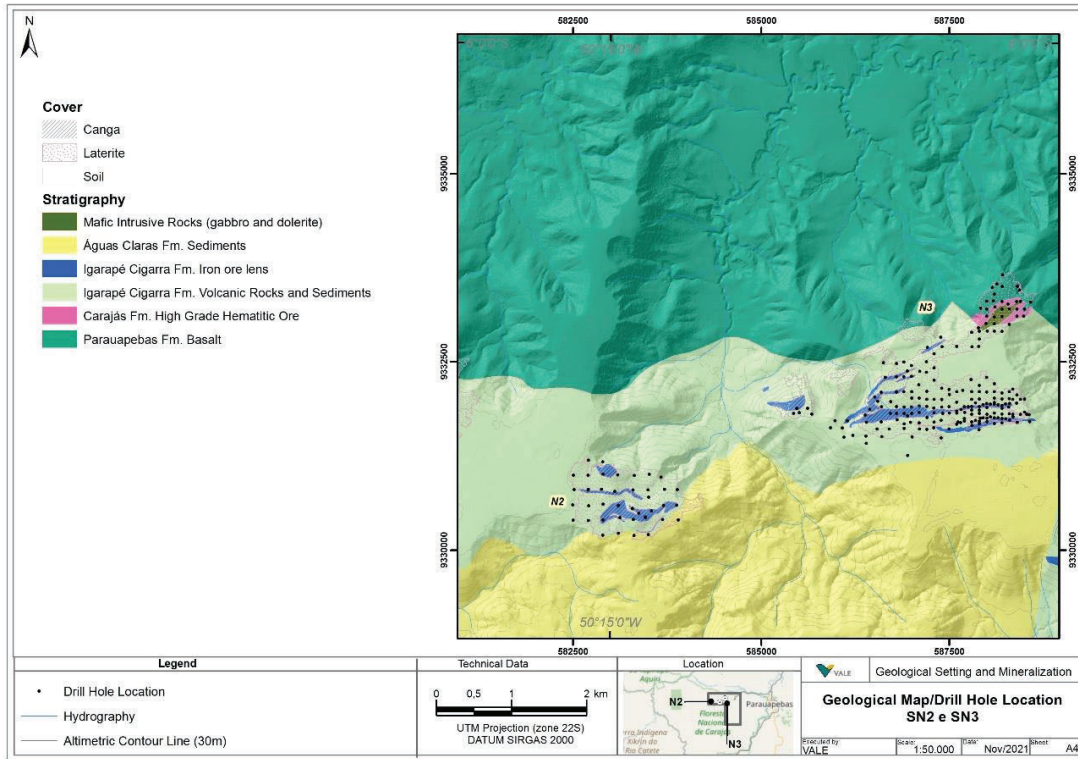


Figure 7-2 - Spatial distribution of the long-term geological drilling in the N2 and N3 deposits.

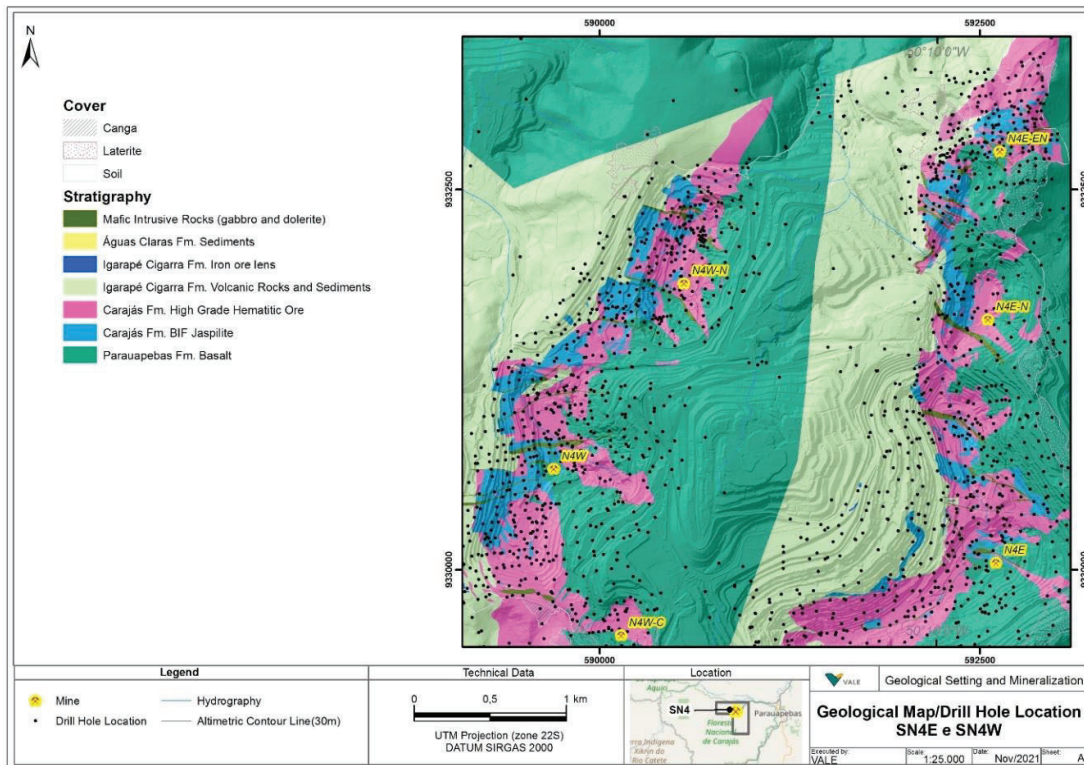


Figure 7-3 - Spatial distribution of the long-term geological drilling in the N4E and N4W deposits.

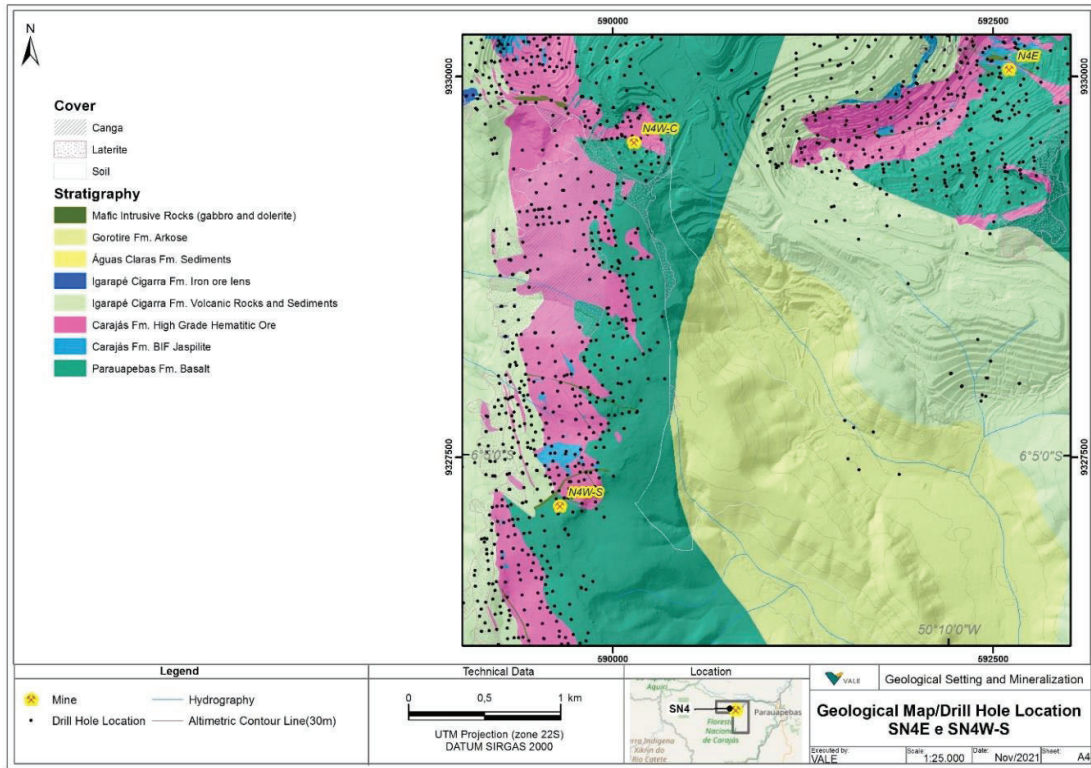


Figure 7-4 - Spatial distribution of the long-term geological drilling in the south portion of N4E and N4W deposits.

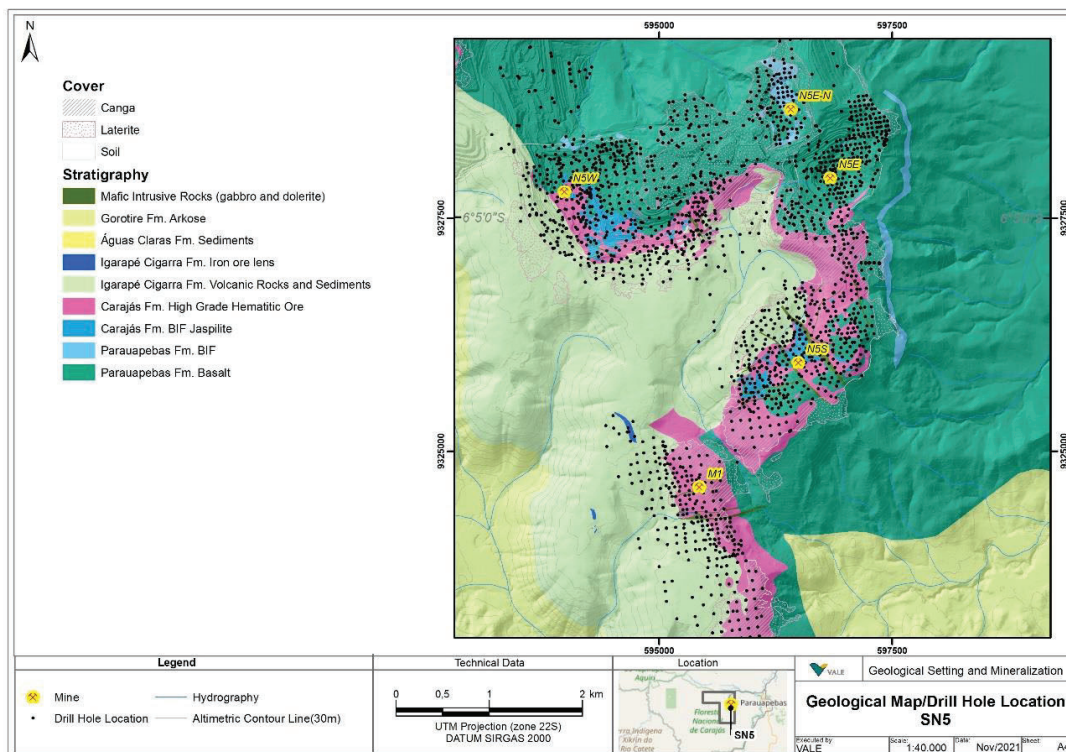


Figure 7-5 - Spatial distribution of the long-term geological drilling in the N5 deposit.

7.2.3. Drilling excluded for estimation purposes

Boreholes that showed inconsistencies during the database validation process were either fixed in the database or excluded from the resource estimate. Further discussions on this item are presented in the sample regularization process for grade estimates and resource classification in Chapter 11 (Mineral Resource Estimates).

7.2.4. Drill methods

The drilling type is conventional rotary diamond drill and most drillholes are vertical to sub-vertical. The drilling diameters are variable over time between HW (76.2mm), HQ (63.5mm), or even NW (54.7mm), NQ (47.3mm), BW (42mm), and BQ (36.4mm). The last two diameters are adopted only in some situations due to operational issues.

7.2.5. Logging

In the Serra Norte deposits, the geological logging of the holes drilled between 1968 and 1972 were recorded in the research report prepared at the end of the campaign. Since 1991, the core logging was made in field notebooks and from 2003 onwards, carried out directly in digital media. In addition to the geological logging, geotechnical descriptions were also performed in several holes, using a standard spreadsheet, in which macroscopic characteristics were described, such as degree of alteration, consistency, type of discontinuity, roughness, type of filling and RQD (Rock Quality Designation), among others. For all these items, there were standardized codes for filling in the worksheet. There was also a descriptive field for relevant observations.

Since 2012, the description standards defined by Ferrous Geology and Drilling Management are used. The procedure for all Serra Norte areas stipulates standard sampling of 15m for brown field projects and mines in Carajás, and 10m for exploration areas. This sample support can vary 50% for the minimum length and 10% for the maximum length. In this case, the minimum length can be 7.5m and the maximum 16.5m for mining areas. The collection is made on the left side of the box, along its length, keeping the remaining 50% in the core boxes. The friable materials are collected with the help of a metal shovel with standardized dimensions, according to the drill hole diameter and compact materials, such as compact hematite (HC), jaspilite (JP), and unaltered mafic rocks (MS), are cut lengthwise using a diamond saw.

Currently, most drillholes are stored in the Serra Norte Core Shed located at the N5 mine.

7.2.6. Recovery

Core recovery is good at all deposits of Serra Norte Complex. The average recovery of the drillholes core is about 90%. Areas of poor recovery are typically limited to fault and shear zones. Drillholes below 50% recovery are excluded from the database.

7.2.7. Collar surveys

The drillhole coordinates data is obtained through topographic surveys and stored in Geological Database Management System. Currently, this data is collected about Horizontal Datum SAD69 and Vertical Datum PD4, projected at UTM-22S.

7.2.8. Down hole surveys

Different surveying equipment was used, such as the Maxibor I, Maxibor II, Deviflex and Reflex gyroscopes. Surveying was also carried out using Tropari equipment; however, the data was not used in geological modeling due to interference from the magnetism of the iron formation.

7.2.9. Comments on material results and interpretation

Drilling and surveying were conducted in accordance with industry-standard practices at the time the drilling was performed and provide adequate coverage of the zones of iron ore mineralization. Generally, the collar and down hole survey methods used provide reliable sample locations. The drilling methods provide good core recovery. The logging procedures provide consistency in the descriptions.

This data was suitable for mineral resource and mineral reserve estimation. There are no drilling or core recovery factors in the drilling to support the estimates known to QP that could materially impact the accuracy and the reliability of the results.

7.3. Hydrogeology

7.3.1. Overview

Hydrogeological characterization mainly starts during exploration campaign phase, observing and gathering geological and groundwater information, which will serve as a basis to studies developed during all phases of a mine site.

In this phase, the monitoring program is implemented, and it's composed by rainfall gauges, piezometers, water level indicators, and flowmeters installed on springs, streams and rivers. At this stage, a pre-dewatering program is established if necessary, and all monitoring data will be used to set up drawdown targets.

To build the hydrogeological model, the available database 2015 to N4 and N5 mines, 2018 to N1 and N2 mines, and 2021 to N3 mine was used. A complete Vale's QA/QC program for the hydrogeological database is under development. Currently, the data is analyzed by Vale and sent to consultants responsible for building the hydrogeological models, which make a cross check validation from all data used as input.

The demand for water in this mining complex is supplied by surface and underground sources. Surface water is collected at the Igarapé Gelado dam and used as raw water for the industrial process of the iron ore processing plant. Underground water is collected through deep tubular drill holes drilled in mines N4 and N5, being destined for industrial use, supplying WTP, spraying roads, water replenishment in the Jacaré and Buriti streams. The remainder is destined to the Pêra and Gelado dams.

7.3.2. Parameters

According to Beale & Read (2013), laboratory tests are the more accurate determination method for water flow parameters; however, there is disadvantage that the used samples may not be representative and can be disturbed during sampling, transport, and handling. For this reason, in Vale mines multiple-hole tests in field and comparison with literature were preferably used to determine the main aquifer parameters (transmissivity, hydraulic conductivity, and storage coefficient).

7.3.3. Groundwater model

Hydrogeological models are tools used to represent the dynamics of groundwater in a simplified way and enable simulation of different scenarios. The main objectives in these models are estimate outflow rates, water availability, and provide water level data which will be used as input to geotechnical stability analysis.

The dewatering is done by pumping wells and or dewatering tunnels located in the iron formation, which also corresponds to the main aquifer. The slope depressurizations are performed by pumping wells, horizontal drain holes and natural discharge.

To build the hydrogeological model, the following steps were followed:

- Data compilation: Compilation, verification, and analysis of preexisting hydrogeological monitoring data: groundwater level, rainfall, stream gauge, in addition to the geological information.
- Hydrogeological conceptual model: Interpretation of the data compiled into a model which will serve as a “sketch” for the numerical model, containing the hydrogeological units, potentiometric surface, recharge zones, discharge zones, and pumping wells.
- Preparation of the numerical model: From the conceptual model, the data is entered into the modeling software (Visual MODFLOW or FEFLOW), where the governing flow equations and mass balance calculations will be solved.
- Calibration of the numerical model (permanent/transient): Calibration consists of comparing the calculated hydraulic heads with those observed in the monitoring instruments (water level indicators and piezometers). The hydrodynamic input parameters are modified by a factor called nRMS (Normalized Root Mean Squared), which works as an indicator of confidence. The best factor reaches a value of less than 10% (nRMS<10%), as well as the evaluation of the mass balance (inputs/outputs) of the boundary conditions used in the model. The models were calibrated to ensure the confidence between the monitored and the calculated data.

The database used to build the model data was considered satisfactory to achieve the main objective as the model was calibrated, and for Serra Norte complex mines, it is shown in Table 7-2 which summarizes the main information and the variables considered in the analysis stages, considering the results of the simulated flows for the maximum drawdown of the pits as well.

Table–7 2 - Summary of the general conditions used and the results of the numerical simulations

Contracted Company	Pit	Calibrated model year	Software	nRMS (%)	Drainage flow rate (m ³ /h)	Number of instruments considered in the calibration
HIDROVIA	N1	2018	FEFLOW	2.32	670	16
HIDROVIA	N2	2018	FEFLOW	2.32	164	16
MDGEO	N3	2021	Visual MODFLOW	9.84	539.6	5
MDGEO	N4W e N4E	2015	Visual MODFLOW	1.80	2,636	24
MDGEO	N5	2015	Visual MODFLOW	2.50	1,490	12

7.3.4. Comment on results

The monitored data was considered satisfactory to achieve the main objective, which is build, calibrate and simulate future mining scenarios in a groundwater numerical model.

Vale is currently improving its ground water monitoring network and the QA/QC program is under development, which will increase the confidence on data and numerical models.

The Qualified Person’s opinion is that the database analysis and the quality control procedures are sufficient to provide reliable data to support the estimation of mineral resources and mineral reserves.

7.4. Geotechnical

7.4.1. Overview

The geotechnical information is constituted of previous experience in closer mines and data obtained during early stage. The geotechnical evaluations are complemented by data obtained during the mining activities.

Geotechnical core logging and geotechnical mining mapping are the main data collection methods. The core logging follows an internal procedure (PRO-030016 rev0) which defines the steps to be followed for the geotechnical description, essential to obtain the adequate individualization and characterization of the geotechnical intervals. For site mapping, geological, geotechnical, and structural data described is used to define the geotechnical domains. The structural mapping is obtained from regional and local surface geological mapping and drillhole interpretation.

Main structures with failure trigger potential are joints, bedding and pervasive foliations. The structural domains and their respective stereonet were used for kinematic analyses and failure mechanism interpretation.

For core logging or mapping, the collected data follows the tables proposed by ISRM (1997), Bieniawski (1989) and Martin & Stacey (2018) adjusted by Vale (2019) to fit the iron formation deposits. The described geotechnical parameters are compressive strength, weathering, degree of fracturing, RQD, type of discontinuity, alpha angle of main discontinuity, main discontinuity conditions (opening, roughness, spacing, wall alteration, wall filling, type, and thickness). These characterization parameters are applied to define different rock mass classification systems used in Vale's mines.

Vale's open pits are mainly composed of weak and friable rocks. To classify these rocks, the Weak Rock Classification presented by Martin & Stacey (2018) is used, applied to materials whose uniaxial compressive strength is less than 10 MPa, equivalent to the compressive strength range bellow R2- (Figure 7-6). Rocks with compressive strength equal to or greater than R2+ are classified according to RMR (1989).

The GSI classification is also used and obtained through empirical correlation with the RMR value proposed by Hoek (2001), where $GSI = -RMR - 5$. For some mines, where this correlation has been tested, it is possible to have a different empirical value, and in some cases, GSI are obtained from mine site superficial GSI mapping.

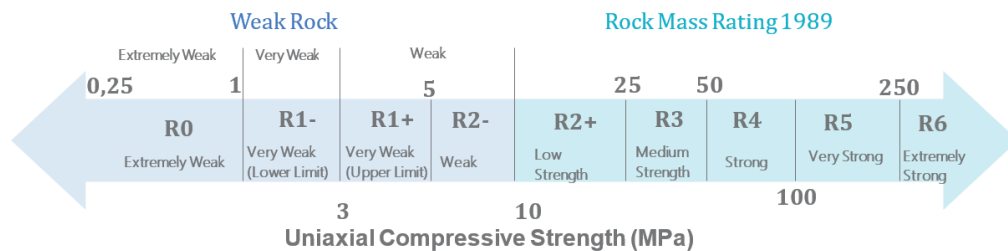


Figure 7-6 - RMR and Weak Rock classifications as a function of the material strength (Modified from Martin & Stacey (2018)).

Typical structural characterization consists of describing and defining joint sets (including bedding and foliation), faults, shear zones, and dykes through structural mapping. The use of geophysical core logging (televviewer surveys, electrical resistivity and sonic method) is still in the stage of testing and implementation at Vale to determine geotechnical intervals and parameters, such as Poisson ratio, Young's module, total porosity, bulk density, and structures dip-direction.

The geomechanical models of all mines located at Serra Norte Mine Complex were build using about 476,300 m geotechnical logging and 12,363 geotechnical superficial mapping points. These databases were made and/or validated by independent consultants.

Samples for geotechnical tests (disturbed and undisturbed) are obtained from drill cores and in situ (mines surface). Sampling methods follow internal criteria that guarantee the sample quality, control, and representativeness.

Routine site visual inspections and monitoring made by internal geotechnical team to identify geotechnical anomalies, such as tension cracks, problems with surface drainage inefficiency, blasting overbreak, rockfall hazard or any feature that can impair the slope stability are conducted to guarantee the continuous operational safety control. All identified non-conformities are registered and forwarded directed to the responsible for operational solution through an internal system.

The use of integrated monitoring systems with prisms (TDR), water level indicators, piezometers, inclinometers, extensometers, crack meter, ground radar and orbital radars supported by routines visual inspections guarantee early alarms and continuous monitoring 24/7 for specific slopes controlled by a proper monitoring center.

The hydrological model is used to promote the operational pits superficial dewatering. The Surface Drainage Master Plan was elaborated for control and direction of the superficial water from the dewatering and rainwater. It guides the planning and operational teams on the drainage system project in the pits.

The purpose of the mine drainage system is recovery and reuse of mine water within the mining operations for ore processing, material conveyance, operational use (e.g., dust suppression), and environmental protection, specifically related to the impacts of the mining water on surface water and groundwater resources. Off-site run-off water can also be diverted away from the mine and waste facilities to reduce the water volume to be treated.

Local regulatory requirements stipulate mine water discharge quality or associated discharge pollutant loads. Mine drainage treatment may be a component of overall mine water management to support a mining operation over the entire life of the mine and enhances post-closure and sustainable use of the mine property long after the ore deposit is depleted.

7.4.2. Parameter Determinations

The used strength and elastic parameters are obtained from direct geotechnical testing which typically comprises: triaxial shear tests (CU, CD and Hoek cell), direct shear test, UCS (Unconfined Compressive Strength), Brazilian-tensile test, P and S waves velocities, as well as indirect methods, such as Schmidt Hammer and PLT (Point Load Test). The direct geotechnical tests are carried out by several private laboratories and public institutions, which follow international and national standards for execution, and in general, are ISO 9001 certified. The main tests use the methodologies set out in: ASTM D4767, ASTM D7181, ASTM D5407, ASTM D7012, ASTM D3080, ASTM D4543, ASTM D3967, ASTM D4428, ASTM D5873 and ASTM D5731.

The indirect methods and tactile-visual tests, based on geological hammer blows or other elements for strength assessment, are applicable during mapping or in the description of drill cores (ISRM, 1997) and are carried out by internal geotechnical team in warehouses for the storage and description of drill cores and follow the standards described in internal procedures. For weak rocks (compressive strength below or equal to R2-), Mohr Coulomb strength envelope were obtained from existing geotechnical tests. Materials with strength anisotropy were tested in different directions (parallel, perpendicular, and oblique). The strength properties of hard rocks (compressive strength above or equal than R2+) were directly obtained through laboratory geotechnical tests and the rock mass parameters were obtained according to the Generalized Hoek-Brown criterion (Hoek, 2001).

The discontinuity properties were obtained through direct shear tests in which the maximum strength (pick resistance) occurs on the discontinuity surface itself. In addition, from surface mapping data and drill, core descriptions were obtained, according to Barton and Bandis criterion (1990), setting JRC (Joint Roughness Coefficient) and JCS (Joint Compressive Strength) parameters. For the lithotypes without tests in the evaluated mine, the parameters obtained for nearby mines with similar lithostratigraphic, tectonic and geomechanical contexts were used.

7.4.3. Slope stability analysis

Two-dimension slope (2D) stability analyses were made by the Equilibrium Limit Method (ELM), using software Slide2®, developed by Rocscience Inc., to assess potential non-circular and/or circular failures, considering the most actual geological, hydrogeological, and geotechnical models,

possible failure mechanisms and strength parameters. These analyses were made along the entire pit, based on the representative sections that may influence instabilities (critical sections), evaluating mainly inter-ramp and overall slope scale failures. Bench scale analyses were made through Kinematic analyses and specific analysis. Based on the analysis made, the bench, inter-ramp and overall angles were defined to design the pit.

Additionally, the water table used was supported by final pit drawdown simulations from the hydrogeological models.

In general, final pit slopes design with no near mine interferences may reach deterministic Safety Factor (FoS) equal to or greater than 1.3. However, final pit slopes design with near mine interferences (external roads, waste piles, railway, neighborhoods and other) should be dimensioned to reach FoS equal to or greater than 1.5. The acceptance criteria specificities were based on international references and good practices suggested by Read & Stacey (2009) as presented in Table 7-2.

Table 7-2 - Typical FoS acceptance criteria values. Source: Modified from Read & Stacey (2009)

Slope Scale	Consequences of Failure	Acceptance Criteria ^a	
		FoS _(min) (static)	FoS _(min) (dynamic)
Bench	Low-high ^b	1.1	NA
Inter-ramp	Low	1.15–1.2	1.0
	Moderate	1.2	1.0
	High	1.2–1.3	1.1
Overall	Low	1.2–1.3	1.0
	Moderate	1.3	1.05
	High	1.3–1.5	1.1
^a Needs to meet all acceptance criteria.			
^b Semi-quantitatively evaluated.			

As Brazil is located in an intracratonic region, the occurrence of high magnitude earthquakes is not expected, but the seismic activity in Brazil is known and monitored internally (Vale has a set of seismographs installed in several mines that contribute to this national seismographic network) and by external institutes. Local seismic studies for the Iron Quadrangle and Carajás regions are under development. For this reason, theoretical seismic accelerations were adopted.

Pseudo static (dynamics) slope stability analyses that consider earthquakes effects, were made basically for post mine closure. In operational and short-term assessments, the seismicity is not considered due to the low incidence and the low levels of the earthquakes. Additionally, for post mine closure recovery of the water level to the original levels (pre mining level) was considered. In general, the expected safety factor must meet the safety assumption FoS ≥ 1.1 as established in 2009 by Stacey & Read (Table 7-2).

7.4.4. Quality assurance and quality control

A complete Vale QA/QC program for the geotechnical core logging description is under development. Currently, the cross-validation techniques used were based mainly on three empirical correlations. The first cross validation for iron formations correlates Vale's crusher test with the estimates of rock compressive strength. The second correlates the estimated compressive strength with the weathering degree for each material. The third criterion consists of the relationship between the fracture degree, RQD and joint spacing.

The strength and elastic laboratory test results were validated by Vale's geotechnical team or independent supplier companies. Specimens with inconsistent and/or inconclusive results were discarded.

Duplicated samples were required, when evaluation errors were identified. Additionally, duplicate samples are sent to different laboratories, but there is no routinely established control program or even external audits to assess the equipment and the test results to ensure that all information and recommendations are consistent. On this issue, Vale has been setting up an internal rock and soil geotechnical laboratory following international standard since 2019. This laboratory will be used to carry out periodic check routine and audits in the private and public laboratories used by Vale.

Actually, quality assurance resumes to demand regular calibration of equipment by outsourced laboratories and own equipment (according to criteria specified for each of them). The contracts with the laboratories follow international quality assurance criteria and standards for the delivered result, incorporating actions to be taken if the test results do not comply with the required specifications. These verification systems are still not implemented as mandatory; however, it includes occasional checks in transport, storage, testing and presentation of results, seeking protection against physical damage, quality, and control of the tested samples, including information on test types, test quantity and evaluation measures.

7.4.5. Comment on the results

A combination of historical, near mine, and current geotechnical data, with the mining site experience of internal teams supported by national and international consultants, are used to establish internal guidelines and procedures in the slope stability design and operation of Vale's open pit mines based on international standards and best practices. Analytical methods are used to assess the behavior of the intact rock, rock mass and influence geological structure.

Vale is currently improving its laboratory tests and drill holes investigation in waste rocks to support the geotechnical models and slope stability analysis better and QA/QC program is under development, which will increase the confidence on data and numerical models.

The Qualified Person's opinion is that the sample preparation, analysis, quality control, and safety procedures are sufficient to provide reliable data to support the estimation of mineral resources and mineral reserves.

8. Sample preparation, analyses and security

8.1. Overview

The Vale corporate governance process supports the acquisition of reliable data for Mineral Resource and Mineral Reserve estimation. Each operation has documented protocols and internal controls for drilling, sampling, sample preparation, and assaying procedures approved by Vale's Resource Management Group. Documentation of the protocols is kept as current and the personnel receive adequate training to apply them. All data is properly identified by unique reference numbers so that drill hole information can be reliably restored from the independent collar, survey, geology, physical properties, and assay tables. All data is verified and checked before entry in the database. The sampling practices and assaying methodologies are clearly described and supported. The proficiency and the technical capabilities of the sample preparation and assaying facilities are confirmed by periodic reviews—and - or audits. The database contains all relevant information for Mineral Resource and Mineral Reserve estimation. The database used in estimation contains unbiased and representative data, and any major issues identified by QA/QC programs have appropriate corrective actions applied and disclosed.

8.2. Sampling methods

The drill core samples are taken in Vale core sheds, with the sampling plans prepared by geologists shortly after the description and the collection carried out by the technical assistants, usually from contracted companies. Between 1960 and 1979, physical preparation and chemical assays were carried out internally in laboratories located in Serra Norte (N1 area) and Belo Horizonte, Minas Gerais. In 1989, VALE'S laboratory was inaugurated at the N4E mine, currently belonging to the Ferrous North Management of Process Development and Laboratories. The laboratory performs physical preparation activities and chemical analysis of exploration and production samples of iron and manganese ores. Between August 2008 and mid-August 2009, the samples from geological exploration were prepared in an outsourced laboratory of the company SGS Geosol Laboratório Ltda. located in the city of Parauapebas, in state of Pará. Between mid-August 2009 and April 2013, the samples were prepared by the company Intertek do Brasil Inspeções Ltda. in the physical preparation laboratory of GAMIK/VALE, located in the N5 mine, later using the laboratory in the city of Parauapebas. The physical preparation work outsourced to SGS Geosol and Intertek was carried out under supervision by VALE (Laboratories Management). Since April 2013, samples began to be prepared in VALE's laboratory, located at the N4 mine (Ferrous North Management of Process Development and Laboratories), where chemical assays are also carried out.

During the different drilling campaigns carried out in the Serra Norte deposits, the samples were assayed in different analytical flowcharts. The main differences between the analytical flows are the number of particle size fractions, the number of size fractions with chemical analysis, and the measured analytes, in addition to the type of sieving (dry or wet). Since mid-November 2008, a general review was carried out on the physical preparation flows of geology samples and a new standard flowchart was defined, which is in use until now. In this flow, several sieves are used (relief of the load in the sieving process), but only five granulometric fractions are generated, resulting from the mass composition of the various sieves. For the five fractions generated (+19 mm, -19+8 mm, -8+1 mm, -1+0.15 mm, and -0.15 mm), aliquots are taken for chemical assays. The sieving is done in dry process.

For the modeling work, a single file was generated with the samples grouped in particle size ranges: G1: +8 mm; G2: -8+0.15 mm and G3: -0.15 mm, with G1 and G2 being subdivided into G1A: +19 mm, G1B: -19+8 mm, G2A: -8+1 mm and G2B: -1+0.15 mm. The G2A and G2B ranges have mass results but no chemical assays. The long-term geological model database contains the results for the following analytes: Fe, SiO₂, P, Al₂O₃, Mn, LOI, CaO, MgO, TiO₂, FeO, K₂O, and Cu. The short-term database contains the analytes Fe, SiO₂, P, Al₂O₃, Mn, LOI, CaO, MgO, and TiO₂.

8.3. Sample security methods

8.3.1. Quality assurance and quality control

The historical QA/QC data, prior to 2012, related to control samples, twin samples, field duplicates, crushed material duplicates, pulverized material duplicates, external duplicates and standards did not reveal points of attention (in frequency and/or magnitude) regarding precision and accuracy (of sampling and chemical assays) that compromise the databases used for geological modeling and resource estimation purposes, resources and reserves classification of areas and mines in the Serra Norte and Serra Sul Complexes of the Carajás Mineral Province.

The current QA/QC data, since 2012 stored in the Geological Database Management System (GDMS), shows that in the period from 2012 to July 2019, the Carajás Lab processed samples from geological exploration, short-term and long-term geology according to the analytical flows of global chemistry and chemistry by particle size fractions from Serra Sul and Serra Norte areas.

Assays for Al₂O₃, Fe, Mn, P, LOI, and SiO₂ follow Vale standard PTP-000915 Version 02 of 08/08/2019 and relate to the following quantities: 1,640 crushed material duplicates, 3,380 pulp duplicates, and 1,938 samples of 7 types of standards.

Checks between different Vale laboratories (Carajás, Alegria and Timbopeba) and external laboratories (Intertek and SGS Geosol) were also carried out. The results of 470 external duplicates related to the following interlaboratories were evaluated: Carajás x Alegria (179 duplicates), Carajás x Intertek (54 duplicates), Carajás x SGS Geosol (105 duplicates) and Carajás x Timbopeba (132 duplicates).

The last laboratory QA/QC assessment was done in April 2019 by Vale personnel. In general, the laboratory performance is classified as satisfactory (conforming results \geq 90% or very close to 90%) and/or admissible (conforming + acceptable results \geq 90% or very close to 90%). In most cases, sampling/chemical assays accuracies are good and analytical biases/flaws are small or insignificant compared to the grade ranges involved.

For the Fe, the technical performance of the laboratory is satisfactory and considered acceptable. For contaminants, the technical performance varied from satisfactory to unsatisfactory (there are some points of attention at lower grades). Crushed material duplicates and pulp duplicates DP show higher percentages of non-conforming results and higher mean relative inaccuracies (although still acceptable), most likely influenced by the higher frequency of lower grades for Al₂O₃, Mn, P, LOI and SiO₂ analytes.

External duplicates assayed in the Intertek laboratory indicate a slight trend of overestimation at lower grades (still acceptable and conservative bias) for analyte P. External duplicates assayed in the SGS Geosol laboratory indicate a slight trend of overestimation and underestimation at lower levels (bias still acceptable) for P (conservative bias) and LOI (non-conservative bias), respectively.

The standard control samples indicate a trend of small overestimation at very low grades for Al₂O₃, Mn and P. The most relevant points of attention are under investigation by geology and laboratories teams.

Routine laboratory inspections are made to check organization and storage, equipment (scales, ovens, sieves, crushers, mills/pulverizers, splitters), operating procedures, and records related to the internal QA/QC program. QA/QC data revealed general indicators of non-conformity, precision and accuracy considered satisfactory, not compromising the database related thereto.

8.3.2. Database management system

The main information of the database of short- and long-term drillholes, as well as geotechnical holes, are organized in three tables: Header, Survey, and Assay.

The basic data comprised in the Header table are hole identification, east and north coordinates, elevation, depth, recovery in percentage, hole completion date, DATUM and whether the hole has been profiled or not.

For the Survey table, in addition to the hole identification, there is information about the azimuth, dip and depth of the hole.

The Assay table is composed of the following data: hole identification, sample code, intervals from/to, sample length, sample lithology, global chemistry of the different analytes, particle size in the ranges corresponding to the flowchart, chemistry by range of the different analytes, granulometric closure, chemical closure, recovery of samples in percentage, identification of the analytical flowchart used, date on which the results were made available by the laboratory and the type of sample.

8.3.3. Header table validations

The items below describe the validations made in the Header table in long, short-term and geotechnical drillholes of Serra Norte database.

Validation of Holes with Topography

Validation of the position of the holes, verifying the existence of conflicts of positioning in relation to the original and current topographies. All holes that showed differences greater than 10m were checked. Some holes were identified with elevation above the original topography or below the current topography, but these differences do not correspond to errors, as these holes are located in dump areas.

Validation of New Holes in the Database

This verification is done by comparing the database of the previous model with the current one. Thus, it is possible to check the difference in the total depth of the two databases and identify the new holes.

Drillhole Recovery Validation

For this check, the recovery column was considered, making a formula to indicate the holes with recovery below 50%. Holes with low recovery were discarded.

Validation of Duplicate Coordinates

This validation aims to identify holes with the same East and/or North coordinates. Holes with identical coordinates were discarded or there was partial use of the data. This can occur in cases of holes interrupted by operational problems that had to be re-drilled later.

DATUM Validation

This validation intended to assure that all hole position data is in the same Coordinate System and Datum. Vale defined Horizontal Datum SAD69 and Vertical Datum PD04 projected at UTM-22S for Serra Norte.

Coordinate Validation

In this validation, the coordinates of the original files from the Survey Monitoring spreadsheet are compared to the coordinates taken from the Geological Database Management System. No errors were found.

8.3.4. Survey table validations

The acquisition of the Survey table was made by extracting the GDMS data, original logging files and validated Header table data taken from GDMS. The items below describe the validations carried out in the Survey table in the database of Serra Norte model.

General Profile Validation

The general check of the profiling is done after the preparation of the Survey spreadsheet with all necessary data, namely: Hole, Depth (Prof.), Azimuth (Azim) and Inclination (Dip). Typically, the trajectory deviation data is required to cover at least 85% of the hole total length. The checks involve Azimuth differences, Dip differences, whether the hole has been profiled or not, the type of range and overall check of the difference between subsequent readings. The latter is the verification of the intervals whose dip or azimuth difference is greater than or equal to 1.4°/m.

Header x Survey Depth Validation

In this validation, the final depth of the Header table versus the final depth of the Survey table is checked.

Validation of Dip and Azimuth x Drilling Follow-up Worksheet

This validation refers to the comparison of the Dip and Azimuth values used in the modelling versus the original values in the Survey Monitoring spreadsheets (data considered official).

Dip and Azimuth Consistency Validation

The purpose of this validation is to check whether the holes with Azimuth equal to 0 are vertical and vice versa. There shall be azimuth for holes which are not vertical. We can also check the minimum and maximum values of dip and azimuth. It is important the dip always to be negative.

8.3.5. Assay table validations

The items below describe the validations performed in the Assay table of Serra Norte database.

Duplicate Sample Validation

This validation serves to identify the presence of duplicate samples in the database. No errors of this type were found.

Gap and Overlap Validation

This is one of the main checks in the database. It serves to identify the correct arrangement of the intervals, considering the “From” and “To” interval. This validation aims to highlight Gap errors (intervals with missing length) or Overlap (intervals with overlapping length). The check is done directly by crossing “From” and “To” information. No errors were found.

Validation of Calculated Global Content

This validation aims to check the global chemical values of all analytes calculated in the samples with particle size and range analysis. This calculation is made through a weighted average of the content by mass in the granulometric ranges using the formula:

$$GL = (Fe1A*G1A+Fe1B*G1B+Fe2A*G2A+Fe2B*G2B+Fe3*G3)/(G1A+G1B+G2A+G2B+G3)$$

No errors were found in the global grade calculations.

Validation of Anomalous Values

The check of anomalous values consists in verification of whether the maximum and minimum values are coherent with each analyzed element. It is possible, for example, to highlight column changes (P and Al₂O₃, for example). In the database, there cannot be chemistry values equal to 0, the minimum must always be the limit of detection. It is also possible to detect negative values. No inconsistent values were found in this check.

Granulometry Versus Chemical Validation by Range

This check is just to assure that necessarily, there is chemistry per range for any ranges with granulometry.

Validation of Equal Analytical Results in Different Samples

This is a simple but important check that considers the existence of equal results for some analytes. The check is done in the Assay, element by element, sorting and checking the difference or existence of equal results. This check must be done for all analytes and its considered an error when there are the same results for two different samples. No equal global results were found between two samples on all elements.

Sample Recovery Validation

The check must be done with a filter considering minimum recovery of 60% according to the “Manual of Good Practices of the Resource Estimation Management”. There may also be intervals with recovery lower than 60%, but they are intervals with NR-NS identification (not recov–red - not sampled).

Particle Size Closing Validation

To check the Particle Size Closing, the sum of the granulometry values must be considered. Subsequently, compare with the value taken from the Assay Table. The acceptable limit for particle size closing is from 99% to 101%.

Chemical Closing Validation

It verifies the stoichiometry of the chemical results and the sum of the granulometric fractions. In this validation step, it is checked whether the closure has been calculated correctly and whether the closure limits are acceptable. For this calculation, the following equation was used:

$$(\text{Fe} \cdot 1.4297) + \text{SiO}_2 + (\text{P} \cdot 2.2913) + \text{Al}_2\text{O}_3 + (\text{Mn} \cdot 1.2912) + \text{CaO} + \text{MgO} + \text{TiO}_2 + \text{K}_2\text{O} + (\text{Cu} \cdot 1.2518) + \text{LOI}$$

Although this check shows chemical closures below or above an accepted range, this is not a reason to invalidate the samples. Therefore, all these samples remain in the database, they were used in the geological modeling and it will be geostatistically assessed whether they will be used in the estimates.

Depth Validation between Assay, Header and Survey Tables

This is one of the main database checks. Basically, it consists of comparing the depth of drillholes in the three tables. The total depth of each hole must be the same in all tables.

8.4. Density Determinations

Density is an attribute with direct impact on quantifying of the mass of any mineral deposit, and exactly because of that, it is handled as a highly relevant item in VALE's iron ore geological models. Several works have been developed by professionals from the company over the years applying different methodologies to determine the density values, among which the following stand out: traditional methods (Santos, 2006), geophysical logging (Almeida, 2011), and normative mineralogical calculation (Ribeiro et al., 2014; Motta et al., 2016). Currently, the density values attributed to the blocks are made combining the three methods and the results can be seen in Chapter 11.

The validation of each method adopted, as well as the final value, was done through the analysis of descriptive statistics, visual inspection of vertical sections and review of the chemical analysis of each material. The validation aims to observe the consistency between the average, minimum and maximum values compared to those used in previous models and results from conventional methods.

8.4.1. Direct acquisition methods

The most used methods were Volume Fill and Sand Flask for friable materials or Volume displacement and Hydrostatic weighing method for compact materials. Below, a brief description of each methodology:

- Volume Fill Method: Consists of digging a hole with regular walls, removing the material and weighing it, coating the hole with thin plastic, and filling it with a known volume of water.
- Sand Flask Method: Consists of digging an opening in the floor with regular walls, removing and weighing the extracted material. This hole is then filled with selected sand of known density, and from the selected sand volume and mass data, the material density is determined.
- Volume Displacement Method: Density is calculated from the relationship between sample weight and water displacement caused by immersing the sample in a graduated container.
- Hydrostatic Weighing Method: Density is derived from the ratio between the weight of the sample divided by the loss of weight when the same sample is immersed in water, using the Jolly scale.

Moisture is obtained by drying an aliquot of the sample, comparing the dry (M) and the wet mass of the sample (M+MH₂O). This is very important because in Vale iron ore mine evaluations, the tonnage calculations are carried out with the density in the natural base (ρ_u), considering the mass of free water (MH₂O) obtained from the moisture measurements (u). In all conventional density determination methodologies, natural density and moisture values are determined, and dry density is calculated.

8.4.2. Indirect acquisition methods

Gamma-gamma or gamma backscattered geophysical logging is based on the interaction of radiation with the surrounding matter. The gamma-gamma probe has a radioactive source and a scintillation meter. This probe emits gamma radiation, and depending on the electron density present, it is deflected. The scintillation meter measures the amount of radiation scattered through the medium, so the denser the rock, the smaller the scattered amount. The technique continuously records variations in the specific masses of rocks traversed by a hole. The measurement of the total density of a rock, with the density profile, is made through a monoenergetic beam of gamma rays that bombards the walls of the hole.

8.4.3. Mineralogical Normative Calculation (CNM)

The normative calculation works were developed by Ribeiro (2003) for the lithotypes of Banded Iron Formations of the Iron Quadrangle, complemented by observations made by Voicu et al. (1997) regarding the calculation of the paragenesis of rocks with a relevant weathering profile. The first studies coordinated by Ribeiro in Vale's internal project was carried out in 2010 only for siliceous compact itabirites, where the paragenesis is basically composed of quartz and iron oxides. Considering the proportions of each mineral, obtained based on global chemistry, and their respective theoretical densities, the total density of each sample was calculated. The correlations obtained by comparing these results with the data collected by direct methods were very good, and therefore, it was decided to extend the application of this technique to the other iron-enriched lithotypes in VALE deposits.

Case studies carried out later by Motta et al. (2016) considering the particle size partitions to obtain the paragenesis and density calculation, also showed good correlations (Figure 8-1). This work represents progress in the methodology itself by handling the difference between the density of the finest and the coarsest part of the material because, implicitly, it considers the porosity of each particle size fraction.

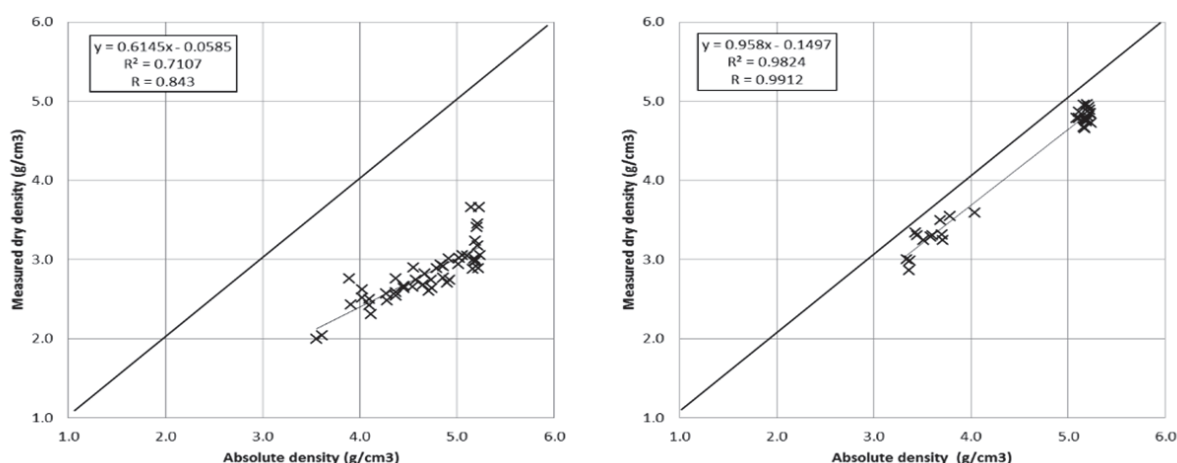


Figure 8-1 - Linear regression between the mineralogical density and the measured dry base density for friable (left) and compact (right) samples, according to Motta et al. (2016).

Recent studies based on pycnometer tests carried out in the laboratories of the Mineral Development Center (CDM) and in the Technological Research Center (CPT) of VALE confirm the mineral density values calculated with this methodology. The database contains 267 samples of pulverized material from chemical analysis of density samples by direct acquisition.

8.5. Qualified person's opinion on sample preparation, security and analytical procedures

The sample preparation, analysis, quality control, and security procedures applied in Serra Norte Complex have changed over time to meet industry practices and frequently were industry-leading practices.

The Qualified Person's opinion is that the sample preparation, analysis, quality control, and security procedures are sufficient to provide reliable data to support estimation of mineral resources and then mineral reserves.

9. Data verification

9.1. Internal data verification

9.1.1. Data collection and storage

The mineral exploration management responsible for the geological description, data collection, and QA/QC has daily checks procedures from the drilling to the reception of chemical results from the laboratory analyses.

During the drilling process, several processes are checked by the drilling inspectors, from the depth of the hole, recovery in each maneuver, until the transportation of the core boxes to the core shed. After the hole is drilled, the spatial trajectory deviation logging is carried out followed up by the drilling inspector and with validation of the obtained data.

For the receiving, checkout, and arrangement of the boxes in the core shed, there is a quality management protocol aimed at physical integrity, identification of the boxes, arrangement of the boxes on the pallets (lined for plastic boxes or stacked for wooden boxes), strapped boxes, unlocked pallets, checkout of the head sign, correct numerical sequences, depth, progress and recovery of the maneuvers.

The hole is exposed in the numerical sequence of each box and photographed. Geotechnical description, geological description, elaboration of the sampling plan for chemical analysis, elaboration of the sampling plan for density, and collection of samples is carried out. The core samples collected for physical and chemical analysis are placed in plastic bags properly labeled with barcode labels.

The boxes with half-core or non-sampled intervals are archived as defined in the core disposal procedure.

Vale has consistent QA/QC programs, including robust quality procedures and protocols, where precision and accuracy are assessed in most preparation and chemical analysis stages of the geological samples. Twin samples and field duplicates are used to monitor sampling errors. Crushed and pulverized material duplicates for assessment of the physical preparation (subsampling error). External duplicates and standards for chemical analysis (analytical error). For mitigation and possible reanalysis, the pulverized material residual are kept in identified plastic boxes. Continuous inspections are carried out in non-commercial internal and external commercial laboratories, thus guaranteeing effective process improvement.

Processes aimed at quality control and assurance and data integrity are under development and used in topographical data validation, spatial trajectory logging, geological description, sample collection and density tests. Among them, we can highlight peer reviews of the generated information, data validations, and error and mitigation reports.

All technical records related to the borehole, spatial and geophysical trajectory logs, photographs of core boxes, description, density tests, samples, petrography, physical and chemical results, among others, which constitute a source of data and information, are kept in the repository(ies) and - or information technology system(s) adequate and accessible for check and - or investigation, whenever necessary. There are operating procedures for all these processes, which are under the responsibility of the data acquisition team in the ferrous mineral exploration management. Vale staff also conducts regular laboratory reviews and audits.

9.1.2. Mineral resource and mineral reserve estimates

A Mineral Resource and Reserves Committee was established within Vale's Ferrous Division to document the information supporting the mineral resource and mineral reserve estimates, including all technical and economic assumptions, and ensure its reliability. The committee is composed by qualified person/competent persons from different areas, and departments (resources, reserves, mineral processing, geotechnics (pit, project and dam), hydrogeology, production, strategy, environmental, speleology, finance, mining rights, mining future use, engineering) who sign off or

certify the assumption for the work related to preparation of mineral resource and mineral reserve estimates.

Mineral Reserves and Mineral Resources are estimated in accordance with Global and Vale Ferrous Guidelines and Standards for Mineral Resource and Mineral Reserve Reporting protocols. The guidelines may be subject to review throughout the year, based on certain circumstances, such as external opinions or amendments to external regulations.

The people in charge of operations are responsible to assure that the mineral reserve and mineral resource estimates, technical documents, and other scientific and technical information for their operation are consistent with Vale's Global and Ferrous Guidelines. Other experts include individuals in marketing, legal, corporate affairs, finance (tax), strategic and business planning and sustainability (environment, social, governance). These experts are responsible for providing the information that may be required by the ferrous committee of qualified persons to ensure that the reports supporting mineral resource and mineral reserve disclosure contain all pertinent information.

Local short term mine planning and mining geology staff are typically responsible for coordinating with other specialists to obtain all information necessary to prepare the estimates. The specialists are knowledgeable in areas such as geostatistics, block modeling, sampling and assaying procedures, diamond drilling, geotechnical, geomechanical, hydrogeology, hydrology, scheduling, cost estimation, lands administration, economic analysis, finance, law, and environment.

The mineral resource and reserves qualified persons are responsible for developing and maintaining mineral resource and mineral reserve estimation and reporting standards, ensuring that such standards and guidelines follow the best practices of the industry, and meet Vale's corporate requirements, as well as the legal requirements.

Technical reviews of the mineral reserve and mineral resource estimates are made by the Resource Management Group annually (or as needed) for each operation and mine. The Ferrous Mineral Resource and Reserves Committee prepares and issues a technical review report to each mine and operation with identified risks. All identified risks require mitigation and addressing, consistent with the risk rating attributed thereto, to be consistent with the disclosure requirements of SK1300, and to be compliant with Vale Global Guidelines for Mineral Resources and Mineral Reserves Management.

9.1.3. Studies

Vale staff performs several internal studies and reports to support the Serra Norte Mineral Resource and Mineral Reserve estimation. These include reconciliation studies, mineability and dilution evaluations, investigations of grade discrepancies between model assumptions and drilling data, drill hole density evaluations, long-term plan reviews, and mining studies to meet internal financing criteria for the project progress.

9.1.4. Reconciliation

The Serra Norte short-term staff perform monthly, quarterly, and yearly reconciliation evaluations. Long-term Mineral Resource staff perform quarterly and annual evaluation, long-term mine planning/reserves perform annual reconciliation. The annual consolidated results report comparison of short-term model, mineral resource, and reserves model, furthermore, production grades and tons are discussed in annual technical meeting to promote continuous improvement of all involved areas. The results indicate that the ore tonnages and grades of the long-term model are controlled within acceptable limits.

9.2. External data verification

The Serra Norte complex was audited in 2008 and again in 2010 when the N5 deposit was included in the mineral reserves. The previous audits included a technical site visit, audit and review of drilling, sampling and assay practices; development of the geologic model; interpretation of grade variations, validation of resource and reserve calculations, mining and processing costs, regulatory permits and approvals. In 2016, these deposits were submitted to another audit process, where Runge Pincock

Minarco (RPM) reviewed the mineral resource and reserves estimation techniques and concluded that they comply with the industry standards for iron deposits. In 2019, the N4 and N5 deposits were audited by RPMGlobal, which highlighted, in addition to the quality of the geological models and the resource estimation, the quality of the geological descriptions and the preservation of the drill cores in the conclusion of their report. The most recent external data verification programs for each deposit are summarized in the table below.

Table 9-1 - External data verification, Serra Norte Operations.

Deposit	Auditor	Year
N1	RPM	2016
N2	RPM	2016
N3	RPM	2016
N4	RPM	2019
N5	RPM	2019

9.3. Qualified person’s opinion on data suitability

Data verified on upload to the database, and checked using the layered responsibility protocols, is acceptable for use in Mineral Resource and Mineral Reserve estimation.

10. Mineral processing and metallurgical testing

10.1. Summary

Serra Norte deposit are characterized by high iron content, requiring few metallurgical tests to define the process route and monitor the process. In general, the process route is defined based on the evaluation of the chemical analysis of the geological model of the deposit. This analysis makes it possible to determine whether ROM of given deposit should be concentrated or not.

For additional characterizations that may be necessary, samples can be collected from the mine or directly from the plants in operation.

The Serra Norte Operation consists of three processing plants (Plant I, II, and III) capable of treating together up to 150 Mta of ore from different open pit mines within the complex.

In Serra Norte, there are deposits with iron contents above 65% that do not require concentration to obtain the products, except the Pellet Feed product from Plant I whose content is around 64% Fe, obtained via magnetic concentration.

The process route considers the processing with crushing and screening operations to adjust the product granulometry and concentration of -0.15mm. However, there is an ongoing project to adapt Plant I for 100% natural moisture processing. The completion of this project is forecast between 2024 and 2025. Tests for this project were not necessary since part of the plant is already operating at 100% natural moisture.

Serra Norte currently produces and processes ore in which the main iron-ore mineral is hematite. The plants have iron ore mass recoveries typically ranging from 92% to 100%, depending on the ore characteristics and which plant it will be treated in.

10.2. Test laboratories

Beneficiation testing is primarily done either at the Technological Research Center (CPT) of Vale or external process laboratory. There is no international standard of accreditation provided for beneficiation testing laboratories or beneficiation testing techniques. All chemical analysis are carried out using the facilities of Vale's laboratories where the entire production chain is performed.

10.3. Recent testwork

The most recent metallurgical testwork made for Serra Norte is related to improvement of the pellet feed product quality, which is destined to São Luis pellet plant.

The pellet plant in São Luis is fed with the Pellet Feed product from Plant I, and the current process route for the generation of this product is desliming. Processing alternatives were studied to produce more commercially attractive pellet in São Luiz plant, aiming to reduce the alumina content of the pellet feed product. The best results were obtained through the magnetic concentration route, which reduced the alumina content to levels below 1.65%, with mass recovery around 61%. A series of magnetic concentration tests were carried out on a pilot plant in Serra Norte. The results are shown in Figure 10-1.

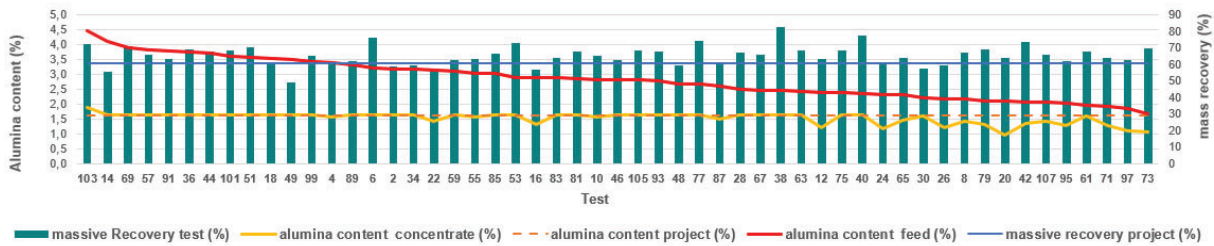


Figure 10-1 - Pellet Feed Magnetic Concentration Testwork Results.

The dashed line in the graph (alumina content project %) represents the Alumina grade target. The yellow line represents the alumina content of the tests. The blue line represents the mass recovery goal (61%) and the green bars, the mass recovery of each test. The red line represents the alumina content of the magnetic concentration test feed. The tendency is for the alumina content in the feed to have values below 3% obtaining a product within the specification of this element and ensuring the expected mass recovery. This stage of concentration came into operation in 2021 and is now ramping up.

10.4. Current Performance

Serra Norte operates at natural moisture and at metallurgical recovery from 92% to 100%.

10.5. Deleterious elements

The deleterious elements for iron ore products are silicon, alumina, phosphorus and manganese. The contents of natural moisture productions are directly controlled by the quality of ROM itself and for those productions.

The Serra Norte mine are characterized by a high iron content with low contaminants. The Sinter feed is generally used to adjust the content of Vale's south and southeast systems in the ports when it is not sold directly on the market. Therefore, there is no impact on the pricing of the final product.

With the entry of fines concentration (-0.15mm), the São Luis Pellet product will become more competitive due to the reduction of deleterious.

Due to the high quality of Serra Norte products, no commercial penalties are applied to its products.

10.6. Qualified person's opinion on mineral processing and metallurgical testing

The performance of ore bodies in beneficiation plants is well known. The production experience and the most recently developed projects provide a solid basis to forecast production.

It is natural there to be some variations in recovery of the wet concentration process due to changes in the type of ore; however, these variations are expected to trend the expected recovery value.

As geological knowledge progresses, from time to time, this may lead to requirements to adjust cut-off grades, modify the process flowchart or change the plant parameters to meet quality, production and economics targets.

11. Mineral resource estimate

11.1. Summary

Resource estimation includes geological modeling, grade estimation, and mineral inventory classification. This details the nature of the deposit and the reliability of the geological information with which the lithological, structural, mineralogical, alteration, or other geological, geotechnical, and geo-metallurgical characteristics used in typological domains are recorded.

Once the deposit geological modeling step is completed, using explicit, implicit, or hybrid techniques (combining the two methods), this information is interpolated in the block model. The lithological variable is assigned to the block using indicator kriging estimates (explicit modeling) or attributed (*flagged*) from 3D solids (implicit modeling). For both cases, the majority lithology is assumed. This variable is used as mandatory in the grades interpolation and classification of the mineral inventory.

Grade interpolation uses multivariate estimation methods by ordinary (co)kriging based on intrinsic correlation models (ICM). The estimate is attributed to the lithological domains using the hard boundary principle. That is, blocks belonging to one domain can be estimated only with samples from the same domain.

The mineral inventories of the block models are classified based on the calculation of the “Risk Index” (RI), which follows the classification method originally proposed by Amorim and Ribeiro (1996) and later reformulated by Ribeiro et al. (2010).

The following flowchart presents the main macro steps from the database, geological modeling, grade estimation, and classification of the mineral inventory of Vale’s iron ore deposits (Figure 11-1).

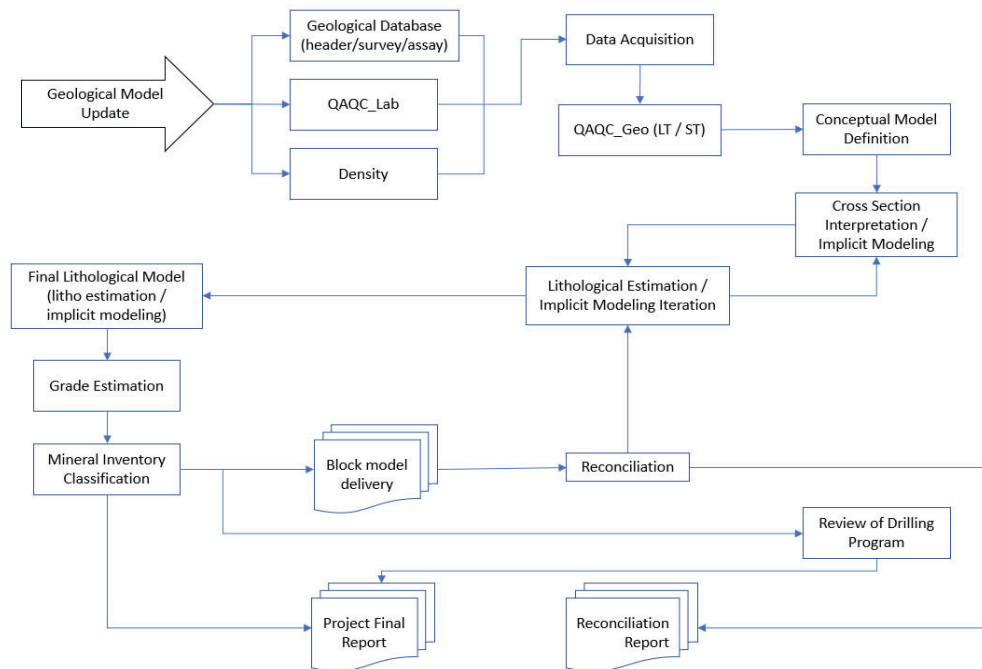


Figure 11-1 - Macro processes flowchart of modeling, grade estimation, and classification of mineral inventory of ferrous deposits

The Serra Norte Complex is composed of five different mines/deposits listed as follows: N1, N2, N3, N4 and N5. The N4 deposit is composed of N4E deposit and N4W deposit. Those mines share the same logistic facilities and have operational integrations and synergies. The procedures for Mineral Resources Estimation are standardized in Vale's Ferrous Department. They will be described as a single process to avoid repetition. Wherever necessary, the differences or particularities in the procedures of the mines that comprise the Serra Norte Mining Complex will be highlighted and listed in this section of the Technical Report.

11.2. Resource database

The database used to estimate the grades of the Serra Norte deposits is composed of chemical assays of Fe, SiO₂, P, Al₂O₃, Mn, LOI, TiO₂, MgO, and CaO. These elements were assayed in different fragment size fractions and later grouped into 4 fractions, G1A (+ 19 mm), G1B (-19 + 8 mm), G2 (-8 + 0.15 mm) and G3 (-0.15 mm). The update of the geological and block models of the Serra Norte deposits was completed after extensive review of the entire database.

11.2.1. Database verification

The main database verification points are as follows:

- Chemistry data grouping: with the inclusion of the chemistry data for the different fragment size fractions, the global grades of many samples were recalculated using this information, so it was necessary to consolidate the calculated and assayed global chemistry data into a single group of variables;
- Exclusion of intervals without chemistry (FEGL = -99). Number of excluded samples: 2,325.
- Exclusion of samples without global SiO₂ and Al₂O₃ (SIGL and ALGL = -99): 356 samples that contain only global chemistry information and do not present SiO₂ and Al₂O₃ results were discarded;
- Exclusion of samples without PGL (01 samples), ALGL (12 samples), MNGL (20 samples), and LOIGL (08 samples);
- Samples with poor global chemical closure, below 94% or above 105%, were discarded. Five samples with closure less than 94% were excluded. A value of 94%, not 95%, was used in this analysis to preserve FM samples;
- The samples that presented a recovery result by interval were evaluated, and intervals with recovery less than 60% were discarded. 10 samples were eliminated in this condition;
- The formula for closure calculation for global chemistry and fragment size fractions, considering only elements that participated in the estimate, is:

$$FQGL = FEGL * 1.4297 + SIGL + PGL * 2.2913 + ALGL + MNGL * 1.2912 + PFGL + TIGL + MGGL + CAGL$$

11.3. Geological interpretation

The geological modeling of the lithotypes is based on the chemical, granulometric, and/or mineralogical homogeneity that differentiates them from each other. In addition, they must have well-defined contacts, with relatively sharp passages in between. The genetic nature of the contact must also be understood for its continuity in-depth to be modeled. The models were completed from vertical geological sections, with their interpretation supported by drill holes and subsurface mapping.

The geological model for mine N1 was built based on 52 vertical geological sections in NE-SW direction, with 48 vertical sections with 200 m spacing and 4 sections spaced 100 m apart (Figure 11-2). The model satisfactorily reproduces the continuity of the mineralized bodies, their host rock, overburden, and intrusive rocks present in the N1 deposit. This model was audited by RPMGlobal in 2016.

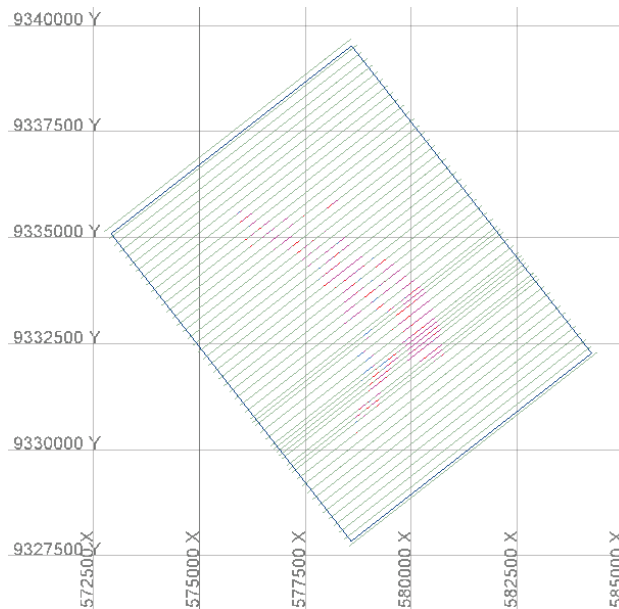


Figure 11-2 - Arrangement of vertical geological sections interpreted in the N1 Model

In the geological model of N2, 14 vertical sections spaced 200 m apart, and 3 intermediate sections were interpreted, totaling 17 vertical sections with NS direction.

In the geological model of N3, 19 vertical sections were interpreted, with 18 spaced 200 m apart and 1 intermediate section. The N3 model has been supported by several drilling campaigns carried out by different companies since 2002. It satisfactorily reproduces the continuity of the mineralized bodies, their host rock, and overburden.

As this is an active mine, most of the information for the model of the N4 deposit was obtained by geological mapping on a 1:2,000 scale, carried out along the mine benches by the Short-Term Geology team. Interpretation was also supported by diamond drill cores. 167 vertical geological sections of E-W direction were interpreted in the geological model of N4, as follows:

- N4W: 106 vertical sections spaced 100 m apart and 7 intermediate sections in the center pit, spaced 50 m apart.
- N4E: 54 vertical sections with 100 m spacing. In the north and central portions of the pit, the vertical sections are displaced 25 m to the south with respect to the set of N4W sections mentioned above. This displacement justifies better positioning of the sections with the drilling grid, avoiding projecting drill holes onto distant sections.

For the geological model of the N5 mine, 145 vertical geological sections were interpreted, in E-W direction, with spacing of 100 x 100 m, locally concentrated to 50 x 50 m, as it can be seen in Figure 11-3.

The geological model supported the mine planning and was audited in 2016 by RPMGlobal. This model satisfactorily reproduces the continuity of mineralized bodies, their host rocks, and overburden.

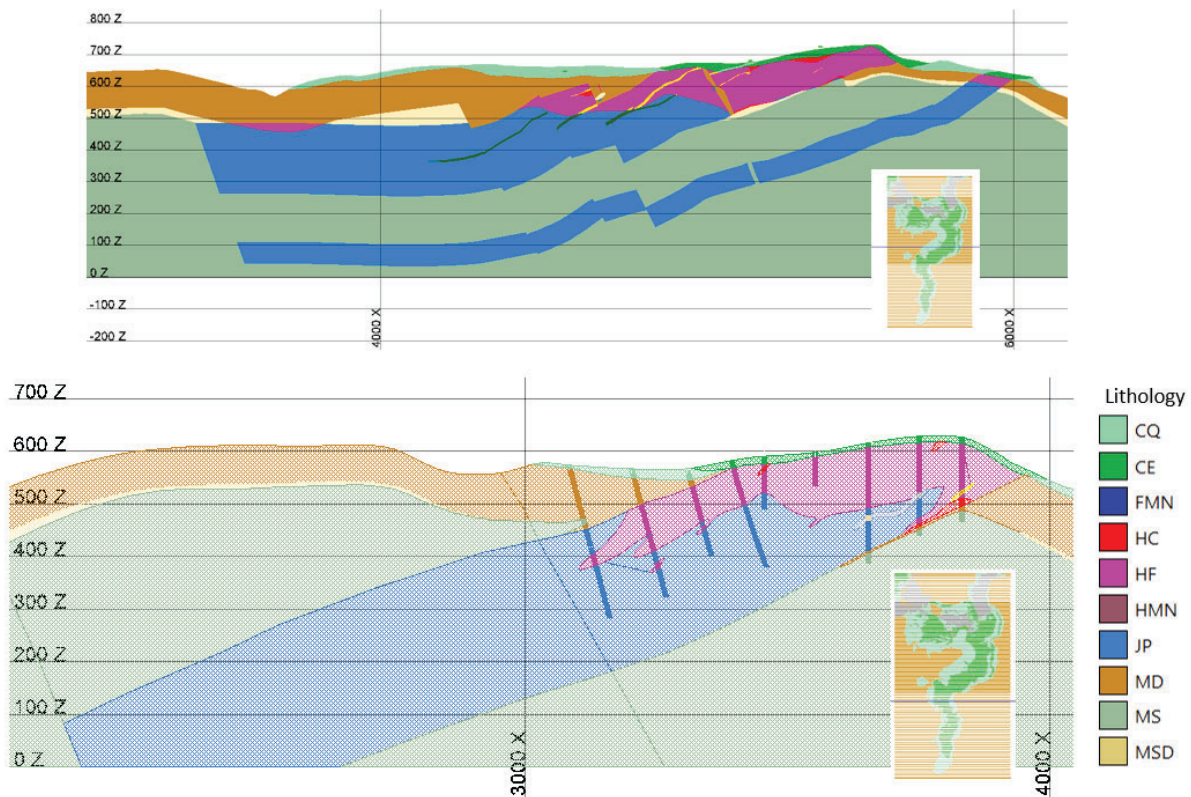


Figure 11-3 - Typical vertical geological sections of the northern portion of the N5 Mine

11.4. Geological modelling

11.4.1. Geological modeling methodology

The construction of mass models at VALE Ferrosos is done using a mixed method that combines geostatistical estimation of categorical variables and 3D modeling. The method of estimating these categorical variables combines the use of direct data (description of drill cores) and indirect data (geological map and geological interpretations). Lithological estimation aims to transfer the geological continuity interpreted during modeling (two-dimensional sections) to a three-dimensional space represented by block models.

The geological modeling of the geometry of the bodies is responsible for predicting the tonnages to be mined. The spatial modeling of the grade distribution is carried out by mathematical and geostatistical methods and is strongly linked to the definition of lithotypes and the geometric modeling strategy (Guimarães et al., 2005).

Explicit modeling with indicator estimation

Explicit modeling from the interpretation of vertical sections is generated with the help of Vulcan® software. Vertical sections are preferably perpendicular to the mineralized bodies. The spacing between sections will depend on the spatial arrangement of the drilling information, which can normally vary between 50 m and 100 m. As exception, places that lack this information may have their sections more spaced, but this will impact the efficiency/robustness of the interpolator directly. The interpretation is made using half of the space between sections that influence the section, in which each drill hole belonging to this corridor is projected into the section, or in case of divergent information, the closest to the section prevails.

The geological interpretation in sections is materialized directly in the block model using the indicator kriging method (IK). This method consists of transforming a set of lithological data into indicator

variables, respecting the procedures of ordinary kriging. These spatially distributed and spatially dependent variables are transformed into binary variables (0 or 1), where the probability of each variable belonging or not to a lithological group in each spatial position is calculated. This methodology was developed by Journel (1983), where the author proposed a conditional cumulative distribution function for estimating spatial data.

The methodology adopted in this work was developed by Ribeiro and Carvalho (2002) and modified by Roldão et al. (2006). The authors propose the combination of conventional modeling methods with the indicator kriging estimation method, in which the interpreted sections are gridded and used in the estimation process together with the drilling database and short-term information (maps and/or samples). The allocation of the lithologic variable is based on pseudo-probability calculated for each lithologic indicator, assuming the majority value. Figure 11-4 presents a flowchart with the steps for acquisition, estimation, and validation of the lithological variable.

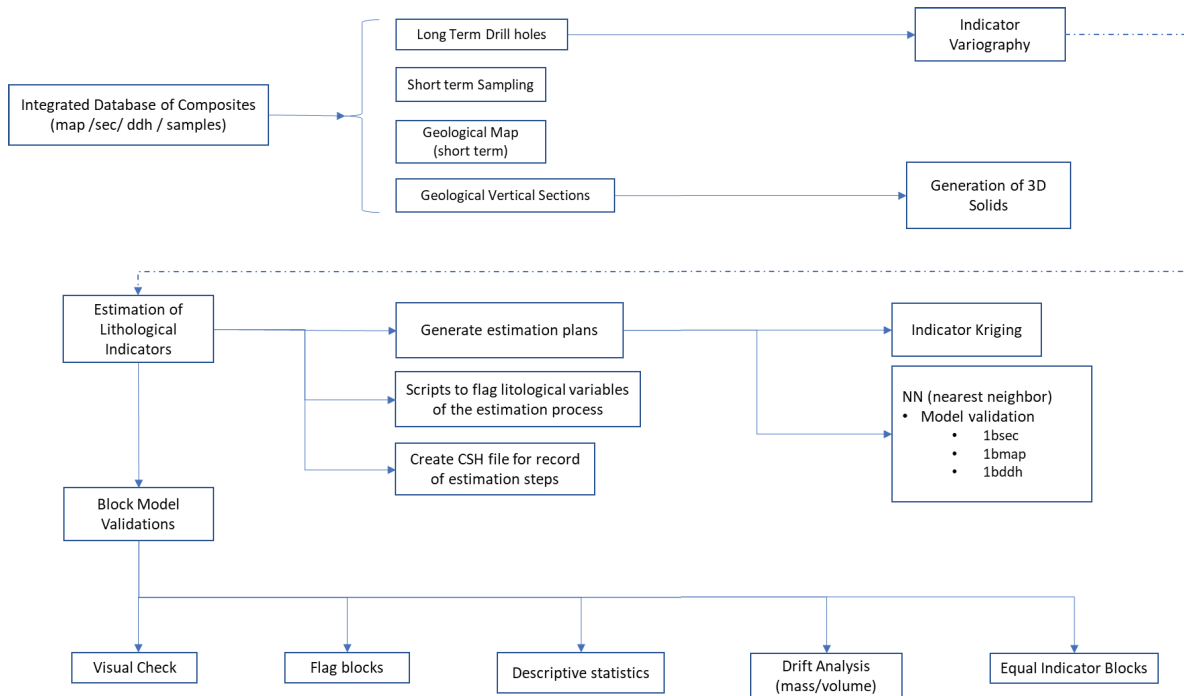


Figure 11-4 - Flowchart of macro-processes for modeling and estimation of grades and classification of the mineral inventory of iron ore deposits

11.4.2. Serra Norte lithological estimation

The Serra Norte models were built using the Indicator Kriging (IK) method (Ribeiro and Carvalho, 2002; Roldão et al., 2006).

The IK lithology estimation method was adopted in this work to reduce the time spent in the generation of horizontal sections ("mechanical" work). The method was validated by Roldão et al. (2006), and the authors present IK as an effective and more agile technique than the conventional methods used in the past (extrusion method of horizontal sections).

Lithology Indicators Database

The geostatistics process for estimation of lithotypes considers long-term and short-term information, and for this purpose, the binary indicator variable **V_IND** was created, which represents the presence of the lithotype in the regularized sample (1 if present and 0 if absent). Other V_IND variables are usually created (V_IND1, V_IND2, V_IND3, etc.) to test different distributions of indicators, aiming to find the one that best represents the spatial continuity of the lithotypes to be estimated.

Indicator variables are attributed to the geocode field (lithotype). For example, a regularized HF geocode sample will have value "1" attributed to its indicator variable "IHF", while value "0" will be attributed to the other indicator variables (for the other lithotypes). For lithotypes that will not be estimated by IK, value "-99" is attributed to the fields of the indicator variables.

11.4.2.1. N1 – Lithotypes

Variographic Analysis of Indicators

The variographic study of the N1 model was carried out from the analysis of a single variogram for all indicators, based on the hypothesis that the indicators would have intrinsic correlation, that is, their variograms would have the same range and would vary only in the vertical scale (sill). All variography steps were performed with the help of Vulcan® and Isatis® software. Long-term and short-term database samples/intervals (N1flp_1215_var_entry.csv) were used for the variographic analysis.

The choice of the lithotypes of the composites that participated in the variography as a binary variable was: 1 for lithotypes HF, HC, and HMN and 0 for lithotypes CE, CQ, FM, JP, MS, MSD, MS. The three types of mafic lithotypes are different in the form of occurrence, whether dyke (DK: MDDK, MSDDK, MSDK) or sill (SL: MDSL, MSDSL, MSSL), in addition to the occurrence as host rock (top and base of the iron formation, MD, MSD, MS). However, for the lithological estimation, the mafic groups are consolidated. Thus, we have the decomposed mafic (MD) group, which comprises MD, MDDK, MDSL, the semi-decomposed mafic (MSD) group, which comprises MSD, MSDDK, MSDSL, and the fresh mafic (MS) group, which comprises MS, MSDK, MSSL.

Structural sectors

The N1 model was divided into 7 structural sectors as a function of variations in the dip and the directions of the layers of the ore bodies. These sectors were important to represent the differences in the attitude of the ore bodies and add better lithological representation of the deposit. Structural Sectors were applied throughout the N1 model for the lithology estimation.

Indicators interpolation

In the construction of the block model of the lithological indicator, the initial step is the generation of the model of waste lithologies blocks from the construction of 3D solids based on the vertical sections. After this step, the estimation of lithological indicators is carried out within the limit defined as iron formation. Ordinary kriging was used to estimate the lithological indicators, with each lithotype estimated by IK representing an indicator variable, totaling 10 variables (icq, ice, ihf, ihc, ihmn, ifm, ijp, imd, imsd, ims).

The NN method was adopted to validate the kriging estimate. At this stage, the same parameters used in kriging were reproduced in NN estimation. Estimation plans were created so that the block model would honor the interpreted section (1bsec) and the drilling information (1bflp). These plans are explained in Table 11-2.

Table 11-2 - Parameters used in lithotype estimation plans

Parameters	Kriging	NN	1bflp	1bsec
Group	15MFLP/SEC		15MFLP	SEC
Min. samples	1	1	1	1
Max. samples	16	1	1	1
Octant	2	-	-	-
Block discretization	1 x 1 x 1	1 x 1 x 1	1 x 1 x 1	1 x 1 x 1
Search range	450 x 150 x 50		15 x 15 x 9	

Validation

To validate the variable “litho” estimated by IK, a series of checks is performed:

Estimate Summary – evaluates the number of blocks estimated for each kriging plan. For kriging plans with the same estimation parameters, it is mandatory to have the same number of estimated blocks.

Visual check – is defined as the main validation, in which it is visually assessed block by block whether the IK managed to reproduce the continuity of the geological interpretation proposed by the geologist, Figure 11-5. The visual validation is carried out in vertical, horizontal, and longitudinal sections. This validation is always done together with the modeling geologist, and the need to generate sections in different orientations to reproduce the geological continuity interpreted by the geologist is evaluated.

Empty blocks – 60 empty blocks were identified in the estimation process. This was fixed by applying NN estimate to these blocks.

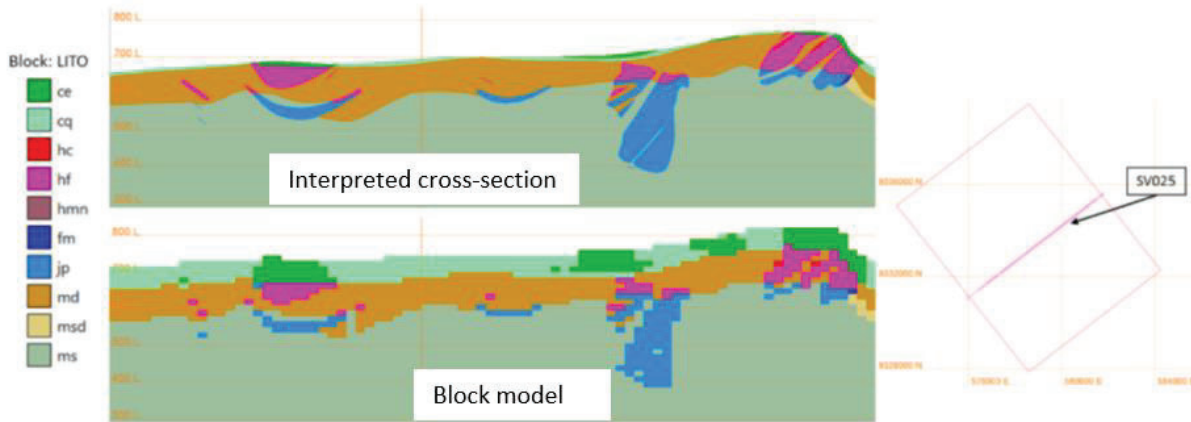


Figure 11-5 - Comparison between interpreted geological vertical section (SV_025) and block model section

Flag blocks – The objective of this check is to validate the adherence between the lithotype of the samples and the lithology of the block model. The procedure consists of attributing the sample with the lithology of the block to which it belongs and comparing this attribute with the lithology of the sample in the database. In general, the discrepancies are related to samples of short length (much smaller than the size of the block) in which it is possible to find more than one sample within the block.

Drift Analysis (Nearest Neighbor (NN)) – Drift analysis is made to assess whether the estimation process is biased with respect to the samples. Among the ore lithotypes, the comparison between the proportions presented by the different methods for HF and JP lithotypes showed good results. On the other hand, the FM, HMN, and HC lithotype graph showed greater relative bias. This is due to the small amount of FM, HMN, and HC in the model, in addition to the fact that the IK process has a smoothing character. However, due to the better continuity of the estimate by IK, it was decided on the result of the kriging of the lithological indicators.

11.4.2.2. N2 – Lithotypes

Variographic analysis of indicators

The variographic study of the N2 model was carried out from the analysis of a single variogram for all indicators based on the hypothesis that the indicators would have intrinsic correlation, that is, their variograms would have the same range and would vary only in the vertical scale (sill). All variography steps were performed with the help of Vulcan® and Isatis® software. Only long-term database samples/intervals (N2flp_var_entry.csv) were used for the variographic analysis.

The choice of the lithotypes of the composites that participated in the variography as a binary variable was: 1 for lithotypes HF, HC, HMN, CE, CQ, FMN, and JP and 0 for lithotypes MS, MSD, MS, and QT.

Structural sectors

The model was estimated as a single sector. Structural Sectors were not applied in the estimation of lithologies, as the structure of the rocks does not present abrupt changes in direction and/or dip.

Indicators interpolation

In the construction of the block model of the lithological indicator, the initial step is the generation of the model of waste lithologies blocks from the construction of 3D solids based on the vertical sections. After this step, the estimation of lithological indicators is made within the limit defined as iron formation.

Ordinary kriging was used to estimate the lithological indicators, with each lithotype estimated by IK representing an indicator variable, totaling 12 variables (icq, ice, ihf, ihc, ihm, ifmn, ijp, imd, imsd, ims, iqt, iin).

Table 11-3 presents the relation of the lithotypes modeled by 3D and those estimated by IK.

To validate the kriging estimate, the NN method was adopted. At this stage, the same parameters used in kriging were reproduced in NN estimation. Estimation plans were created so that the block model would honor the interpreted section (1bsec) and the drilling information (1bflp).

Table 11-3 - Parameters used in lithotype estimation plans

Parameters	Kriging	NN	1bflp	1bsec
Group	15MFLP/SEC		15MFLP	SEC
Min. samples	1	1	1	1
Max. samples	16	1	1	1
Octant	2	-	-	-
Block discretization	1 x 1 x 1	1 x 1 x 1	1 x 1 x 1	1 x 1 x 1
Search range	400 x 200 x 50		15 x 15 x 9	

Validation

To validate the variable "litho" estimated by IK, the same procedures as in N1 are used: estimate summary, visual check (Figure 11-6), empty blocks, flag blocks, and drift Analysis NN (Figure 11-7).

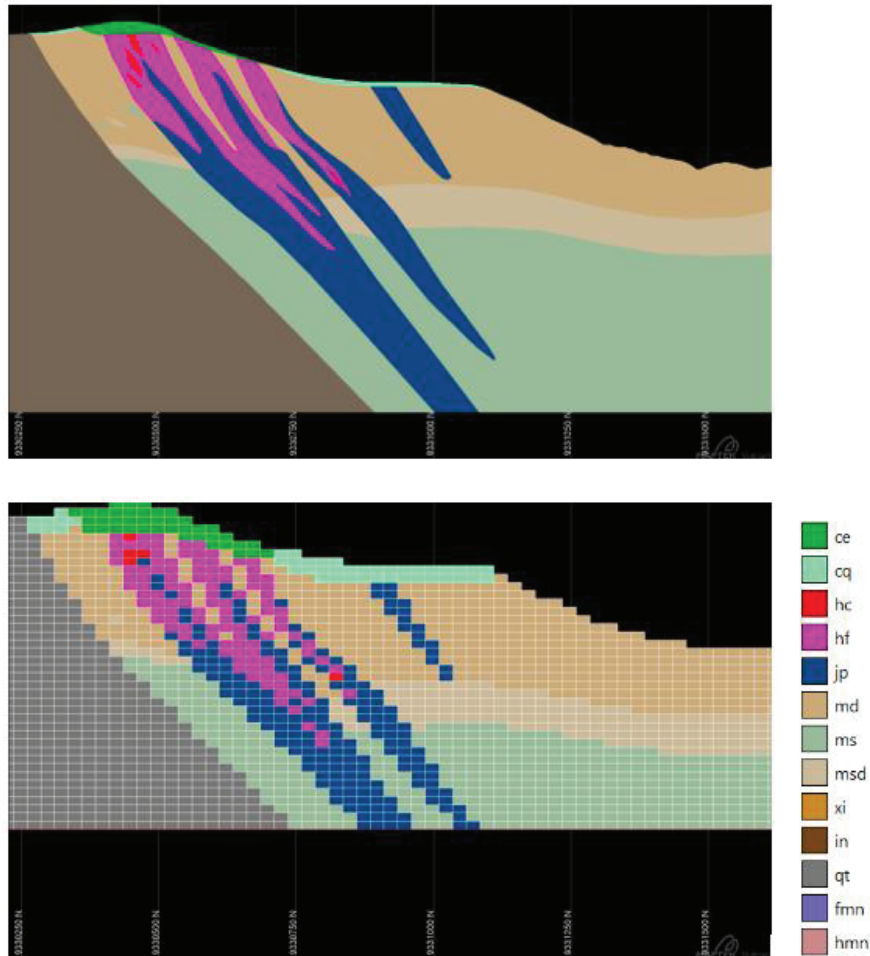


Figure 11-6 - Comparison between interpreted geological vertical section (SV_10) and block model section

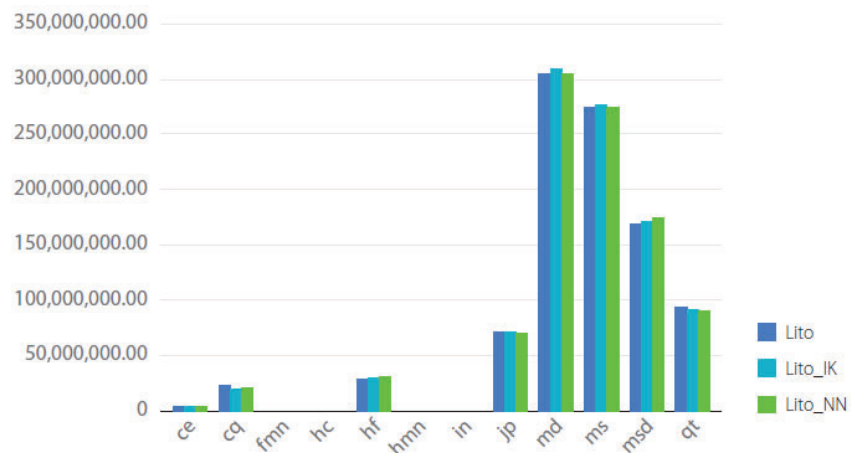


Figure 11-7 - Drift analysis

11.4.2.3. N3 – Lithotypes

Variographic analysis of indicators

The variographic study of the N2 model was carried out from the analysis of a single variogram for all indicators, based on the hypothesis that the indicators would have intrinsic correlation, that is, their variograms would have the same range and would vary only in the vertical scale (sill). All variography steps were performed with the help of Vulcan® and Isatis® software. Only long-term database samples/intervals (n3_n3flp_var_entry.csv) were used for the variographic analysis.

The choice of the lithotypes of the composites that participated in the variography as a binary variable was: 1 for the iron formation lithotypes (HF, HC, HMN, CE, FMN, JP) and 0 for the waste lithotypes (XI, MS).

Structural sectors

Initially, the structural sectors for the estimation of lithological indicators were defined in the block model. These sectors are intended to represent the interpreted geological continuity. Two structural sectors were created: 1) north (Azimuth 60°/ Plunge 0°/Dip -60°); 2) south (Azimuth 85°/ Plunge 0°/ Dip -50°). The boundaries between the north and south sectors were defined by solids created from the interpreted vertical sections.

Indicators interpolation

The first step in the construction of the block model of the lithological indicator is the generation of a model of waste lithology blocks from the construction of 3D solids based on vertical sections. After this step, the estimation of lithological indicators is made within the limit defined as iron formation.

Ordinary kriging was used to estimate the lithological indicators, with each lithotype estimated by IK representing an indicator variable, totaling 11 variables.

To validate the kriging estimate, the NN method was adopted. At this stage, the same parameters used in kriging were reproduced in NN estimation. Estimation plans were created so that the block model would honor the interpreted section (1bsec) and the drilling information (1bflp). These plans are explained in Table 11-4 and Table 11-5.

Table 11-4 - List of lithotypes modeled by solid (3D) and/or estimated by IK

Modelled Lithotypes	3D Modelling	File Name	Indicator Kriging	Lithotype Indicator
CE	x	solido_3d_n3_ce.00t solido_3d_n3_ce1.00t solido_3d_n3_ce2.00t		ice
CQ	x	solido_3d_n3_cq.00t solido_3d_n3_cq1.00t		icq
HF			x	lhf
HC			x	lhc
HMN			x	lhmn
JP			x	ljp
FMN			x	lfmn
MS	x	solido_3d_n3_ms.00t		ims
MSD	x	solido_3d_n3_msd.00t		lmsd
MD	x	solido_3d_n3_md.00t		lmd
XI	x	solido_3d_n3_xi.00t		ixi

Table 11-5 - Parameters used in lithotype estimation plans

Parameters		Kriging	NN	1bfp	1bsec
Samples	Database	N3 n3.cik.isis			
	Group	15MFLP/SEC		15MFLP	SEC
	Min. samples	1	1	1	1
	Max. samples	16	1	1	1
	Octant	Yes	-	-	-
Blocks	Discretization	1 x 1 x 1	1 x 1 x 1		
	Search range	400 x 180 x 30		15 x 15 x 9	15 x 15 x 9

Validation

To validate the variable “litho” estimated by IK, the same procedures as in N1 are used: estimate summary, visual check (Figure 11-8), empty blocks, flag blocks, and drift Analysis NN (Figure 11-9).

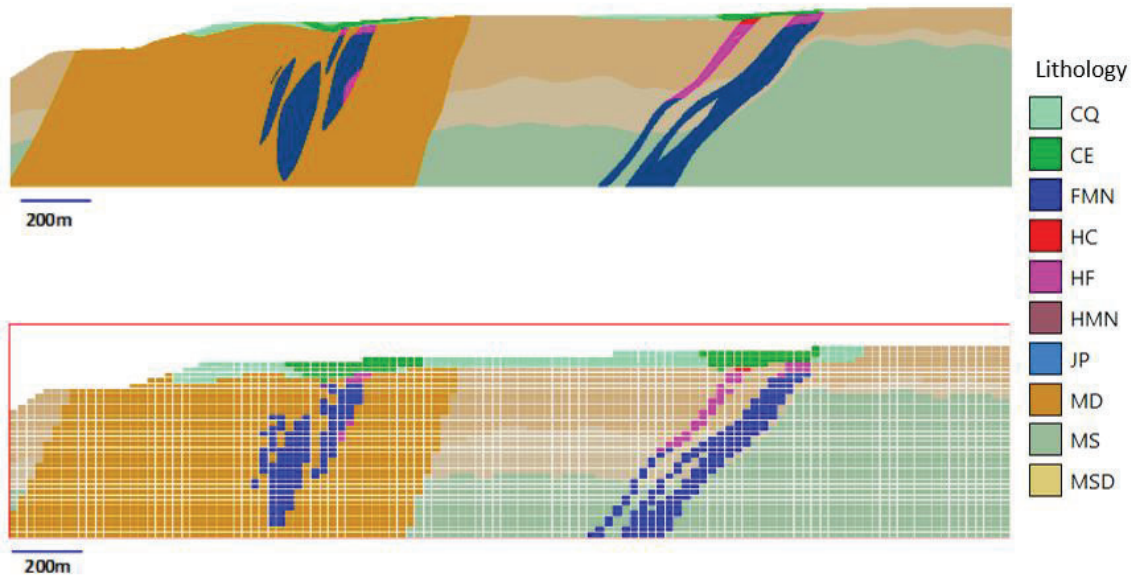


Figure 11-8 – Comparison between interpreted geological vertical section (SV_13) and the same section in the block model

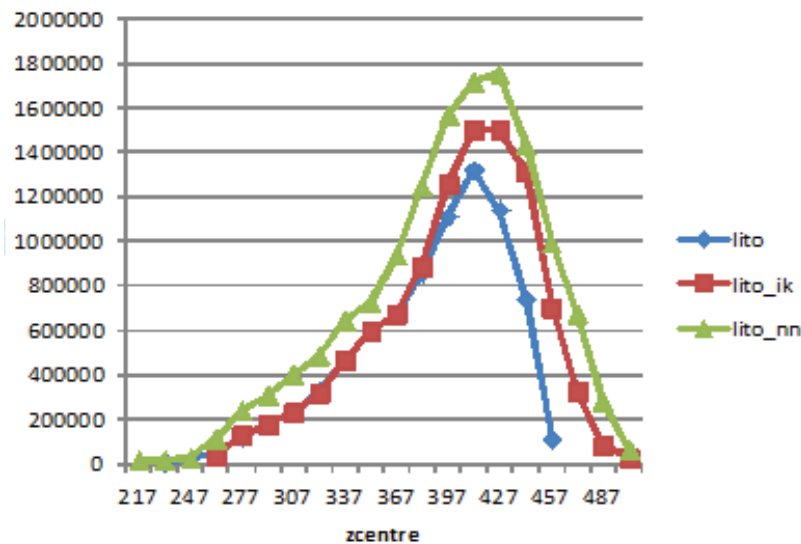


Figure 11-9 – Volumetric comparison between lito (final lithotype attribute), Lito_ik (estimate by IK) and Lito_nn (estimate by NN) of friable hematite from the N3 model

11.4.2.4. N4 – Lithotypes

Variographic analysis of indicators

The variographic study of the N1 model was carried out from the analysis of a single variogram for all indicators, based on the hypothesis that the indicators would have intrinsic correlation, that is, their variograms would have the same range and would vary only in the vertical scale (sill). All variography steps were performed with the help of Vulcan® and Isatis® software. Exploration and ore control database samples/intervals were used for the variographic analysis.

The choice of the lithotypes of the composites that participated in the variography as a binary variable was: 1 for lithotypes HF, HC, and HMN and 0 for lithotypes CE, CQ, FMN, JP, MS, MSD, MS. The three types of mafic lithotypes are different in the form of occurrence, whether dyke (DK: MDDK, MSDDK, MSDK) or sill (SL: MDSL, MSDSL, MSSL), in addition to the occurrence as host rock (top and base of the iron formation, MD, MSD, MS). However, for the lithological estimation, the mafic groups are consolidated. Thus, we have the decomposed mafic (MD) group, which comprises MD, MDDK, MDSL, the semi-decomposed mafic (MSD) group, which comprises MSD, MSDDK, MSDSL, and the fresh mafic (MS) group, which comprises MS, MSDK, MSSL.

Structural sectors

For the N4 mine model, four structural sectors were created, which were attributed in the block model, numbered 1 to 4. Sectors 1 and 2 represent the main structure of the N4E body, and sectors 3 and 4, the main structure of the N4W. In the estimation, horizontal search ellipsoids were used for the mafic host rocks and overburden. The orientation of the ellipsoids varies according to the sector, with different dip for iron formation lithotypes and mafic sills. For the dikes, azimuth 310° and 75° dip were used.

Indicators interpolation

In the construction of the block model of the lithological indicator, the initial step is the generation of the model of waste lithologies blocks, from the construction of 3D solids based on the vertical sections interpreted using Vulcan® software. Solids were built using Leapfrog® software. After this step, the estimation of lithological indicators is carried out within the limit defined as iron formation

To validate the kriging estimate, the NN method was adopted. At this stage, the same parameters used in kriging were reproduced in NN estimation. Estimation plans were created so that the block model would honor the interpreted section (1bsec) and the drilling information (1bflp). These plans are explained in Table 11-6 and Table 11-7.

Table 11-6 - List of lithotypes modeled by 3D and those estimated by IK

Lithotype	3D Modelling	IK	Indicator Lithotype
AG	x		
CQ	x	x	icg
CE	x	x	ice
HF		x	ihf
HC		x	ihc
HMN		x	ihmn
FMN		x	ifmn
JP		x	ijp
MD	x	x	imd
MDDK	x	x	imddk
MDSL		x	imdsl
MSD	x	x	imsd
MSDDK	x	x	imsddk
MSDSL		x	imsdsl
MS		x	ims
MSDK	x	x	imsdk
MSSL	x	x	imssl

Table 11-7 - Lithological indicator estimation parameters

Parameters		Kriging	NN	1bflp	1bfcf	1bsec
Samples	Database	Sn4sn4.cik.isis				
	Group	15MFLP/15MFCF/SEC		15MFLP	15MFCF	SEC
	Min. samples	1	1	1	1	1
	Max. samples	16	1	1	1	1
	Octant	Yes	-	-	-	-
Blocks	Discretization	1 x 1 x 1	1 x 1 x 1	-	-	-
	Search range (m)	400 x 300 x 100		12.5 x 12.5 x 7.5		
	Sectoring	Yes		-	-	-

Validation

To validate the variable "litho" estimated by IK, the same procedures as in N1 are used: estimate summary, visual check (Figure 11-10), empty blocks, flag blocks, and drift Analysis NN (Figure 11-11).

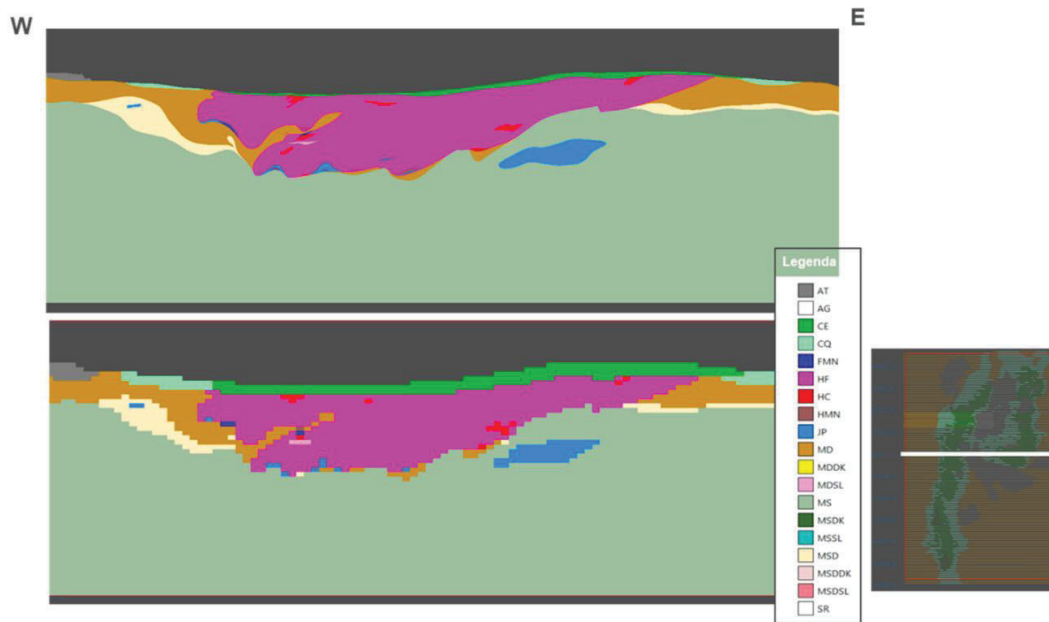


Figure 11-10 - Comparison between interpreted geological vertical section (SV_0100N) and block model sec

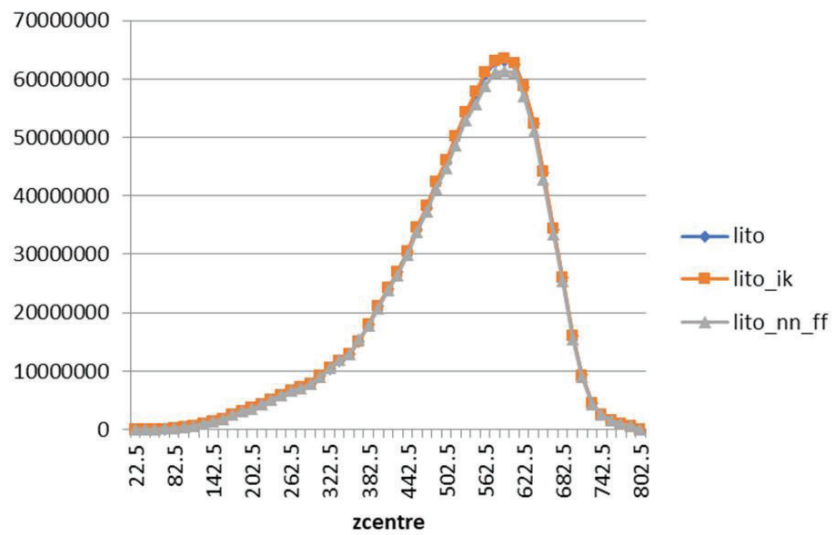


Figure 11-11 – Volumetric comparison between litho (final flagged lithotype), lito_ik (estimate by IK), and lito_nn_ff (estimate by NN) of the friable hematite of the N4 mine model

11.4.2.5. N5 – Lithotypes

Variographic analysis of indicators

The variographic study of the N5 model was carried out from the analysis of a single variogram for all indicators, based on the hypothesis that the indicators would have intrinsic correlation, that is, their variograms would have the same range and would vary only in the vertical scale (sill). All variography steps were performed with the help of Vulcan® and Isatis® software. Long-term and short-term database samples/intervals were used for the variographic analysis.

The choice of the lithotypes of the composites that participated in the variography as a binary variable was: 1 for lithotypes HF, HC, HMN, FMN, JP, CE and 0 for lithotypes MS, MSD, MD, MDDK, MSDDK, MSDK, MDSL, MSDSL, MSSL, CQ, CQL. The three types of mafic lithotypes are different in the form of occurrence, whether dyke (DK: MDDK, MSDDK, MSDK) or sill (SL: MDSL, MSDSL, MSSL), in addition to the occurrence as host rock (top and base of the iron formation, MD, MSD, MS).

Structural sectors

Due to the complexity of the lithological contacts, the conventional search strategy, which considers fixed search angles, was not applied. The dynamic anisotropy method was selected to estimate the N5 model whose search ellipsoid orientation follows different azimuths and dips that best represent the lithological behavior. Three domains were identified: a structural, a supergene and the external sector. For the structural and supergene sectors, the surfaces that best represent the lithological behavior interpreted in the vertical sections were used as a basis. For regions outside the control surfaces, the general direction of the variogram was used.

The information that allows for dynamic anisotropy, azimuth and dip values for each block is obtained using guide surfaces. These surfaces are composed of a high number of small triangles and with the help of scripts, it is possible to calculate the vector components of each one, creating a database whose coordinates of the points are the central points of each triangle and the variables are the vector components. These components are estimated in the blocks and a calculation is made to convert the values of the vector components into azimuths and dips. Finally, at the time of estimation, the software identifies which azimuth and dip values are present in the block to be estimated and applies them in the estimation process. Azimuth and dip information is recorded in the block model as a guide variable with the prefix “dyna” followed by the abbreviation that represents the control surfaces.

Indicators interpolation

Ordinary kriging was used to estimate the lithological indicators with each lithotype estimated by IK representing an indicator variable, totaling 17 variables (icgl, ice, icq, ifmn, ihc, ihf, ihm, ijp, imd, imddk, imdsl, imsd, imsdsk, imsdsl, ims, imsdk, imssl). Only the dump lithologies (AT) and the iron formation that came from N4 were attributed by solids, all the others were estimated using indicator kriging.

To validate the kriging estimate, the NN method was adopted. At this stage, the same parameters used in kriging were reproduced in NN estimation. Estimation plans were created so that the block model would honor the interpreted section (1bsec) and the drilling information (1bflp, long-term drilling; 1bfcp, short-term drilling) in addition to the short-term maps (1bmap). These plans are explained in Table 11-8.

Table 11-8 - Lithological indicator estimation parameters

Parameters		Kriging	NN	1bflp	1bfcp	1bsec	1bmap
Samples	Database	N5N5.cik.isis					
	Group	15MFLP/15MFCP/SEC/MAP	15MFLP	15MFCP	SEC	MAP	
	Min. samples	1	1	1	1	1	
	Max. samples	16	1	1	1	1	
	Octant	Yes	-	-	-	-	
Blocks	Discretization	1 x 1 x 1	1 x 1 x 1	-	-	-	
	Search range (m)	540 x 490 x 45			15 x 15 x 9		
	Sectoring	Yes			-	-	-

Validation

To validate the variable “litho” estimated by IK, the same procedures as in N1 are used: estimate summary, visual check (Figure 11-12), empty blocks, flag blocks, and drift Analysis NN (Figure 11-13).

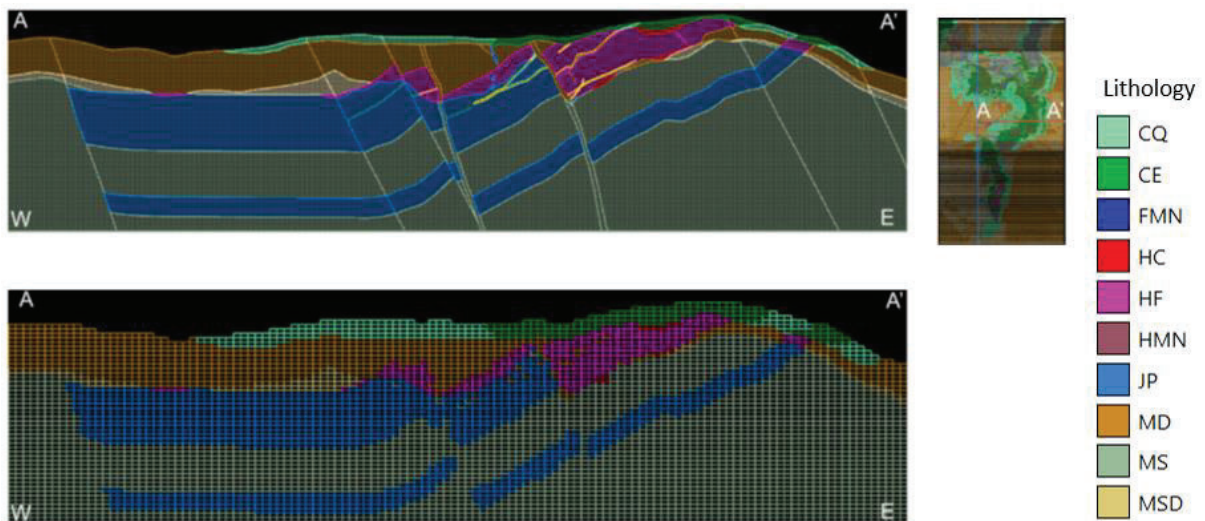


Figure 11-12 – Comparison between interpreted geological vertical section and section of the block model

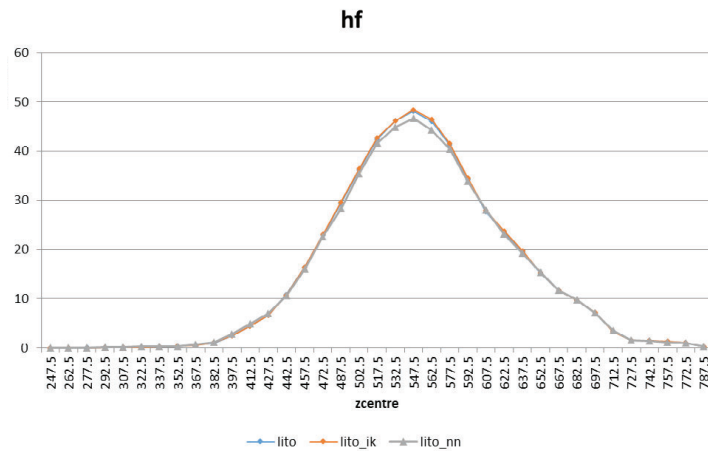


Figure 11-13 – Volumetric comparison between litho (final lithotype flag, in the block model), litho_ik (IK estimate), and litho_nn (NN estimate) for friable hematite of the N5 mine model

11.5. Domain modelling

11.5.1. Methodology

For the domain modeling, a definition of lithotypes is considered using geological databases, geological mine maps, and regional mappings as references.

The database contains information referring to drill holes with macroscopic visual geological descriptions of the drill cores and a variable of visual classification (CLV), as per Vale internal standards. The same criteria are used for geological description in databases that include mine sampling.

From the visual description (CLV) of the intervals that make up the geological database and the lithotypes macroscopically identified in the mine, from surface mappings, the definition of the lithotypes that will be modeled is made. In the modeling stage, the definition of relatively homogeneous geological zones is carried out in which the contacts are well defined and marked by mineralogical, chemical, and/or granulometric discontinuities.

A mathematical classification key (CLM) is generated to define the lithotypes that will be modeled based on visual, mineralogical, chemical, and granulometric characteristics, looking for the signature of each lithotype. Studies are carried out with statistical analysis (histograms, cluster analysis, contact analysis, etc.) to define the mathematical classification.

An example of a mathematical classification key for Serra Norte is shown in Table 11-9 and Figure 11-14.

Table 11-9 - Serra Norte mathematical classification key

Lithotype	Iron grade	Manganese grade	G1 (>8mm)
CE – Ore cover	>=55%		
CQ – Chemical cover	<55%		
HF – Friable hematitite	>=60%	<2%	<50%
HC – Compact hematitite	>=60%	<2%	>=50%
HMN – Manganiferous hemtitite	>=55%	>=2%	
JP – Jaspilite	<60%	<2%	
FMN – Iron-manganese	<55%	>=2%	

The contacts between the types of iron formation are generally well defined, with sharp differences in grades and/or compactness that define the lithotypes. Figure 11-14 shows a detail of a vertical geological section with an example of the differences in grades and particle sizes of the lithotypes.

Figure 11-15 shows a contact analysis between two lithotypes (HF and JP), in which the average of the Fe contents relative the distance to contact is calculated.

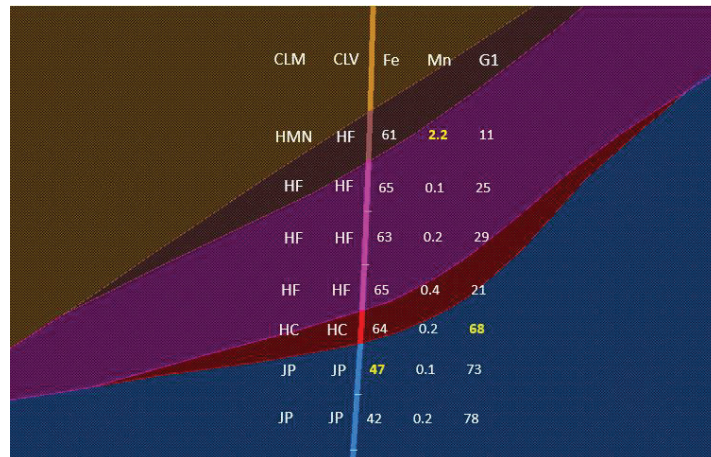


Figure 11-14 - Drillhole detail in vertical geological section showing visual (CLV) and mathematical (CLM) classifications, iron (Fe) and manganese (Mn) contents and retained mass percentages in G1 (>8 mm), in the different lithotypes (sudden changes in values indicate the presence of contact).

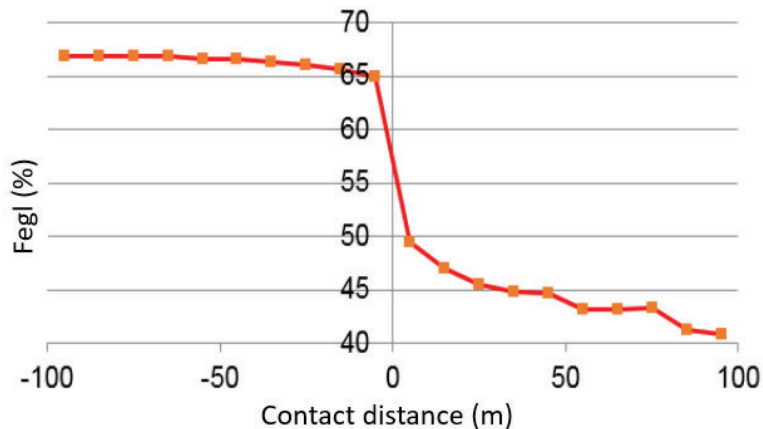


Figure 11-15 - Global Fe mean contents in the contact region between friable hematite (HF) and jaspilite (JP)

From the compatibility of the visual classification of the lithotypes (CLV), their chemical and granulometric characteristics (CLM), and the geological context of each interval, the lithotypes are modeled and classified under an “interpreted classification” code, called CLI. CLI represents the lithotype classification according to the interpretation of the geological model, considering visual, mineralogical, chemical, and granulometric characterization, in addition to the geological context.

Figure 11-16 shows the interpreted (CLI), mathematical (CLM), and visual (CLV) classifications, the iron (Fe) and manganese (Mn) contents and the percentages of mass retained in the G1 grain size fraction (> 8 mm), in drill holes of a vertical geological section. The Interpreted Classification (CLI) corresponds to the final classification of each interval/sample with identification of the lithotype, as interpreted in the model.

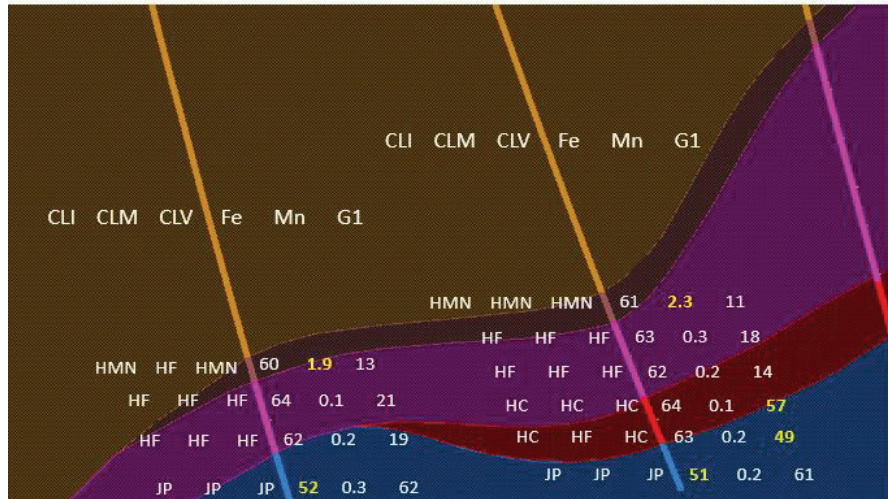


Figure 11-16 - Detail of a vertical geological section showing the interpreted (CLI), mathematical (CLM), and visual (CLV) classifications, in addition to iron (Fe) and manganese (Mn) contents and percentages of mass retained in G1 (> 8 mm).

11.5.2. Serra Norte modeled lithotypes

The different types of iron formation and host rocks of the Serra Norte district are described below. The mean grades mentioned refer to the average grades of the samples (weighted by length) of each lithotype modeled in this review, considering the interpreted classification (CLI).

The cangas represent a product of weathering on the rock sequences typical of the region. For modeling, they are divided into two different types: structural canga (CE) with iron contents greater than or equal to 55%, products of the weathering of iron formation, and chemical canga (CQ), which occurrence is covering the mafic rocks.

Chemical canga (CQ) – represents the iron-aluminous crusts that usually cover the decomposed mafic rocks. It has a colloform texture and high porosity. It often has a high content of Al₂O₃GL, evidenced by the light coloring of gibbsite and clay minerals. Hematite fragments are scarce or absent. In general, the iron content is under 55%, with high phosphorus and Al₂O₃GL.

Structural canga (CE) – term commonly used by Vale to designate ferruginous lateritic crusts. It is usually located over iron ore outcrops *in situ*. It also occurs as transported canga, but at a short distance from the source area, being a good indicator of the location of ore bodies. The thickness is variable, reaching more than 20 meters. It has iron content above 55% and relatively low Al₂O₃GL and phosphorus grades, thus allowing its potential use as iron ore.

Jaspilite (JP) – banded iron formation, usually of the oxide facies, composed of alternating bands of opaque minerals, such as hematite (predominantly), magnetite or martite, and reddish or white bands composed of jasper and/or chert. Hematite crystals occur mainly in the form of microcrystalline and lamellar hematite, in addition to martite and magnetite, magnetite is uncommon and generally martitized, with kenomagnetite relicts (Lobato et al. 2005). The jaspilite is reddish-gray and represents the ore protolith of the Carajás iron deposits. It occurs predominantly at the base of the iron formations, in contact with mafic rocks or as lenses, immersed in large mass of friable hematite. The thickness of the lenses is usually small (a few meters), ranging from centimeters to about 20 m. The jaspilite in the basal portion can reach up to 350 m in thickness, the continuity in-depth in some regions of the mine is unknown. In the large mass of jaspilite, which constitutes the base of the iron formation, hematite lenses, more commonly friable hematite, are observed in regions close to the jaspilite/hematite top contact.

Friable hematite (HF) – is the predominant type of ore, occurring throughout all Serra Norte mines. It is commonly banded, locally showing primary lamination planes. It consists of a gray friable hematite material with a metallic luster with high porosity. It can be powdery or disaggregate into small fragments (placoid or not).

Hematite crystals occur mainly in the form of microcrystalline, lamellar, anhedral-subhedral, and euhedral-subhedral hematite, in addition to martite, as magnetite pseudomorphs (Lobato et al. 2005). It is predominantly formed by the supergenic enrichment of the ore protolith (jaspilites). It has variable thickness in the enrichment profile, reaching up to 350 m and great continuity throughout the dip.

Compact hematite (HC) – a material rich in iron and, like HFs, generated from the weathering alteration of jaspilite. Its color varies from black to reddish-brown, the latter is typical for goethite/limonite cementation, which is understood to be responsible for the high compactness of this lithotype. HC occurs subordinately throughout the entire deposit, like lenses inside the large friable hematite mass, usually with thicknesses around 5 to 10 m, without considerable lateral continuity (few tens of meters). Locally, it can reach thicknesses of up to 50 m. The color of HC is bluish-gray color with metallic luster. It is dense, with low porosity, and it can be banded, characterized by the original banding of the preserved jaspilite, defined by compact layers alternating with porous or brecciated layers. This lithotype can also be massive, with the original texture destroyed, composed of aggregates of hematite crystals. The Fe contents are between 59 and 69%. Al₂O₃GL represents an important contaminant in this lithology.

Manganese hematite (HMN) – The color of manganese hematite is dull dark gray, occurring in lenses with thicknesses ranging from 5 to 10 m, and it may locally reach thicknesses of 60 m, without much lateral continuity, dispersed within the mass of friable hematite. HMN is a material rich in Fe and with Mn contents greater than 2% (global). It is usually positioned at the base of the hematite bodies, a probable zone of accumulation of Mn leached from the weathered horizons.

Iron manganese (FMN) – It is a material that apparently represents an intermediate product of the weathering alteration of jaspilite, enriched in Mn. It occurs as small lenses (usually a few meters thick, reaching up to 30 m), with little lateral continuity, within the mass of friable hematite.

Mafic rocks – They are the host rocks of the iron formation, occurring both at the base and at the top of it. They are represented by the mafic rocks of the Grão Pará Group, the Parauapebas (bottom) and Igarapé Cigarra (top) formations, according to Macambira (2003). Mafic rocks mainly correspond to basalts. For geological modeling purposes, they were not classified in the mentioned stratigraphic units, being considered only as mafic rocks, discriminated into decomposed mafic (MD), semi-decomposed mafic (MSD), and fresh mafic (MS). In addition to their occurrence as host rock (top and base of the iron formation), they also occur as sills and mafic dykes in iron formations.

Decomposed mafic (MD) – It presents a high degree of alteration, poorly structured, with color ranging from reddish to yellowish, clayey, with predominantly soft consistency.

Semi-decomposed mafic (MSD) – It is an intermediate term between MS and MD, sometimes still showing relicts from the original texture of the rock, but already with deep mineralogical transformation, and consequently, in its color.

Fresh mafic (MS) – rock not affected by weathering, systematically chloritized, and corresponding to the product of the hydration of basalts and diabases. Its color is dark green, sometimes with typical volcanic structures such as quartz amygdules. Compositional variations and even non-ferrous clastic and chemical sediments were grouped under this name to simplify the geological interpretations.

11.6. Resource assays

11.6.1. Exploratory data analysis

Vale performed exploratory data analysis (EDA) for each estimation domain, including univariate statistics, histograms, cumulative probability plots; box plots to compare geology domain statistics, and contact plots to investigate grade profiles between estimation domains.

The box-plot showing the distribution of global iron (FEGL) and descriptive statistics of the main lithotypes modeled in the N1 deposit is presented below (Figure 11-17) as an example.

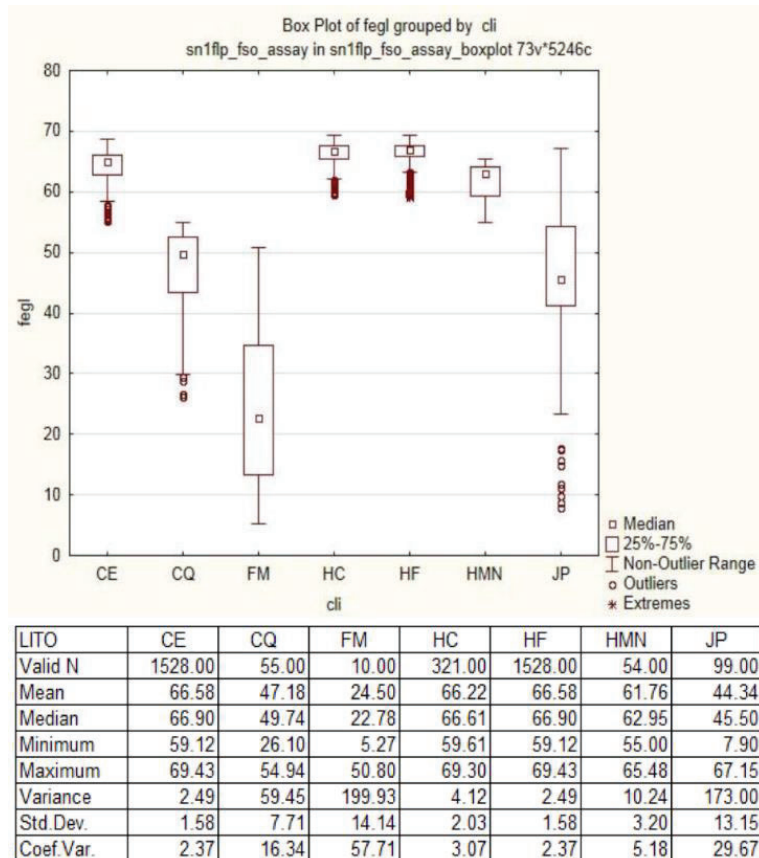


Figure 11-17 - Box-plot graph and descriptive statistics of global Fe grades

11.7. Treatment of high-grade assays

Anomalous values were handled separately in the estimation process. For this purpose, a cut of outliers in the database was applied from the statistical analysis of the distribution of grades (histograms, cumulative frequency plots). The blocks estimated as outliers were those located within the ellipsoid of size 150 x 75 x 15 meters for HC and 200 x 100 x 15 meters for HF. The orientation of the ellipsoid respected the orientation defined for the domain containing the block. For blocks attributed as outliers, the estimation process uses the entire database (no database restriction), but for blocks that were not attributed as outliers, only samples characterized as “OUT” were used.

11.8. Compositing

For the variographic analysis and grade estimation processes, the database was submitted to an isotopy process and subsequent regularization in composites of 15 m. The drilling intervals are regularized respecting the height of the mine bench and the lithological contacts. The method adopted for regularization (composites) is the Vulcan standard, which respects the pre-established constant length and lithological contacts. The acceptance limit of broken intervals (residuals) during regularization in the grade estimation step is 30% of the bench height. The sum of all broken intervals is less than 2% of the total meters in the database.

11.9. Trend Analysis

11.9.1. Grades spatial continuity analysis – N1

Variographic analyses were made to acquire the necessary parameters to estimate grades via the Intrinsic Correlation Model (IMC). For this purpose, the FEGL experimental variogram was calculated, and from the variogram model of this variable, the parameters (variance and ranges) for the IMC were obtained, assuming that the variables have intrinsic correlation.

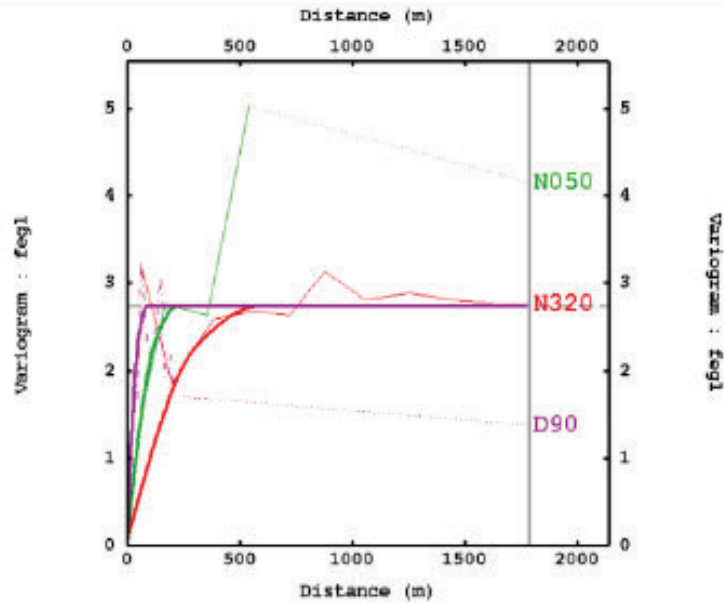
Then, the following cross experimental variograms were obtained, as well as their respective models:

- Global grades (Fe, Si, P, Al, Mn, and LOI), totaling 36 cross and direct variograms.
- Fractions (retained percentage) + accumulated values of Fe, Si, P, Al, Mn, and LOI of the fractions G1A, G1B, G2, and G3, totaling 28 variables that result in 784 cross and direct variograms.

After the 784 variographic models were created, they were adjusted based on the ranges and proportions of the variances obtained in the FEGL variographic model. The adjusted variographic models were later graphically checked for validation and verification of any impacts this procedure may result in. The following are the Isatis® parameters used in experimental variograms and variographic models:

- Database;
- Selection;
- Isatis parameter files of the experimental variogram;
- Isatis variographic model parameter files;
- Direction of experimental variograms and variographic models (specific for each deposit):
 - Azimuth, Dip and Plunge;
 - Angular tolerance;
 - Lags;
 - Number of lags.

Figure 11-18 shows an example, with the FEGL variogram model used for IMC of hematites in N1. This variographic model was used to estimate the lithotypes: CE, CQ, HF, HC, HMN, FM, JP, MD, MS. The MSD lithotype was not estimated, as there were not enough analytical results to estimate this lithology.



Isatis

Figure 11-18 - FEGL variographic model for grade estimation, example of N1 deposit

11.10. Search strategy and grade interpolation analysis

11.10.1. Grade interpolation

The interpolation of grades was performed using the principle of ordinary (co)kriging of intrinsic correlation variographic models (ICM). As explained above, based on the method, both the independent kriging of the variable and the (co)kriging have the same results since the variograms are proportional. For the estimate, normalized sills were used. This standardization of the sills is a simplification of the method that makes the estimation process feasible for software based on basic geostatistics modules. The N1 model was estimated in the Geostats module (GSLIB algorithms) of the Vulcan software.

Nine global variables (Fe, SiO₂, P, Al₂O₃, Mn, PF, TiO₂, MgO, and Cao) and 36 granulochemical variables accumulated by the 4 fragment size fractions were estimated. Also, the 4 fragment size fractions (G1A (+19 mm), G1B (-19+8 mm), G2 (-8+0.15 mm) and G3 (-0.15 mm) were estimated.

Although lithological grouping was used to adjust the variographic model, the lithological units were respected in the kriging process; that is, composites of certain lithotype estimate only blocks of the same lithotype.

In the N1 model, 09 distinct lithological domains were estimated: CE, CQ, HF, HC, HMN, FM, JP, MD, and MS.

In the N2 model, 09 distinct lithological domains were estimated: CE, CQ, HF, HC, HMN, JP, FMN, IN, and MD. For MD, the estimated blocks are limited to the contacts with the iron formation, as they are intended to be used only in the dilution calculation. Thus, an auxiliary database was generated with the centroids of the hematite and jaspilite blocks, and from this grid, the decomposed mafic blocks (MD) within a radius of 60 x 60 x 30 m were attributed with the NN estimated grade.

In the N3 model, 7 separate lithological domains were estimated: CE, CQ, HF, HC, HMN, JP, and FMN. Due to the small number of mafic rock samples, these were not estimated.

In the N4 and N5 models, 08 distinct lithological domains were estimated: CE, CQ, HF, HC, HMN, FMN, JP, and MD.

Estimation parameters

Table 11-10 presents the list of parameters adopted for the estimation of grades of the N1 model. For all iron formation lithotypes (hematites, jaspilites, and cangas), the estimated blocks are 25 x 25 x 15 m, but for the waste mafic lithotypes, some blocks of size 100 x 100 x 15 m were estimated. Table 11-11 presents the list of parameters adopted for the estimation of grades of the N2.

Table 11-10 - Parameters used in estimating the global grades and granulo-chemistry of the N1 model

Parameters		(co) Kriging Global and granulo-chemistry		Nearest Neighbor Global and granulo-chemistry	
		P1	P2	P1	P2
Samples	Database	Sn1flp_1215.cac.isis			
	Min. samples	1		1	
	Max. samples	16		1	
	Octant	Yes		No	
	Weight	Length >= 4.5 m		Length >= 4.5 m	
	Outliers treatment	Yes		Yes	
Blocks	Discretization	5 x 5 x 2		1 x 1 x 1	
	Search range (m)	450 x 150 x 50	4500 x 1500 x 500	450 x 150 x 50	4500 x 1500 x 500
	Block size	25 x 25 x 15		25 x 25 x 15	
	N° of structural sectors	7		7	

P1 – First pass of the estimate–; P2 - Second pass of the estimate

Table 11-11 - Parameters adopted in the estimation of N2 model grades

Parameters		(co) Kriging Global and granulo-chemistry		Nearest Neighbor Global and granulo-chemistry	
		GL + P1	P2	GL + P1	P2
Samples	Database	N2_flp.fac.isis			
	Min. samples	1		1	
	Max. samples	16		1	
	Octant	Yes		No	
	Weight	Length >= 4.5 m		Length >= 4.5 m	
	Outliers treatment	Yes		Yes	
Blocks	Discretization	5 x 5 x 2		1 x 1 x 1	
	Search range (m)	200 x 100 x 30	2000 x 1000 x 300	200 x 100 x 30	2000 x 1000 x 300
	Block size	25 x 25 x 15		25 x 25 x 15	
	N° of structural sectors	1		1–	

GL - Estimate of global chemistry; P1 – First pass of the estimate–; P2 - Second pass of the estimate

For N3 model, two sectors were defined for the grade estimation as a function of the geometry of the deposit: one in the E-W direction and the other, NE-SW. The variograms and search ellipsoids for each sector are rotated following the main directions of continuity (Figure 11-19).

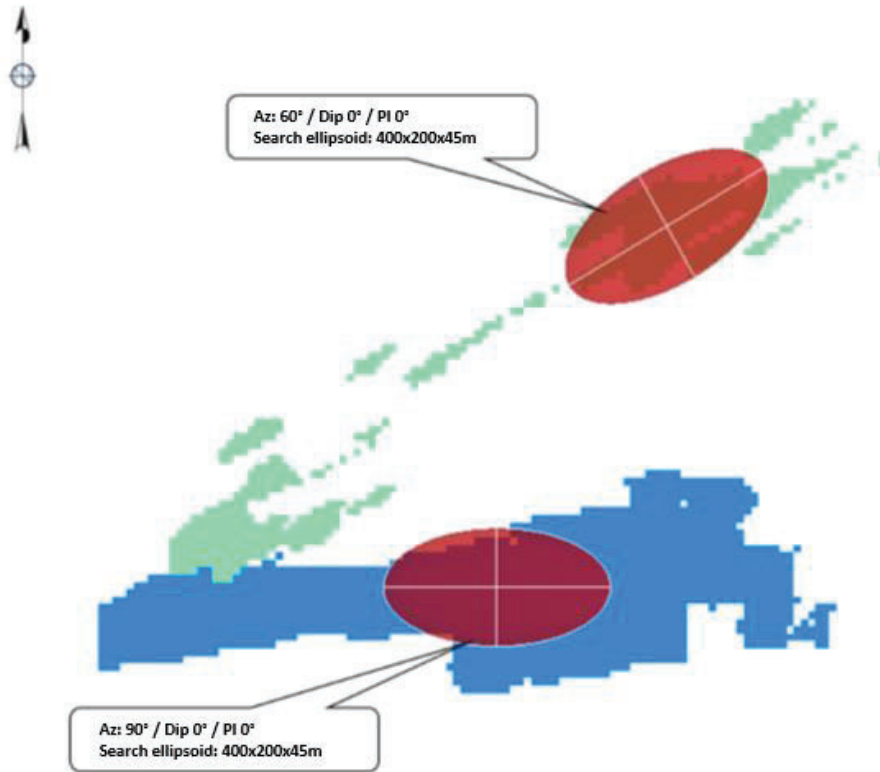


Figure 11-19 - Search parameters for N3 model

Table 11-12 presents the list of parameters adopted for grade estimation of the N4 model, Figure 11-20 illustrates the orientation of the search ellipsoid for grade estimation.

Table 11-12 - Parameters used in estimating the global content and granulochemistry of the N4 model

Parameters		(co) Kriging Global and granulo-chemistry		Nearest Neighbor Global and granulo-chemistry	
		GL + P1	P2	GL + P1	P2
Samples	Database	Sn4sn4.cac.isis			
	Min. samples	1		1	
	Max. samples	16		1	
	Octant	Yes		No	
	Weight	Length >= 4.5 m		Length >= 4.5 m	
	Outliers treatment	Yes		Yes	
Blocks	Discretization	5 x 5 x 2		1 x 1 x 1	
	Search range (m)	400 x 250 x 50	4000 x 2500 x 500	400 x 250 x 50	4000 x 2500 x 500
	Block size	25 x 25 x 15		25 x 25 x 15	
	Sectoring	Yes		Ye-	

GL - Estimate of global chemistry; P1 – First pass of the size fractions chemical estimat-; P2 - Second pass of the size fractions chemical estimate

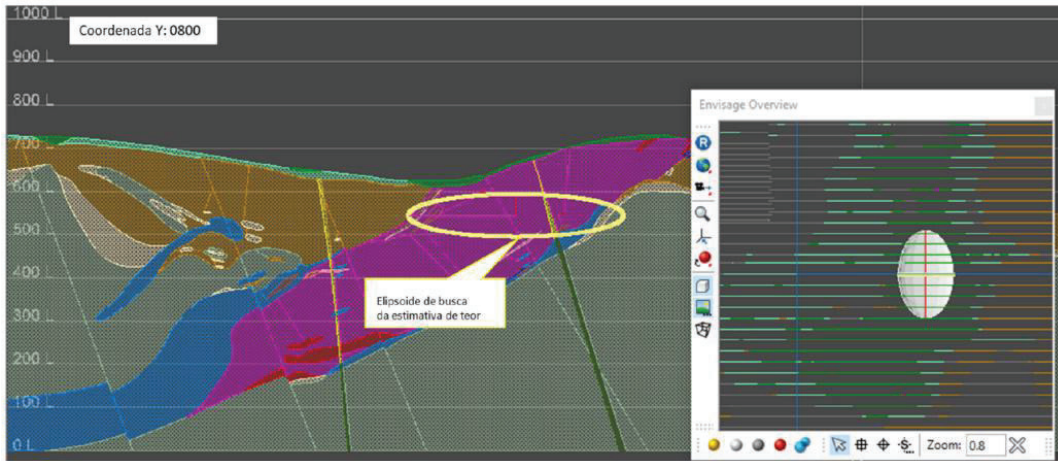


Figure 11-20 - Search ellipsoid for estimating N4 mine grades

Table 11-13 presents the list of parameters adopted for the estimation of grades of the N5 model, and Figure 11-21 illustrates the orientation of the search ellipsoid for grade estimation.

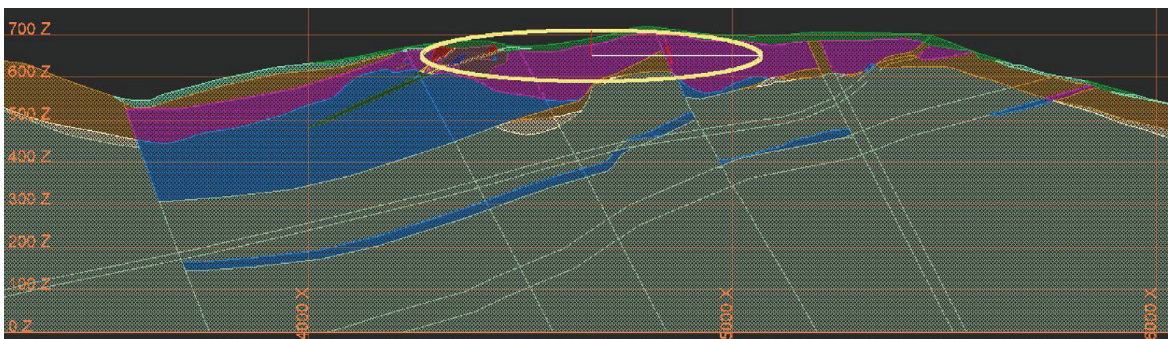


Figure 11-21 - Search ellipsoid of the estimated grades of the N5 mine, North-4200

Table 11-13 - Parameters used in estimating the global grades and granulochemistry of the N5 model

Parameters		(co) Kriging Global and granulo-chemistry		Nearest Neighbor Global and granulo-chemistry	
		GL + P1	P2	GL + P1	P2
Samples	Database	n5n5.cac.isis			
	Min. samples	1		1	
	Max. samples	16		1	
	Octant	Yes		No	
	Weight	Length >= 4.5 m		Length >= 4.5 m	
	Outliers treatment	Yes		Yes	
Blocks	Discretization	5 x 5 x 2		1 x 1 x 1	
	Search range (m)	400 x 200 x 60	4000 x 2000 x 600	400 x 200 x 60	4000 x 2000 x 600
	Block size	25 x 25 x 15		25 x 25 x 15	
	Sectoring	Yes		Yes-	

GL - Estimate of global chemistry; P1 - First pass of the size fractions chemical estimate-; P2 - Second pass of the size fractions chemical estimate

Kriging process

A notable feature in the history of data acquisition in the Carajás deposits is the diversity of sample preparation fluxes and the analytical methods adopted. Thus, the disproportion between the amount of global chemistry data, as opposed to the chemistry data by grain size fractions, results in a heterotopic database that requires a series of adaptations to the kriging plans, as well as additional calculations in the post-process stage. In this work, the global chemistry and granulochemistry data were estimated, the latter in two steps: the first pass (P1), performed with the same search radii as the global chemistry estimate, and the second pass (P2), with search radii 10 times larger than the first. This is necessary because there are regions of the model where samples that contain only global chemistry data predominate. Therefore, some blocks have the global grades estimated, but still without particle size and chemistry data by fraction. The reason for the Second Pass (P2) is to complement the particle size data of these blocks.

After the end of the estimation process, the post-processing step was started. Post-processing is done following the flow exemplified in Figure 11-22, where the following checks were made:

- Existence of blocks with negative grades: the correction was to apply the NN estimated grade for the granulochemistry and the detection limit for the negative grades in the global Mn, Ti, Mg, and Ca. The G1A particle size fraction was set to "0", where applicable;
- Treatment of blocks without CaO, MgO, and TiO₂ estimated grades: as a result of the heterotopic database used in the estimate, blocks had no CaO, MgO, and TiO₂ estimated grades. The correction was made considering the average grades of the blocks estimated for each lithotype and the chemical closure for each fraction. In cases where the chemical closure was equal to or greater than 100%, the laboratory detection limits were applied. When the chemical closure was smaller, the difference was proportionally distributed among the 3 variables;
- Compatibility of the chemistry of the grain size fractions with the estimated global;
- Identification and correction of anomalous stoichiometric closing values: blocks with values less than 95% and greater than 105% were marked. In blocks with deviations in relation to the stoichiometric closing for some fraction, the estimated grades in the granulometric fraction were replaced by the global estimated grades;
- Identification and correction of Fe grades above the maximum, by fraction and global grade, of the database were performed.

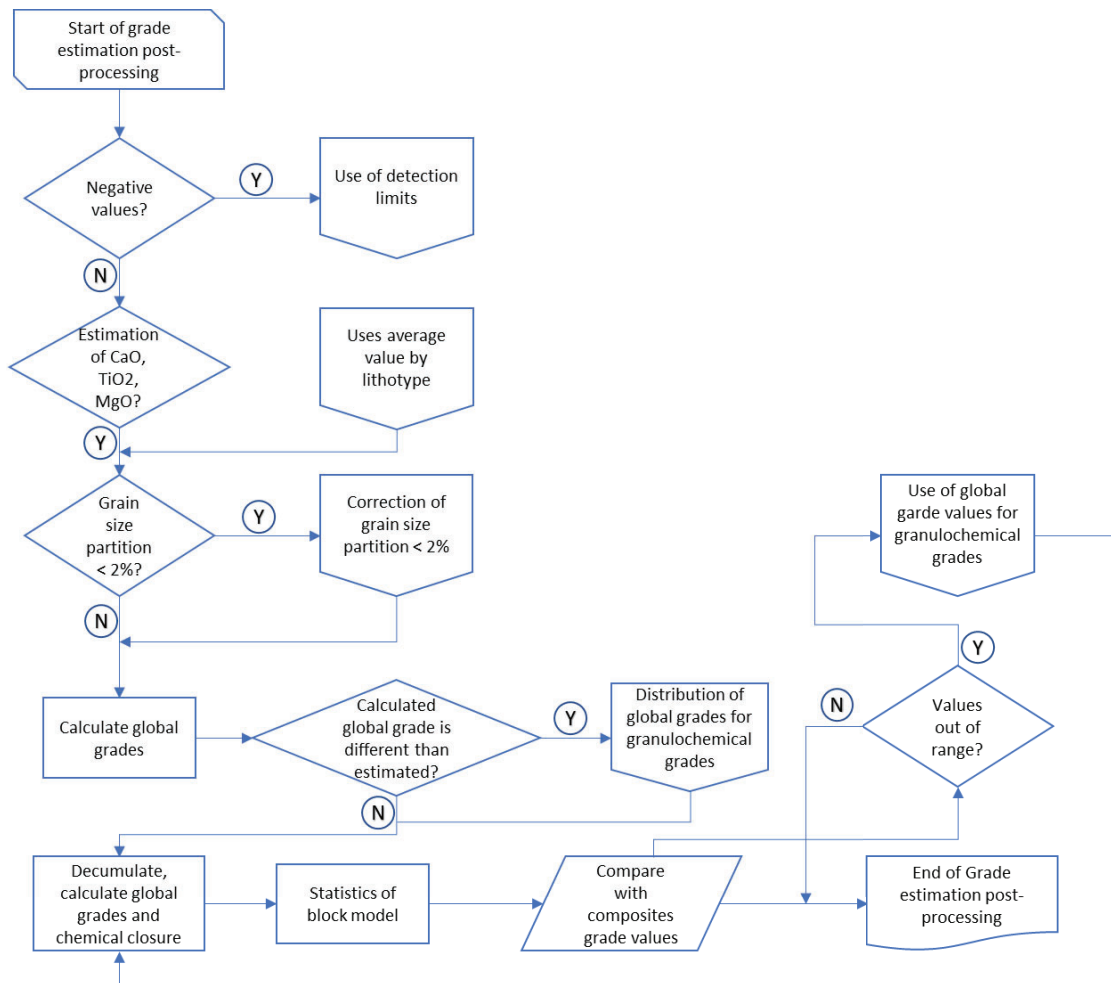


Figure 11-22 - Flowchart of post-processing of grade estimation

11.11. Bulk density

Samples collected by direct methods of conventional density (volume displacement, volume filling, sand flask, and hydrostatic weighing) and gamma-gamma geophysical drill hole logs were used to determine the densities of the different lithotypes of the Serra Norte mines. The gamma-gamma survey data were validated by the geophysics team from the Ferrous Geology and Drilling area and by the Ferrous Mineral Resources area.

The mean values weighted by the number of samples are representative of the density of each lithotype (Table 11-14 to Table 11-18). The weighting considered the results from gamma-gamma geophysical logging and/or conventional direct tests.

Moisture is obtained by drying an aliquot of the sample and comparing the dry and wet mass of the sample. The importance of this determination is that, for evaluations of Vale iron mines, the tonnage measurements are made with the density in the natural base, considering the free water mass obtained from the moisture measurements.

Table 11-14 - Summary of N1 deposit densities

Lithotype	Meters/Samples	Natural Density (g/cm ³)	Method
Structural Canga - CE	3.15 meters	3.32	GG
Chemical Canga - CQ	12.64 meters	2.80	GG
Compact Hematite - HC	12 samples	3.81	DV
Friable Hematite - HF	16.41 meters	3.03	GG
Mn Hematite – HMN	4.13 meters	3.24	GG
Jaspilite – JP	38.24 meters	2.92	GG
Iron Manganese – FM	17.42 meters	3.20	GG
Weathered Mafic – MD	177.33 meters	2.67	GG
Semi-weathered Mafic – MSD	39.86 meters	2.87	GG
Mafic - MS	302.98 meters	2.91	GG

Methods: GG – Gamma-gamma geophysical profiling; DV – Volume displacement. / Note: Humidity determined only for HC (0.29%).

Table 11-14 - Summary of densities and moistures of the N2 deposit

Lithotype	Meters/Samples	Natural Density (g/cm ³)	Moisture (%)	Method
Structural Canga - CE	25.84 meters	3.17	3.47	GG
Chemical Canga - CQ	8.87 meters	2.66	9.21	GG
Compact Hematite - HC	25 samples	3.90	1.17	DV
Friable Hematite - HF	74.97 meters	3.28	6.92	GG
Mn Hematite – HMN	19 samples	3.15	7.10	PV
Jaspilite – JP	49.53 meters	3.32	0.33	GG
Iron Manganese – FM	5.24 meters	3.14	10.18	GG
Weathered Mafic – MD	211 samples	1.88	22.02	PV
Semi-weathered Mafic – MSD	25 samples	2.35	11.01	PV
Mafic - MS	156 samples	2.89	0.10	DV
Quartzite - QT	316.02 meters	2.38	0.10	GG

Methods: GG – Gamma-gamma geophysical profiling; DV – Volume displacement; PV – Volume Filling / Obs.: * Quartzite: The average values of the N2 Mine – Model N4_0316 were considered, except for Quartzite (QT): gamma-gamma geophysical survey in a drill hole at N2 deposit

Table 11-15 - Summary of densities and moistures of the N3 deposit

Lithotype	Meters/Samples	Natural Density (g/cm ³)	Moisture (%)	Method
Structural Canga - CE	25.84 meters	3.17	3.47	GG
Chemical Canga - CQ	8.87 meters	2.66	9.21	GG
Compact Hematite - HC	25 samples	3.90	1.17	DV
Friable Hematite - HF	74.97 meters	3.28	6.92	GG
Mn Hematite – HMN	19 samples	3.15	7.10	PV
Jaspilite – JP	49.53 meters	3.32	0.33	GG
Iron Manganese – FM	5.24 meters	3.14	10.18	GG
Weathered Mafic – MD	211 samples	1.88	22.02	PV
Semi-weathered Mafic – MSD	25 samples	2.35	11.01	PV
Mafic - MS	156 samples	2.89	0.10	DV
Schist - XI	-	1.88	22.02	PV

Methods: GG – Gamma-gamma geophysical profiling; DV – Volume displacement; PV – Volume Filling / Obs.: * shale: adopted the same value as decomposed mafic (MD). / The average values of the N4 mine – Model N4_0316 were considered.

Table 11-16 - Summary of densities and moistures of the N4 mine

Lithotype	Samples	Natural Density (g/cm ³)	Moisture (%)
Structural Canga - CE	399	3.22 ^{*3}	4.39
Chemical Canga - CQ	137	2.71 ^{*3}	7.18
Compact Hematite - HC	1,008	3.59 ^{*3}	1.01
Friable Hematite – HF	7,827	3.24 ^{*3}	6.15
Mn Hematite – HMN	283	3.16 ^{*3}	7.14
Jaspilite – JP	4,524	3.10 ^{*3}	0.22
Iron Manganese – FM	11	3.06 ^{*3}	10.53
Weathered Mafic – MD	3,551	2.27 ^{*3}	22.51
Semi-weathered Mafic – MSD	621	2.39 ^{*3}	0.10
Mafic - MS	7,361	2.73 ^{*3}	0.10
Clay – AG ^{*1}	-	2.27	-
Landfill – AT ^{*2}	-	2.00	-

*1 Adopted the lithotype MD value. / *2 Historical Value. / *3 Weighted average of values obtained by gamma-gamma geophysical survey and conventional density methods, using the number of samples/composites as a weight.

Table 11-18 - Summary of densities and moistures for the N5 mine

Lithotype	Samples	Natural Density (g/cm ³)	Moisture (%)
Structural Canga - CE	176	2.96	4.82
Chemical Canga - CQ	495	2.62	10.47
Compact Hematite - HC	170	3.65	0.82
Friable Hematite - HF	151	3.30	8.22
Mn Hematite – HMN	24	3.00	11.06
Jaspilite – JP	3,357	3.43	0.10
Iron Manganese – FM	1	3.01	10.49
Weathered Mafic – MD	4,257	2.23	18.36
Semi-weathered Mafic – MSD	181	2.32	-
Mafic - MS	777	2.85	0.10
Landfill – AT ^{*1}	-	2.00	-
Conglomerate ^{*2}	-	2.48	10.47

*1 Considered historical values. / *2 Value relative to CQ by conventional methods.

11.12. Block models

N1 wireframes were filled with blocks in Vulcan software. The block model was sub-celled at wireframes boundaries with parent cells measuring 100 m by 100 m by 100 m and minimum sub-cell sizes of 25 m by 25 m by 15 m. The block model setup is shown in Table 11-18.

Table 11-18 - N1 Block Model Setup

Parameter	X	Y	Z
Origin (m)	578,584	9,327,842	10
Bearing/Dip/Plunge	52	0	0
Block Size (m)	100	100	15
Min.Sub Block size (m)	25	25	15
Number of blocks	72	92	66

N2 wireframes were filled with blocks in Vulcan software. The block model (SN2_0616_LP.BMF) was not sub-celled at wireframes boundaries in a single scheme with parent cells measuring 25 m by 25 m by 15 m. The block model setup is shown in Table 11-18.

Table 11-19 - N2 Block Model Setup

Parameter	X	Y	Z
Origin (m)	582,163	9,329,760	150
Bearing/Dip/Plunge	90	0	0
Block Size (m)	25	25	15
Min.Sub Block size (m)	25	25	15
Number of blocks	95	78	56

N3 wireframes were filled with blocks in Vulcan software. The block model was sub-celled at wireframes boundaries with parent cells measuring 25 m by 25 m by 15 m and minimum sub-cell sizes of 12.5 m by 12.5 m by 15 m. The block model setup is shown in Table 11-20.

Table 11-20 - N3 Block Model Setup

Parameter	X	Y	Z
Origin (m)	584,738	9,331,110	200
Bearing/Dip/Plunge	90	0	0
Block Size (m)	25	25	15
Min.Sub Block size (m)	12.5	12.5	15
Number of blocks	174	116	40

N4 wireframes were filled with blocks in Vulcan software. The block model was sub-celled at wireframes boundaries with parent cells measuring 100 m by 100 m by 15 m and minimum sub-cell sizes of 25 m by 25 m by 15 m. The block model setup is shown in Table 11-21.

Table 11-21 - N4 Block Model Setup

Parameter	X	Y	Z
Origin (m)	588,420.02	9,331,110.7	10
Bearing/Dip/Plunge	82.64	0	0
Block Size (m)	100.04	100.04	15
Min.Sub Block size (m)	25.01	25.01	15
Number of blocks	65	103	60

N5 wireframes were filled with blocks in Vulcan software. The block model was not sub-celled at wireframes boundaries in a single scheme with parent cells measuring 25 m by 25 m by 15 m. The block model setup is shown in Table 11-22.

Table 11-22 - N5 Block Model Setup

Parameter	X	Y	Z
Origin (m)	593,799.21	9,320,695.16	10
Bearing/Dip/Plunge	83.64	0	0
Block Size (m)	25.01	25.01	15
Min.Sub Block size (m)	25.01	25.01	15
Number of blocks	212	376	60

RPM reviewed the block model in 2016 and opined that the block sizes are appropriate, based on the drill spacing and proposed mining method, and are suitable to support the estimation of Mineral Resources and Mineral Reserves.

11.13. Net value return and cut-off value

The calculation of the economic cut-off grade considers the sale price of the metal, mineral processing, commercial, mining, processing, transport and marketing costs, grade, and process plant recovery. The cut-off grade is not defined as a matter of the iron grade itself but as a technological approach at each processing plant recovery and productivity stage to estimate Mineral Resources and Mineral Reserves. The decision to mine a specific block will be determined in the final pit generation due to product price and all related costs.

Each ore lithology destination and recovery are defined by processing equations that will search for lithotypes totally or partially routed to the operational processing route of Vale site or that had a processing route successfully tested at the project/study level.

11.14. Classification

11.14.1. Mineral inventory classification

The mineral inventories of the block models for Vale iron ore deposits are classified based on the calculation of the “Risk Index” (IR), which follows the classification method originally proposed by Amorim and Ribeiro (1996) and later reformulated by Ribeiro et al. (2010).

Risk index methodology

The Risk Index method uses a single index, combining geological continuity, measured by the “ore” kriging indicator (IK), and estimation error, measured by the variance of the indicator kriging (σ^2_{IK}), to classify the blocks into measured, indicated, and inferred. IR is calculated by the following equation, which represents simplification of the original 1996 equation:

$$IR(u) = \sqrt{[1 - I_k(u)]^2 + [\sigma_{IK}^2(u)]^2}$$

where:

$I_k(u)$ - is the indicator estimated by kriging, associated with the support of given block, located at position u ;
 $\sigma_{IK}^2(u)$ — is the variance of the kriging indicator of the block at position u , using a normalized semivariogram model, with unitary sill.

The graphic representation of IR can be seen in Figure 11-23. The horizontal axis represents the geological continuity as $1 - I_k(u)$. The vertical axis is the estimation error, $\sigma_{IK}^2(u)$. The vector IR and the limits used for the classification, into Measured, Indicated, and Inferred blocks.

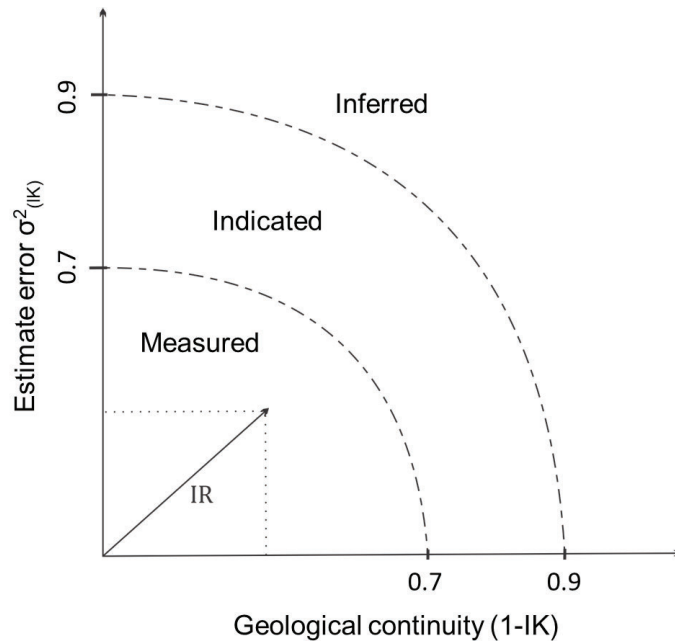


Figure 11-23 — Graphic representation of the IR calculation and class limits

The validation of the method (IR), including the chosen Risk Indices, is carried out by comparing it with another classification method: the dilation and erosion method. The dilation and erosion method is a geometric method in which, in general, blocks belonging to a 100 x 100 m mesh are considered as measured, indicated for a 200 x 200 m mesh, and the other blocks with estimated grades are considered as inferred.

11.14.2. Classification of the Serra Norte mineral inventory

Serra Norte deposits use a binary code, attributing 1 (one) to the regularized drilling intervals considered “ore” (cangas and hematites) and 0 (zero) for the lithotypes considered “waste.” In the N2 and N3 deposits, although jaspilite and iron-manganese lithotype are not currently ore, they received indicator 1 for the variographic analysis due to the small number of samples in the database. For the estimation, the indicators of these lithotypes were attributed with zero (Table 11-23).

Table 11-23 — Indicators used to characterize the lithologies considered as waste and ore from the Serra Norte deposits

Deposit	Indicator 1 (ore)	Indicator 0 (waste)
N1	CE, HF, HC, HMN	CQ, FM, JP, MD, MSD, MS
N2	CE, HF, HC, HMN, JP, FMN	CQ, MD, MSD, MS, IN, QT
N3	CE, HF, HC, HMN, JP, FMN	CQ, MD, MSD, MS, XI
N4	CE, HF, HC, HMN	CQ, FMN, JP, MD, MDSL, MDDK, MSD, MSDSL, MSDDK, MS, MSSL, MSDK, AG
N5	CE, HF, HC, HMN	CQ, FMN, JP, MD, MDSL, MDDK, MSD, MSDSL, MSDDK, MS, MSSL, MSDK, AG

Block kriging and classification according to the Risk Index were performed using Vulcan® software. The radii of the sample search ellipsoid for the construction of the block kriging matrix were 450 x 150 x 50 m for N1, 200 x 100 x 30 m for N2, 400 x 200 x 45 m for N3, 400 x 250 x 50 m for N4 and

N5, in the three main directions of continuity. These distances correspond to a maximum acceptable grid for exploring iron ore resources in the horizontal plane and approximately three benches of extrapolation in the vertical direction. For the estimation, the composites of the exploration and ore control drill holes databases for N4 and N5 were used. For N1, N2, N3 deposits, still under project development phase, only exploration drill holes databases were used. The ellipsoids search directions were the same directions used for grades estimation.

The minimum and maximum samples were 1 and 16, respectively, considering two samples per octant as optimal, and the discretization of the blocks was 4 x 4 x 2.

After estimating the IK variable (Risk Index indicator) and during the process, the IK variance for the kriged blocks (var_ik) was obtained. From these variables, the Risk Index is calculated using a script. The classification follows these criteria: measured for IR up to 0.6, indicated for IR between 0.6 and 0.9 (in general) and inferred for IR above 0.9. The indexes are defined by analyzing the textures (visual) of the block model and comparing them with an auxiliary method (dilation and erosion method).

The final classification of measured, indicated, and inferred were conditioned to contain valid grade values; otherwise, the block is attributed as “n” (potential). Blocks classified as measured but estimated by a single drill hole were downgraded to indicated.

11.14.3. Validation of Serra Norte mineral inventory classification

The validation of the classification of the mineral inventory is done mainly through visual inspection, throughout the model, in vertical and plan sections, to notice possible inconsistencies and distortions of the method. Another validation technique used is the comparison of classification by the Risk Index method with the traditional classification by dilation/erosion, from the drilling grid, as it can be observed in one example, for N5 (Figure 11-25).

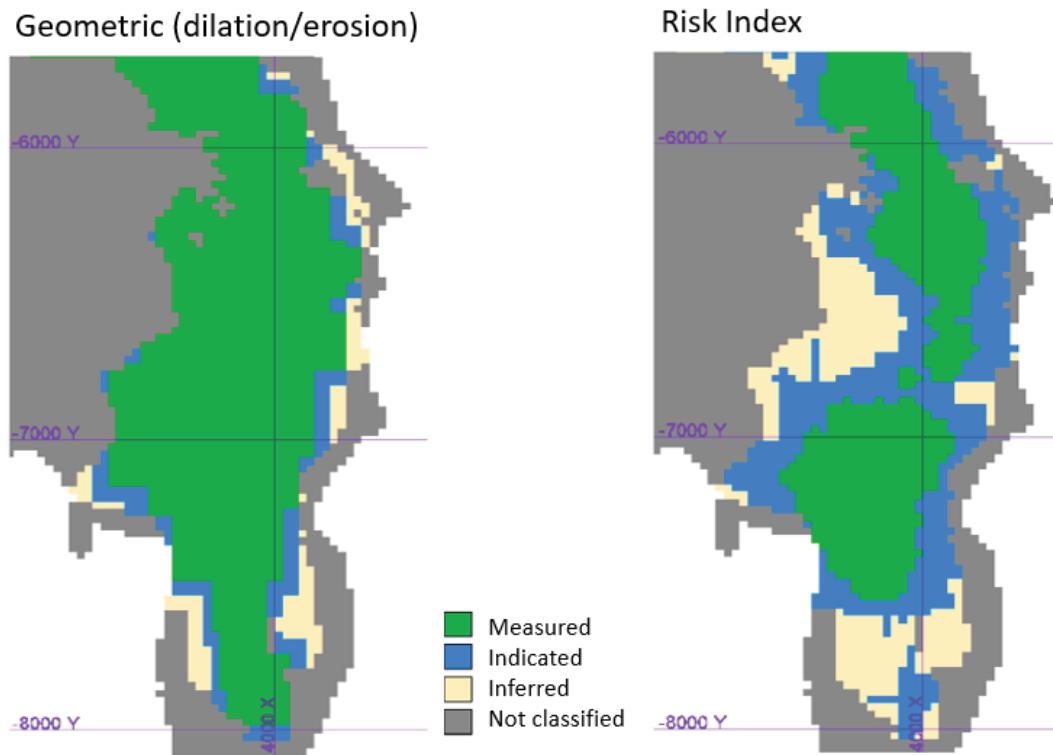


Figure 11-24 — Visual comparison between classification methods at elevation 525 in the N5 mine, Morro1 region: dilation/erosion (left) and Risk Index (right).

11.14.4. Serra Norte mineral inventory

The Classified Mineral Inventory corresponds to the set of geological blocks of iron formation in the mineral inventory that was classified into measured, indicated, and inferred using the Risk Index methodology, representing the lower geological uncertainty for the measured inventory and the higher for the inferred one.

11.15. Block model validation

11.15.1. Grades validation

Block model grade validation follows Vale internal procedures, for all deposits at Serra Norte. The main validation steps are described below.

- Estimation plans summary – this check identifies whether there are any problems with the estimation that have led to estimating a different number of blocks for the same process.
- Block Length – checks whether all blocks with estimated grades have the same dimensions (25x25x15m), proving that the block model has not been corrupted during the estimation process.
- Sampling range – is done through the statistical analysis of the kriged grades compared to the regularized samples file (Table 11-24).

Table 11-24 – Comparison between kriging estimated grades and regularized samples for N2

Lithotype	Variable	Database			Block Model			Differences	
		N°	Min.	Max.	N°	Min.	Max.	Min.	Max.
CE	FEGL	22	55680	66720	1270	55680	66720	0	0
CQ	FEGL	9	39668	53472	756	42173	53472	2505	0
HC	FEGL	20	61519	68062	107	62748	67814	1229	247
HF	FEGL	112	60767	68545	2294	60767	68533	0	12
HMN	FEGL	11	55293	64599	34	55293	63687	0	913
JP	FEGL	7	30157	59890	526	30157	59890	0	0
FMN	FEGL	3	30240	52430	6	30240	49477	0	2953

Drift analysis – is a local and global bias check, in which a “Nearest Neighbor” estimation model is generated, and the results are compared globally by 15 m levels (bench height). Some examples of this validation are presented below (Figure 11-25).

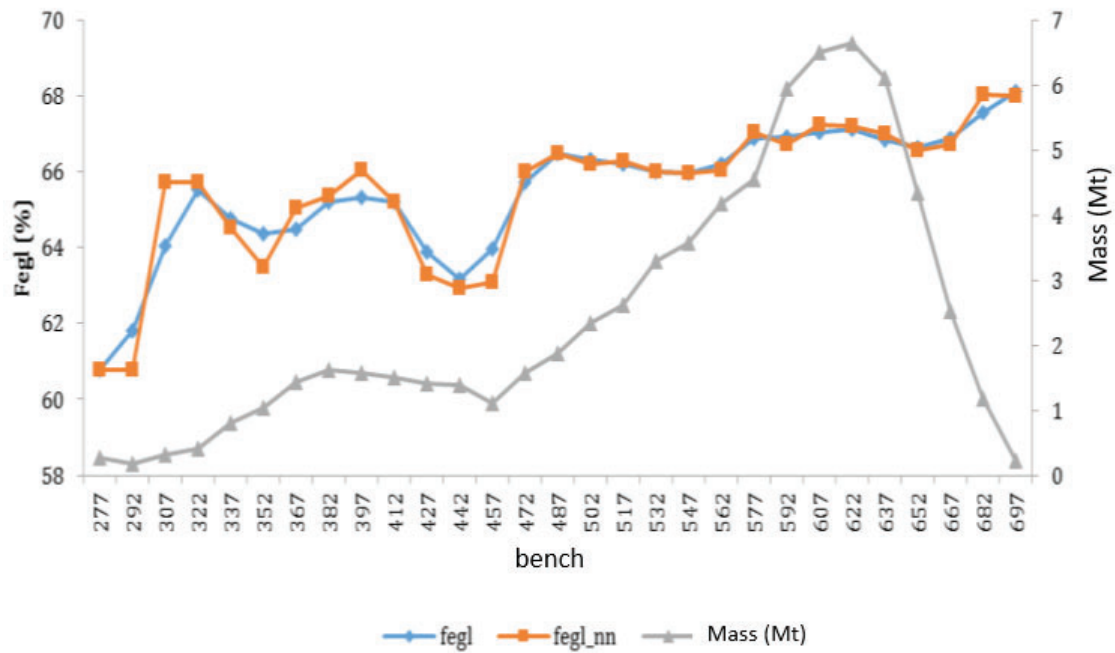


Figure 11-25 – Global iron bias check of friable hematites (HF) for N2

In addition to the global comparison, visual inspections were also performed on the estimated block model (Figure 11-26).

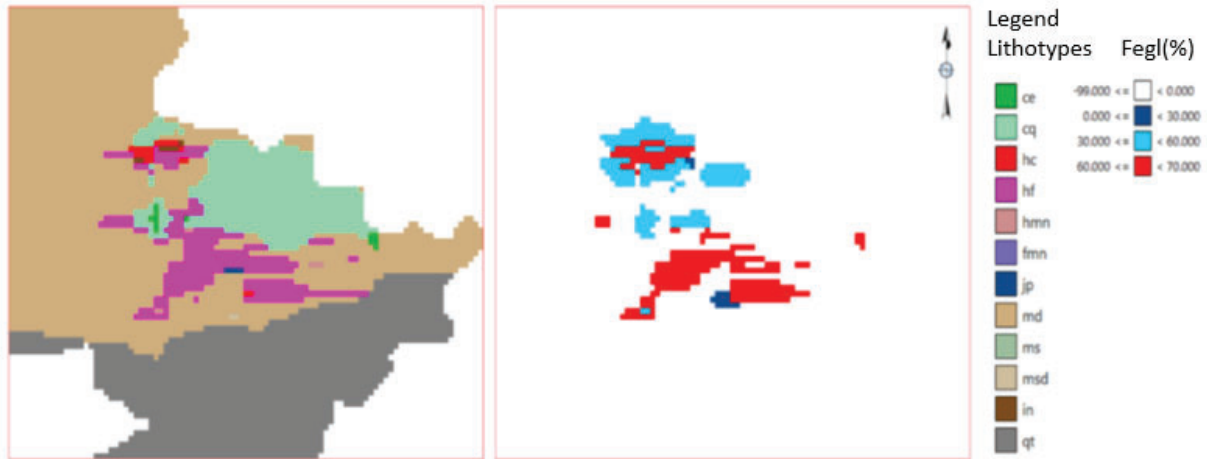


Figure 11-26 — Visual comparison of the geological model (left) with the estimated global iron grades (right) for bench 622.5

Sample density by mineral inventory class – the evaluated values are the average number of samples used in the block grades estimate, by mineral class (Figure 11-27).

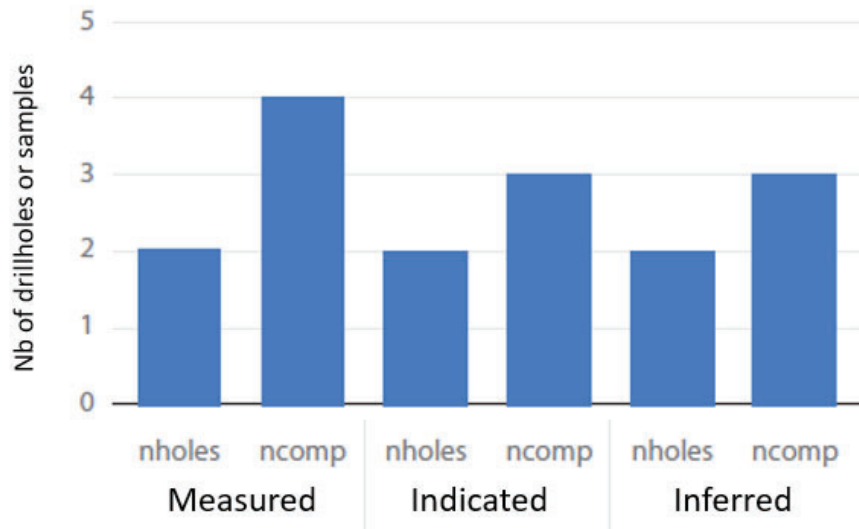


Figure 11-27 — Average number of samples per mineral inventory class of model N2

11.16. Mineral resource reporting

11.16.1. Assessment of the reasonableness for eventual mineral extraction of mineral resources in the northern logistic corridor

The Mineral Resource is not the inventory of all drilled or sampled mineralization, regardless of cut-off grades, likely mine dimensions, location, or continuity. It is a realistic mineralization inventory that, depending on assumed and justified technical and economic conditions, could become economically mineable, in whole or in part.

For this evaluation, some technical parameters were applied to the Classified Mineral Inventory (mining method, geotechnical, process engineering, restrictions of conservation units, hydrogeological, speleological and surficial restrictions, mining rights, among others) and economic (cost and price) for delimitation of the mass that will be declared as a Mineral Resource.

The NPV Scheduler (CAE ®) software was adopted for optimization of the open pit through the Lerch-Grossman optimizing algorithm, in which the generated mathematical pits search for all classified iron formation (measured, indicated, and inferred) that presents reasonableness of mineral processing, mining method, and infrastructure associated with any mineral project at a minimum level of conceptual study (FEL 1). In addition, analyses of masses blocked by the main restrictions existing in this deposit were made. Before, during, and after carrying out all these optimization steps, statistical validations of the lithotypes, mineral processing destinations, geotechnical parameters, costs, prices, recovery equations, and product quality are carried out, in addition to 2D and 3D visual validations.

11.16.2. Assessment of reasonableness for eventual mineral extraction for Serra Norte mineral resources (N1, N2, N3, N4, and N5)

The Mineral Resource is not the inventory of all drilled or sampled mineralization, regardless of cut-off grades, likely mine dimensions, location, or continuity. Instead, it is a realistic mineralization inventory that, depending on assumed and justified technical and economic conditions, could become economically mineable in whole or in part.

For this evaluation, some technical parameters were applied to the Classified Mineral Inventory (mining method, geotechnical, process engineering, restrictions of conservation units, hydrogeological, speleological and surficial restrictions, mining rights, among others) and economic (cost and price) for delimitation of the mass that will be declared as a Mineral Resource.

The NPV Scheduler (CAE ®) software was adopted for optimization of the open pit using the Lerch-Grossman algorithm. Before, during, and after all these optimization steps, statistical validations of the lithotypes, mineral processing destinations, geotechnical parameters, costs, prices, recovery equations, and product quality are carried out, in addition to 2D 3D visual validations.

Price and cost parameters

As a general assumption, Vale long-term CIF price curves (price delivered in China), adjusted for moisture content, were adopted, according to the long-term pricing policy of the company. The considered average moisture of the product was 8.17% in this price analysis.

- The prices of products from these deposits were regularized only with the Fe grades curves above 60%, considering that Vale uses blending centers in Asia to sell its products (BRBF – Brazilian Blend Fines);
- Mine costs were defined as the average cost per mined ton (ore+waste) calculated from the assumptions of mine costs and mine movements used in the Strategic Planning Cycle/Master Plan;
- Mineral processing costs were defined by the average cost per ton of ROM fed into the long term mine planning of the deposit, recorded in the Strategic Planning Cycle/Master Plan;
- Commercial costs, including logistics, administration, etc., were calculated by the average current costs and investments per ton of product from the stockpiles of the mineral processing plants to the port in China and were properly used to build the final pit to define the mineral resources of each deposit of Serra Norte Complex.

Mineral process parameters

The block model was populated with a value “NSR” which represents the qualities and respective mass recoveries, block by block. These are obtained from equations provided by the Vale process engineering team. Due to the quality of the material and as the processing will be based on natural moisture, the mass recovery was inferred at 99.5%, which is the standard for the current processing plants at the Serra Norte Mining Complex.

The equations search for lithotypes that are routed, totally or partially, to the operational processing route of a Vale site, or that had a processing route successfully tested at the project/study level, that is:

- ce: structural canga;
- hc: compact hematite;
- hf: friable hematite;
- hmn: manganese hematite;
- Such lithotypes are grouped into the following groups:
 - Hematites (HEM): hc, hf, hgo, and hmn;
 - Rolled (ROL): ce.

Mining method parameters

Due to the characteristics of the deposit, which presents superficial to subsurface iron mineralization, low ore/waste ratio, and similarity to deposits that are already mined at the Carajás Mining Complex, the open-pit mining method was chosen. Based on internal reconciliation and operation studies, it was adopted that mining recovery is 96% and the operational dilution was established at 1.35%. As for the optimization of reserves, the additional cost of deepening of US\$ 0.0045/m was considered.

The suggested ore and waste method of transport is by trucks. However, further engineering studies of the mineral project will be necessary to assess crushing plants closer to the pits (semi-mobile crushing), to reduce DMT and its related operating costs.

Geotechnical parameters

The slope stability evaluations have the geomechanical model as their starting point considered for the mine rock mass, based on geological and structural database. This information is mainly collected in the geological-geotechnical description of drilling cores and surface mapping. Detailed information regarding to geotechnical procedures is presented in section 7.4.

The NPV Scheduler software requires geotechnical inputs from individual "slope region", which defines the geotechnical parameters for each lithology and geotechnical domain. The values of the inter-ramp slope angles (grouping by lithologies) applied in each block were assigned, grouping the lithologies according to Table 11-28.

Locally, the operational reserves pit may exceed the resource pit, which is perfectly acceptable due to the definitive geotechnical sectors of the mines, the geomechanical and structural characteristics of the materials, and the final design of ramps and accesses for this pit.

The demand for water in this mining complex is supplied by surface and underground sources. Surface water is collected at the Igarapé Gelado dam and used as raw water for the industrial process of the iron ore processing plant. Underground water is collected through deep tubular drill holes drilled in mines N4 and N5, being destined for industrial use, supplying WTP, spraying roads, water replenishment in the Jacaré and Buriti streams. The remainder is destined for the Pêra and Gelado dams. Table 11-25 shows geotechnical parameters used in generating the resource pit.

Table 11-25 – Geotechnical parameters

Deposit	Lithologies	Overall NPV Angle
N1	AT	22
	MD	31
	MSD	34
	CE-CQ	36
	FM-HF-HMN	41
	HC-JP-MS	46
N2	AT	22
	IN-MD	31
	CE-CQ	33
	QT	36
	FMN-HF-HMN-MSD	41
	MS	46
	HC-JP	48
N3	AT	22
	XI-MD	31
	CE-CQ	36
	FMN-HF-HMN-MSD	41
	MS	46
	HC-JP	48
N4	AT	22
	AG-MD	31
	CE-CQ	36
	FMN-HF-HMN-MSD	41
	HC-MS-JP	46
N5	AT	22
	MD	31
	CE-CGL-CQ	36
	MN-FF-HF-HMN-MSD	41
	HC-MS-JP	46

Waste/tailings disposal parameters

The waste generated by the resource pit are contained in the Northern Corridor Waste and Tailings Master Plan, whose projects are at a conceptual development level, requiring additional studies to define their technical, economic, and environmental feasibility for their implementation as needed in the Ferrous Master Plan and the LOM of that deposit.

Mining/surficial rights parameters

Vale mining rights (DM) cover the entire area of the model box, therefore it is not a restriction for the the development of a mineral resource pits (Figure 11-28).

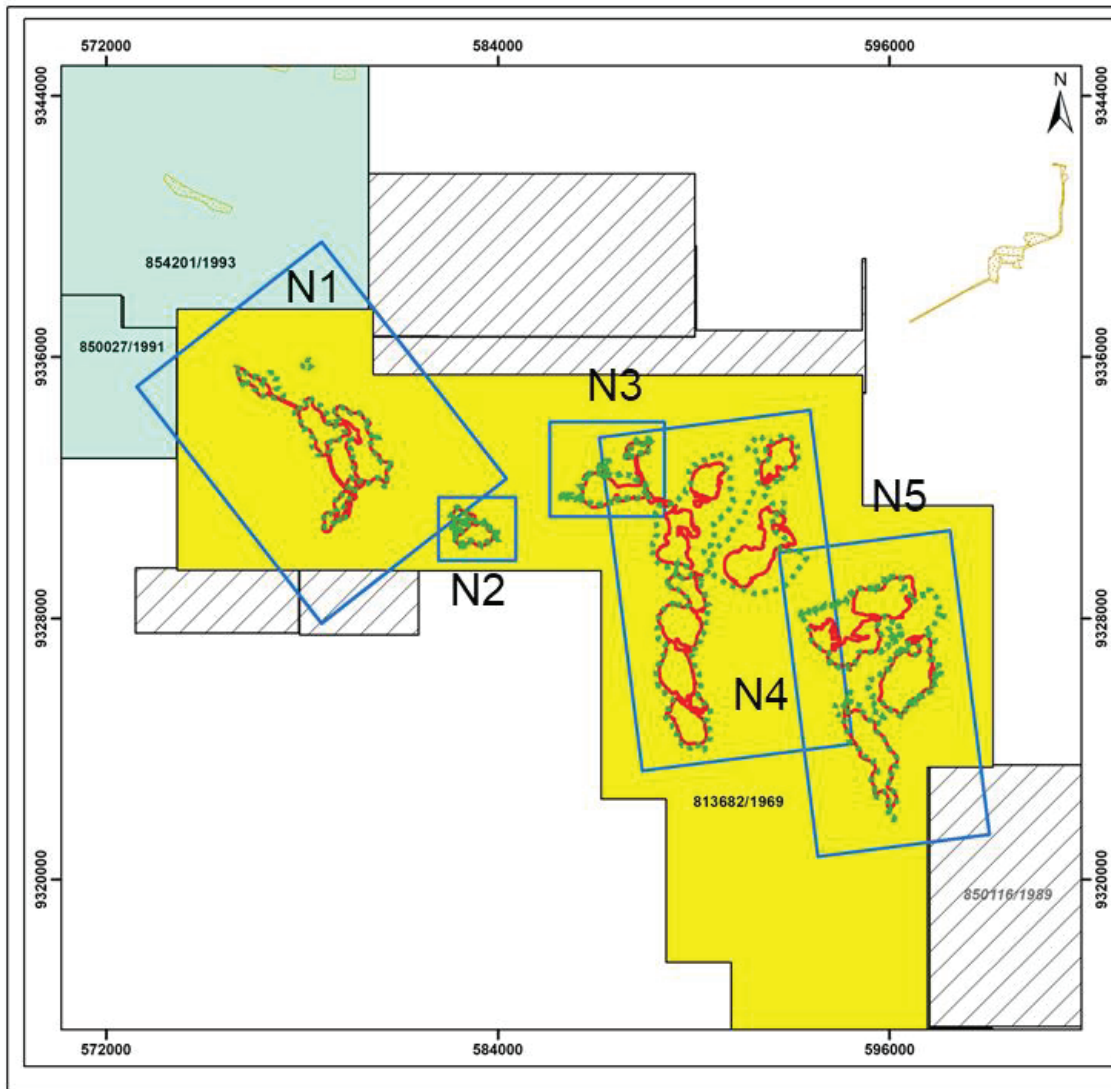


Figure 11-28 – DMs Vale boundaries and Serra Norte geological model box boundaries (blue polygons), Vale's mining concession in yellow.

Environmental / sustainability / speleological parameters

The deposits covered in this report are located in the Carajás National Forest (FLONACA). This conservation unit was approved by Ordinance No. 45 on 04/28/2004 and reviewed on May 9, 2016. Currently, the N4 and N5 mines operate under environmental licenses LO 267/2002, which allow the exploitation (exploration, mining, and processing) of iron ore from existing pits and expansions, as well as LP 488/2014, which allows for the expansion of the mines in the bodies named N4WS and N5S (2nd stage), Morro 1 and Morro 2, as well as the use of some pits for disposal of waste. The N1, N2, and N3 deposits are waiting for the approval from the respective environmental agencies. There is a reasonable expectation to obtain all environmental licenses (prior, installation, and operation) for these projects in the next 5 years. Licenses for possible expansions of pits in operation and pits of resources and reserves of the deposits with a project completed at a FEL2 level will be requested within the time required for the mining of these respective areas, according to the Ferrous Production Plan (Master Plan).

The Mining Zone of this conservation unit includes licensed (N4 and N5) and licensing in process (N1, N2, and N3) iron ore deposits. The northwestern region of N1 and N5 (an area called Morro 2) was kept outside the mining zone (considered a sustainable management zone). The purpose of this zone is to concentrate mining activities, minimizing the impact on adjacent areas and other zones

(Carajás National Forest Management Plan – ICMbio-2016). Primitive Zones in which no mining and processing activities are allowed were considered absolute restrictions in N4 and N5.

The buffers with a radius of 150m around the most relevant iron ore caves, categorized as maximum relevance with low probability of change.

Physical structure constraint parameters

Mobile or semi-mobile primary crushing, TCLDs, offices, and plant feed internal piles were not considered as restrictions for the Serra Norte deposits, as these structures can be relocated and have little or no interference with the resource pit. Only the 100 m protection polygon around Plant 2 on N4 was considered as a definitive restriction.

11.16.3. Mineral resource definitions

The resource pit was unable to reach the entire classified inventory.

Due to the restrictions imposed by the environmental limits described and the economic reasonability, not all the mineral inventory was converted to mineral resources. The resource/inventory conversion rate for Serra Norte models was greater than 78%.

For all Serra Norte deposits, the mathematical pit of the NPV Scheduler with the price factor of 110% was used for each deposit in a more flexible approach compared to mineral reserves.

Table 11-26 to Table 11-31 show the tonnage/grade numbers of the Mineral Resources (exclusive of Reserves) for the N1, N2, N3, N4E, N4W and N5 deposits, respectively, separated by lithotype, considering the optimized Resource pits.

Table 11-26 – Mineral Resources (exclusive of Mineral Reserves) of N1 deposit by lithotype

Mineral Resource exclusive of Mineral Reserves	Measured		Indicated		Inferred		TOTAL	
	Tonnage	FeGL	Tonnage	FeGL	Tonnage	FeGL	Tonnage	FeGL
Lithology	Mt	%	Mt	%	Mt	%	Mt	%
ce	6.4	64.6	13.3	64.2	4.0	62.8	23.7	64.1
hc	13.6	66.3	7.1	65.9	3.1	65.2	23.8	66.0
hf	107.3	66.6	112.2	66.5	45.6	66.7	265.0	66.6
hmn	0.9	61.6	0.8	61.6	-	-	1.8	61.5
Total	128.1	66.5	133.4	66.2	52.8	66.3	314.2	66.3

Table 11-27 – Mineral Resources (exclusive of Mineral Reserves) of deposits N2 by lithotype

Mineral Resource Exclusive of Mineral Reserves	Measured		Indicated		Inferred		TOTAL	
	Tonnage	FeGL	Tonnage	FeGL	Tonnage	FeGL	Tonnage	FeGL
Lithology	Mt	%	Mt	%	Mt	%	Mt	%
ce	0.0	61.7	1.0	61.2	1.2	61.7	2.2	61.5
hc	0.1	64.4	0.1	62.7	-	-	0.2	63.2
hf	1.7	66.2	16.7	65.6	12.0	65.5	30.4	65.6
hmn	0.0	62.5	0.4	61.6	-	-	0.5	61.7
Total	1.8	66.1	18.2	65.3	13.2	65.2	33.2	65.3

Table 11-28 – Mineral Resources (exclusive of Mineral Reserves) of deposits N3 by lithotype

Mineral Resource exclusive of Mineral Reserves	Measured		Indicated		Inferred		TOTAL	
	Tonnage	FeGL	Tonnage	FeGL	Tonnage	FeGL	Tonnage	FeGL
Lithology	Mt	%	Mt	%	Mt	%	Mt	%
ce	0.1	61.9	0.8	61.8	0.2	61.5	1.1	61.8
hc	0.3	66.5	0.4	66.6	0.2	66.3	0.9	66.5
hf	7.0	66.2	19.6	66.0	23.3	66.2	50.0	66.1
hmn	0.1	61.5	0.3	58.4	0.2	57.8	0.7	58.5
Total	7.5	66.1	21.1	65.7	24.0	66.1	52.6	66.0

Table 11-29 – Mineral Resources (exclusive of Mineral Reserves) of N4E deposit by lithotype

Mineral Resource exclusive of Mineral Reserves	Measured		Indicated		Inferred		TOTAL	
	Tonnage	FeGL	Tonnage	FeGL	Tonnage	FeGL	Tonnage	FeGL
Lithology	Mt	%	Mt	%	Mt	%	Mt	%
ce	3.7	62.2	3.2	60.7	1.1	62.9	8.0	61.7
hc	10.6	66.6	11.8	66.6	8.4	66.7	30.9	66.6
hf	72.9	65.6	49.5	65.6	25.1	65.3	147.6	65.6
hmn	3.7	61.3	1.1	61.1	0.1	60.4	4.8	61.2
Total	91.0	65.4	65.6	65.5	34.7	65.5	191.3	65.5

Table 11-30 – Mineral Resources (exclusive of Mineral Reserves) of N4W deposit by lithotype

Mineral Resource exclusive of Mineral Reserves	Measured		Indicated		Inferred		TOTAL	
	Tonnage	FeGL	Tonnage	FeGL	Tonnage	FeGL	Tonnage	FeGL
Lithology	Mt	%	Mt	%	Mt	%	Mt	%
ce	5.7	62.4	6.2	62.6	1.7	63.4	13.6	62.6
hc	1.5	64.0	0.6	64.0	0.2	65.5	2.3	64.1
hf	89.1	66.3	65.0	66.2	36.4	66.0	190.5	66.2
hmn	2.7	62.6	0.9	61.6	0.2	60.6	3.7	62.3
Total	99.1	66.0	72.7	65.8	38.4	65.8	210.1	65.9

Table 11-31 – Mineral Resources (exclusive of Mineral Reserves) of N5 deposit by lithotype

Mineral Resource exclusive of Mineral Reserves	Measured		Indicated		Inferred		TOTAL	
	Tonnage	FeGL	Tonnage	FeGL	Tonnage	FeGL	Tonnage	FeGL
Lithology	Mt	%	Mt	%	Mt	%	Mt	%
ce	21.6	64.0	17.5	64.0	7.1	62.3	46.2	63.7
hc	15.9	67.0	10.6	66.2	4.0	65.5	30.5	66.5
hf	223.8	67.3	148.9	66.8	118.8	66.5	491.6	67.0
hmn	4.0	61.4	3.5	60.9	0.4	58.0	7.9	61.0
Total	265.2	66.9	180.5	66.4	130.3	66.2	576.1	66.6

The Mineral Resources estimate (exclusive of Mineral Reserves) is effective as of December 31, 2021 of in situ. The estimate of Mineral Resources (exclusive of Mineral Reserves) is between the minimum topographic bases between December/2010 and September/2021 for the operating mines of N4 and N5. For N1, N2, and N3 (projects under development) laser aerial survey, delimited by resource pits with economic reasonableness. The iron grades are expressed on a dry basis and the mass is on a natural basis.

The generation of Resource pits was completed using economic, legal, geotechnical, and environmental assumptions and other modifying factors.

The totals in the table are rounded to reflect the uncertainty of the estimate. Total numbers of tons and grades may differ due to this rounding.

The Mineral Resources are in accordance with the United States Securities and Exchange Commission's (SEC) Modernized Property Disclosure Requirements for Mining Registrants as described in Subpart 229.1300 of Regulation S-K, Disclosure by Registrants Engaged in Mining Operations (S-K 1300) and Item 601 (b)(96) Technical Report Summary.

11.16.4. Conclusions and recommendations of the technical responsible

Regarding the geometry of the resource pit, the pit shape is fully adherent to the resource classification and is only limited by environmental and social constraints (primitive zone of the Carajás National Forest Management Plan). Despite these restrictions, there is potential for the conversion of Inferred to Measured or Indicated Resources and an increase in Mineral Resources, especially in the northern portion of the N5W pit and in the deposit called Morro 2. The development of mineral processing studies for marginal materials (jaspelites, chemical canga, manganese, and decomposed mafic formations) should continue aiming at evaluating the impact of these materials on current processing plants and future adaptations.

Condemnation studies and drilling must be carried out in the vicinity of the mineralized bodies to characterize potential areas for waste piles, crushing, and TCLDs for possible expansion of current operations.

11.16.5. Uncertainties that may affect the mineral resource estimate

- Areas of uncertainty that may materially impact all the mineral resource estimates include:
- Changes to long term metal price and exchange rate assumptions;
- Changes in local interpretations of mineralization geometry with additional drillings campaigns; faults, dykes and other structures; and continuity of ore bodies;
- Changes to geological and grade shape, and geological and grade continuity assumptions;
- Changes to variographical interpretations and search ellipse ranges that were interpreted based on limited drill data, when closer-spaced drilling becomes available;
- Changes to metallurgical recovery assumptions;
- Changes to the forecast dilution and mining recovery assumptions;
- Variations in geotechnical, hydrogeological and mining method assumptions;
- Changes to environmental, permitting and social license assumptions.

12. Mineral reserve estimates

12.1. Summary

Table 12-1 summarizes the Mineral Reserve estimate effective as of December 31, 2021.

Table 12-1 – Mineral reserve estimate

Pit/Operation	Classification	Tonnage (Mt)	Fe (%)
N1	Proven		
	Probable	323.6	66.1
	Subtotal Proven + Probable	323.6	66.1
N2	Proven		
	Probable	42.9	66.3
	Subtotal Proven + Probable	42.9	66.3
N3	Proven		
	Probable	91.8	65.3
	Subtotal Proven + Probable	91.8	65.3
N4	Proven	337.7	66.5
	Probable	295.1	66.3
	Subtotal Proven + Probable	632.8	66.3
N5	Proven	126.6	65.0
	Probable	372.5	64.9
	Subtotal Proven + Probable	499.1	64.9
Total	Proven	464.3	66.1
	Probable	1,125.9	65.7
	Total Proven + Probable	1,590.2	65.8

1. The estimate has an effective date 31/Dec/2021.

2. Iron Ore Reserve estimates stated as metric million tonnes inclusive moisture and dry %Fe grade (Fe₂O₃); Serra Norte moisture of 6,41%. The point of reference used is in situ tons.

3. The mineral reserve economic viability was determined based price curve with the long-term price being US\$70/dmt for 62% iron grade

4. The estimate assuming open pit mining methods uses the following key input parameters: mining cost 1.9 US\$/t mined; process cost from 1.6 US\$/t processed; other cost include sells cost from 31.2 US\$/t product. Mining recovery of 98.9% and dilution of 1,35%.

5. Numbers have been rounded.

The Mineral Reserves were estimated by Vale and reviewed by Vale QP. Measured and Indicated Mineral Resources were used as inputs for conversion into Proven and Probable Mineral Reserves respectively.

Reserve modifying factors were first added to the optimization software. The software NPVScheduler® was used to generate the pit shell but there is no economic cut-off grade applied to the mineral reserve and this is mainly because of the grade of the resource, which has an average of 60% Fe and the recovery factor is 99.5%, thus all material is handled as ore. The surface wireframe from October 2020 was used to deplete the resource block model. Environmental constraints, the presence of iron ore caves and the limits to mining concessions are also uploaded to NPVScheduler® prior to pit optimization.

The economic value of each block is calculated by the software using mining, procession and G&A costs, recovery factor, selling cost and commodity selling price. The pit shells are generated, and the final pit shell is chosen based on technical and economic criteria, which can vary between mines, from the characteristic of a specific mine, NPV maximization if the pit has a higher strip ratio or in some cases, the pit shell of revenue factor equal to 1 for a lower strip ratio.

An ultimate pit is designed and then returned into NPVScheduler® and the pit optimization is re-run. Economic phases are generated and afterwards, a production schedule. Mineral Reserves are reported as diluted. Vale QP certifies that these were fully scheduled in an appropriate LOM plan and applied to a discounted cash flow model. The Mineral Reserve estimate has demonstrated viable economic extraction.

Vale QP is not aware of any risk factors associated with or changes to any aspect of the modifying factors, such as mining, metallurgical, infrastructure, permitting, or other relevant factors that could materially affect the Mineral Reserve estimate.

12.2. Methodology

12.2.1. Dilution

Dilution is estimated by the reconciliation between what was fed into the plant and what was planned, over a year. The grade is assayed every two hours from the sampling of the crusher feed and consolidated for the entire current year to date and compared with the grade estimated from the short-term mining plan. From this comparison, the dilution factor for pit optimization is defined.

12.2.2. Mining Recovery

The calculation of mine recovery is obtained through the reconciliation between the mass fed into the plant and the planned mass for each year. The crushed mass is provided by date from the scales at the plant and consolidated by month. The production for the year is compared with the short-term plan and the mining recovery factor is determined comparing the production plan to the actual achieved.

12.2.3. Net value return and cut-off value

An NR cut-off value is determined using the Mineral Reserve metal prices, metal recoveries, transport, treatment, and mine operating costs. The metal prices used for the Mineral Reserves are based on a market estimated model, upon which are considered clients characteristic, offer and demand for exported iron ore, bonus and penalties according to the quality of the product.

The cut-off value used for the reserves is based on a positive profit of the block.

Costs and other parameters used to calculate the cut-off grade are shown in Table 12-2. The cut-off grade is 11% considering Serra Norte plants parameters. There is no economic cut-off grade applied to the mineral reserve and this is mainly because of the grade of the resource, which has an average of 60% Fe and is above an estimate of the cut-off grade. The cutoff is not material to the estimate of the Reserves. Nevertheless, a check is performed.

Table 12-2: Cut-off grade parameters for Serra Norte plant

Item	Units	Parameters
Metallurgical Recovery	%	98.9
Fe Product Payable	%	65.5
Price	US\$/t product	64.5
Mining Cost	US\$/t rock.	1.9
Processing Cost	US\$/t fed	1.6
Selling Cost	US\$/t product	31.2

12.2.4. Costs

The cost was based on the operations and base projection of the operational indicators, which includes support infrastructure, environmental studies and continued operational feasibility. Table 12-3 presents the costs used in the pit optimization.

Table 12-3 - Modifying factors for pit optimization

Item	Unit	Costs
Mining	US\$/t _{rock}	1.46 to 3.67
Processing Plant	US\$/t crusher feed	1.60
Other costs	US\$/t product	31.2
Vertical rate cost	US\$/m	0.0045
Mining recovery	%	96.4
Mining dilution	%	1.35

12.2.5. Price

The price curves are provided by Vale Market department and elaborated from a market estimated price model, upon which client characteristic, offer and demand for iron ore transoceanic, bonus and the deleterious according to the quality of the product are considered. As a reference price it was used US\$ 60/dmt (62% Fe) which varies according to the iron ore grades.

12.2.6. Caves

Iron ore cave limits are updated in a special database. The classification of these caves is regulated by Brazilian Federal law. A stand-off distance of 150 m as an exclusion zone for caves of maximum relevance.

12.2.7. Mass Recovery

A constant recovery factor of 99.5% was used as the process does not have concentration. It is used historical data based on mass balance in and out.

12.2.8. Wall Slope Angles

The pits are generated with the overall slope angles provided for each lithology. The company policy considered two factors safety:

- 1.3 in other areas of the pit;
- 1.5, in regions where there are structures, such as piles, industrial facilities, railways, highways, etc.

After the pit optimization, the results are sent to the geotechnical team that proceeds with the geotechnical sectoring which will then be used in the operation of the pits.

12.3. Factors, which might affect the mineral reserve estimate

The following factors may affect the results of the obtained Mineral Reserves:

- Prices of the iron commodities.
- American dollar exchange rate.
- Brazilian inflation rate.
- Geotechnical assumptions (including seismicity) and hydrogeological.
- Changes in the capital input and operating costs estimate.
- Change in the operating cost assumptions.
- Stockpile assumptions.
- Capacity of the mining operation to fulfill the annual production rate.
- Recoveries of the process plant and the capacity to control levels of deleterious elements within the expectations of the LOM plan.
- Capacity to meet and keep environmental licenses and permits, and capacity to maintain a social license to operate.

According to the knowledge of QP, there are no other environmental, licensing, legal, title, tax, social-political or marketing issues that could affect the mineral reserve estimate materially, which have not been discussed in this Report.

13. Mining methods

13.1. Summary

Serra Norte has been operating since 1985, with production rates of approximately 100 Mtpa in recent years. The mine is an open pit by berms and benches and uses large truck and shovel equipment. Mining is carried out in five separate orebodies.

N4 and N5 mines, currently in operation, utilize open pit mining and are operated by large loading and hauling equipment, namely, hydraulic excavators with loading capacity up to 80 ton, cable excavators with loading capacity up to 109 ton and front-end-loader with loading capacity of 72.6 ton. The haulage is carried out by truck with payload capacity of 400, 363 and 290 Tons.

In some regions of these mines, where maximum relevant iron ore caves are presented, continuous miners are utilized, which eliminates drilling and blasting thereby reducing ground vibrations caused by blasting and avoiding damage to the caves near the mining areas.

13.2. Mine design

The mine design includes benches with heights 15m, berms with widths of 12m, face angles between 26 and 85 degrees, all according to the lithology in the mine. Ramp access is 40m wide with 10% gradient. The ore is either hauled to stockpiles or dumped straight into the crusher bins. The open-pit designs are presented in Figure 13-1 to Figure 13-6.

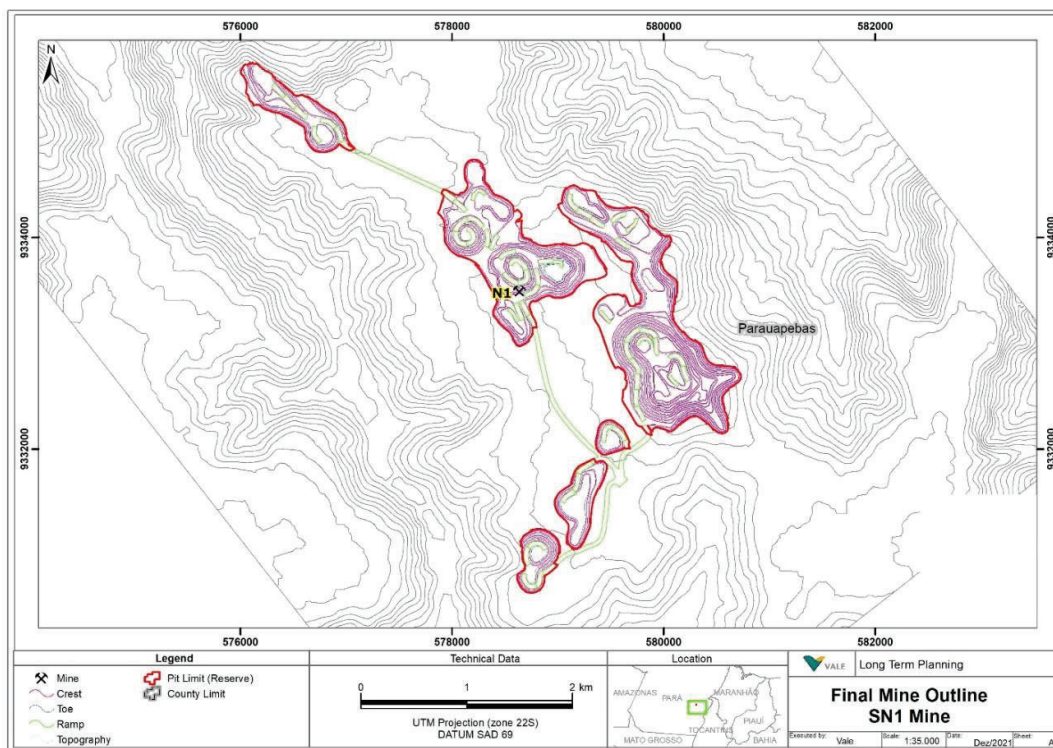


Figure 13-1 - Plan view of N1 open pit mine design.

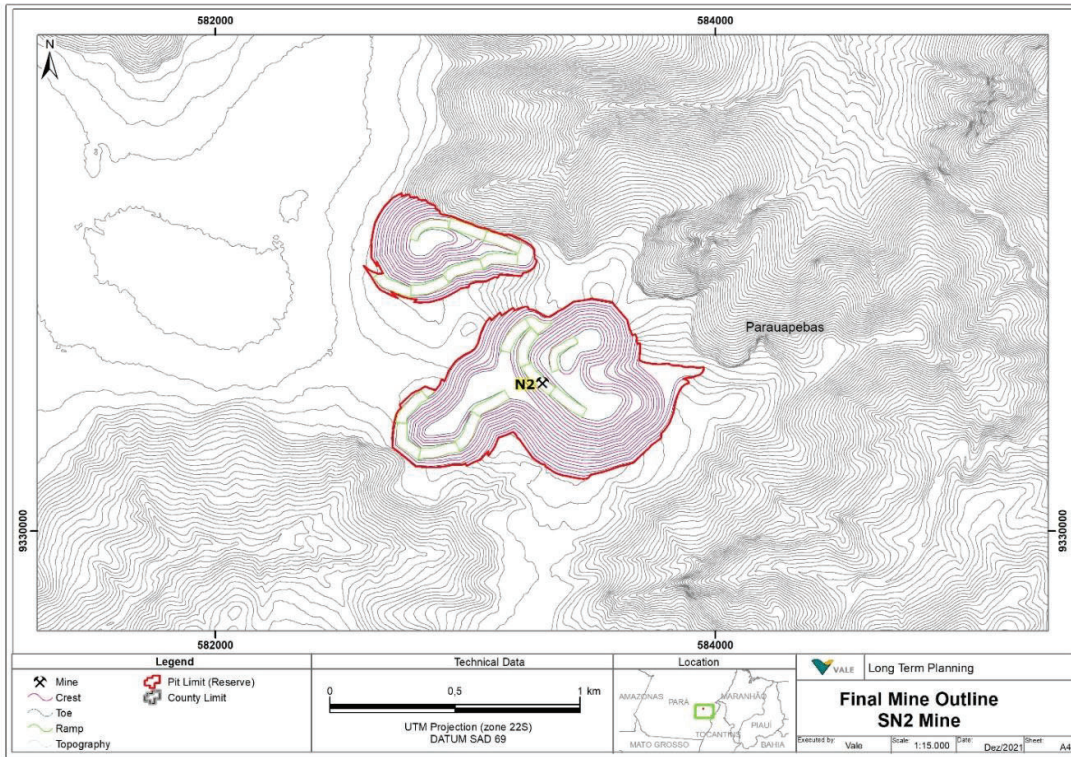


Figure 13-2 - Plan view of N2 open pit mine design.

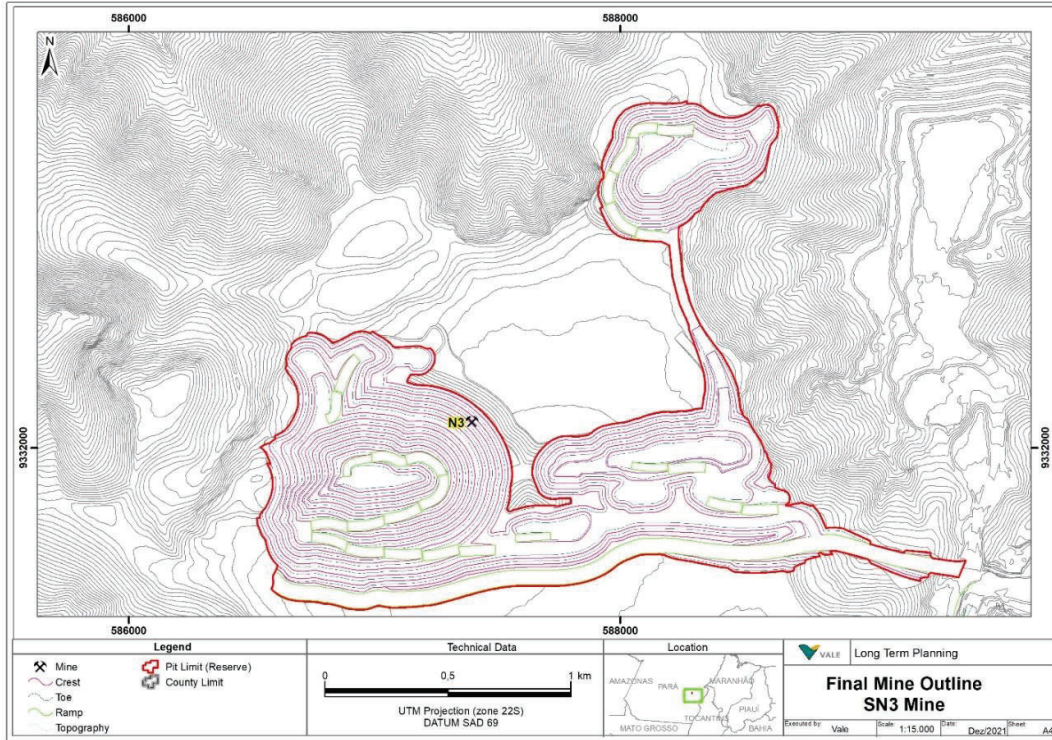


Figure 13-3 - Plan view of N3 open pit mine design.

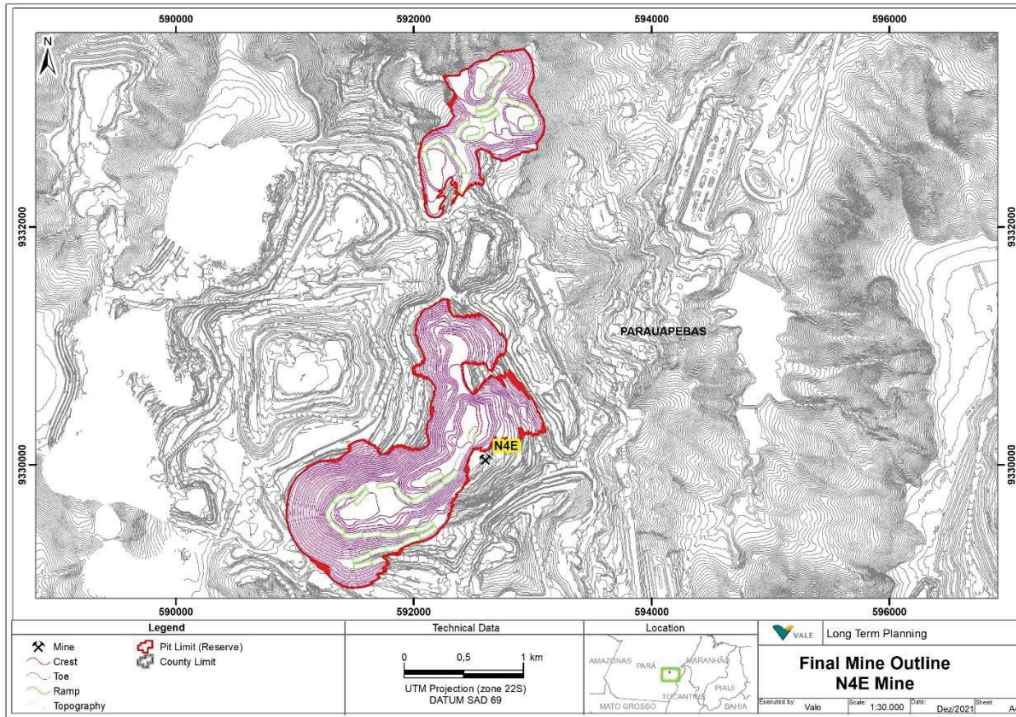


Figure 13-4 - Plan view of N4E open pit mine design.

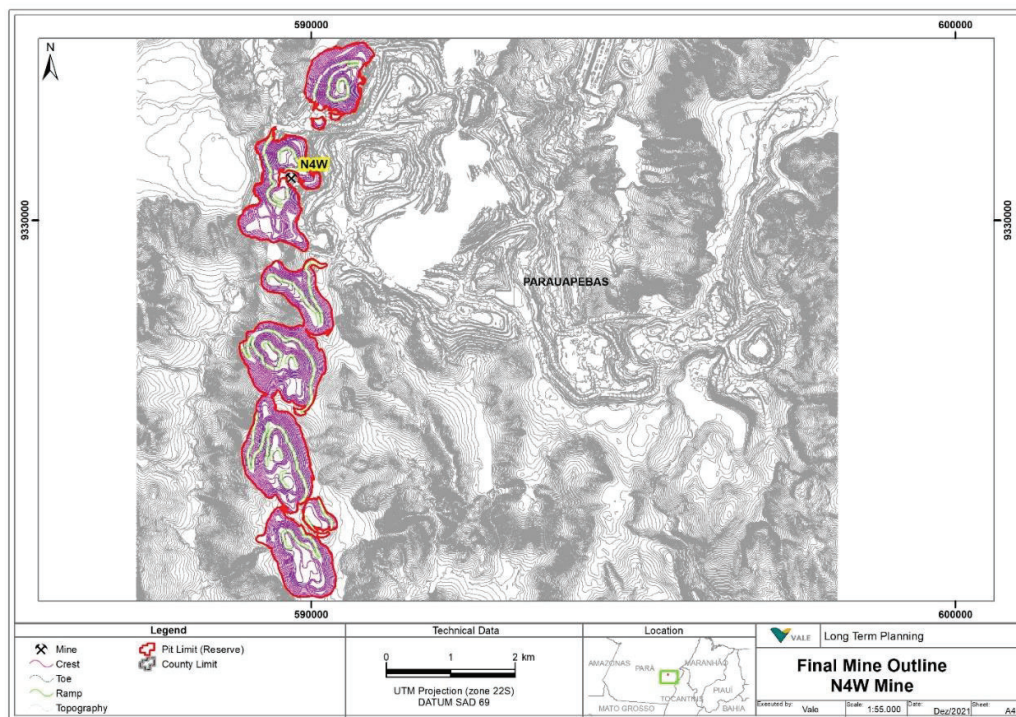


Figure 13-5 - Plan view of N4W open pit mine design.

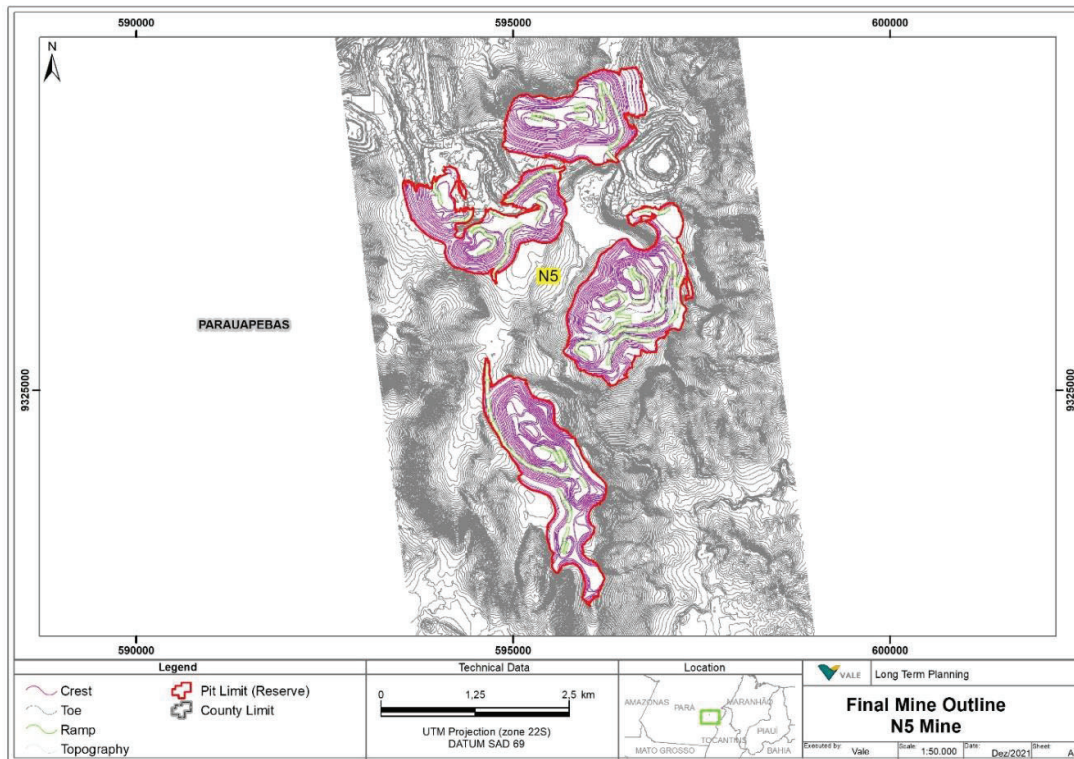


Figure 13-6 - Plan view of N5 open pit mine design.

13.3. Mine method

The mining method at Serra Norte is open pit, as a normal standard operation used across the mining industry. Part of the material is free digging and other parts require blasting. The ore is loaded into the haul road trucks and dumped straight into the crusher. Blending is required to adjust the average Fe grade.

13.4. Geotechnical considerations

Final slope design geotechnical evaluations are developed by internal team and follows the methodology presented below. To support the geotechnical assessments for Serra Norte Complex previous evaluations were used: Vale in 2016 and 2020, Geoestrutural in 2014 and 2016, TEC3 in 2016, WALM in 2019 and 2020.

WALM completed a geomechanical 3D modeling exercise and evaluation of the overall stability conditions within the mine. These assessments provide recommended design standards for the ultimate pit and end-of-period designs.

13.4.1. Geotechnical overview

The main lithological units have been described and modeled with acceptable detail to support geotechnical characterization and hazard evaluation related to mining activities. As related to the mining method (Open pit) employed at the time of the assessment, rock mass conditions are well understood and appropriate for the current mining depths, the rock reinforcement types, and geotechnical input into the mine production.

The geotechnical mapping and data analysis protocols include industry-standard practices, such as detailed descriptions of the various structural domains and their characteristics. This work is based on field mapping, geological modeling, and limited geotechnical core drilling.

The geotechnical evaluation of the geometric parameters for the ultimate pit for N1, N2, and N3 were sourced from the 3D geomechanical model elaborated by WALM in 2020, and N4 and N5 also elaborated by WALM but in 2020, with the main purpose to assess the global stability of the mine for actual and long-term conditions. This model permits the evaluation of the rock mass response in terms of slopes and mine working stability.

The used 3D Geomechanical model was compiled by including logging from the geotechnical drill holes and mapping carried out by BVP in 2011, WALM in 2019 and 2020.

13.4.2. Geotechnical and rock mass models

The Serra Norte mine complex (N1, N2, N3, N4 and N5) geomechanical models were built according to RMR and Weak Rock classifications, subdividing the rock mass in the following classes: I, II, III, IV, Weak, Very Weak and Extremely Weak. The structural mapping, presenting the main structures domains and their respective stereonet and the reports with general information used to build the geomechanical and structural models for Serra Norte mine sites are summarized at Table 13-1.

Table 13-1 - Summary reports used to build structural model and 3D geomechanical model – Serra Norte Mine Complex

Mine	Consultants responsible for Structural Mapping and Geomechanical Model	Year of Structural Mapping / Year of Geomechanical Model	Drillholes with geotechnical assay		Surface Mapped Points	Geomechanical Vertical Sections
			Amount of drillholes	Total drilled (m)		
N1	Geoestrutural / Walm	2014 / 2020	62	12,848	217	52
N2	Geoestrutural / Walm	2014 / 2020	41	7,286	99	17
N3	Geoestrutural / Walm	2014 / 2020	80	17,205	137	19
N4	BVP & Walm / Walm	2011 & 2019 / 2019	1,950	281,000	8,450	52
N5	BVP & Walm / Walm	2011 & 2019 / 2019	1,076	158,000	3,460	39

The geotechnical parameters were defined according to the lithotype obtained from the geological model, the rock mass classification from the geomechanical model and the structural features (anisotropies and discontinuities) were obtained from structural mapping and geological sections. The strength laboratory tests report used to define the geotechnical parameters used in Serra Norte mine Complex slope stability analysis are summarized at Table 13-2. For the lithotypes that do not have tests in the evaluated mine, the parameters of nearby mines with similar lithostratigraphic, tectonic, and geomechanical contexts were used.

Table 13-2 - Geotechnical laboratory tests reports– Serra Norte Mine Complex

Laboratory Test	Company	Year	Number of Tests
Consolidated Drained Triaxial Shear Test (CD)	CESP	2006	4
Consolidated Undrained Triaxial Shear Test (CU)	CESP	1991	2
	CESP	1996	12
	CESP	2006	20
	CESP	2012	1
	INFRAGEO	2017	4
	GEOMINAS	2018	13
Direct Shear	CESP	2006	8
Unconfined Compressive Strength (UCS)	CESP	1991	3
	CESP	2012	5

13.4.3. Hydrological model

The Surface Drainage Master Plan with the layout and devices sizing was developed in 2020 by TEC3 (RL-1020KN-X-00005-00, RL-1020KN-X-00006-00, RL-1020KN-X-00008-00 and RL-1020KN-X-00004-00), for N1, N2, N3, N4, and N5 pits.

13.4.4. Slope stability analysis

Deterministic limit equilibrium analyses were made to assess potential translation failures (circular and non-circular), based on geotechnical model. The water level used were presented in Chapter 13.5.

These analyses were made along the entire pit, based on the representative sections of conditions that may influence instabilities (critical sections) in the inter-ramp or overall scale and the evaluated cross sections are presented in Figure 13-7 to Figure 13-12.

The main failure mechanisms identified along Serra Norte Complex Mines are circular and non-circular mainly at Friable Hematites and Decomposite Mafics, predominantly classified as Weak in the geomechanical model. Other failure surfaces were influenced by shear zone on contacts of Decomposed Mafic/ Iron Formation.

The slope stability analyses results summary represented by FoS, the near mine interferences considered in each section and other information are presented in Table 13-3 to Table 13-7.

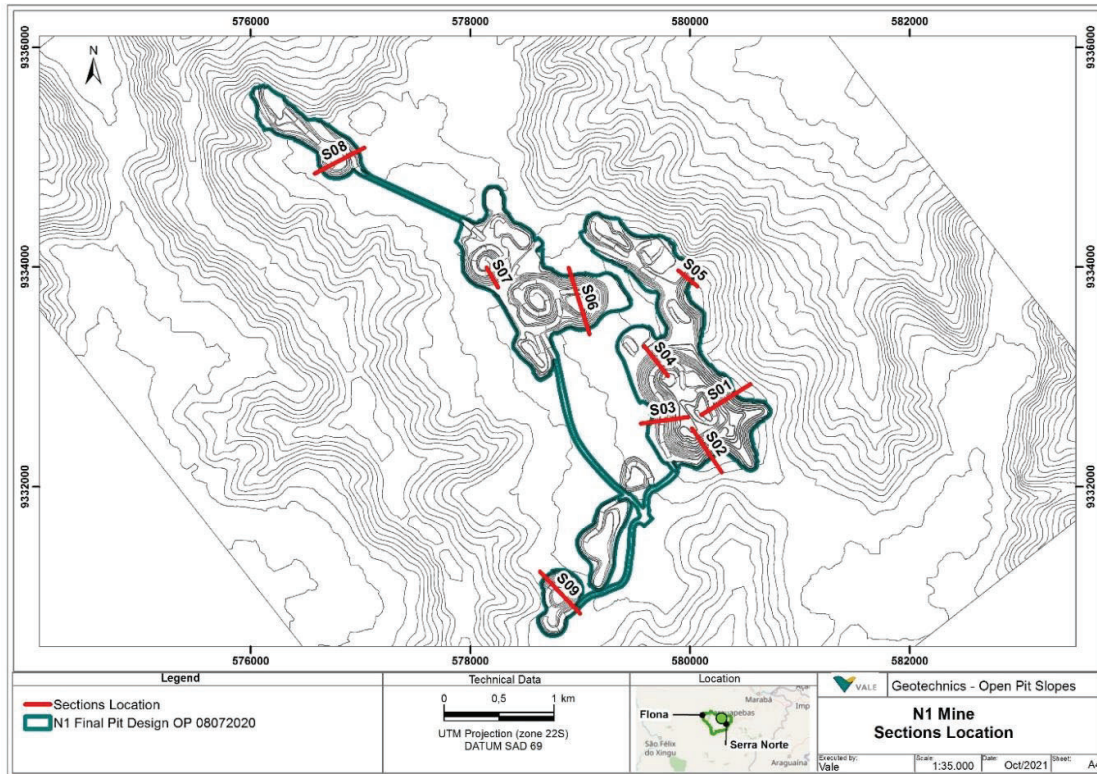


Figure 13-7 - Slope stability analysis cross section location – N1 Mine.

Table 13-3 - Factor of safety and other information from N1 final pit slope design

Pit	Section	Acceptable criteria		Results			
		FoS (required)	Near mine interference	FoS	Surface Type	Failure Scale	Failure Trigger
N1	S01	1.30	-	1.64	Circular	Inter-ramp	Intact rock strength
	S02	1.30	-	1.48	Circular	Overall	Intact rock strength
	S03	1.30	-	1.82	Non-Circular	Overall	Intact rock strength
	S04	1.30	-	1.56	Non-Circular	Overall	Intact rock strength
	S05	1.30	-	1.56	Circular	Overall	Intact rock strength
	S06L	1.30	-	1.50	Circular	Overall	Intact rock strength
	S06R	1.30	-	1.59	Non-Circular	Overall	Intact rock strength
	S07	1.30	-	1.65	Circular	Overall	Intact rock strength
	S08L	1.30	-	1.90	Circular	Overall	Intact rock strength
	S08R	1.30	-	1.79	Circular	Inter-ramp	Intact rock strength
	S09L	1.30	-	1.63	Circular	Overall	Intact rock strength
S09R	1.30	-	1.53	Circular	Overall	Intact rock strength	

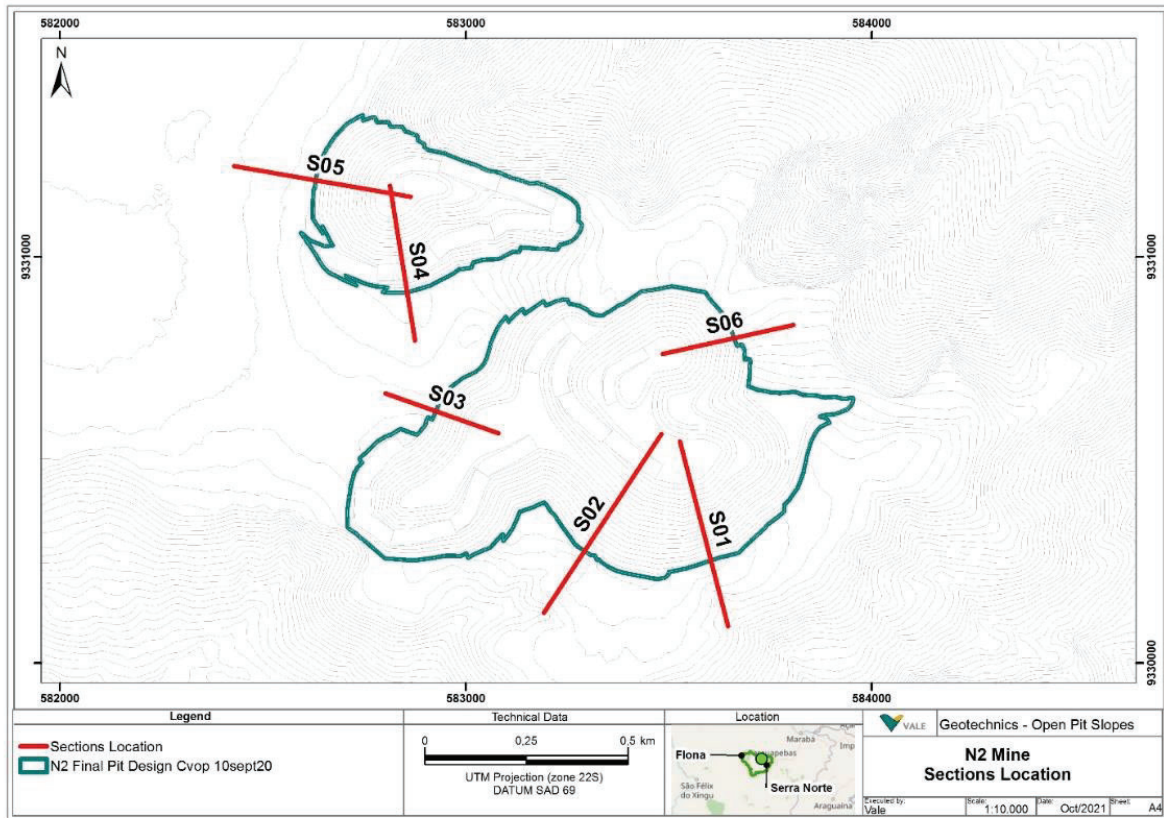


Figure 13-8 - Slope stability analysis cross section location – N2 Mine.

Table 13-4 - Factor of safety and other information from N2 final pit slope design

Pit	Section	Acceptable criteria		Results			
		FoS (required)	Near mine interference	FoS	Surface Type	Failure Scale	Failure Trigger
N2	S01	1.30	-	2.46	Circular	Local	Intact rock strength
	S02	1.30	-	1.42	Non-Circular	Global	Intact rock strength
	S03	1.30	-	1.68	Circular	Local	Intact rock strength
	S04	1.30	-	1.61	Circular	Local	Intact rock strength
	S05	1.30	-	1.33	Circular	Global	Intact rock strength
	S06	1.30	-	1.53	Non-Circular	Inter-ramp	Intact rock strength

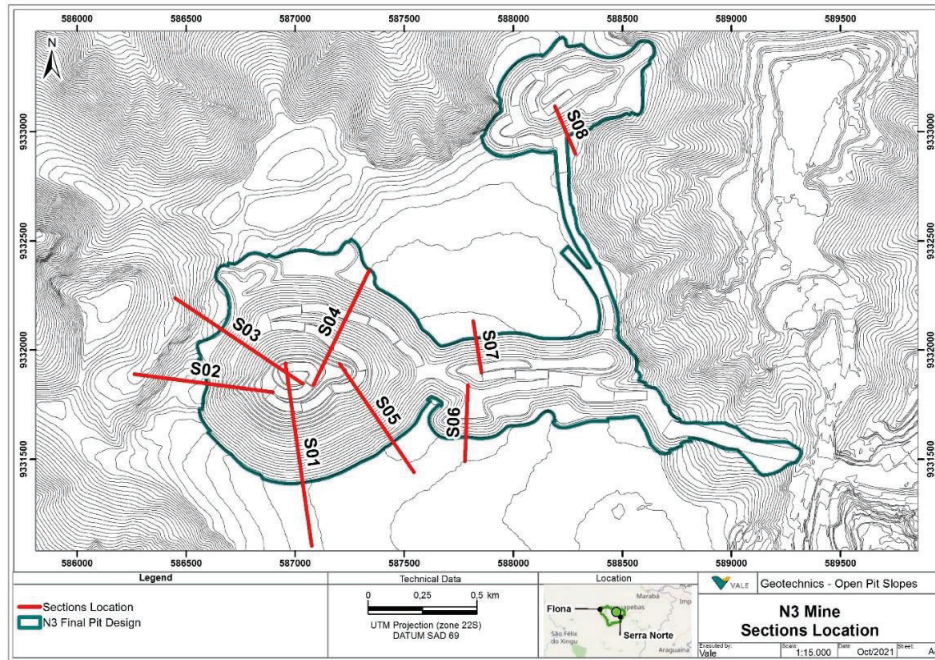


Figure 13-9 - Slope stability analysis cross section location – N3 Mine.

Table 13-5 - Factor of safety and other information from N3 final pit slope design

Pit	Section	Acceptable criteria		Results			
		FoS (required)	Near mine interference	FoS	Surface Type	Failure Scale	Failure Trigger
N3	S01	1.30	-	1.38	Non-Circular	Inter-ramp	Geological Contact
	S02	1.30	-	1.30	Non-Circular	Inter-ramp	Geological Contact
	S03	1.30	-	1.51	Circular	Inter-ramp	Intact rock strength
	S04	1.30	-	1.33	Circular	Overall	Intact rock strength
	S05	1.30	-	1.46	Circular	Overall	Intact rock strength
	S06	1.30	-	1.57	Non-Circular	Inter-ramp	Geological Contact
	S07	1.30	-	1.60	Non-Circular	Inter-ramp	Intact rock strength
	S08L	1.30	-	2.15	Non-Circular	Inter-ramp	Intact rock strength
	S08R	1.30	-	2.40	Non-Circular	Inter-ramp	Intact rock strength
	S09	1.30	-	1.33	Circular	Inter-ramp	Intact rock strength
S10	1.30	-	1.34	Circular	Inter-ramp	Intact rock strength	

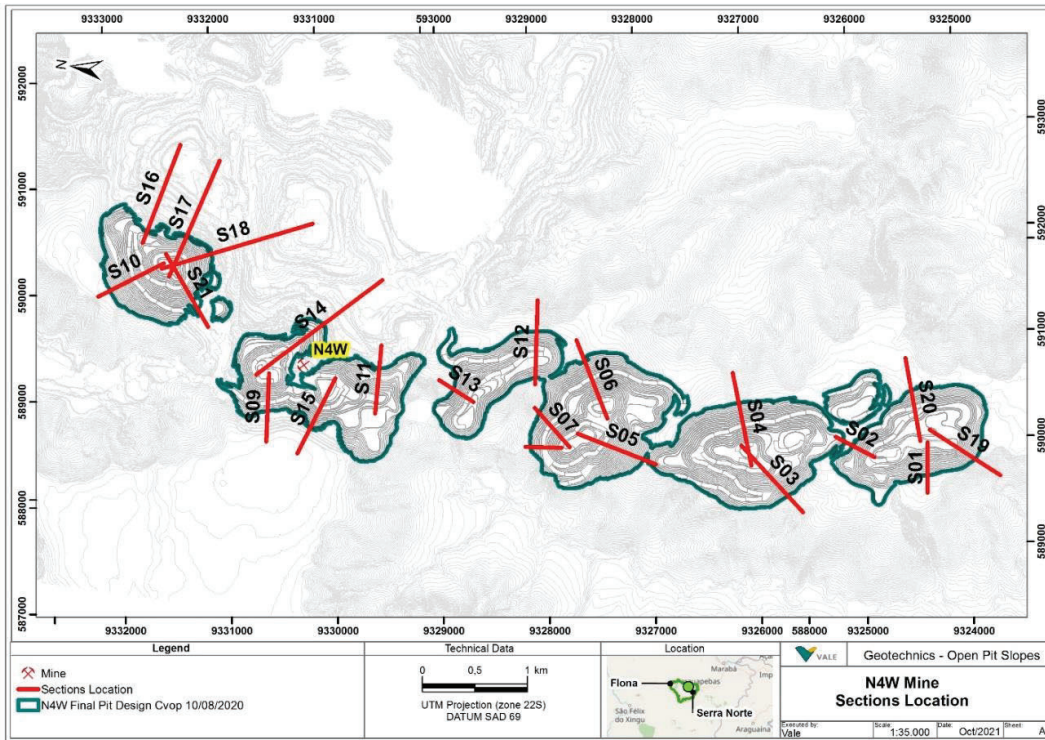


Figure 13-10 - Slope stability analysis cross section location – N4W Mine

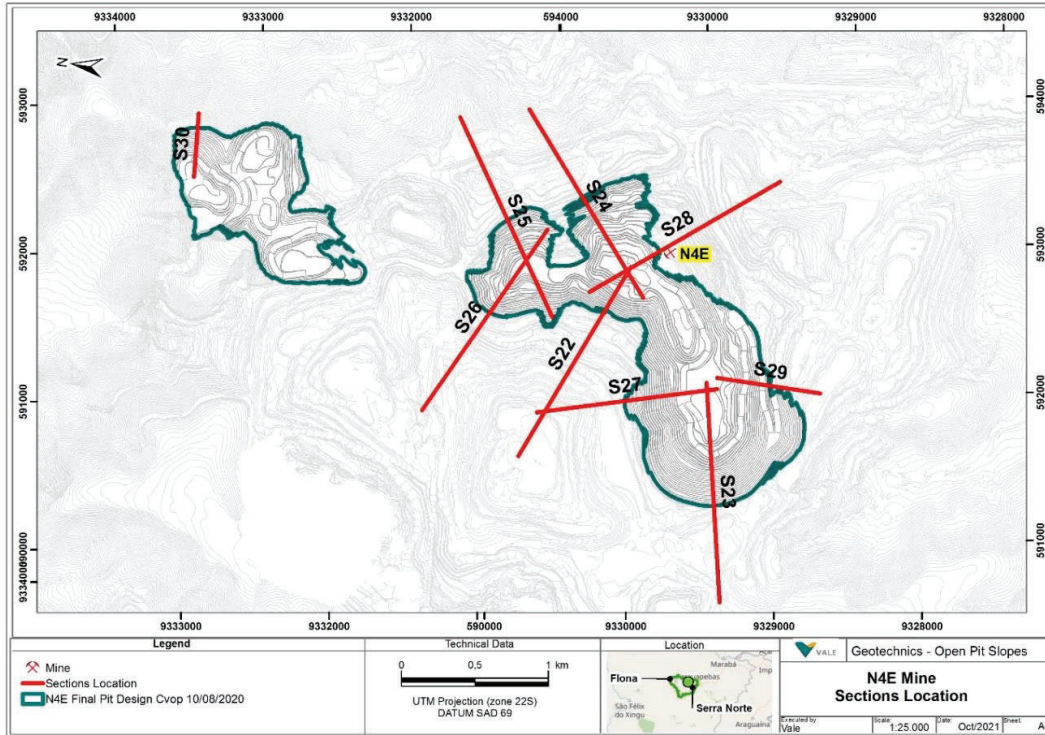


Figure 13-11 - Slope stability analysis cross section location – N4E Mine.

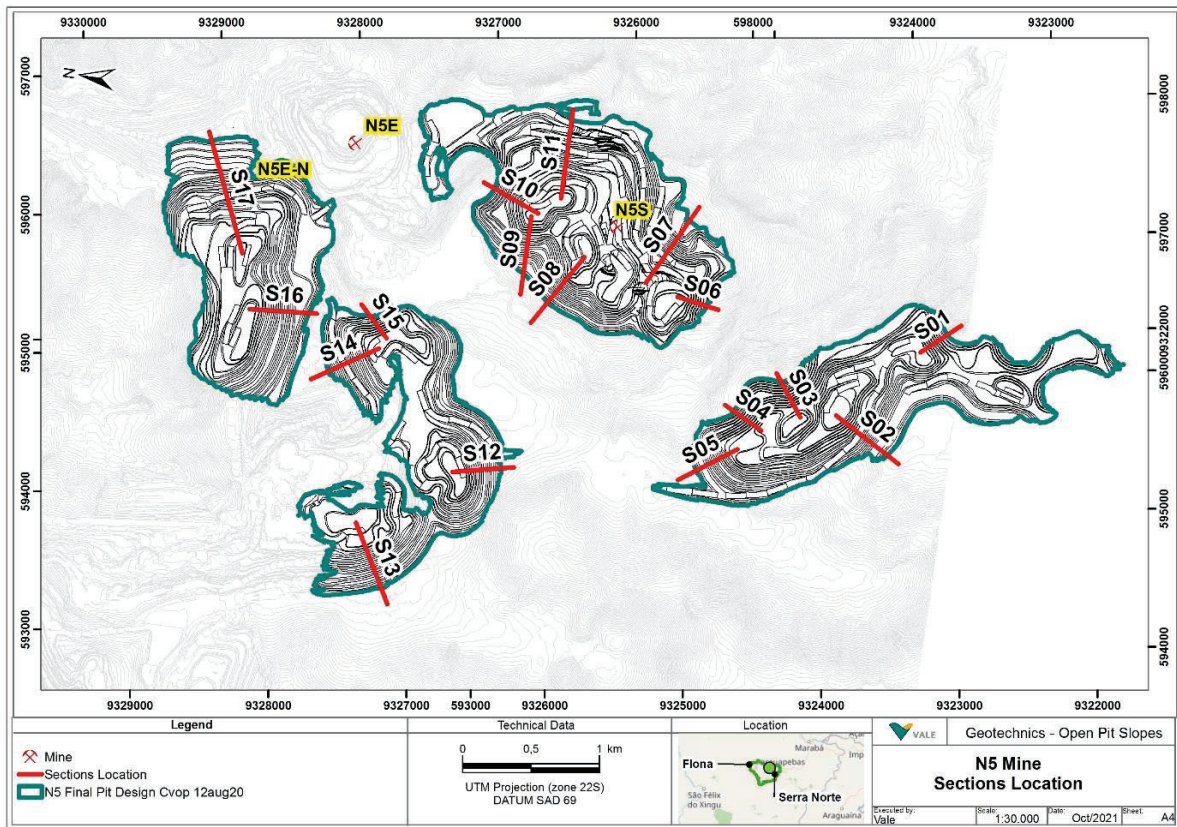


Figure 13-12 - Slope stability analysis cross section location – N5 Mine

Table 13-6 - Factor of safety and other information from N4 final pit slope design

Pit	Section	Acceptable criteria		Results			
		FoS (required)	Near mine interference	FoS	Surface Type	Failure Scale	Failure Trigger
N4W	S01	1.30	-	1.36	Circular	Overall	Intact rock strength
	S02	1.30	-	2.59	Circular	Bench scale	Intact rock strength
	S03	1.30	-	1.38	Non-Circular	Inter-ramp	Intact rock strength
	S04	1.30	-	2.05	Circular	Bench scale	Intact rock strength
	S05	1.30	-	1.35	Non-Circular	Inter-ramp	Shear zone
	S06	1.30	-	2.08	Circular	Bench scale	Intact rock strength
	S07	1.30	-	1.48	Circular	Inter-ramp	Intact rock strength
	S08	1.30	-	1.51	Non-Circular	Overall	Intact rock strength
	S19	1.30	-	1.72	Circular	Inter-ramp	Intact rock strength
	S20	1.30	-	1.60	Circular	Inter-ramp	Intact rock strength
	S09	1.30	-	1.70	Non-Circular	Inter-ramp	Intact rock strength
	S10	1.30	-	1.52	Non-Circular	Inter-ramp	Intact rock strength
	S11	1.30	-	1.30	Non-Circular	Overall	Shear zone
	S12	1.30	-	1.77	Circular	Bench scale	Intact rock strength
	S13	1.30	-	1.63	Non-Circular	Overall	Intact rock strength
	S14	1.30	-	1.30	Non-Circular	Inter-ramp	Shear zone
	S15	1.30	-	1.34	Non-Circular	Inter-ramp	Intact rock strength

	S16	1.50	Waste Dump	1.99	Non-Circular	Inter-ramp	Intact rock strength
	S17	1.50	Waste Dump	1.51	Non-Circular	Bench scale	Shear zone
	S18	1.50	Waste Dump	1.54	Circular	Inter-ramp	Intact rock strength
	S21	1.30	-	1.49	Non-Circular	Bench scale	Shear zone
N4E	S22	1.50	Waste Dump	1.51	Non-Circular	Inter-ramp	Intact rock strength
	S23	1.50	Waste Dump	1.50	Planar	Overall	Intact rock strength
	S24	1.50	Industrial facilities	1.69	Non-Circular	Inter-ramp	Shear zone
	S25	1.30	-	2.06	Circular	Bench scale	Intact rock strength
	S26	1.50	Waste Dump	1.52	Non-Circular	Inter-ramp	Intact rock strength
	S27	1.50	Waste Dump	2.64	Non-Circular	Inter-ramp	Intact rock strength
	S28	1.30	Waste Dump	1.80	Non-Circular	Inter-ramp	Shear zone
	S29	1.50	Waste Dump	2.18	Non-Circular	Inter-ramp	Intact rock strength
	S30	1.30	-	1.47	Circular	Overall	Intact rock strength

Table 13-7 - Factor of safety and other information from N5 final pit slope design

Pit	Section	Acceptable criteria		Results			
		FoS (required)	Near mine interference	FoS	Surface Type	Failure Scale	Failure Trigger
N5	S01	1.30	-	1.44	Circular	Overall	Intact rock strength
	S02	1.30	-	1.61	Non-Circular	Bench scale	Intact rock strength
	S03	1.30	-	1.47	Circular	Inter-ramp	Intact rock strength
	S04	1.30	-	1.47	Circular	Inter-ramp	Intact rock strength
	S05	1.30	-	1.76	Non-Circular	Bench scale	Intact rock strength
	S06	1.30	-	1.53	Circular	Overall	Intact rock strength
	S07	1.30	-	1.40	Circular	Inter-ramp	Intact rock strength
	S08	1.30	-	1.49	Non-Circular	Inter-ramp	Intact rock strength
	S09	1.30	-	1.50	Non-Circular	Inter-ramp	Intact rock strength
	S10	1.30	-	1.31	Planar	Bench scale	Anisotropic rock mass
	S11	1.30	-	1.82	Non-Circular	Overall	Intact rock strength
	S12	1.30	-	1.30	Circular	Overall	Intact rock strength
	S13	1.30	-	1.51	Circular	Inter-ramp	Intact rock strength
	S14	1.30	-	1.44	Non-Circular	Inter-ramp	Intact rock strength
	S15	1.30	-	1.55	Circular	Inter-ramp	Intact rock strength
	S16	1.30	-	1.44	Non-Circular	Overall	Intact rock strength
	S17	1.50	Waste Dump	1.50	Non-Circular	Inter-ramp	Intact rock strength

13.4.5. Comment on results

The slope stability analyses made in Serra Norte mine Complex (N1, N2, N3, N4 and N5) obtained satisfactory safety factor, superior to the minimal international standards (Read & Stacey, 2009). Therefore, the proposed geometry was considered geotechnically practicable.

13.5. Hydrogeological considerations

13.5.1. N1 and N2 Hydrogeological Models

This simulation used a FEFLOW numerical model (HIDROVIA, 2018) which encompasses N1 and N2 plateaus. The maximum drawdown simulated is approximately 190 m in the middle of the area (Figure 13-13).

The maximum simulated dewatering flow rate is 670 m³/h. Sixteen water level monitoring points were considered and the nRMS obtained was 2.32%, showing that the calibration process was successful.

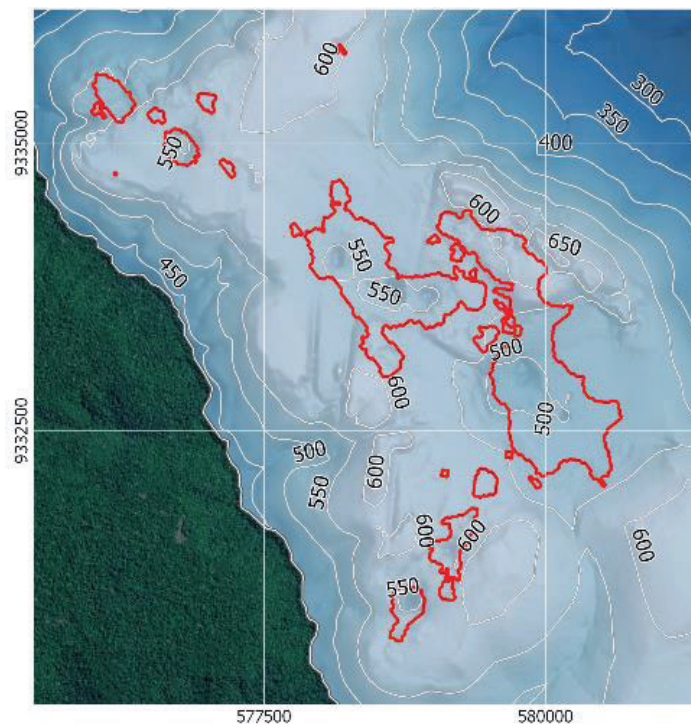


Figure 13-13 - Maximum drawdown equipotentials at N1 and N2 mines.

13.5.2. N3 Hydrogeological Model

The maximum simulated dewatering flow rate to N3 project is 539.6m³/h. Five water level monitoring points were considered and the nRMS obtained was 9.84%, showing that the calibration process was successful.

The areas where the main aquifer is less expressive, mainly at central and north pits, should have horizontal drains or specialized wells to promote depressurization of slopes. Figure 13-14 shows maximum drawdown equipotentials at N3 mine.

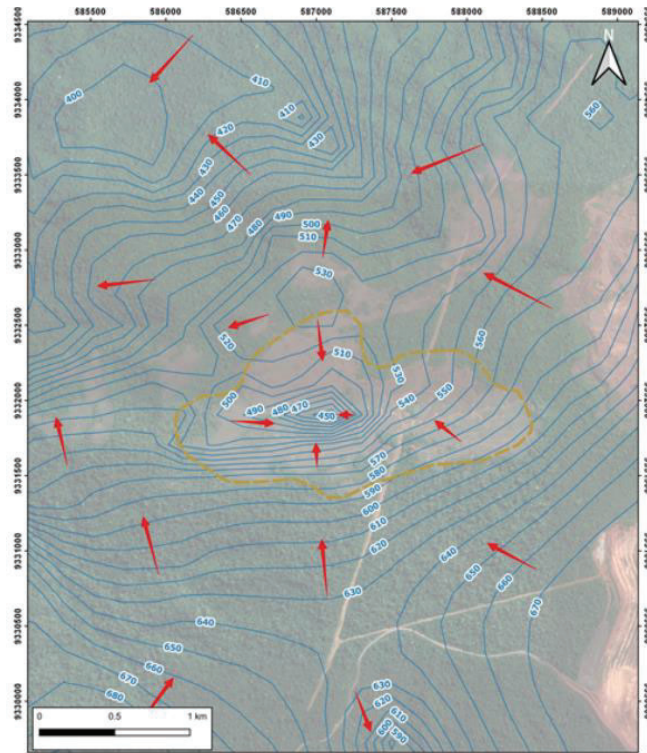


Figure 13-14 - Maximum drawdown equipotentials at N3 mine.

13.5.3. N4 and N5 Hydrogeological Models

For N4 mine, a MODFLOW numerical model (MDGEO, 2015) was used with 24 groundwater monitoring points and nRMS of 1.8%.

The maximum dewatering flow rate was 2,636m³/h to N4 mine. Maximum drawdown equipotential are exhibited in Figure 13-15.

For N5 mine, a MODFLOW numerical model (MDGEO, 2015) was used with 12 groundwater monitoring points and nRMS of 2,5%.

The maximum dewatering flow rate was 1,490m³/h to N5 mine. Maximum drawdown equipotential are exhibited in Figure 13-16.

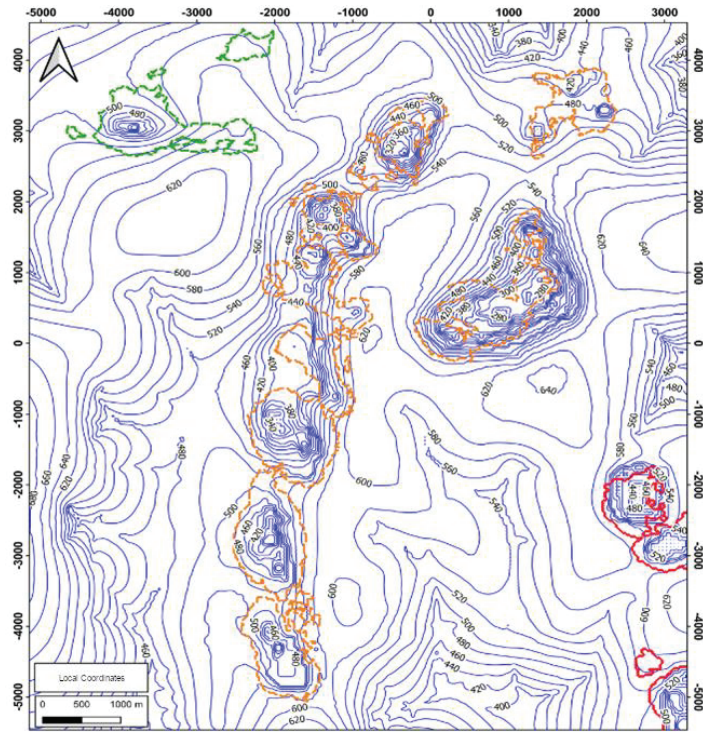


Figure 13-15 - Maximum drawdown equipotentials at N4 mine

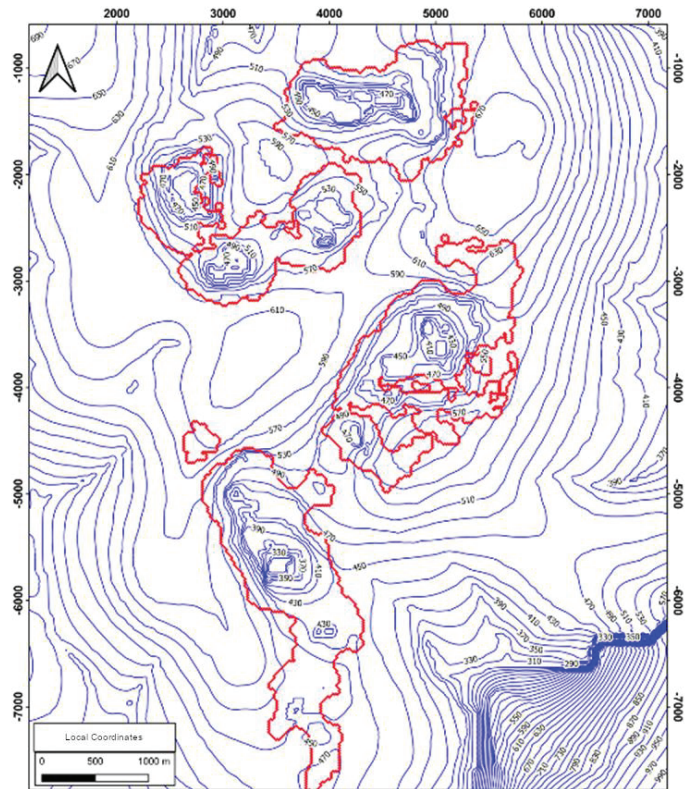


Figure 13-16 - Maximum drawdown equipotentials at N5 mine.

13.11. Life of mine plan

The life of mine production plan is shown in Figure 13-17. The production of from 2022 through 2038 will include approximately 1.5 Bt with average grades of 65.7 % FeGL, 1.4 % SiO₂GL, 1.2 % Al₂O₃GL, 0.046 % PGL, 2.2 % LOI. Stripping ratio for the LOM is 1.

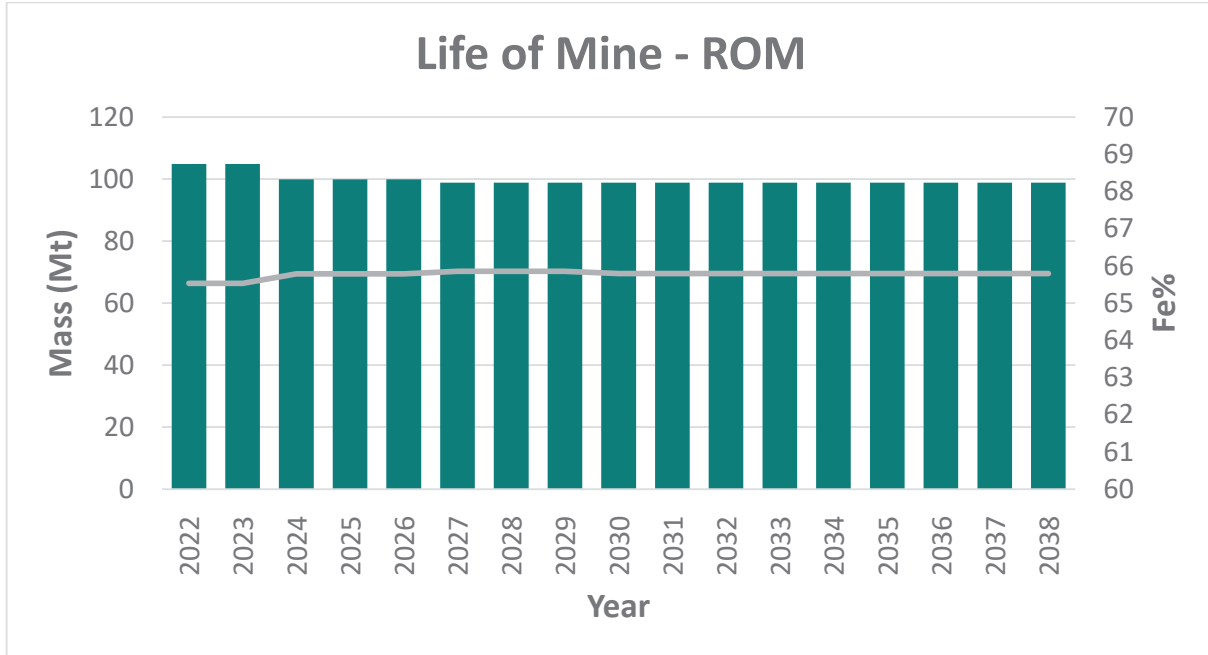


Figure 13-17 - Life of Mine vs Fe grades

13.12. Infrastructure

13.12.1. Workshops

In the Serra Norte area, there is a complete Maintenance Workshop (three units located in the N5, N4W, and Central mines) equipped with bays for large mobile equipment, as well as workshops for machining, maintenance of diesel generators, electrical, electronics; warehouse, and tooling. It is build of a metallic structure and there is an office and a locker room attached to the shed, made of masonry. In areas adjacent to the General Maintenance Workshop shed, there are the Lube Bay, the Vehicle Washing Bay, the Tire Shop, the Heavy and Light Vehicle Refueling Station, the Parking Lot, and the patio.

13.12.2. Laboratory

All quality control of the ore is carried out using the structures of the Carajás Iron Mine Laboratory, where physical tests and assays of the entire production chain are carried out.

13.12.3. Offices

Masonry offices are grouped in the administrative areas of Vale S.A. and its contractors. It is made up of offices for senior management, management, coordination, meetings, technicians, files, reception, and restrooms, which serve all administrative personnel.

13.12.4. Warehouses

The warehouse, built partly of masonry and partly of metallic structure, is surrounded by an outdoor area surrounded by gates. The covered area includes service desks, offices, and restrooms, and the external area for storage of materials currently includes annexes for the storage of lubricants, fuels, and tires. The fuel storage is equipped with horizontal tanks for filtered diesel, with drainage basins and a water-oil separation system.

13.12.5. Meal room

There is a canteen that serves all staff, both in-house and outsourced, and provides lunch, dinner, and snacks. Its operation is outsourced by Vale as in other operating units of the company.

13.12.6. Clinic

The clinic is installed in masonry construction and is intended to house a small office for first aid care and a restroom. The clinic is equipped for first aid care, and the more serious cases are sent to the existing hospital in the urban center, in which case an ambulance is available, parked next to it with a driver on permanent standby.

13.12.7. Firefighting system

The firefighting water is stored in concrete tanks, divided into two compartments that allow the tank to be cleaned, keeping half of the fire water reserve available for use.

13.12.8. Housing

Part of the company's staff resides in the urban center of Carajás and part in the city of Parauapebas, with no need to build new accommodation in the industrial area.

13.12.9. Mine equipment

The peak requirement for primary and auxiliary mining equipment is provided in Table 13-8.

Table 13-8 - Mining equipment

Equipment	Units
Loading	30
Hauling	116
Drilling	17
Auxiliary Equipment	97

13.12.10. Workforce

The workforce of Serra Norte consists of company personnel and contractors. The Vale personnel and the lists of main contractors for mining operations are presented in Table 13-9 and Table 13-10, respectively. The number of Vale employees required for the mining operations is not expected to change significantly for the foreseeable future. The number of contractors varies month by month depending on labor requirements at the mine site.

Production is carried out by the company mine personnel, while contractors carry out the auxiliary services. Administrative staff works on 5x2 roster in 8 hours shift, and operation and maintenance either on a 3x3 roster in 11h shift or 4x2 roster in 10h shift.

Table 13-9 - Vale's Workforce

Serra Norte	Manager	Supervisor	Coordinator	Staff and Technical Specialist	Total
Mine	18	103	14	3,536	3,671
Plant	11	108	13	2,152	2,284
Others	9	23	13	764	809
Total	38	234	38	6,452	6,764

Table 13-10 - Contractor's Workforce

Serra Norte (Contractors)	Permanent	Project	Part time	Total
Mine	442	178	75	695
Plant	591	51	23	665
Others	1,347	1,714	214	3,275
Total	2,380	1,943	249	4,635

14. Processing and recovery methods

14.1. Summary

There are 3 processing plants at Serra Norte mine site: Plant I, Plant II, and Plant III. Plant I has the biggest processing capacity in Carajás (85 Mta) and receives ore from BSM's (semi-mobile crushers) 2, 3, and 4, and from primary crushers. Part of ROM of the plant is processed wet and another part natural moisture. Lump, Sinter Feed and Pellet Feed are produced in this plant, with mass recovery of around 93%.

There is an ongoing project is to adapt Plant I for 100% natural moisture processing. This project is forecast to be completed between 2024 and 2025.

Plant II processes ROM at natural moisture and can produce 40 Mta. This plant receives ROM from BSM 05, generating only Sinter Feed, with 100% recovery.

Plant III capacity is 20 Mta and consists of two lines called rescreening 2 and 6. The ROM is processed at natural moisture, the material above 19 mm is removed from this plant and fed into Plant I, because there is no crushing in this plant and the material less than 19 mm represents the Sinter Feed product, with a mass recovery around 92%. Table 14-1 shows the average mass recoveries, utilization and capacities of each processing plant.

Table 14-1 - Plant Recoveries, Utilization, and Capacities

Plant	Metallurgical Recovery (%)	Physical Utilization (%)	Nominal Capacity (Mta)
Plant 1	96 a 97	73.1	85.0
Plant 2	100	79.2	40.0
Plant 3	95 a 97	52.7	20.0

14.2. Plant I

Plant I is the largest in Carajás, with a production capacity of approximately 85 Mta. It consists of crushing, screening, classification and magnetic concentration, and produces Lump, Sinter Feed and Pellet Feed products.

The primary crushing of Plant I consists of a system of fixed crusher and four semi-mobile crushers, called BSM 2, 3, 4, and alternatively, BSM 5.

After primary crushing, the material is directed to the primary screening, in which screen oversize (+70 mm) is directed to the secondary crushing. The product of secondary crusher returns to primary screening, closing the circuit. The undersize (-70 mm) is sent to the secondary screening, with 17 lines, 11 operating in wet, and 6 in natural moisture.

In natural moisture lines the undersize (-19 mm) is considered the Sinter Feed product, and the oversize (+19 mm) is directed to the tertiary crusher. The product of the tertiary crusher is directed to the tertiary screening in which the oversize returns to the tertiary crushing closing the circuit and the undersize is considered Sinter Feed product.

In the wet screening, the material retained in the first deck (+31.5 mm) is sent to the same tertiary crusher previously described. The material between 31.5 mm and 19 mm is considered the Lump product, and the material below 19 mm is directed to the quaternary screening. At the quaternary screening, the fraction above 1 mm is considered Sinter Feed product. The fraction below 1 mm is targeted for classification consisting of spiral classifiers.

The underflow (thicker fraction) of spiral classifiers (-1 mm + 0.15 mm) is considered Sinter Feed, and the overflow is directed to the magnetic concentration. The concentrate of the magnetic concentration, after a thickening stage, is directed to filtering in disc and press filters and the Pellet

Feed product is obtained. The tailing is directed to the dam after thickening stage. Figure 14-1 shows Plant I flowsheet. The current mass recovery of Plant I is 93%.

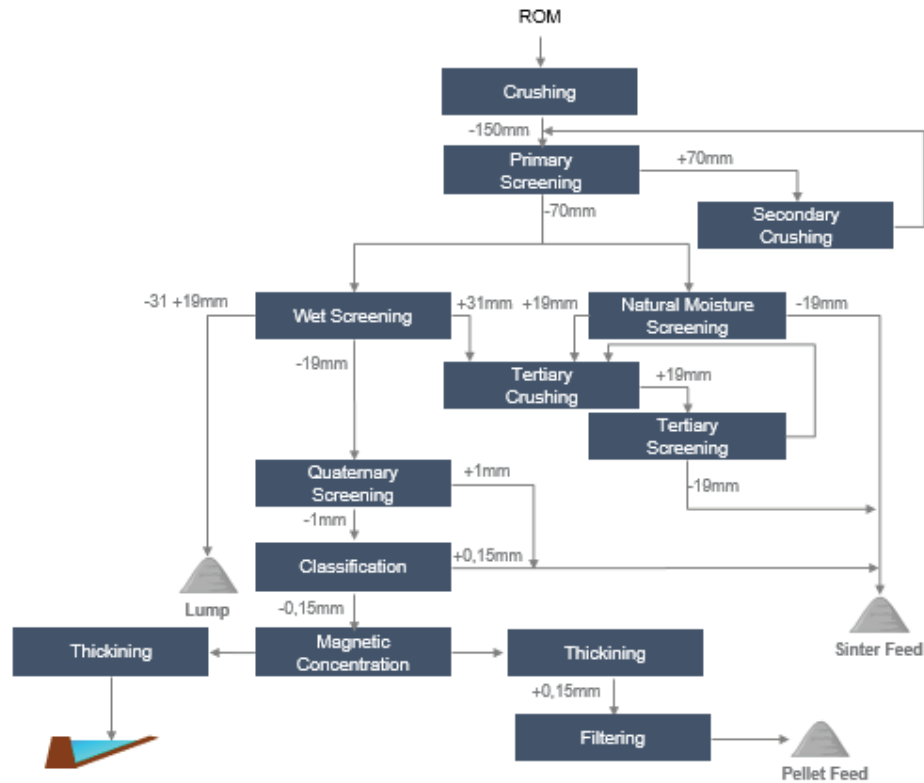


Figure 14-1 - Plant I Flowsheet

14.3. Plant II

The Plant II has capacity of 40 Mta and consists of crushing and screening operations to produce Sinter Feed product with 100% mass recovery.

Plant II is fed exclusively through the semi mobile crusher 5 (BSM 5). The crusher product is sent to the secondary crusher, through four long distance belt conveyors (3.8 km long).

After primary crushing, the ore is directed to the secondary screening and the material greater than 90mm (oversize) is directed to the secondary crusher. The product of the secondary crusher and the undersize of the secondary screening is directed to the homogenization yard, and subsequently, directed to the tertiary screening. The oversize (+19 mm) is directed to the tertiary crusher in which the product of the crushing returns to the tertiary screening. The undersize is considered Sinter Feed product. Figure 14-2 shows Plant II flowsheet.

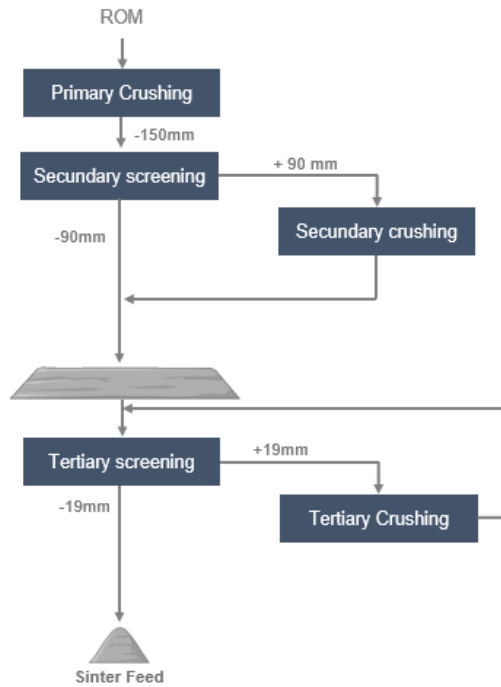


Figure 14-2 - Plant II Flowsheet

14.4. Plant III

Plant III consists of two plants, called Re-Screening 2 and Re-Screening 6. The production capacity of these two plants is 20 Mta. The material less than 19 mm is considered Sinter Feed product, and the material greater than 19 mm feeds Plant I. Figure 14-3 shows Plant III flowsheet, both plants have the same flowchart.

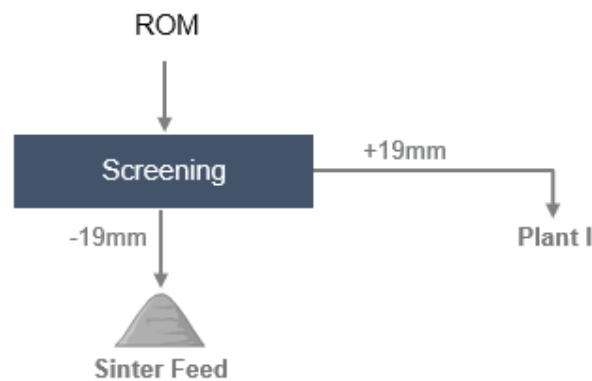


Figure 14-3 - Plant III Flowsheet

14.5. Production, recovery, quality and equipment

Table 14-2 summarizes the current production, quality, and recovery of Plants I, II and III, and Table 14-3 summarizes the main process equipment list for each plant.

Table 14-2 - Production, recovery and quality carried out

Year	Production (Mt)	Fe (%)	SiO ₂ (%)	Mass Recovery (%)
2016	143.6	65.35	1.74	94.4
2017	142.7	65.37	1.90	96.2
2018	131.5	65.00	2.22	94.7
2019	115.3	65.33	1.79	95.3
2020	109.1	65.18	2,09	95.7
2021	109.3	65.36	2.31	97.7

Table 14-3 - Equipment list of Plants I, II and III

Plant	Unit operation	Quantity	Type of Equipment	Dimensions/Model
BSM 2	Primary Crushing	1	Jaw crusher	CJ815
BSM 3	Primary Crushing	1	Jaw crusher	C160
BSM 4	Primary Crushing	1	Jaw crusher	CJ815
BSM 5	Primary Crushing	1	Jaw crusher	CJ 815
Plant I	Primary Crushing	1	Gyratory crusher	48" x 74"
Plant I	Primary Screening	8	Vibrating screen	8' x 21'
Plant I	Secondary Crushing	4	Cone crusher	17" x 84" (3) CS660 (1)
Plant I	Secondary Screening	17	Vibrating screen	8' x 21'
Plant I	Tertiary Screening	6	Vibrating screen	10 x 20 (2), 8 x 20 (1) e 8 x 21 (3)
Plant I	Tertiary Crushing	6	Cone crusher	HP500
Plant I	Spiral classifier	6	-	84"
Plant I	Desliming rougher	100	Hydrocyclone	10"
Plant I	Desliming scavenger	500	Hydrocyclone	4"
Plant I	Tailing Thickening	2	Thickener	Diameter: 80 m
Plant I	Concentrate Thickening	3	Thickener	Diameter: 26 m (2) Diameter: 34 (1)
Plant I	Filter	8	Disc Filter	Area 100 m ²
Plant I	Filter	12	Press Filter	10 (132 m ²) 2 (80 m ²)
Plant II	Secondary Crushing	1	Cone crusher	CH895
Plant II	Secondary Screening	10	Vibrating screen	8' x 32'
Plant II	Tertiary Crushing	6	Cone crusher	HP500
Plant III	Screening	8	Vibrating screen	8' x 20'

14.6. Logistics

Serra Norte mine is integrated with a mine-railroad-port system.

The EFC ("Estrada de Ferro Carajás") railroad connects the productive complexes of Serra Norte (Mina de Carajás), Serra Sul (Mina do S11D) and Serra Leste, all located in the Brazilian state of Pará, to the Ponta da Madeira port complex, in São Luís, State of Maranhão. The trains are loaded at Carajás terminal or Serra Sul terminal. The unloading process takes place at the Ponta da Madeira terminal.

Connected to EFC, the Ponta da Madeira Maritime Terminal (TMPM) is located near the city of São Luís, in the State of Maranhão. The port configuration enables operation of high-capacity vessels, such as Valemax.

15. Infrastructure

A surface plan showing the mine site infrastructure is provided in Figure 15-1. The in-situ and operating infrastructure at Serra Norte includes the following:

- Three open-pit mines which are accessed by approximately 10 main ramps;
- Surface ore stockpiles and waste rock dumps;
- Three processing plants with a total of 130Mtpa of crusher feed;
- One TSF;
- Main site power supply;
- Site access roads;
- Mine shops, offices, warehouse facilities.

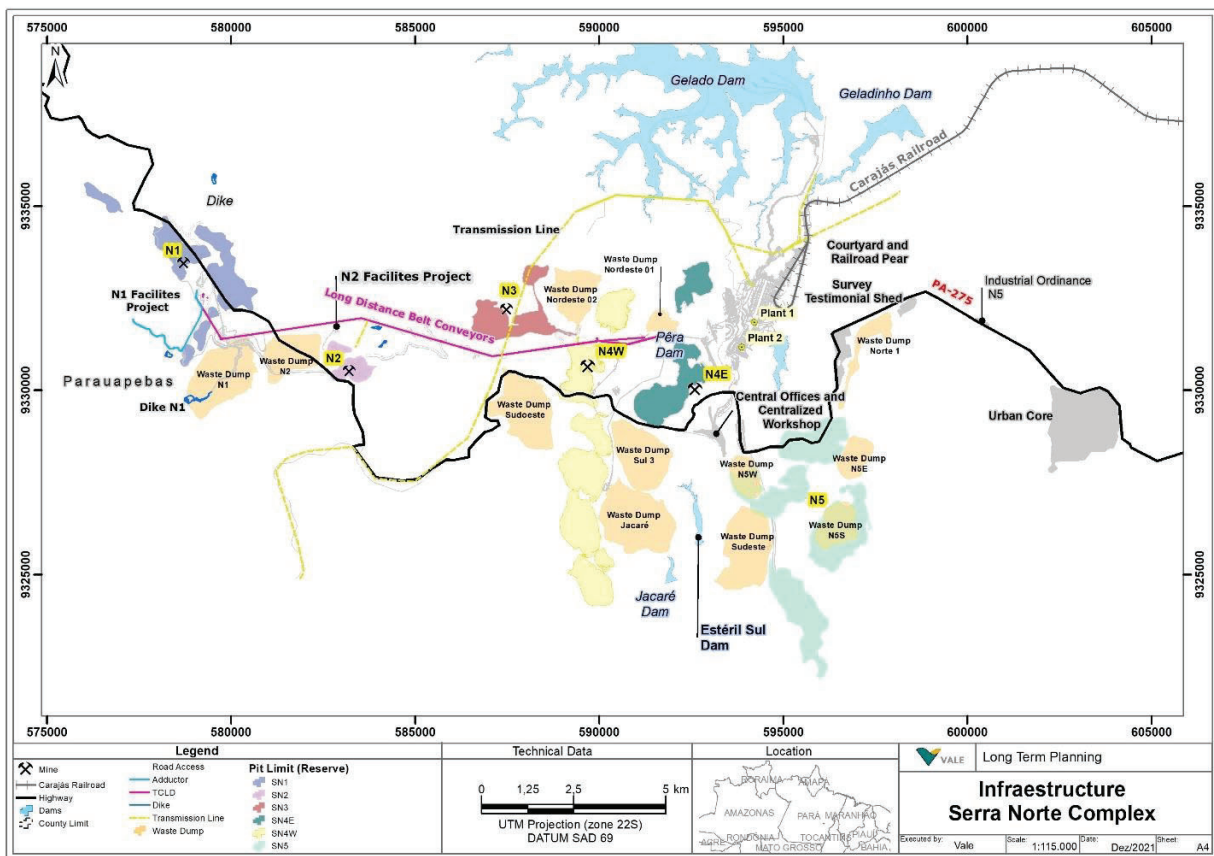


Figure 15-1 – Infrastructure map.

15.1. Site access

Provided on chapter 3.

15.2. Power supply

The Serra Norte operational complex (Carajás) fully provided by Sistema Interconectado Nacional (SIN) and is connected by 230kV via two transmission lines to the Carajás Substation owned by Eletronorte (Eletrobrás).

The internal distribution system is carried out through Vale's 34.5KV networks. Consumption in 2020 was about 468,794 MWh, 68.9% of which fed the mineral processing plants, 27.6% was distributed to the N4/N5 mines and the remaining 3.6% was consumed by the Urban Center and other support structures.

15.3. Water supply

Currently, in the N4E, N4W, and N5 mines there are 39 downgradient wells in operation with flow capacity of around 3,800 m³/h. The main purpose of pumping is to lower the water levels of the mines, 95% of the pumped volume is released into the drainages around the mines and the other 5% is used in the industrial process, human supply, and dust control.

15.3.1. Industrial water collection and supply

Water consumption is estimated at 0.232m³/ton of ROM with a reuse rate of 69.60%. The water catchment sites come from the Gelado and Pera dams.

15.3.2. Drinking water supply system

All drinking water used to supply the mines comes from mine downgradient wells. The water, after treatment at the Water Treatment Plant (ETA), is sent to the consumption units through pumping and a pressure network, stored in reservoirs which are periodically cleaned.

The water from the downgradient wells is used to wash floors and equipment and for human consumption, used in bathrooms and canteens. Vale also uses water in its industrial process, and this water is collected directly from the Igarapé Gelado and Pêra Dams.

15.4. Site buildings

Site facilities are distributed around the mines at Serra Norte. Facilities include offices, warehousing and storage areas, maintenance shops, fuel station, processing plants, canteen and locker room.

15.5. Mine waste and tailing management

15.5.1. Introduction

The operation and the development of projects for disposal of waste dumps and tailings follow the best national and international practices. In this report, the waste rock dumps will be represented by the acronym "PDE".

15.5.2. Tailings management

Plant 1 generates 4 to 5Mton of tailings per year at Serra Norte. The Tailings pass through a thickener before pumping to TSF to facilitate reuse of the process water.

15.5.3. Tailing storage facility

According to the GEOESTAVEL report (Mar./2020), Gelado dam is located at Serra Norte Mine, Carajás Complex, in the town of Parauapebas (PA). On the left bank of the reservoir, there is also the saddle dike 06. Gelado dam was built to provide process water for the Iron Ore Processing Plant, to contain tailings from the mine processing plants of N4 and N5, and to contain sediment from waste rock dumps.

According to the report of GEOESTAVEL (Dec./2019), Gelado dam was implemented in three stages. The design volume of this structure is around 152.9 Mm³.

For the geotechnical monitoring of the dams, field inspections are carried out every two weeks, automatic monitoring with piezometers, water level gauge, prisms, surface marks, inclinometer, orbital radar and CCTV cameras are used.

15.5.4. Waste dumps

The Waste rock from the open pit mining operations is deposited on the locations at the mine site:

Table 15-1- Waste Dump in operation

Waste Dump	Volume Mm³
PDE JACARÉ	107.0
PDE N5 LESTE	7.9
PDE N5W	70.5
PDE NORTE 1	0.5
PDE NOROESTE 1	2.0
PDE NOROESTE 2	76.0
PDE SUL 3	200.0

The region planned for the construction of PDE N1 is located at Serra Norte Mine, Carajás Complex. According to report RL-1190KN-X-87572 (GEOESTAVEL, Mar./2020), PDE N1 will contribute to the operational continuity of Carajás Iron Mining Complex, formed by the waste rock from the mining process in pit N1. The predicted volume of waste disposal in this structure is 41.9 Mm³. According to the same report, a sediment containment system including a sump and a clarification tank is planned for this waste rock dump.

The region planned for the construction of PDE N2 is located next to PDE N1 in Serra Norte Mine of Carajás Complex. According to report RL-1190KN-X-87573 (GEOESTAVEL, Mar./2020), PDE N2 will be formed of waste rock from N2 pit, with a sediment containment system including a sump and a clarification tank. The volume of waste is estimated at 24.1 Mm³.

PDE Sudoeste (N4W) is located at Serra Norte Mine and will be built for waste rock disposal in compliance to the Master Plan. The conceptual project is currently being developed, with expected date for completion in August of 2022. The estimated waste rock volume is 203.9 Mm³.

The Southeast PDE (N5) is located at Serra Norte Mine and will be built to place waste rock from the mining pit N5, in compliance to the Master Plan. The conceptual project is currently being developed, with expected date for completion in August of 2022. The volume of waste rock is estimated in 260.8 Mm³. Other projects under development are presented in Table 15-2.

Table 15-2 - Waste Dump under development

Waste Dump	Volume Mm ³
PDE Jacaré Expansão	194.2
PDE N1 - Fase 02 (Eng.)	45.5
PDE N2 - Fase 02 (Eng.)	23.8
PDE South-west N4W	203.9
PDE Southeast N5	260.8
PDE South N5 - SN 09	799.0

16. Market studies

16.1. Markets

16.1.1. Introduction

Iron ore is one of the core products that Vale commercialize globally. Its price and premiums can fluctuate along the year according to changes in the balance between its supply and demand and short-term trends on market's sentiment.

Vale operates four systems in Brazil for producing and distributing iron ore, which we refer to as the Northern, Southeastern, Southern and Midwestern Systems. Each of the Northern and the Southeastern Systems is fully integrated, consisting of mines, railroads, maritime terminals and a port. The Southern System consists of two mining complexes and two maritime terminals.

Under the economic recovery from the pandemic, iron ore prices faced a price fly up moment in the first half of 2021, as the demand recovery largely overpassed supply. In the second part of the year the energy crises in the main markets helped balance demand and supply bring iron ore prices closer to its cost support.

16.1.2. Demand

China has been the main driver of global demand for minerals and metals over recent decades. In 2021, Chinese demand represented 74% of global demand for seaborne iron ore. Therefore, any contraction of China's economic growth or change in its economic profile could result in lower demand for our products, leading to lower revenues, cash flow and profitability.

In 2021, China's crude steel production was 1032.79 Mt, a decrease of -3% year-on-year. The economic recovery in the country continued in 2021, with GDP growth rate reaching 8.1% year-on-year in 2021 vs. 2020. Industrial production and exports continued outperforming in the fourth quarter of 2021. GDP growth in the fourth quarter of 2021 reached 4.0% year-on-year, slowing from 4.9% year-on-year in the third quarter of 2021, as Fixed Asset Investment (FAI) moderated in fourth quarter driven by property and infrastructure. In the rest of the world, easing of restrictions with the rollout of vaccines, rebound of economic activity, manufacturing and supply chain improvements in 2021 contributed to steel demand leading to a total steel production of 879.1Mt, an increase of 12.1% year-on-year. Major steel producing regions such as Brazil and EU28 have fully recovered compared to pre-pandemic levels of 2019 whereas JKT and USA are still slightly below pre-pandemic levels.

The move towards a more efficient steel industry, with the enforcement of stricter environmental policies in China, should support the demand for high quality ores that enable productivity and lower emission levels like pellets and Carajás fines (IOCJ). For 2022, the World Steel Association (WSA) forecast in October 2021 that steel demand should grow by 2.2% to 1,896.4Mt. Demand is expected to continue and strengthen its recovery momentum following reduction in supply chain bottlenecks, continued pent-up demand and rising business and consumer confidence.

In China, a weaker real estate sector and government environment targets might limit growth in steel output in 2022. While rising inflation and demand deceleration in China can present a downside risk, progress on vaccinations across the world and potential new variants being less damaging and disruptive compared to previous waves can support the recovery trend.

For the longer term, the slow down on China's economic growth might impact iron ore demand

16.1.3. Supply

The global iron ore and iron ore pellet markets are highly competitive. The main factors affecting competition are price, quality and range of products offered, reliability, operating costs and shipping costs.

Our main competitors are different locations than our sites and compete with Vale mainly on their regional markets. For the Asian market, the main competitors are in Australia and include

subsidiaries and affiliates of BHP, Rio Tinto Ltd (“Rio Tinto”) and Fortescue Metals Group Ltd. For the European market our main competitors are Luossavaara Kiirunavaara AB (“LKAB”), ArcelorMittal Mines Canada Inc., Iron Ore Company of Canada, a subsidiary of Rio Tinto., Kumba Iron Ore Limited and Société Nationale Industrielle et Minière. Vale also has competitors within the Brazilian market. Several small iron ore producers, some steel companies, including Gerdau S.A. (“Gerdau”), Companhia Siderúrgica Nacional (“CSN”), Vallourec Tubos do Brasil S.A., Usiminas and ArcelorMittal, compete to feed iron ore for the local steel production.

While for 2022 there is no relevant iron ore capacity addition from main competitors, for the longer term the global supply might face reduction of supply due to the depletion of current operations, especially for the ores with lower cost and higher quality. Additionally, to depletion, as several iron ore reserves are located in countries differently from the nationality of the mining company, the risk of nationalization of the reserves and operations it is present, as it happened in the past, as new iron ore frontiers will need to be explored to attend global demand.

16.1.4. Price outlook

Looking into 2022, most analysts expect that China policymakers will continue their strict control on crude steel production at least during the first quarter, when the Winter Olympic games will be held in Beijing and the country will focus on keeping air quality at higher levels and blue sky during the event. However, if China does not relax its stance against property speculation and deleveraging developers in 2022, most analysts believe that investment in infrastructure will be brought forward to sustain GDP growth. This should be positive for steel demand in 2022, supporting iron ore prices during the year.

By the time this report was prepared, the price consensus for iron ore prices at 62% Fe in 2022 of the analysts was \$112/t (table below – prices in USD), with a downward trend going forward until prices reach the long-term level of around \$70/t. Additionally, we believe that the expected future production, relative to our iron ore reserves, can be absorbed by the market in the long term given the expected demand by market analysts. Figure 16-1 shows the iron ore price for 62% Fe.

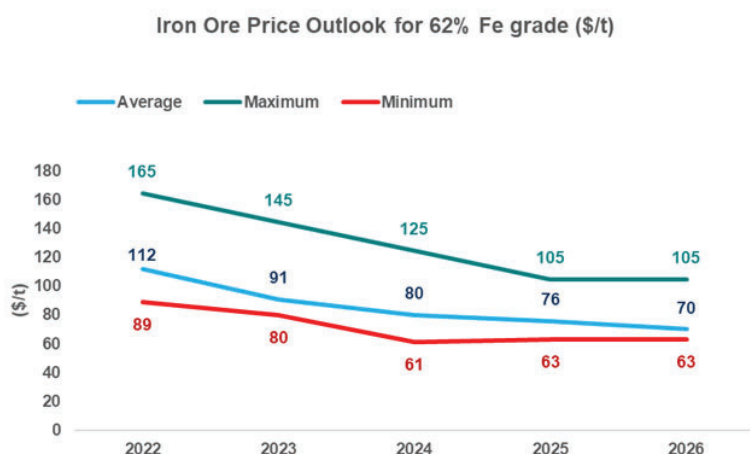


Figure 16-1 – Iron ore price outlook for 62% Fe grade (US\$/t). Source: Bank reports published between September and October 2021

The price differential between the 65% index and the 62% depends on a few market-based driven fundamentals. Besides the environmental benefits of using high-grade ores to produce steel, a higher share of these ores in the blast furnace increases productivity as more Fe is added to the process and less fuel (coke) is required to reduce the ore into iron. So, during periods where mills are trying to get the most of their process (achieving high margins) or when coke costs increase, the demand and consequently the price differential of high-grade ores over medium grades will increase. In recent years, clear evidence of this point was the implementation of the winter cuts in China, where steel production was curbed to reduce emissions. The cut on steel supply led to higher steel

prices that were followed by a spike on the 65% price differential. In 2021, the higher steel margins and high coking coal prices lift the 65% premium to historical highs.

By the time this report was prepared, the price consensus for iron ore prices at 65% Fe in 2022 of the analysts was \$127/t (table below – prices in USD), with a downward trend going forward until prices reach the long-term level of around \$84/t. Figure 16-2 shows the iron ore price for 65% Fe.

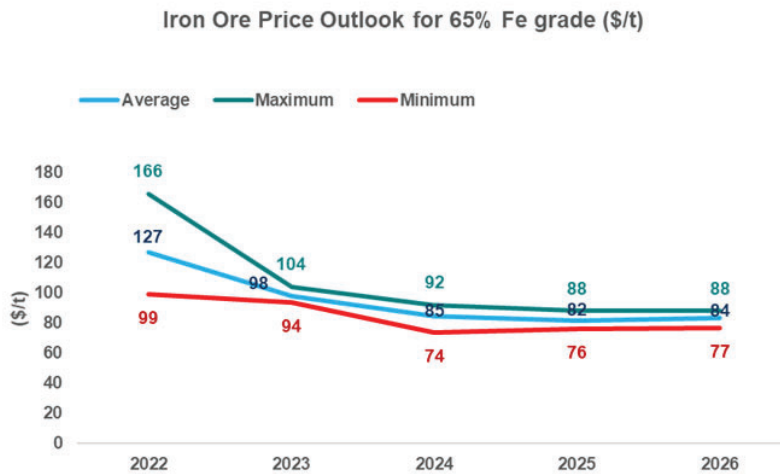


Figure 16-2 - Iron ore price outlook for 65% Fe grade (US\$/t). Source: Bank reports published between September and October 2021

As the trend for 2022 for both steel margins and coal/coke prices remain positive, most market analysts are forecasting that premiums for high grade materials will remain well supported.

The value-in-use (VIU) per additional percentage point of Fe CFR China was projected by dividing the price presented in the “Consensus / Average” line of the 62% Fe CFR China table by its Fe content (62%). This methodology is robust when comparing historical means. In addition, there are ore sales in the market using this methodology for iron adjustment. The forecast values are in Table 16-1.

Table 16-1 - VIU per additional percentage point of Fe (US\$/dry metric ton)

	2022	2023	2024	2025	2026	LT
VIU per additional percentage point Fe	1.81	1.46	1.28	1.22	1.29	1.13

For comparison and information only, the table below shows iron ores prices realized over the last 5 years or Platts 62% Fe IODEX CFR China (Table 16-2).

Table 16-2 -Platts iron ore for 62% Fe (US\$/dry metric ton)

	2017	2018	2019	2020	2021	Average
Platts iron ore 62% Fe IODEX CFR China	71.3	69.5	93.4	108.9	159.5	100.5

16.2. Contracts

16.2.1. Northern System operations TRS: logistics/distribution contracts

We operate the EFC railroad under a concession agreement, which has been recently renewed and will expire in 2057. The EFC railroad links our Northern System mines in the Carajas region in the Brazilian state of Para to the Ponta da Madeira maritime terminal, in São Luis, in the Brazilian state of Maranhão.

We rely on long-term contracts of affreightment to secure transport capacity and enhance our ability to offer our products in the Asian market at competitive costs on a CFR basis. To support our commercial strategy for our iron ore business, we have long-term agreements with seventeen ports in China, which also serve as distribution centers.

16.2.2. Northern System operations TRS: logistics – full

Our production from Serra Sul is transported by railway to the port through Carajas railroad (“EFC”). The EFC railroad links our Northern System mines in the Carajas region in the Brazilian state of Para to the Ponta da Madeira maritime terminal, in São Luis, in the Brazilian state of Maranhão. We operate the EFC railroad under a concession agreement, which has been recently renewed and will expire in 2057. EFC extends for 997 kilometers from our Carajas mines to our Ponta da Madeira maritime terminal complex facilities. Its main cargo is iron ore, principally carried for us. VLI has rights to purchase railroad transportation capacity on our EFC railroad. In 2021, the EFC railroad transported 188,335 thousand metric tons of iron ore. In 2021, EFC had a fleet of 298 locomotives and 21,175 wagons, which were operated by Vale and third parties.

We operate ports and maritime terminals mainly to complete the delivery of our iron ore and iron ore pellets to bulk carrier vessels serving the seaborne market. Production from Serra Sul is exported through Ponta da Madeira maritime terminal. Our Ponta da Madeira maritime terminal is located in the Brazilian state of Maranhão. Pier I can accommodate vessels of up to 420,000 DWT and has a maximum loading rate of 16,000 metric tons per hour. Pier III, where there are two berths and three shiploaders, can accommodate vessels of up to 210,000 DWT at the south berth and 180,000 DWT at the north berth (or two vessels of 180,000 DWT simultaneously), subject to tide conditions, and has a maximum loading rate of 8,000 metric tons per hour in each shiploader. Pier IV (south berth) is able to accommodate vessels of up to 420,000 DWT and there are two ship loaders that work alternately with a maximum loading rate of 16,000 metric tons per hour. In 2018, Vale received the customs authorization for the operations of Pier IV (north berth). Cargo shipped through our Ponta da Madeira maritime terminal consists of the Northern system production of iron ore, pellets and manganese. In 2021, 182.9 million metric tons of iron ore, pellets and manganese were shipped through the terminal. The Ponta da Madeira maritime terminal has a storage yard with static capacity of 7.2 million metric tons.

We rely on long-term contracts of affreightment to secure transport capacity and enhance our ability to offer our products in the Asian market at competitive costs on a CFR basis. To support our commercial strategy for our iron ore business, we operate two distribution centers, one in Malaysia and one in Oman and we have long-term agreements with seventeen ports in China, which also serve as distribution centers.

In 2015, we launched the Brazilian blend fines (BRBF), a product resulting from blending fines from Carajas, which contain higher concentration of iron and lower concentration of silica in the ore, with fines from the Southern and Southeastern Systems, which contain lower concentration of iron in the ore. In August 2018, Metal Bulletin launched a new index, the 62% Fe low-alumina index, which is based on our BRBF. During 2020, the 62% Fe low-alumina index traded with a premium of US\$1.2 per dmt over the 62% Fe index. The resulting blend offers strong performance in any kind of sintering operation. It is produced in our Teluk Rubiah Maritime Terminal in Malaysia and in the seventeen distribution centers in China, which reduces the time to reach Asian markets and increases our distribution capillarity by using smaller vessels. In 2019, we announced the launch of GF88, a new product to supply the growing market of pellet production in China, which consists of Carajas fines

(IOCJ) obtained through a grinding process, opening a new market for our high-quality products portfolio.

17. Environmental studies, permitting, and plans, negotiations, or agreements with local individuals or groups

The Serra Norte Mining Complex, also known as the Carajás Iron Miner Complex, is in the town of Parauapebas, and it is the largest open-pit iron ore mine in the world.

There are different environmental and protected areas located in the vicinity of Serra Norte complex, such as the National Forests of Tapirapé-Aquiri, Itacaiúnas and Carajas; Campos Ferruginosos National Park; Tapirapé Biological Reserve; Xikrin Indigenous Land of the Cateté River; and Igarapé Gelado. The total area comprises approximately 1.2 million hectares, relatively well preserved, in contrast to the anthropized regions in the surroundings.

The environmental restrictions that affect Serra Norte are presented below:

Presence of conservation units

Serra Norte is part of the Carajás National Forest, which is part of a group of conservation units designed to protect biodiversity, qualified as an area of extreme importance. Regionally, the set of these protected areas includes forest reserves and other conservation units, called special use areas, together with the set of indigenous lands. The Carajás National Forest belongs to the group of “sustainable use” protected areas that foresee multiple uses within its limits, including mining.

Currently, discussions are underway with the conservation unit's managing agency to change the zoning of the Carajás National Forest Management Plan, which will allow advance in areas currently considered restricted for mining in N1/N2.

Underground natural caves

Supported by federal legislation and specific normative instructions, it establishes that caves must be classified according to their degree of relevance (Maximum, High, Medium and Low) and defines the necessary studies and compensation possibilities in case of impacts on the caves with High, Medium and Low relevance degree.

The caves with a maximum degree of relevance cannot be subject to irreversible negative impacts around their 250 m buffer until their respective areas of influence are validated by the Agency's licensing bodies corresponding to the respective licensing processes.

In the context of studies and licenses, VALE has been obtaining specific and individual authorizations per cave for controlled mining in areas of influence of less than 250 meters (average of 150 m), where the projects are monitored by the environmental agency through monitoring reports on the physical and biological conditions thereof. Vale has also been successful in claims for reclassification of relevance from maximum to non-maximum degree (High, Medium or Low), and consequently, become eligible for environmental compensation processes in accordance with the law, thus recovering blocked reserves.

Also, regarding cave compensation, in order to obtain a balance of caves suitable to be offered as compensation, Vale carries out campaigns to identify caves in areas without mining interests, seeking greater predictability of their needs and anticipating demands.

17.1. Environmental aspects

The Serra Norte Complex is located in Federal Areas, within the Carajás National Forest (Flona de Carajás), established in 1998. According to the Resolution of the National Environmental Council - CONAMA No. 237/1997 and Federal Law LC No. 140/2011, the environmental licensing for mining projects is under the responsibility of the corresponding state, except when it directly impacts more than one State, is located in indigenous lands, or when in federal lands.

In this sense, the environmental licensing of Serra Norte is under the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA), which analyzes and technically approves the proposed projects for mining activities in this type of area.

In Brazil, the environmental licensing process which allows a company to operate within the technical and legal aspects established by law has three phases:

Preliminary Permit (LP): it is requested even in the planning phase of the activity or project, approving its location and conception, attesting to the environmental feasibility and establishing the basic requirements to be met in the next phase of project implementation;

Installation Permit (LI): authorizes the installation of the project or activity in accordance with the specifications in the approved plans, programs and projects, including environmental restrictions and control measures;

Operation Permit (LO): authorizes the operation of the project, after verification of effective compliance with the conditions established in the two previous licenses, with environmental restrictions and control, mitigation and compensation measures determined for the operation.

The Serra Norte mines, specifically N4 and N5, have reached the operation permit (LO) which allows them to operate under conditions established by the federal licensing agency since 2002. Currently, the operating permit is being renewed at IBAMA when the environmental performance is evaluated to allow the issuance of the 10th. rectification.

The expansions that have taken place over time have largely maintained the conditions established in the initial issuance of the license, with parameters, monitoring points and some new programs being adjusted to ensure environmental assessment, control and mitigation of environmental impacts arising from the operation. Table 17-1 shows the list of licenses in Serra Norte.

Table 17-1 - Environmental Permit in Serra Norte

Authorization / Environmental Permit	Environmental agency	Description	Expiration Date	Status
LI nº 1172/2017	IBAMA	Adequacy of the facilities of the beneficiation plant	12/07/2021	License under revalidation (Process No. 02001.002197/2002-15) ⁽¹⁾
LI nº 1207/2018	IBAMA	Extension of the Conveyor Belt of the Mobile Waste Handling System	20/03/2020	License under revalidation (Process nº 6407759/2019) ⁽¹⁾
LI nº 1307/2019	IBAMA	Reprocessing Project for the Gelado Dam's Tailings	25/08/2023	Valid License
LI nº 1333/2019	IBAMA	Crushing system at the Morro I Mine	20/12/2021	Valid License
LO nº 267/2002 (10 ^a Rectification)	IBAMA	Exploitation of iron ore from bodies N4 and N5 and extensions	27/03/2021	License under revalidation (Process nº 02001.002197/2002-15) ⁽¹⁾
LO nº 1570/2020	IBAMA	LT 230kV Carajás and Substation Serra	27/03/2021	License under revalidation (Process nº 02001.011540/2020-96) ⁽¹⁾
LI nº 1142/2016 02001.002197/2002-15	IBAMA	Apinha road	20/02/2023	Valid License

⁽¹⁾ According to Brazilian legislation we can continue to operate during the renewal process.

The company has also prepared and submitted the necessary environmental and social studies for the continuity of the operations. These processes are in different stages, as shown in Table 17-2:

Table 17-2 - Processes for Serra Norte complex

Project	Process in the Environmental Body	Status	Structures	Process	Forecast to Obtain the License
				Formalization	
N3 Mine	02001.003830/2015-07	LP	N3 Mine	16/05/2018	2022
	IBAMA				
N1 and N2 Mine	02001.111331/2017-46	LP	N1/N2 Mining	02/01/2020	2023
	IBAMA				

17.1.1. Climate

The current climate in the Amazon region and consequently in the Serra Norte region is a combination of several factors, the most important of which is the availability of solar energy, through the energy balance. The location between the 5° north and 10° south range receives constant and intense flows, providing that the air temperature presents a small variation throughout the year. Thus, typical climate is consolidated, with a lot of days of convection rain. Therefore, the region of interest has a typical climatic characteristic of equatorial regions; however, microclimatic aspects must be considered.

The region has two well-defined seasons: the rainy season, November to April, when it rains 80% of the annual total, and the dry season, which runs from May to October, with the driest quarter (June, July, and August) and monthly means of 24 mm. The average annual rainfall for the region varies from 1,500 to 1,900 mm, and the yearly average temperature is between 23.5 and 25.5°C, with the maximum temperature of the monthly average reaching 32.5 and the minimum being never lower than 18°C.

The air humidity in the region remains between 70 and 85% average. In the driest months, humidity is slightly reduced, reaching minimum levels of around 50% and average around 70%. During the rainy months, from October to May, the maximum average can exceed 95%. Figure 17-1 shows Serra Norte annual precipitation:

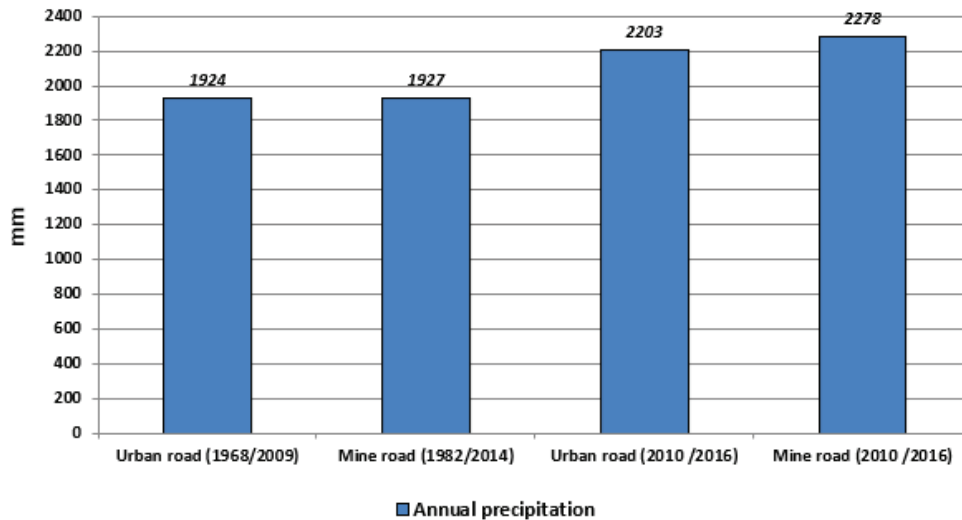


Figure 17-1 - Serra Norte annual precipitation

17.1.2. Hydrology

Serra Norte mine is in the domain of the Parauapebas River sub-basin, a tributary of the Itacaiúnas river that flows into the Tocantins River in the city of Marabá.

The Parauapebas river rises in the Serra Arqueada through the Caracol stream and the Onça stream. It flows in south-north direction, receiving the following tributaries: Goiaba creek, Sossego river, Taboca creek, Jacaré creek and Gelado creek (also known as Cigano or Mombuca), on the left bank; and the Plaquê and Verde rivers, the Ilha do Côco creek and the Novo and Caracol rivers, on the right bank.

17.1.3. Vegetation

There are two main types of vegetation in Serra Norte area, forest and fields, also known in the region as canga vegetation.

Areas of canga vegetation occur on iron outcrops, generally characterized by species of herbs and bushes. The forest clumps are small areas of forest that arise in the middle of the canga vegetation. The forest vegetation area is where trees predominate, together with herbs, shrubs, palm trees, and vines.

17.2. Environmental management

The main environmental management programs are described below.

17.2.1. Environmental management system

Through an environmental management system, Vale implements plans and procedures to identify non-conformities, develop correction plans and continuous improvement actions. The management system aims to prevent and control potential environmental and social impacts identified in the impact assessments submitted to the regulatory agencies.

Currently, in the Northern System, the N4 and N5 mines are certified with ISO 14001:2015.

17.2.2. Removal and storage of top soil

The surface soil of suppressed areas, formed by layers with higher organic matter content are stored and used in the process of rehabilitation of degraded areas. This material is rich in nutrients and has propagules from native vegetation, important for the recovery of altered or degraded areas.

17.2.3. Liquid effluent management

Water-oil separators are used to treat effluents generated in the maintenance workshops and from the refueling of vehicles. The sanitary effluents generated in the administrative areas are treated in the Sewage Treatment Plant.

17.2.4. Drainage system

Operational areas and access roads are equipped with drainage systems to direct the rainwater to watersheds decantation ponds. Drainage systems are also important to conduct the water and prevent erosion. Those systems are constantly monitored and technically adjusted when necessary.

17.2.5. Solid Waste management

The generated solid waste is segregated and packaged properly, according to its characteristics, until the destination.

17.2.6. Air quality

Emission of particulate material is controlled through humidification of unpaved roads with water trucks, use of fixed sprinklers, setting vehicles speed limits, washing paved roads, carrying out maintenance on machinery and equipment, revegetation of piles and mining areas, and active monitoring.

The monitoring of air and meteorological quality in the mine site is carried out by 03 automated stations that continuously generate data through specific analyzers and sensors. These stations are in the Urban Center of Carajás, in the Mine, and the Gelado Dam. These stations monitor the following parameters: Total Suspended Particles (PT) and Inhalable Particles (PI).

17.2.7. Noise and vibration monitoring

This monitoring aims to assess noise and vibration, through periodic seismographic monitoring, allowing comparison with the standards defined by the current legislation.

At the Carajás Mining Complex, this monitoring is carried out periodically through a sampling network, in points distributed in the following locations: mine and plants, highway, natural forest and dams. The obtained information is stored in a database and submitted annually to IBAMA in a consolidated report.

As complementary to this program, Vale has been developing the Bioindicators Monitoring Program to monitor the impact of noise on fauna, with 15 points specifically intended for such monitoring.

17.2.8. Bioindicators

This monitoring aims to assess how the project affects the dynamics of fauna and flora. The monitoring network serves the entire Mining Complex of Carajás (Serra Norte and Serra Sul).

17.2.9. Water resources

The water quality management program is responsible for monitoring underground, potable water, and liquid effluents. The results are consolidated in annual reports and provided to the environmental agencies.

17.2.10. Vegetal Suppression

This program aims to apply forest management techniques focusing on the workers' safety and the minimal impact on fauna and flora.

17.2.11. Zoobotanical park

Created in 1985, maintained and administered by Vale, the Zoobotanical Park is the exclusive home to native species of fauna and Amazonian flora. Located within the National Forest of Carajás, in a Federal Conservation Unit, it occupies an area of 30 preserved hectares, which allows free circulation of local fauna. The space receives around 100,000 visitors a year.

17.2.12. Degraded areas recovery plan

This program aims to rehabilitate the areas morphologically altered by mining activities, aiming to restore the ecosystem functionality.

17.2.13. Fire prevention

Vale works in partnership with Ibama and ICMBio to execute fire prevention and firefighting procedures to protect conservation units in Carajás.

17.3. Social or community requirements

The closest community to the Serra Norte Operation is the municipality of Parauapebas, located approximately 30 km south with population of approximately 210.000 residents. The amount invested by Vale in the region in social programs in 2020 was about 12 million dollars.

This section describes the main social actions and results related to the operation.

17.3.1. Environmental education program

This program helps increase the critical awareness of the employees (VALE and third-parties) and the communities about environmental responsibility.

17.3.2. Recruitment program and workforce training

This program intends to hire the highest possible number of employees residing in the municipality where the project operates. Therefore, this program aims to qualify the local workforce through professionalizing technical courses.

17.3.3. Health program

Through partnerships with the government, Vale makes investments in the infrastructure, education, and health areas, which involve construction and refurbishment of health posts, donation of hospital equipment, and ambulances.

17.4. Mine closure and future use

The closure actions of a mining project must consider the regulatory and legal framework, environmental and social standards and good practices, economic issues, and the promotion of the future use of the territory, in accordance with its vocation identified through a process of active listening.

To ensure the success of these actions in all company's mines, Vale establishes an integrated mine closure plan, carried out by multidisciplinary teams in a context of effective governance. Thus, it is possible to meet the technical demands of closure, and at the same time, contribute to the sustainable development of mined territories, with social engagement and shared value.

To guide strategy and actions, the company has internal rules and procedures, notably the Mine Closure Guide and the procedure for the financial provision for asset demobilization, among others. It also participates in the International Council on Mining and Metals (ICMM) Mine Closure discussion group. With the purpose to strengthen the subject in Brazil, Vale also collaborated in the preparation of IBRAM – Brazilian Mining Institute's Mine Closure Planning Guide.

The mine closure issue has gained a prominent position at Vale through a solid governance model which incorporates a layered view of lines of defense in risk management, safety and efficiency throughout the lifecycle of the project.

Its priority is to work to close mines and implement future use with concepts of shared value with the society, in addition to working to stabilize existing geotechnical structures, ensuring long-term safety.

17.4.1. Legal regulations, technical standards, terminology and concepts applied to closing

In the Brazilian legislation, Mine Closure has been undergoing changes, emphasizing regulations that direct the industry to operate more sustainably, with environmental, social and economic balance.

The regulatory regime that serves Mining reflects the normative evolution of the mining law and the institutional arrangement built covers the three levels of the Federation (Union, States and Municipalities) and promotes interfaces between the different fields of Law, mainly the Environmental Law, which has the greatest impact on the Mineral activity, significantly reflecting on the Mine Closure subject.

At present, the concept of “mine closure” is still in the process consolidation in the Brazilian legislation and regulation.

The terms and the concepts applied to mine closure are very diverse. We follow the best technical recommendations in this regard, contained in Brazilian legislation, ABNT standards and brought by the guidelines of the Brazilian Mining Institute.

IBRAM Guide on Good Management Practices for Dams and Tailings Disposal Structures provides a nomenclature of the terms associated with the process of closing the activities of geotechnical structures for retaining mining tailings, specifically dams (Figure 17-2). This guide is in alignment with the guidelines set forth in the mineral legislation.

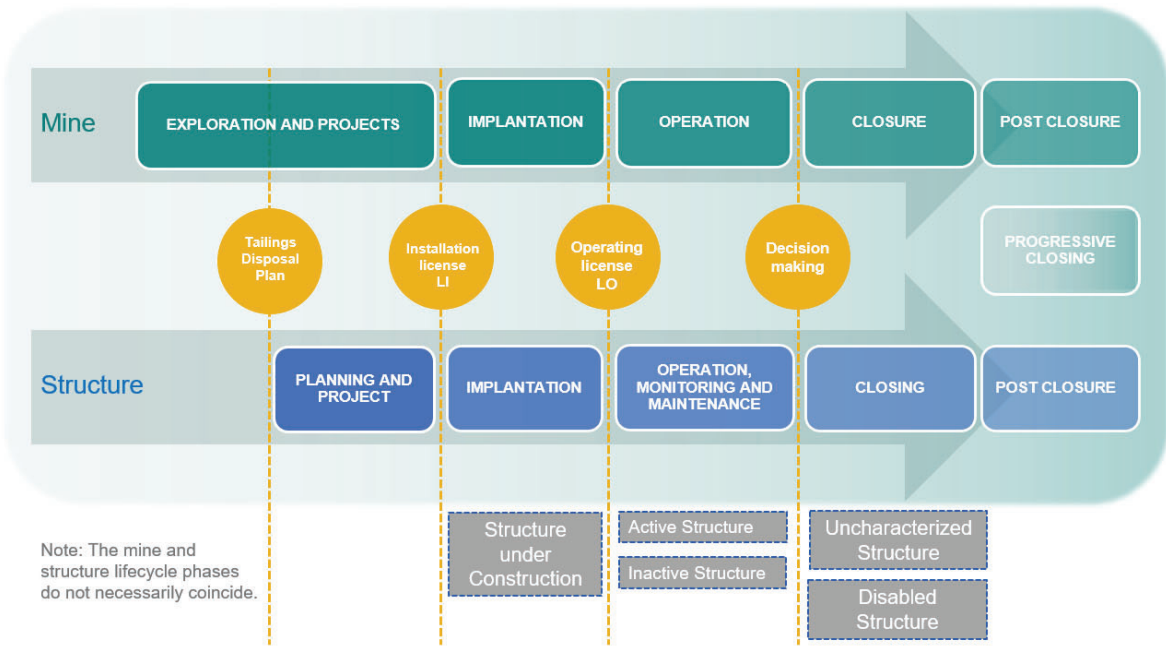


Figure 17-2 - Conceptualization of terms applicable to mine closure at Vale

Vale's asset closure procedures and future cost estimates will be conceptually aligned with best practices and recommendations from the International Council on Mining & Metals (ICMM) through the ARO, LoA, LoM and SLoMARO, LoA, LoM and SLoM visions (Figure 17-3).

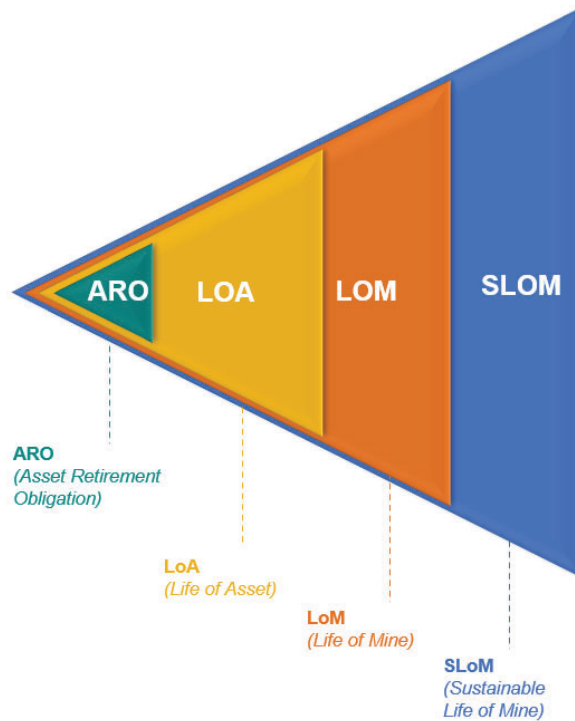


Figure 17-3 – Chart of ARO, LoA, LoM and SLoMARO, LoA, LoM and SLoM visions

The development of a progressive closure process is carried out through LoA planning, focusing on closure actions throughout the entire life cycle of an asset, which comprises design, implementation, operation, closure and post closure phases.

In order to establish the concepts and standardize guidelines to guide the processes related to the progressive closure of assets, and standardize roles and responsibilities of managers linked to the asset closure phase, a management procedure called "Progressive Closure of Ferrous" which presents the way how the asset is managed both from the point of view of evaluation of its condition in the mine closure process and provision of financial conditions for the necessary actions to be carried out.

For the deactivation of the Serra Norte Complex, its main structures were considered: pits, waste piles, containment dykes, basins and sumps, industrial facilities and support infrastructure.

The activities planned for de-characterization or deactivation of the Serra Norte Complex assets in the closure phase are described below, according to their specific characteristics, to adapt them to the required safety standards and the planned closure scenario for the area.

17.4.2. Pits

The activities planned for the closure of the Serra Norte Complex pits are summarized in Table 17-3.

Table 17-3 - Closing activities - Pits

Typology	Structure	Activities
Pit	N1, N2, N3, N4E, N4WN, N4WS, N5EN, N5S, N5W, Morro I. Cava 1, 2 and 3. Cava Granito	- Topographic survey; - Localized slope adjustments; - Localized superficial drainage adjustment; - Geotechnical monitoring system final adjustment; - Water level monitoring system final adjustment; - Localized slope revegetation; - Safety barrier implementation.
	N5E, N5W, N4EN and Cava 1	Waste disposal.

17.4.3. Waste pile

The activities planned to deactivate it are briefly presented in Table 17-4.

Table 17-4 - Closing activities – Waste Pile

Typology	Structure	Activities
Waste Dump	PDE Oeste, PDE Sul III, PDE Sul IV, PDE Noroeste I, PDE Noroeste II, PDE Sudoeste N4W, PDE Norte I, PDE Leste I, PDE Jacaré, PDE Sudeste N5, PDE N5S, PDE N5E, PDE N5W, PDE N1 e PDE N2.	- Topographic survey; - Geotechnical monitoring system final adjustment; - Localized slope adjustments; - Superficial and belt drainage system final adjustment; - Vegetation reinforcement of slope and berm.
	PDE 1, PDE 2 and PDE 3.	- Localized slope adjustments; - Superficial and belt drainage system final adjustment; - Vegetation reinforcement of slope and berm.

17.4.4. Sediment Containment System

The activities planned for the closure of the containment dykes in the Serra Norte Mines are briefly presented in Table 17-5.

Table 17-5 - Closing activities - Sediment Containment System

Typology	Structure	Activities
Dam and Sumps	Gelado Dam, Geladinho Dam, Dike PDE Noroeste II, Estéril Sul Dam, Granito Dike, PDE Jacaré Dike, 2 Pera Dams	<ul style="list-style-type: none"> - Geotechnical monitoring system final adjustment; - Vegetation reinforcement of slope and berm; - Superficial protection of the embankment final adjustment; - Localized superficial drainage adjustment; - Spillway final adjustment; - Revegetation; - Safety barrier implementation.
	Kalunga Dam, Azul Dam, PDE2 Dam	<ul style="list-style-type: none"> - Geotechnical monitoring system final adjustment; - Spillway final adjustment; - Revegetation.

17.4.5. Industrial Facilities and Support Infrastructure

The activities planned for the closure are briefly presented in Table 17-6.

Table 17-6 - Closing activities – industrial facilities and support infrastructure

Typology	Structure	Activities
Industrial Facilities and Structure	Office, storehouse, railway pear, facilities, gas station	<ul style="list-style-type: none"> - Survey of areas with potential contamination; - Systems Deactivation and Structure Disassembly; - Drainage system final adjustments; - Subsoiling; - Revegetation.

17.4.6. Environmental control

The expected condition for the Serra Norte Complex at the end of the operation is shown in Figure 17-4 and Figure 17-5, highlighting the main structures and those with potential future use in the area.

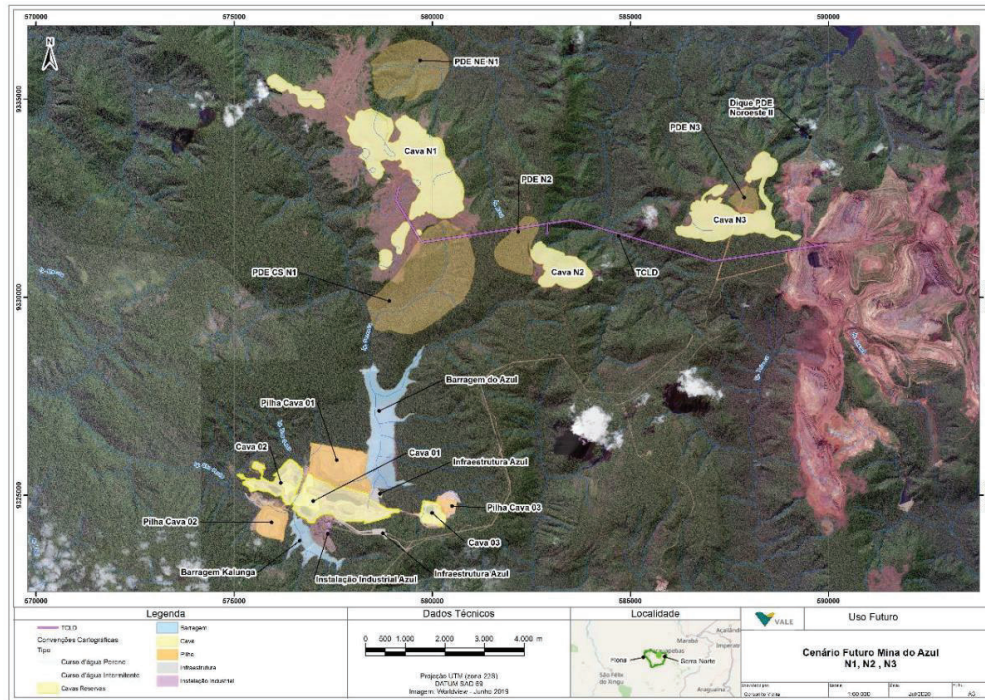


Figure 17-4 - Condition at the end of the operation - Mines Azul, N1, N2 and N3

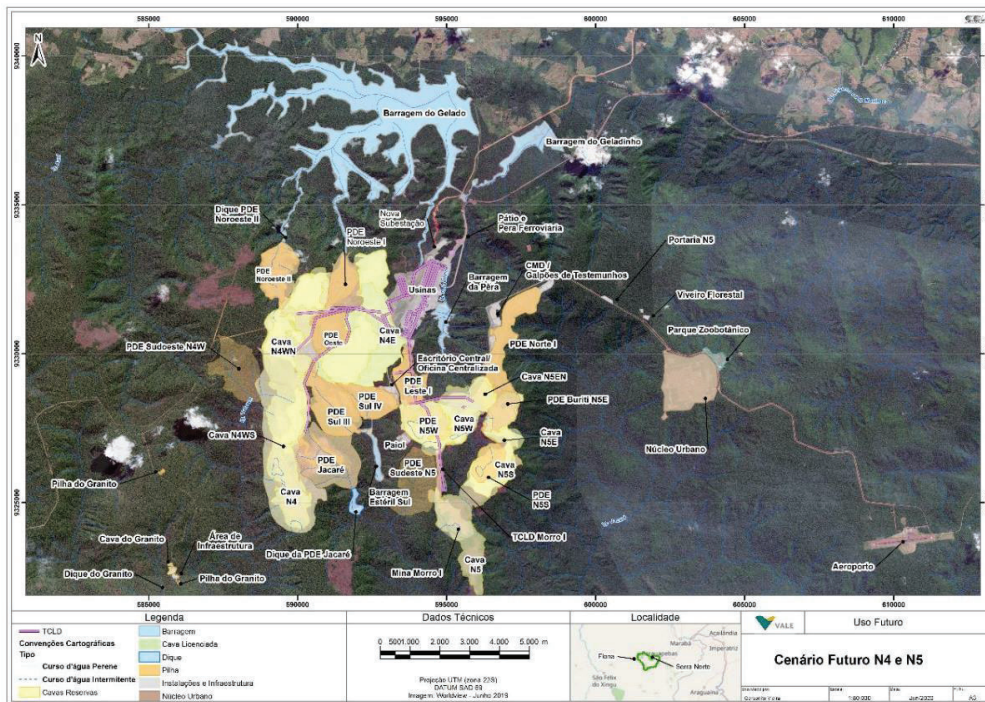


Figure 17-5 - Condition at the end of the operation in N4 and N5.

17.4.7. Monitoring and maintenance

As part of the closure plan for the Serra Norte Complex, the need for geotechnical and environmental monitoring and the maintenance of areas in the post closure stage should be considered. Table 17-7 summarizes the main activities proposed to measure the efficiency of the closure actions for all assets and for the area in general.

Table 17-7 - Post-closure monitoring and maintenance.

Activities	Attention points
Post-closure Monitoring and Maintenance	- Revegetation development. - Geotechnical stability; - Superficial and underground water quality.

17.4.8. Future use proposition

Except the Gelado and Geladinho Dams, which are partially located in the Gelado EPA, all assets of the Serra Norte Complex are located in the Carajás National Forest (FLONA de Carajás) area, an integral conservation unit, whose management is under the responsibility of the Chico Mendes Institute – ICMBio.

The fundamental objectives of Conservation Units (UC's) are protection and conservation of biological diversity and sustainable development based on natural resources, as well as fair and equitable sharing of the benefits generated by them. Therefore, the establishment of such units in the Brazilian territory aims to maintain natural resources in the long term.

Pursuant to Law No. 9,605/2000, which institutes the National System of Conservation Units (SNUC), PAs must have a Management Plan, which must include measures which, in addition to ensuring environmental preservation, also aim to promote the conservation unit for the economic and social life of neighboring communities. The same law also presents the basic objective of a National Forest, as “the multiple sustainable use of forest resources and scientific research, with an emphasis on methods for the sustainable exploitation of native forests”.

With the purpose to reconcile these objectives and comply with the relevant legislation, in 2003, Vale drew up a Management Plan for the Carajás National Forest, based on studies of abiotic, biotic and anthropic factors, together with IBAMA, conceptualized zoning for the FLONACA area and several management and development programs, which are structured in five basic lines: Research and Development, Public Use, Protection, Production and Management

Based on the data collected during the preparation of this report and considering the different variables involved, mainly related to the Management Plan of FLONA de Carajás, the relevant aspects for the establishment of guidelines regarding skills were identified in the territory of the Serra Norte Mines for future use of the area:

- Research and Development: Given the importance of the Amazon Forest, both nationally and internationally, in addition to FLONA de Carajás, with approximately 400,000 hectares, the probable interest of several universities and research centers in development is remarkable, or continuity of projects and studies within the preservation area. The Management Plan, which outlines the possible future uses to be implemented in the Carajás National Forest, presents the Research and Development Program, which aims to form a database on the most diverse aspects of flora, fauna, and human populations and local knowledge about natural resources in the Carajás National Forest. The feasibility of the program is associated with the joint work with Universities and Research Institutions. In this scenario, therefore, the use of remaining structures in the administrative and operational areas of the Serra Norte Mines to allocate the support base for researchers, accommodation, equipment and laboratories of the research units is evaluated;
- Qualification and Biodiversity Conservation: Aiming both at continuing to preserve the Carajás National Forest and at developing activities that generate wealth for the region, the Management Plan sees the need to encourage training and professional training for the local

population, with the purpose to prepare the surrounding community and encourage their participation, for the implementation and development of the plan. Therefore, structures remaining in the administrative areas of the Serra Norte Mines could also be used for the purpose of learning and developing skills, through qualification courses and training;

- **Diversification of Vegetal Agroextractivism:** Agroextractivism integrates the extractive tradition and family agricultural production, both in a sustainable relationship with the forest. These practices have been improving and gaining space in the Amazon productive universe through actions related to agroecology. The diversification of agro-extractivist use of plant resources from FLONA de Carajás is future use for the Serra Norte Mines that complements the proposals in the Management Plan for the Carajás National Forest (STCP, 2003). The main objective would be to contribute to the promotion of sustainable production, through articulation between community organization and technological development, in a way to guarantee the economic and financial autonomy of FLONA de Carajás. As a contribution to the lines of action proposed for FLONA de Carajás, the development of agroextractivism related to Ethnic Art is suggested. Agroextractive artisanal production can combine innovation and ethnic tradition, reaching valued market fields in Brazil and worldwide. The elements of the forest have attracted the attention of designers, conquering the world of fashion and decoration. The cultural tradition and the fascination for Brazilian biodiversity, together with technological innovation, can add value to plant agro-extractivism products;
- **Ecological and Historical Tourism:** The tourist attraction in the region is based on the great beauty of the local landscape (preserved forests, mountains, waterfalls, natural monuments), whose peculiarity has promoted the use of ecological tourism. There is a partnership between the Chico Mendes Institute (ICMbio) and the Carajás Ecotourism Cooperative (Cooperture) which aims to facilitate public visitation of the Carajás National Forest, since 2013. Cooperative members carry out activities related to ecotourism in FLONA and in attractions in its surroundings. As an example of conservation of the mining industrial heritage in other countries and other similar initiatives in Brazil, and the fact that Serra Norte is the largest iron ore production complex in the world, associated a special historical and tourist interest to structures and processes and to the remaining facilities of the Serra Norte Mines.

17.4.9. Financial provision

The closure of activities in the Serra Norte iron ore mines is foreseen in the project to take place in 2037 and for the manganese mines in 2027, with progressive closure considered, with decommissioning and deactivation actions starting in the operational phase. The description of actions planned for closing is presented in Table 17-8, which refers to the provision of financial resources for the demobilization of assets using the ARO model for 2021.

Table 17-8 - Provision of financial resources for the demobilization of assets using the ARO model for 2021

Asset	Total (US\$ M)
Pit	68.75
Waste Dumps	67.85
Dams and Sumps	99.90
Industrial Facilities	114.33
Other structures	33.89
Total	384.72

Note: numbers have been rounded

18. Capital and operating costs

Vale QP reviewed the capital and operating costs required for mining and processing of Mineral Reserves at Serra Norte. Serra Norte is an operating mine, and capital and operating cost estimates were prepared based on the recent operating performance and the current operating budget for 2021. All costs in this section are expressed in US dollars.

All capital and operating cost estimates are based on recent estimates and actual costs and are at least at a pre-feasibility level of confidence, with accuracy level of $\pm 25\%$ and a contingency range not exceeding 15%.

The sole purpose of the presented figures is to demonstrate the economic viability of the mineral reserve, therefore it can differ from other information Vale publishes and should not be considered as a guidance.

18.1. Capital costs

The total capital costs for Serra Norte Life of Mine are shown in Table 18-1. Capital costs are related to new projects to maintain or increase production. The sustaining capital costs are related to maintaining the current production rate and include the replacement of mine equipment, pit pushbacks, a new waste dump, replacement of plant equipment and instrumentation. Additionally, economic assessments of reserves consider capital projects that aim to maintain and/or increase productive capacity. The overall capital cost estimate for LOM or evaluation period is US\$ 6,202 million as shown in Table 18-1.

Table 18-1 - LOM Capital Cost Estimate

Capital Cost Type	Unit	Value
Sustaining CAPEX	US\$ M	5,026
Non-routine	US\$ M	1,126
Mine and plant	US\$ M	794
Waste and tailings piles	US\$ M	332
Routine	US\$ M	3,900
Capital projects CAPEX	US\$ M	1,176
Mine and plant	US\$ M	119
Logistics and Other	US\$ M	1,056
TOTAL	US\$ M	6,202

Note: numbers have been rounded

18.2. Operating costs

LOM average unit operating cost and expenses:

- Mine and plant: 11.0 US\$/ton of product
- Logistics and Distribution: 19.3 US\$/ton of product
- Royalties: 2.5 US\$/ton of product
- Sales expenses, R&D, others: 0.1 US\$/ton of product
- Total average unit operating costs and expenses: 33.0 US\$/ton of product

The overall costs and expenses estimate for LOM or evaluation period is US\$ 51,872 million as shown in Table 18-2.

Table 18-2 - Operating Costs and Expenses

Type of costs and expenses	Unit	Value
Mine and plant	US\$ M	17,264
Logistics and Distribution	US\$ M	30,378
Royalties	US\$ M	3,999
Sales expenses, R&D, others	US\$ M	232
TOTAL costs and expenses	US\$ M	51,872

Note: numbers have been rounded

The average operating cost is based on a 17-year life of mine from 2022 through 2038. The operating cost inputs including labor, consumables, supplies, selling costs, commercial offices, operational and maintenance research & development, and were based on data from Vale's 2021 budget.

18.2.1. Workforce

The workforce breakdown and main contractors list for the entire operation at Serra Norte are shown in Table 18-3 and Table 18-4, respectively. The main contractors at Serra Norte are related to mining, maintenance of the plant and cleaning.

Table 18-3 - Vale's site workforce

Serra Norte	Total
Mine	3,671
Plant	2,284
Others	809
Total	6,764

Table 18-4 – Contractors' workforce

Serra Norte (Contractors)	Total
Mine	695
Plant	665
Others	3,275
Total	4,635

19. Economic analysis

19.1. Forward-looking information caution

The aim of the economic evaluation presented in this chapter is to demonstrate the economic viability of the mineral reserve, therefore the production rates, operating efficiencies, costs and expenditures, taxes and other information presented can differ from other information we publish and should not be considered as a guidance. Note that our planned production extraction may vary due to continuous mineral exploration and technical studies to add new mineral reserves.

19.2. Economic criteria

The economic analysis in this Technical Report Summary is based on the Mineral Reserves, economic assumptions, and the capital and operating costs as presented in Section 18 of this Technical Report Summary.

19.2.1. Physicals

- Open pit ore tons mined: 1,590 Mt (17-year mine life from 2022 through 2038);
- Total ore processed: 1,590 Mt (17-year mine life from 2022 through 2038);
- Mine life: 17 years (between 2022 and 2038);
- Ore grade: 65.78% Fe;
- Average LOM Recovery: 98,9%;
- Recovered Iron Ore: 1,573 Mt (17-year mine life from 2022 through 2038).

19.2.2. Revenue

Commodity prices were discussed in Chapter 16.

The average logistics costs considered for this model are: 19.3 US\$/ton, around 70% of the total sells during Serra Norte mine life considered as foreign market and CFR (cost and freight) model.

The remaining 30% of the production volume is delivered to the domestic market or first transferred to our own pelletizing plants and/or sold to the foreign market on a FOB basis (Free on Board), and although not having the associated maritime logistics costs, the net revenue in this case is lower, since discounts are applicable as the reference prices are CFR China.

To support VALE's iron-ore commercial strategy, the company operates two blend and distribution centers, one located in Malaysia and one in Oman. VALE also has long-term contracts with ports in China, which also serve as distribution centers.

The ore of Serra Norte is sold as IOCJ (Iron Ore Carajás), a premium product with pricing based on the 65% Fe product and as an input to BRBF blend.

19.2.3. Operating Costs

- LOM average unit operating cost and expenses:
- Mine and plant: 11.0 US\$/ton of product
- Logistics and Distribution: 19.3 US\$/ton of product
- Royalties: 2.5 US\$/ton of product
- Sales expenses, R&D, others: 0.1 US\$/ton of product
- Total average unit operating costs and expenses: 33.0 US\$/ton of product

- Overall costs and expenses estimate for the LOM or evaluation period: US\$ 51,872 million.

The mine and plant costs include mining, processing, storage, and shipping of the ore to the loading points. Logistics and distribution costs includes railroad, ports, maritime freight, and distribution centers.

19.2.4. Capital Costs

- Overall capital cost estimate for the LOM or evaluation period: US\$ 6,202 million
- Sustaining CAPEX : US\$ 5,026 million
- Capital projects CAPEX: US\$ 1,176 million

19.2.5. Main Taxation and Royalties

- CFEM Royalty rate: 3.5%
- Income tax rate with SUDAM tax benefit: 15.25 % (2022 – 2024)
- Income tax rate: 34% (2025 – 2038)

19.3. Results of economic analysis

19.3.1. Introduction

VALE has prepared the Serra Norte Operation LOM after-tax cash flow model to confirm the economics of the LOM plan. The economic analysis is based on 100% equity financing and is reported on a 100% project ownership basis.

The mineral reserve only cashflow for Serra Norte is used to confirm the economic viability. The annual cashflow is presented below, with the inputs presented as averages grouped for the first 2 years, followed by 3 years, and subsequently 5 years groups for the Life of Mine Plan.

The cash flow summary is presented in Table 19-1 and Figure 19-1. The currency used to document the cash flow is US\$ and the base case economic analysis assumes constant prices with no inflationary adjustments.

Table 19-1 - Cash Flow table results ⁽¹⁾

Cash Flow (Mineral Reserves only)	Unit	2022-23	2024-26	2027-31	2032-36	2037-41	2042-46	2047-51
Iron Ore Recovered	Mt	102	100	101	93	20	-	-
Total Revenue	US\$ million	9,739	7,134	6,941	6,472	1,356	-	-
Operating costs, expenses, royalties and closure costs	US\$ million	(3,435)	(3,307)	(3,310)	(3,074)	(632)	(42)	(42)
Income Tax and working capital change	US\$ million	(820)	(898)	(1,112)	(1,001)	(130)	-	-
Total CAPEX	US\$ million	(469)	(752)	(303)	(246)	(53)	-	-

⁽¹⁾ The Gelado tailings dam project is not considered in the economic analysis. Gelado project is not classified neither as mineral resources or mineral reserves.

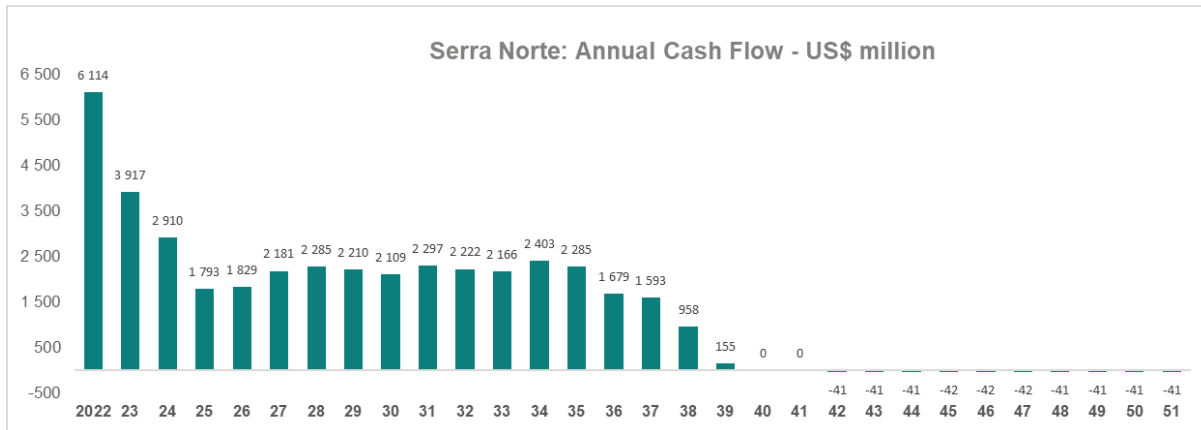


Figure 19-1 - Cash Flow graphic results

19.3.2. Cash flow analysis

The economic valuation model of reserves considered the discounted cash flow method and it took into account annual processed tonnages and grades. The associated process recovery, metal prices, operating costs, logistics costs, royalties, and capital expenditures were also considered. The economic analysis confirmed that Serra Norte are economically viable. The after-tax NPV at a 7.5% discount rate and following a mid-year convention is US\$ 26,215 M. The summary of the results of the cash flow analysis is presented in Table 19-2.

Table 19-2 - Cash Flow analysis

Net present value of overall cash flow	Unit	Value
Total revenue	US\$ M	70,616
Total costs and expenses	US\$ M	-31,163
Mine and plant	US\$ M	-10,343
Logistics and Distribution	US\$ M	-18,150
Royalties	US\$ M	-2,459
Sales expenses, R&D, others	US\$ M	-142
Closure costs	US\$ M	-70
Income Tax and working capital change	US\$ M	-9,134
Operational Cash Flow	US\$ M	30,319
Total CAPEX	US\$ M	-4,104
Free Cash Flow	US\$ M	26,215

For this cash flow analysis, the internal rate of return (IRR) and payback are not applicable as there is no negative initial cash flow (no initial investment to be recovered).

19.4. Sensitivity analysis

Project risks can be identified in both economic and non-economic terms. Key economic risks were examined by running cash flow sensitivities on after-tax NPV at an 7.5% discount rate. The following items were examined:

- Price and VIU;
- OPEX mine, plant and logistics and distribution;

- Exchange rate;
- Total CAPEX;

The sensitivities are shown in Figure 19-2. Upon application of the sensitivity analysis in the main variables, the NPV remains positive, confirming the robustness of the mineral reserves.

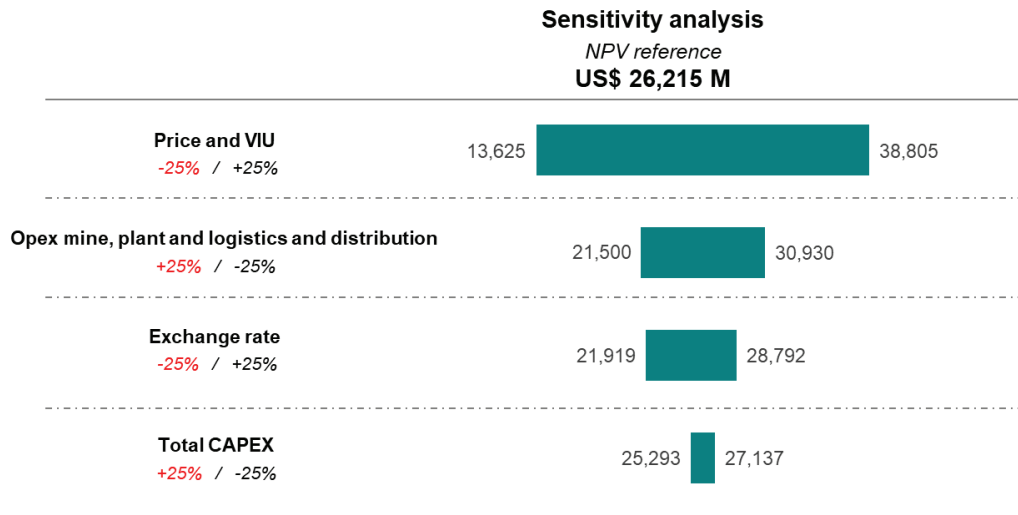


Figure 19-2 - Sensitivity Analysis

20. Adjacent properties

This chapter is not relevant to this Report.

21. Other relevant data and information

This chapter is not relevant to this Report.

22. Interpretation and conclusions

22.1. Property description

The resource and reserve pits of the N1, N2, N3, N4 and N5 mines do not appear to be associated with mining processes of other holders or with mining processes of Vale in previous phases. The mines in operation are N4E, N4W and N5 and have mining licenses in force.

The Serra Norte complex has four mining easements that are contiguous and form a unique contour that circumscribes all current and future industrial facilities in the Serra Norte complex. Two of the easements are authorized and two are in the approval stage.

22.1. Exploration, drilling and sampling

All work developed at the Serra Norte follows strict internal standards and the best practices of the mining industry. The various drilling campaigns carried out over the last decades, as well as all geological data, sampling and chemical analysis originated therefrom were extensively discussed among the involved technical teams to ensure the robustness of the geological model.

22.1.1. Hydrogeological and geotechnical settings

The current geotechnical and hydrological database was considered satisfactory (amount and quality) to achieve the main objectives, which were build and calibrate models able to simulate future mining scenarios capable to provide input to slope stability analysis, support failure mechanism evaluation, provide short and long-term geotechnical information, and provide mining and environmental assistance.

The hydrogeological simulations showed reliable and feasible results with operational flow rates for the drawdown of the pits in the Serra Norte Mine Complex. The geotechnical and hydrological data obtained and used in the slope stability analyses has been a reasonable predictor of current conditions and, therefore, satisfactorily supported the mineral reserve estimates. The slope stability analyses obtained reliable and feasible results, with safety factors consistent with the minimal international standards stabled by Read & Stacey (2009). Therefore, the proposed geometry was considered geotechnically practicable.

It is important to emphasize that any changes in the geotechnical and hydrological assumptions could affect mine planning, indirectly affecting capital cost estimates if any major rehabilitation is required due to a geotechnical or hydrological event, affect operating costs due to mitigation measures that may need to be imposed, and impact the economic analysis that supports the mineral reserve estimates.

22.2. Data verification

The data verification programs concluded that the data collected from the Serra Norte adequately support the geological interpretations and constitute a database of sufficient quality to support the use of the data in mineral resource and mineral reserve estimation.

22.3. Geology and mineralization

The current geological database satisfactorily allows to set a robust structural and stratigraphic model, as like the mineralization associations and understandings. Although it is recommended to keep the geological data collection, with mapping, sampling and developing drilling campaigns (short and long terms), to keep improving the knowledge of the high-grade ores, structural and stratigraphy.

All the current geological models were audited and satisfactorily reproduces the continuity of the mineralized bodies, their enclosing and coverings. The models were built by vertical sections or implicit modelling methods, which represents the geological units acceptably.

The actual presented structural / stratigraphic geometry settings is the result of three successive tectonic events, and a post mineralization mainly by supergenetic enrichment, developed on jaspilites.

22.4. Mineral resource statement

Mineral resources are reported for Serra Norte Mining Complex which comprises the deposits of N1, N2, N3, N4 and N5. Vale has a set of protocols, internal controls, and guidelines in place to support the estimation process, which the estimators must follow. Estimation was made by Vale personnel. The mineral resource estimate is supported by core drilling.

Mineral resources are reported using the mineral resource definitions set out in S-K1300 and are reported without the mineral resources converted into mineral reserves.

Areas of uncertainty that may materially impact the mineral resource estimates include: changes to long-term iron ore price and exchange rate assumptions; changes in local interpretations of mineralization geometry, structures, and continuity of mineralized zones; changes to geological and grade shape and geological and grade continuity assumptions; changes to the input assumptions used to derive the optimized conceptual open pit used to constrain the estimates; changes to the forecast dilution and mining recovery assumptions; variations in geotechnical and mining assumptions; and changes to environmental, permitting and social license assumptions.

Under the assumptions presented in this Report, the Serra Norte Mining Complex has proven to have a reasonable prospect of economic extraction, and therefore the mineral resource estimates can be supported.

22.5. Mineral reserve estimate

Serra Norte mineral reserve estimates follow the definitions established by SEC-SK1300 and were estimated in 2020 and updated in 2021 by qualified Vale personnel. Only part of the measured and indicated mineral resources are converted to proven and probable reserves according to modifying factors. All pits went through a geotechnical validation process and were approved.

Besides the risks associated with prices, costs, process, commodities price volatility as already commented in chapters 11 and 12, we consider as risks the liberation of the radius reductions of caves of maximum relevance in the surroundings of the caverns (N1, N2, N3, N4 and N5), in the necessary time, among other environmental licenses that are beyond our effective control.

As an opportunity we have the cost reduction with the implementation of the Trolley project and the use of autonomous trucks. We also have high potential to increase the reserve if the suppression of the caves of maximum relevance adjacent to the caves that today are treated as blocks in the areas where they are located are released.

A combination of pre mining (historical) and current geotechnical data, with the mining site experience of internal teams supported by national and international consultants, is used to establish internal guidelines and procedures in the slope stability design and operation of Vale's open pit mines. Any changes in the geotechnical and hydrological assumptions could affect mine planning, indirectly affecting capital cost estimates if any major rehabilitation is required due to a geotechnical or hydrological event, affect operating costs due to mitigation measures that may need to be imposed, and impact the economic analysis that supports the mineral reserve estimates.

22.6. Mining methods

Mining in Serra Norte uses the open pit mining method and a fleet of conventional equipment. The mine has its own operation, except in some specific areas, such as re-slope areas.

The production plans aim at average annual production of around 100Mt. It may vary according to the company's production plan throughout the life of the mine.

22.7. Processing and recovery methods

For the processing of ROM with natural moisture, there is no need for process tests for operational control, as it is a technique dominated in the beneficiation of ore, where traditional equipment from the mining industry is used. For the plants to achieve the best performance, it is necessary to ensure that ROM is within the established limits of granulometry, the percentage of lithologies and the quality of each plant, and this procedure is already applied in this complex. Screening at natural moisture requires attention in the rainy season, once ROM with higher moisture generates drop in productivity, in addition to handling problems. During this period, a production drop is already considered in the production planning and an attempt is made to reduce the percentage of hydrated ore, as this type of ore presents greater difficulty in processing.

For the wet plant, there is a routine chemical analysis of the main magnetic concentration fluxes that will allow the necessary operational adjustments to be made. The magnetic concentrators applied for this project are well-known equipment at Vale and allow for the optimization of mass recovery or quality through simple changes in operating parameters. The mass recovery of the magnetic concentration will depend on the feed contents. If there is any deviation that cannot be resolved through adjustments to the operating parameters, samples will be collected for technological characterization and pilot tests to identify the causes of the problem and propose solutions.

22.8. Environmental studies, permitting, and plans, negotiations, or agreements with local individuals or groups

The Serra Norte Complex has environmental controls and monitoring that aim to ensure or quickly identify possible operational deviations that could cause damage to the environment. The current production expansions did not require major expansions of controls and monitoring due to the robustness and adequacy of the controls and programs on the site.

Mining close to the most restricted conditions such as caves have specific programs and monitoring that aim to ensure production without causing irreversible damage.

22.9. Capital costs estimate

Economic valuations consider in cash flows the sustaining CAPEX, necessary for the maintenance of existing assets / operations, and capital projects that aim to maintain and/or increase productive capacity. Sustaining CAPEX can be classified into routine and non-routine.

Routine refers to projects aimed at maintaining the operational capacity of assets, including acquisition and replacement of equipment and readjustment of operating structures. They are estimated based on a diagnosis made by the Engineering area on the asset base, on a maintenance backlog and on the investment target defined by the company for future years.

Non-routine refers to projects that support the business strategy, ensuring compliance with the production plan, but which do not occur frequently. Included in this list: expansion of pits, waste and tailings disposal projects, changes in processes and technologies in the plants, among others. They are estimated based on the expected needs of each operation or production complex over the evaluated horizon. Based on these needs, Vale's multidisciplinary teams estimate the values of the investments considered in the cash flows of the economic evaluations.

The sole purpose of the presented figures is to demonstrate the economic viability of the mineral reserve, therefore it can differ from other information Vale publishes and should not be considered as a guidance.

Additionally, economic assessments of reserves consider capital projects that aim to maintain and/or increase productive capacity. The overall capital cost estimate for LOM or evaluation period is US\$ 6,202 million.

22.10. Operating cost estimates

Operating costs and expenses are grouped as follows:

- Mine and plant Opex: mine and plant costs include mining, processing, storage, and shipping from the ore to the loading points.
- Logistics and distribution costs: logistics and distribution costs include railroad, ports, maritime freight, and distribution centers.
- Sales, R&D and pre-operational expenses: sales, R&D and pre-operational expenses are related to team expenses with sales and offices, expenses on research and development of solutions for projects and/or the maintenance of operations, and pre-operational expenses, when there are projects in implantation.

In summary, the mining Opex is designed considering as a reference, the costs of the operation or similar operations in previous years and their respective operational indicators. Thus, future operational indicators of operations are estimated, based on long-term mine planning. In this way, the estimated costs are projected considering the future changes in the operational indicators of the operations.

- LOM average unit operating cost and expenses;
- Mine and plant: 11.0 US\$/ton of product;
- Logistics and Distribution: 19.3 US\$/ton of product;
- Royalties: 2.5 US\$/ton of product;
- Sales expenses, R&D, others: 0.1 US\$/ton of product;
- Total average unit operating costs and expenses: 33.0 US\$/ton of product;
- The overall costs and expenses estimate for the LOM or evaluation period is US\$ 51,872 million.

22.11. Economic analysis

The aim of the economic evaluation presented in this chapter is to demonstrate the economic viability of the mineral reserve, therefore the production rates, operating efficiencies, costs and expenditures, taxes and other information presented can differ from other information we publish and should not be considered as a guidance. Note that our planned production extraction may vary due to continuous mineral exploration and technical studies to add new mineral reserves.

The economic analysis confirmed that Serra Norte are economically viable. The after-tax NPV at a 7.5% discount rate and following a mid-year convention is US\$ 26,215 million.

For this cash flow analysis, the internal rate of return (IRR) and payback are not applicable as there is no negative initial cash flow (no initial investment to be recovered).

Project risks can be identified in both economic and non-economic terms. Key economic risks were examined by running cash flow sensitivities on after-tax NPV at an 7.5% discount rate. The following items were examined: Price and VIU; OPEX mine, plant and logistics and distribution; Exchange rate; and Total CAPEX.

22.12. Risks and opportunities

22.12.1. Mineral resource estimates

Factors that may affect the mineral resource and mineral reserve estimates were identified in Chapter 11 and Chapter 12, respectively.

Other risks noted include:

- In 2008, a federal decree established a criteria for classification of caves based on their relevance (maximum, high, medium or low). This decree prohibits irreversible negative impacts in maximum relevance caves and, however, it allows impacts on the other caves

categories, following proper environmental permit and/or compensation. A regulation defined a 250 meters buffer as the default area of influence to be preserved around caves. Environmental studies can be submitted to the federal environment regulator to re-evaluate and better define the area of influence, allowing its reduction. Specifically for some maximum relevance caves, the Serra Norte mineral reserve estimation considered a 150 meters buffer for their protection, but, in the case of mineral resources, no constraints was considered. The request for alterations on protective influence area needs to be assessed and approved by the Brazilian federal environmental regulators and, depending on the decision, it can have positive or negative impacts on mineral reserves and resources disclosed. In January 2022, a new federal decree was enacted, revoking the regulation of 1990 and its subsequent amendments and establishing new rules for the protection of caves, including with respect to relevance classifications and forms of compensation, and the impact of it on our operations is under review. This 2022 decree, however, is currently being challenged in the STF by a political party on the grounds that such regulation is unconstitutional since it allegedly reduces the legal protection of caves and it has been temporarily suspended until further decision of the court.

- The Carajás National Forest (FLONA Carajás) was created in 1998 as a conservation unit in which the management of natural resources is allowed. FLONA Carajás has an environmental Management Plan, which defines a land zoning, encompassing the “Mining Zone” category. The Management Plan has legal provision to be reviewed and the last revision was in 2016. A portion of Serra Norte deposit is outside the Mining Zone and depends on the modification of this status to allow mining activities. We have a reasonable expectation that the Management Plan will be revised, depending on the assessment and approval of Brazilian federal environment institutes. If our petition is denied (or partially approved), a portion of the mineral reserves and resources will be affected.
- Geotechnical and hydrological assumptions used in mine planning are based on historical performance, and to date historical performance has been a reasonable predictor of current conditions. As the pit trends deeper; however, additional geotechnical and hydrological data collection is warranted. Any changes to the geotechnical and hydrological assumptions could affect mine planning, affect capital cost estimates if any major rehabilitation is required due to a geotechnical or hydrological event, affect operating costs due to mitigation measures that may need to be imposed, and impact the economic analysis that supports the mineral reserve estimates;

Opportunities include:

- The mineralization of Serra Norte deposits remains open at depth under the current open pit outline. Additional exploration evaluation is warranted;
- Potential conversion of the measured and indicated mineral resources reported exclusive of mineral reserves, with supporting studies, to mineral reserves;
- Potential conversion of inferred mineral resources, with supporting studies, to higher confidence mineral resource classifications;

22.12.2. Mineral reserves statement

In addition to the risks associated with prices, costs, process, commodity price volatility, as already mentioned in chapters 11 and 12, release of radius reductions in caves of maximum relevance around the pits (N1, N3, N4 and N5), in the necessary time, among other environmental licenses that are beyond our effective control, are considered risks.

As an opportunity, we have the cost reduction with the implementation of the Trolley project and the use of autonomous trucks. We also have high potential to increase the reserve if the suppression of the most relevant caves adjacent to the pits, currently treated as blockages in the areas where they are, were released.

23. Recommendations

If applicable, the qualified person must describe the recommendations for additional work with associated costs. If the additional work program is divided into phases, the costs for each phase must be provided along with decision points at the end of each phase.

23.1. Property description

It is recommended to proceed with ANM to issue the report on mining easements under approval.

23.2. Geology and mineralization

It is recommended to keep the routine works of geological data collection with mappings, sampling, and developing drilling campaigns (short and long terms), to keep improving the knowledge of the high-grade ores, structural and stratigraphy.

Further work is required to determine the exploration potential below the current open-pit operations and not operated plateaus. The exploration targets are mainly associated with the outcrops of structured cangas, friable hematites and jaspilites, or geophysical anomalies.

23.3. Hydrogeological and geotechnical

Regarding to the geotechnical and hydrogeological considerations, it is recommended to develop an effective Ground Control Management Plan, a complete Quality Assurance and Quality Control Program, and promote continuous increase in database improvement (drillholes and testing) to reduce the identified database backlog and provide information from new areas. This will provide a robust basis for geotechnical and hydrogeological evaluation, modelling and mitigation measures.

To achieve the maturity level of the geotechnical and hydrogeological studies of the mines throughout the project life cycle, it is necessary to refine the hydro and geotechnical database, models, and monitoring programs continuously.

23.4. Mineral resource statement

The continuity of geological drilling annual plans to better assess the geology in depth increasing the geological knowledge and the confidence to convert inferred and indicated classes to indicated and measured categories.

23.5. Mineral reserves and mining methods

The mining dilution and recovery rates used in the reserve estimates can be more assertive. For this, Vale should plan drilling to improve geological interpretation and grade estimation and improve the reconciliation process by deploying more samplers that can improve the assertiveness of the dilution and loss assumptions that support the reserves statement.

Search for new technologies to minimize the need for lining, especially in the waste dumps and in the mining fronts that have a floor under soft material (mainly decomposed mafic).

23.6. Processing and recovery methods

Verification of existing process controls to identify opportunities, bottlenecks and/or improvements for process optimization, especially in the rainy season when processing productivity is lower.

QP's opinion: The process route for processing the Serra Norte material is highly reliable because it involves traditional beneficiation equipment where Vale has extensive experience in this type of process. Through this route, it can generate high volume of production with satisfactory quality.

23.7. Environmental studies, permitting, and plans, negotiations, or agreements with local individuals or groups

Continue monitoring and environmental programs that ensure the mitigation of environmental impacts arising from operations.

In the context of the Serra Norte complex, it is important to continue the discussions started with the management body of the Conservation Units to develop studies and inform the decision to change the zoning of the management plan to enable the expansion of the mining zone that currently prevents mining expansion.

23.8. Costs and economics

Maintain the focus on the discipline of capital allocation and the elimination of possible inefficiencies, to guarantee, with operational safety, cost competitiveness, and consequently, healthy margins and balance sheets in any price scenario.

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25. Reliance on information provided by the registrant

25.1. Introduction

QPs fully relied on the registrant for the information used in the areas noted in the following sub-sections. QPs consider it reasonable to rely on the registrant for the information identified in those sub-sections, for the following reasons:

- The registrant has been owner and operator of the mining operations since 1984;
- The registrant has employed industry professionals with expertise in the areas listed in the following sub-sections;
- The registrant has a formal system of oversight and governance over these activities, including a layered responsibility for review and approval;
- The registrant has considerable experience in each of these areas.

25.2. Macroeconomic Trends

Information relating to inflation, interest rates, discount rates, and taxes was obtained from the registrant.

This information is used in the economic analysis in Chapter 19. It supports the assessment of reasonable prospects for economic extraction of the mineral resource estimates in Chapter 11, and inputs to the determination of economic viability of the mineral reserve estimates in Chapter 12.

25.3. Markets

Information relating to market studies/markets for product, market entry strategies, marketing and sales contracts, product valuation, product specifications, refining and treatment charges, transportation costs, agency relationships, material contracts (e.g., mining, concentrating, smelting, refining, transportation, handling, hedging arrangements, and forward sales contracts), and contract status (in place, renewals), was obtained from the registrant.

This information is used in the economic analysis in Chapter 19. It supports the assessment of reasonable prospects for economic extraction of the mineral resource estimates in Chapter 11, and inputs to the determination of economic viability of the mineral reserve estimates in Chapter 12.

25.4. Legal Matters

Information relating to the corporate ownership interest, royalties, encumbrances, easements and rights-of-way, violations and fines.

This information is used in support of the property description and ownership information in Chapter 3, the permitting and mine closure descriptions in Chapter 17, and the economic analysis in Chapter 19. It supports the reasonable prospects of economic extraction for the mineral resource estimates in Chapter 11, and the assumptions used in demonstrating economic viability of the mineral reserve estimates in Chapter 12.

25.5. Environmental Matters

Information relating to baseline and supporting studies for environmental permitting, environmental permitting and monitoring requirements, ability to maintain and renew permits, emissions controls, closure planning, closure and reclamation bonding and bonding requirements, sustainability accommodations, and monitoring for and compliance with requirements relating to protected areas and protected species was obtained from the registrant.

This information is used when discussing property ownership information in Chapter 3, the permitting and closure discussions in Chapter 17, and the economic analysis in Chapter 19. It supports the

reasonable prospects of economic extraction for the mineral resource estimates in Chapter 11, and the assumptions used in demonstrating economic viability of the mineral reserve estimates in Chapter 12.

25.6. Stakeholder Accommodations

Information relating to social and stakeholder baseline and supporting studies, hiring and training policies for workforce from local communities, partnerships with stakeholders (including national, regional, and state mining associations; trade organizations; fishing organizations; state and local chambers of commerce; economic development organizations; non-government organizations; and state and federal governments), and the community relations plan was obtained from the registrant.

This information is used in the social and community discussions in Chapter 17, and the economic analysis in Chapter 19. It supports the reasonable prospects of economic extraction for the mineral resource estimates in Chapter 11, and the assumptions used in demonstrating economic viability of the mineral reserve estimates in Chapter 12.

25.7. Governmental Factors

Information relating to taxation and royalty considerations at the Project level, monitoring requirements and monitoring frequency, bonding requirements, violations and fines was obtained from the registrant.

This information is used in the discussion on royalties and property encumbrances in Chapter 3, the monitoring, permitting and closure discussions in Chapter 17, and the economic analysis in Chapter 19. It supports the reasonable prospects of economic extraction for the mineral resource estimates in Chapter 11, and the assumptions used in demonstrating economic viability of the mineral reserve estimates in Chapter 12.

