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Integrated Geostatistical–Geotechnical Modelling and Mining Method Assessment of the Tala Hamza Zn–Pb Deposit, Northern Algeria

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Abstract

The Tala Hamza zinc–lead deposit, located in the Amizour region south of Béjaïa (Northern Algeria), is one of the largest base-metal resources in the Maghreb. This study presents an integrated geological, geostatistical, and geotechnical assessment to improve resource estimation and optimise the mining strategy. Geostatistical analyses of drilling data revealed moderate to strong spatial continuity of zinc and lead grades, with variogram ranges of 120–200 m along the main structural trends. Ordinary Kriging and conditional simulations produced three-dimensional grade and uncertainty models, confirming anisotropy consistent with the tectonic framework and identifying higher uncertainty near fault zones. These results were integrated with geotechnical investigations and FLAC3D numerical modelling to validate the Descending Backfilled Chamber (DBC) mining method. The DBC approach, combined with cemented backfilling, ensures mechanical stability, limits dilution, and maximises ore recovery. This multidisciplinary framework demonstrates the effectiveness of coupling geostatistical and geotechnical modelling for reliable resource evaluation and sustainable mine design, providing a reference for similar base-metal deposits in Algeria and beyond.

Keywords: mining exploration; tala hamza; zn-pb; geostatistical–geotechnical modelling; downward backfill chamber (dbc); mineral resources; Algeria

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1. Introduction

Zinc and lead are two strategic metals essential to numerous industrial sectors, including galvanisation, alloy production, battery manufacturing, and various metallurgical processes. The sustained global demand for these metals continues to drive exploration and development efforts for new deposits across the world (Amiri et al., 2016; Bouabdellah & Large, 2011; Itard & Bouladon, 1986).

In Algeria, several base-metal deposits have been identified, yet the Tala Hamza deposit, located in the Amizour region south of Béjaïa, stands out for its size, grade, and strategic importance. It is now recognised as one of the largest zinc–lead deposits in the Mediterranean region. Despite its potential, the complex geological setting and mechanical behaviour of the host formations necessitate a multidisciplinary approach that combines geological, geotechnical, and geostatistical analyses to support safe and efficient resource exploitation (Aouzellag, 2000; Terramin Australia Ltd., 2020).

The present study aims to provide a comprehensive scientific evaluation of the Tala Hamza deposit through the integration of geological, geostatistical, geotechnical, and mining assessments.

Geostatistical modelling was carried out to characterise the spatial variability of zinc and lead grades, quantify anisotropy, and evaluate the uncertainty associated with grade estimation. These spatial models were subsequently combined with geotechnical and numerical simulations to optimise the design and validation of the mining method. The Descending Backfilled Chamber (DBC) method was then selected as the most suitable extraction technique, ensuring ore recovery, mechanical stability, and reduced environmental impact.

Accordingly, the study focuses on the following aspects:

- The regional and local geology of the Tala Hamza deposit;
- The results of drilling and estimation of mineral resources through geostatistical modelling;
- The geotechnical characterisation of the rock mass and numerical modelling using FLAC3D;
- The selection and validation of the most appropriate mining method;

The metallurgical performance and environmental considerations associated with cemented backfilling (Guiraud and Bosworth.,1999; Souhassou et al., 2019). This integrated approach contributes to advancing the understanding of zinc and lead deposits in North Africa and provides a methodological framework for evaluating and developing complex polymetallic deposits under similar geological and geotechnical conditions. It also demonstrates the importance of coupling geostatistical and geotechnical modelling for modern mine design and sustainable resource management in Algeria and beyond.

2. Study Area

The Tala Hamza deposit is located approximately 15 km south-west of the city of Bejaia, in the municipality of Amizour (Bejaia province, north-east Algeria). The study area is accessible by paved road and is located near the port facilities of Bejaia, facilitating the transport of mining materials and products.

2.1. Location of the Mining Deposit

The exact location of the deposit is shown in Figure 1, which shows the position of the mining site in relation to the city of Bejaia and the main transport infrastructure. The study area covers rugged terrain with relatively steep slopes, which influences the design of access routes and mining facilities.

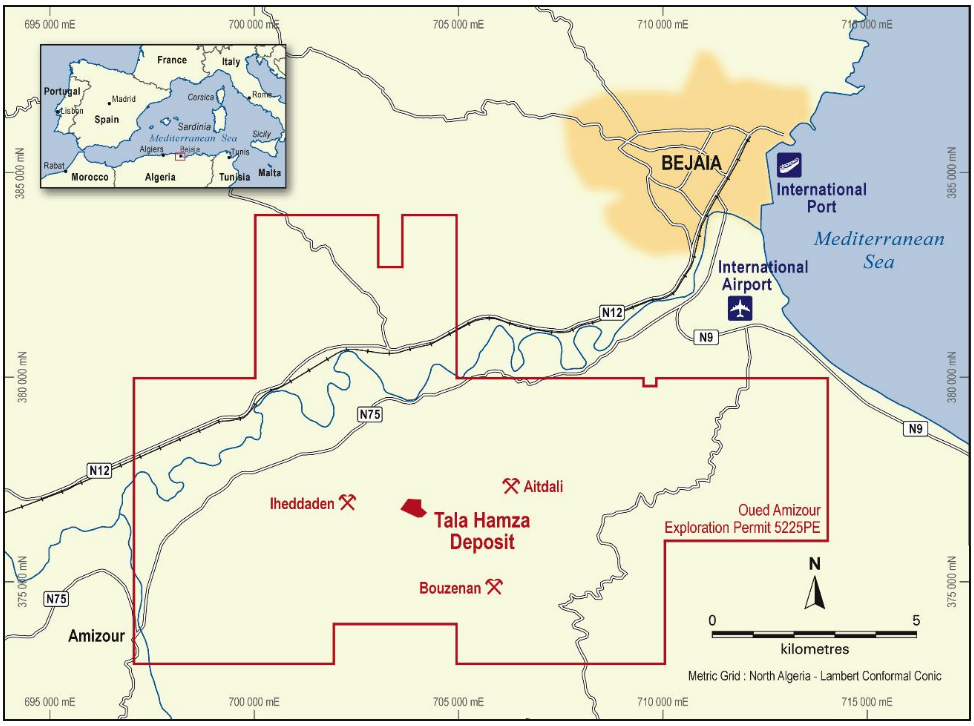

Figure 1. Geographical location of the Tala Hamza-Oued Amizour deposit in the wilaya of Bejaia.

2.2. Geology and Structural Position of the Deposit

The Tala Hamza deposit is located in the internal Tellian domain, characterised by complex geology resulting from Alpine orogenesis. The regional stratigraphy mainly comprises Mesozoic and Cenozoic sedimentary series affected by compressive tectonic structures.

The deposit is enclosed in carbonate and detrital formations affected by folds and faults, which largely control the mineralisation. The mineralisation consists mainly of sphalerite (ZnS) and galena (PbS), accompanied by accessory minerals such as pyrite and calcite. The spatial distribution of the mineralisation is complex, controlled by tectonic structures that give the deposit an irregular geometry. The deposit is still open and there is excellent potential to extend the resource well beyond this. Mineralisation within this resource is divided into five domains (Figure 2) with boundaries defined either by interpreted fault limits or by a nominal 1% Pb + Zn cut-off.

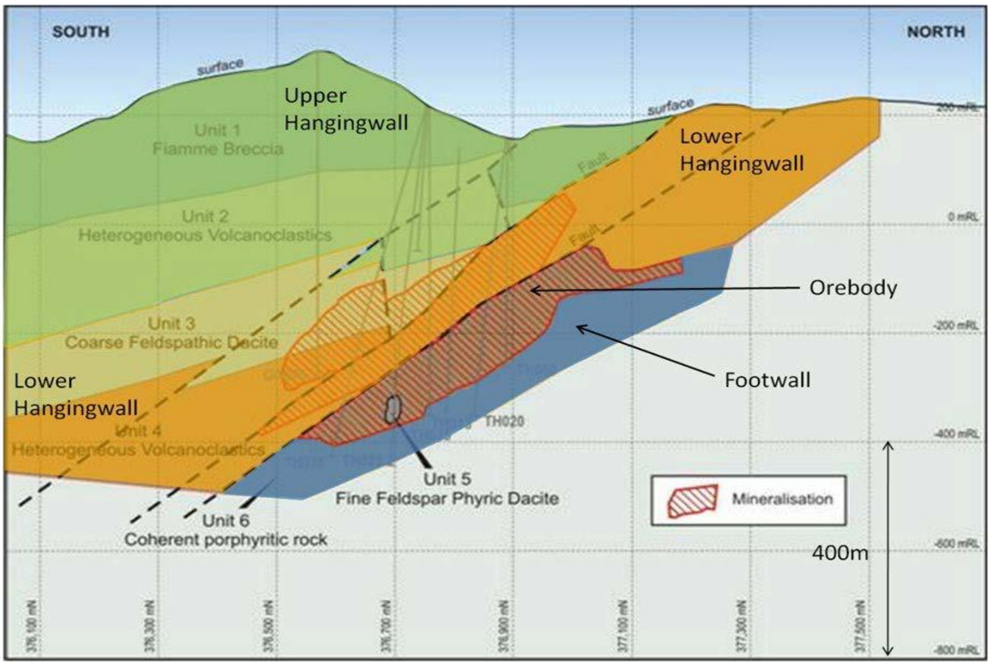

Figure 2. Regional geological context (Northern Algerian Tell) showing the structural position of the deposit. [Dark green: Unit 1 (Fiamme Breccia), Light green: Unit 2 (Heterogeneous volcaniclastic), Yellow: Unit 3 (Coarse feldspathic dacite), Orange: Unit 4 (Heterogeneous volcaniclastic), Grey: Unit 5 (Fine feldspathic dacite), Blue: Unit 6 (Coherent porphyritic rock)].

2.3. Mineral Resources

The identified mineral resources are summarised in Table 1, which presents tonnages and zinc and lead grades according to the different classification categories (measured, indicated and inferred).

Table 1. Mineral resources for a 3% zinc cut-off grade.

Table Category	Mt	Zn (%)	Pb (%)
Measured	-	-	-
Indicated	44.2	5.54	1.44
Measured + Indicated	**44.2**	**5.54**	**1.44**
Presumed	8.9	4	0.7
Total resources	**53**	**5.3**	**1.3**

The depth distribution of mineralisation is illustrated in Figure 3, showing the vertical variability of grades. The Tala Hamza deposit is located in volcanic and volcano-sedimentary rocks and occurs

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as a thick accumulation of Pb-Zn mineralisation measuring 800 m x 600 m and up to 250 m thick. The resource model was prepared by Terramin and validated by Golder using a number of approaches, including visual methods, statistical controls, indicator kriging and conditional simulation.

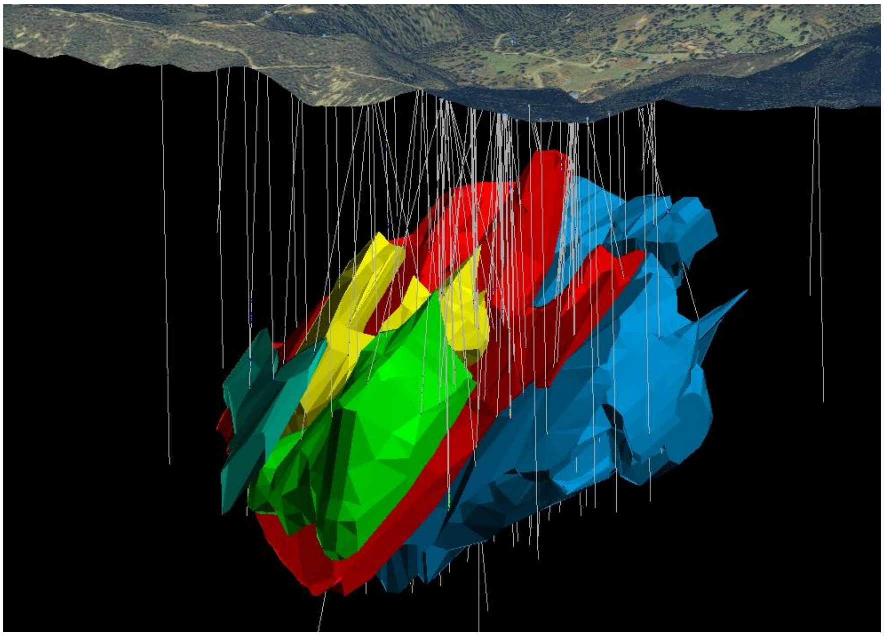

Figure 3. 3D geological model of the deposit, showing the Zn-Pb mineralised bodies.

3. Data And Methods

3.1. Drilling Data And Geological Basis

The Tala Hamza–Oued Amizour zinc-lead deposit has been the subject of several successive drilling campaigns, initially carried out by ORGM and then taken over and completed by Western Mediterranean Zinc (WMZ). This work has made it possible to build up a solid geological and geochemical database, incorporating stratigraphy and lithology as well as the spatial distribution of mineralised zones (Cai et al., 2004; Hoek & Brown, 1997; Li et al., 2017; Stacey, 2001; Wesseloo & Potvin, 2010).

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Table 2 presents a summary of the mineral resource estimates resulting from this work. It shows that the indicated resource amounts to nearly 44 Mt with average grades of 5.54% Zn and 1.44% Pb, while the inferred resource is estimated at approximately 8.9 Mt. The total identified resources thus amount to more than 53 Mt, confirming the importance of the deposit on a regional scale. The mineable portion of the material is estimated at approximately 34 Mt, with grades slightly above the overall average (5.66% Zn and 1.54% Pb). In addition, internal and external waste volumes remain limited, indicating good economic and technical potential for mining.

Table 2. Results of Waste from internal and external sources.

Category	Mt	Zn %	Pb %
	Categories of resources		
Indicated resource	44.17	5.54	1.44
Inferred resource	8.9	4	0.7
Total resources	**53.02**	**5.3**	**1.3**
	Materials used		

Indicated	34.24	5.6	1.5
Dilution (Inf)	0.02	5	1.5
Materials used	**34.26**	**5.66**	**1.54**
Waste from internal and external sources			
Indicated (from the resource)	0.26	1.88	0.36
Ind + Inf from outside the resource	0.16	0.22	0.05
Total waste	**0.42**	**1.25**	**0.24**
Total extracted materials	**34.7**	**5.44**	**1.48**
Unused materials			
Total remaining	**9.47**	**3.66**	**1.11**

Figure 4 illustrates the spatial distribution of mineralised areas based on all the boreholes drilled. It highlights the irregular geometry of the mineralised bodies, which is directly controlled by regional tectonic structures. This map allows us to visualise the lateral continuity of high-grade zones and to identify the areas most favourable for mining.

By combining the quantitative data in Table 2 with the spatial representation in Figure 4, it is clear that the Tala Hamza–Oued Amizour deposit has both significant mineral potential and a complex structural organisation, requiring detailed 3D modelling to optimise mining planning.

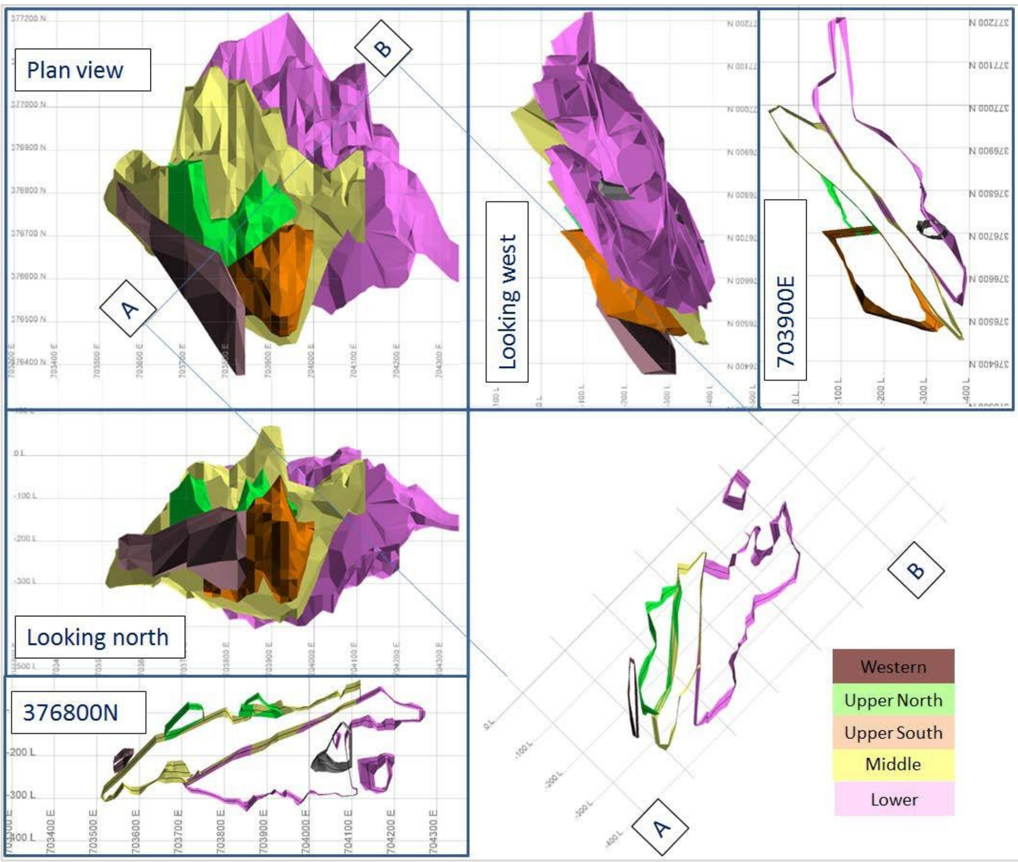

Figure 4. Plan view of the mineralised areas of the Tala Hamza deposit.

3.2. Geological Modelling and Resource Estimation

The geotechnical assessment of the deposit made it possible to characterise the quality of the various lithological and mineralised units using several classification systems, including the Q-System, **RMR** (Rock Mass Rating) and MRMR (Modified Rock Mass Rating). These classifications provide an integrated view of the mechanical condition of the rock mass and are an essential step in guiding mine design and the choice of mining method.

Table 3 summarises the results obtained. It can be seen that rock quality varies greatly depending on the area: andesites and lower eponte rocks generally have good mechanical properties, while fault

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zones and mineralised bodies are characterised by significantly poorer properties, ranging from 'very poor' to 'average'. This heterogeneity reflects a complex geotechnical context, where the stability of excavations will depend largely on the presence of tectonic structures and the nature of the ore.

These results confirm the need for reinforced support and an appropriate mining method capable of managing both competent rock areas and those characterised by low mechanical strength.

Table 3. Classification of rock mass based on geotechnical study.

Geotechnical field	Q	RMR	MRMR
Upper part of the roof	Average to very good rock	Average to good rock, areas of poor rock in the north	Average to good rock, areas of poor rock in the north
Lower part of the roof	Poor to good rock	Average to good rock, areas of poor rock in the north	Average to good rock, areas of poor rock in the north
Andesite	Good rock	Good rock	Average to good rock
Ore	Very poor to average	Poor to average	Very poor to poor
Lower roof	Good rock with areas of poor rock	Average to good rock	Average rock
Fault zones	Very poor to poor	Poor rock	Very poor to poor

3.3. Geotechnical Studies

Laboratory tests were carried out on representative samples to determine the main mechanical and hydromechanical properties of the surrounding rock, in particular unconfined compressive strength (UCS), bulk density and deformation parameters. These analyses were supplemented by in situ tests to assess the natural stress state and actual behaviour of the rock mass. Table 4 summarises the processing parameters: moderate rock strength (23 MPa) requiring appropriate support, good metallurgical yields (87.6% Zn, 68.5% Pb), rich concentrates, low tailings moisture content and a high proportion of cemented backfill, confirming technical feasibility and sustainability.

Table 4. Summary of processing design parameters with a design range.

Parameter	Unit	Design
Production	t/a	2,000,000
Nominal operating days per year	D	360
Operating hours per day	H	24
Crusher availability	%	80
Crushing hours per year	H	6,912
Crushing throughput	t/h	289
Flotation unit availability	%	95
Flotation unit operating hours per year	H	8000
Flotation unit throughput	t/h	250
Crushing		
Unconfined compressive strength (average)	MPa	23
Ball mill operating index (85th percentile)	kWh/t	14.3
Flotation		
Lead content	%	1.54
Zinc content	%	5.66
Lead recovery	%	68.5
Zinc recovery	%	87.6
Lead concentrate content – Pb	%	58
Zinc concentrate content – Zn	%	51
Dewatering		

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Settling rate – lead concentrate	t/m2h	0.25
Settling rate – zinc concentrate	t/m2h	0.25
Settling rate – tailings	t/m2h	0.6
Filtration		
Lead concentrate moisture content	%	11
Zinc concentrate moisture content	%	10
CSF dry stacking moisture content	%	18
Drying		
Lead concentrate moisture content range (TML)	%	10-Jun
Zinc concentrate moisture range (TML)	%	10-Jun
Residues		
Total residues from the CPB plant	%	60-80
Total residues from the CSF plant	%	40-100

3.4. Geostatistical Analysis of Ore Grades

Geostatistical methods were employed to characterise the spatial variability and continuity of zinc and lead mineralisation within the deposit. Drill-hole assay data were first declustered to reduce sampling bias and ensure representative statistical inputs. Directional variogram analyses were then conducted to quantify anisotropy in the grade distribution. Ordinary Kriging (OK) and Indicator Kriging (IK) were applied to interpolate grades and delineate mineralised domains using a 1% Pb + Zn cut-off. In addition, conditional simulations were performed to assess local uncertainty and support risk-based classification of resources. The resulting geostatistical models provided essential inputs for three-dimensional geological modelling and subsequent mine planning.

3.5. Selection of the Mining Method

Based on geological and geotechnical data, several mining scenarios were studied. The Descending Backfill Chamber (DBC) method with cemented backfill (CPB) was selected because it is well suited to the mechanical conditions of the deposit. The basic diagram of the DBC method is shown in Figure 5, illustrating the sequence of excavation, progressive backfilling and continuity of deep mining.

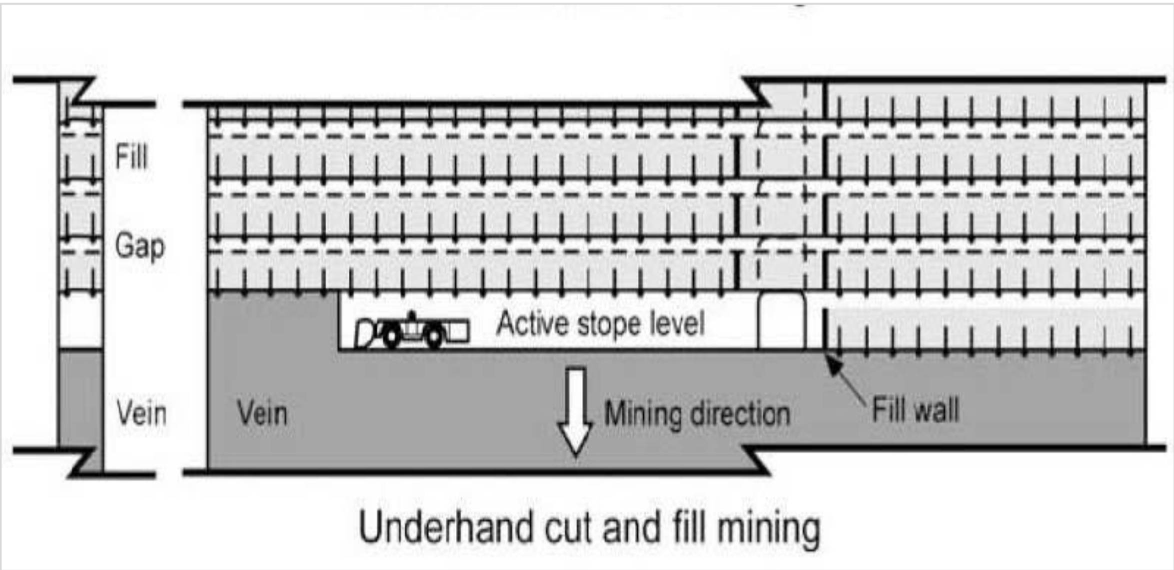

Figure 5. Technical diagram of the DBC mining method and backfilling sequence.

3.6. Metallurgical Tests and Treatment Processes

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Metallurgical tests were carried out to evaluate the performance of the flotation treatment. The tests focused on the recovery of zinc and lead from various composite samples representative of the deposit. A simplified diagram of the treatment circuit is shown in Figure 6.

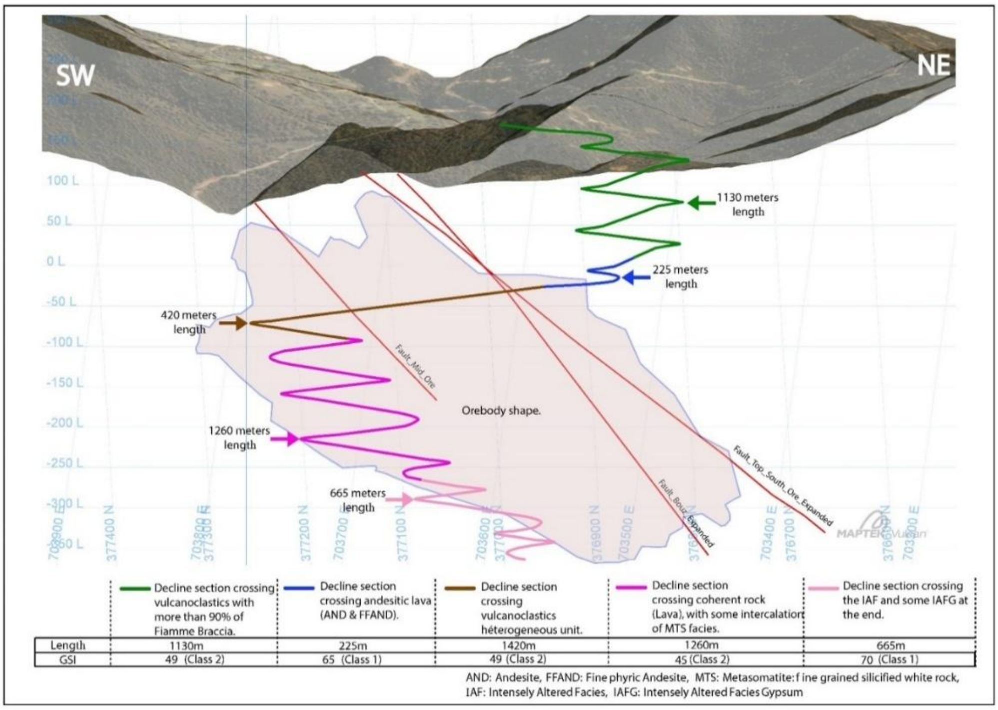

Figure 6. Plan of the main descent shaft and underground mining infrastructure.

4. Results and Discussion

4.1. Geology and Mineral Resources

Drilling and 3D modelling have clarified the spatial extent of zinc and lead mineralisation within the Tala Hamza–Oued Amizour deposit. Figure 7 shows an east-west section through the Dead Zone, highlighting the vertical and lateral distribution of grades. The red and purple coloured intervals correspond to high-grade areas identified along the drill holes. The mineralisation is dominated by sphalerite (ZnS) and galena (PbS), whose heterogeneous distribution is largely controlled by tectonic structures. Average grades are estimated at approximately 5.3% Zn and 1.3% Pb, confirming significant but locally irregular potential. Analysis of classified resources (measured, indicated and inferred) confirms that the richest zones are concentrated around the main structures, while certain portions of the deposit have lower values. This variability highlights the need for detailed geological modelling and appropriate mine planning to optimise ore recovery.

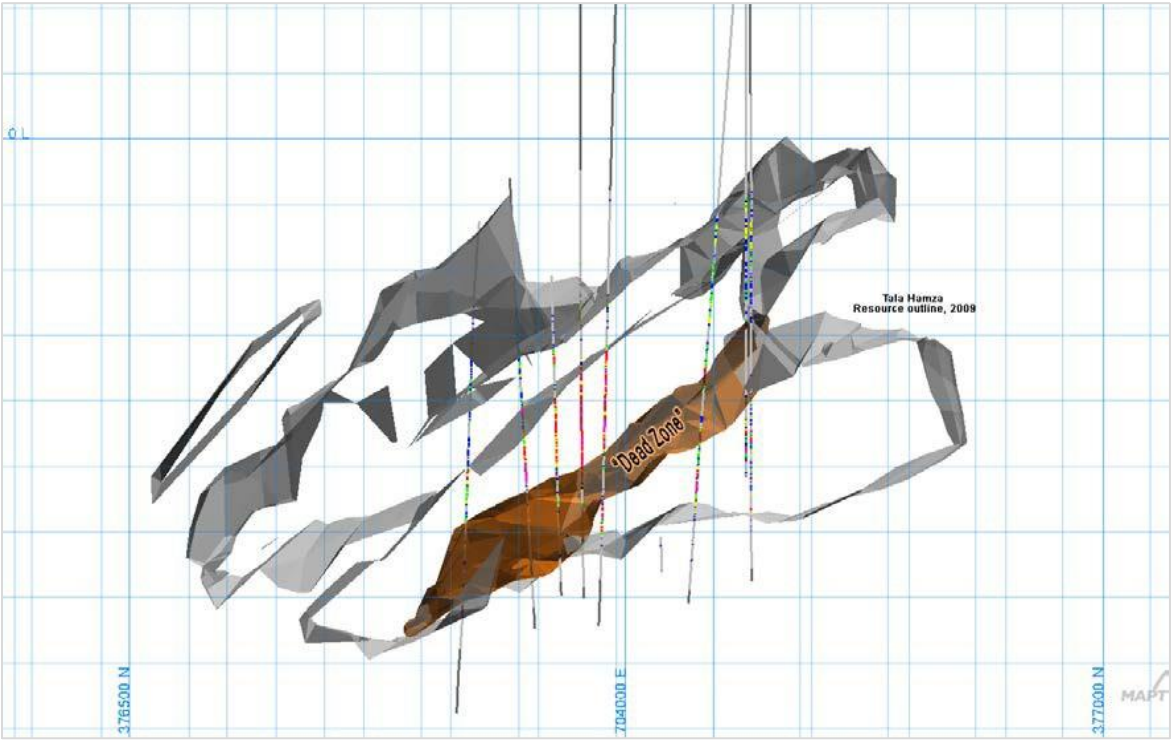

Figure 7. EO section through the Dead Zone. The red and purple intervals represent high grades along the drill holes.

4.2. Caractéristiques Géotechniques

Les essais de laboratoire ont mis en évidence une résistance relativement faible des roches encaissantes, nécessitant un soutènement adapté lors de l'exploitation. La classification des massifs rocheux selon les systèmes RMR et Q est présentée dans le Tableau 4. Ces résultats confirment que le massif se situe majoritairement dans les classes de qualité médiocre à moyenne. La modélisation numérique (FLAC3D) a permis d'évaluer les contraintes et déplacements prévisibles autour des excavations. La Figure 8 illustre les résultats de simulation, mettant en évidence les zones de concentration des contraintes. Ces résultats justifient le choix d'une méthode d'exploitation par chambres remblayées descendantes (DBC) permettant une meilleure stabilité.

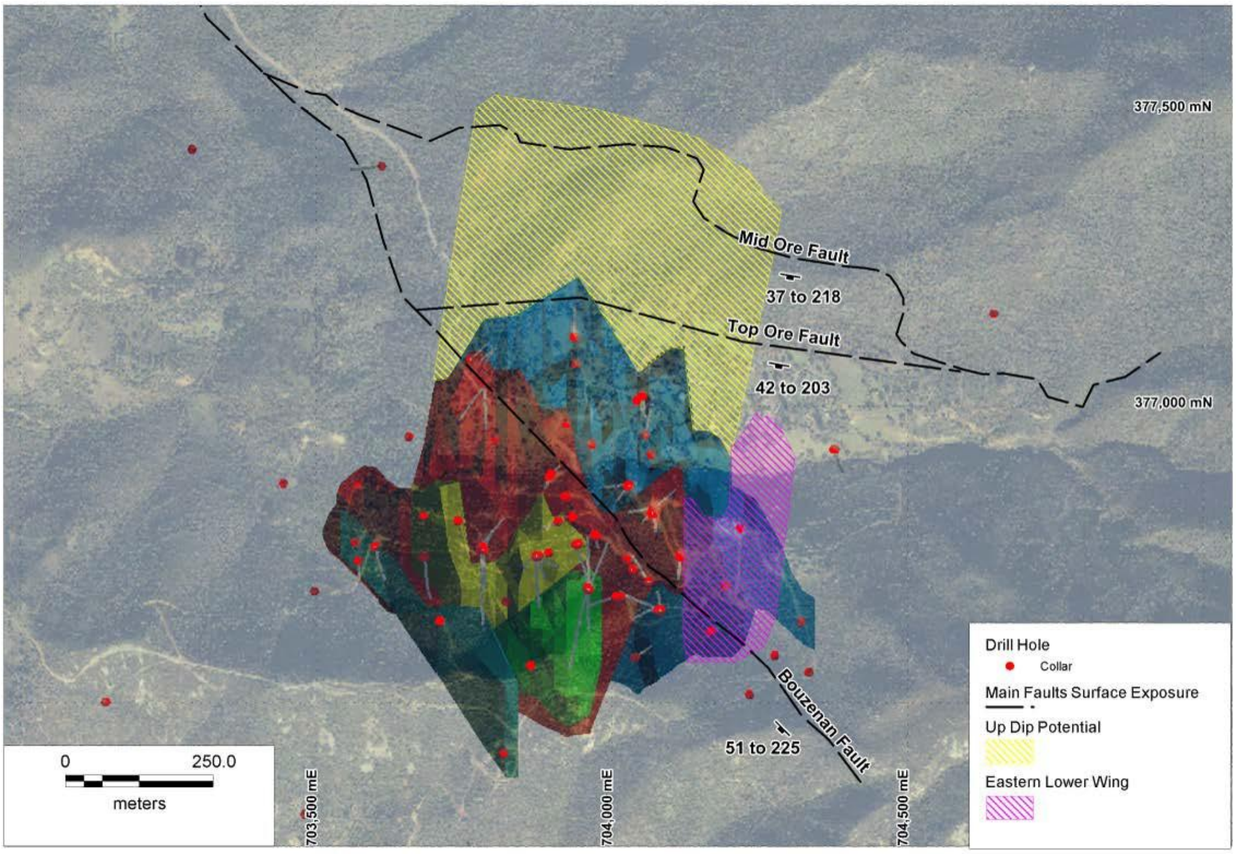

Figure 8. Potential for extension of the deposit towards the east and south-east.

4.3. Mining Method and Mine Design

The cemented backfill (CPB) DBC method was validated as the most appropriate. The main parameters of the mine design (chamber height, pillar thickness, anticipated dilution, ore recovery) are summarised in Table 5.

Table 5. Mine design parameters for the 2Mtpa DBC method.

Category	**Design parameters**
Location of mine entrance	Valley B
Length of transport shaft	4.11 km plus 2.12 km of truck ramps outside the descent tunnel.
Level of transport shaft	1 in 7
Dimensions of transport shaft (h x w)	5.5 mW x 5.7 mH fully arched, when projected, with 0.3 m concrete floor.
Total side opening (excluding ore chute)	33.11km
Total vertical opening	870m
Level of cross-access galleries	±1 in 50 to 1 in 7
Dimensions of transport galleries (w x h)	5.5m x 5.7m, fully arched
Stocks, ventilation shafts, substations, pumping stations, refuge chambers, drilling platforms	5.0m x 5.5mH, fully arched, except for stockpiles, which will be square, and sumps, which will be 4.0mW x 4.0mH
Level access galleries (flitches), branch galleries	5.0mW x 4.0-6.0mH, square profile
Truck loading, secondary fan stripping and truck tipping areas.	7.0mH
Ore tunnel level	1 in 100 to 1 in 200
Ore tunnel dimensions (h x w)	5.0 m x 5.0 m, square profile

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Total waste transport	2.65Mt
Total ore transport	33.98Mt
Number of sub-levels per level	4
Total backfill	19.7Mt

4.4. Integrated Geostatistical and Geotechnical Assessment of the DBC Mining Method

The mining method chosen, the Descending Backfilled Chamber (DBC), is particularly well-suited to the mechanical and spatial characteristics of the Tala Hamza Zn–Pb deposit. To optimise the selection and validate its geotechnical feasibility, both geostatistical and numerical modelling approaches were applied.

Geostatistical modelling results (Figure 9) reveal that zinc and lead grades exhibit moderate to strong spatial continuity, with variogram ranges between 120 and 200 m along the principal structural trends, and shorter ranges in transverse directions. The kriged grade maps clearly display anisotropy consistent with the tectonic framework, confirming the structural control of mineralisation. Conditional simulations further delineate areas of higher uncertainty — primarily along fault zones and peripheral sectors of the orebody — which represent priority targets for future infill drilling and risk reduction in mine planning. These outputs, derived from advanced geostatistical analysis, provide a high-resolution spatial understanding of grade distribution and uncertainty, forming a solid basis for geotechnical design and mining strategy. The integration of these geostatistical findings with **FLAC3D** numerical simulations (Figure 9) highlights the complementarity between geological variability and mechanical behaviour. The stress redistribution and deformation patterns around the excavations confirm that effective support and systematic backfilling are necessary to maintain stability under the DBC scheme. This method also limits dilution, maximises ore recovery, and mitigates geotechnical risks compared to alternative techniques such as longhole stoping or flash mining.

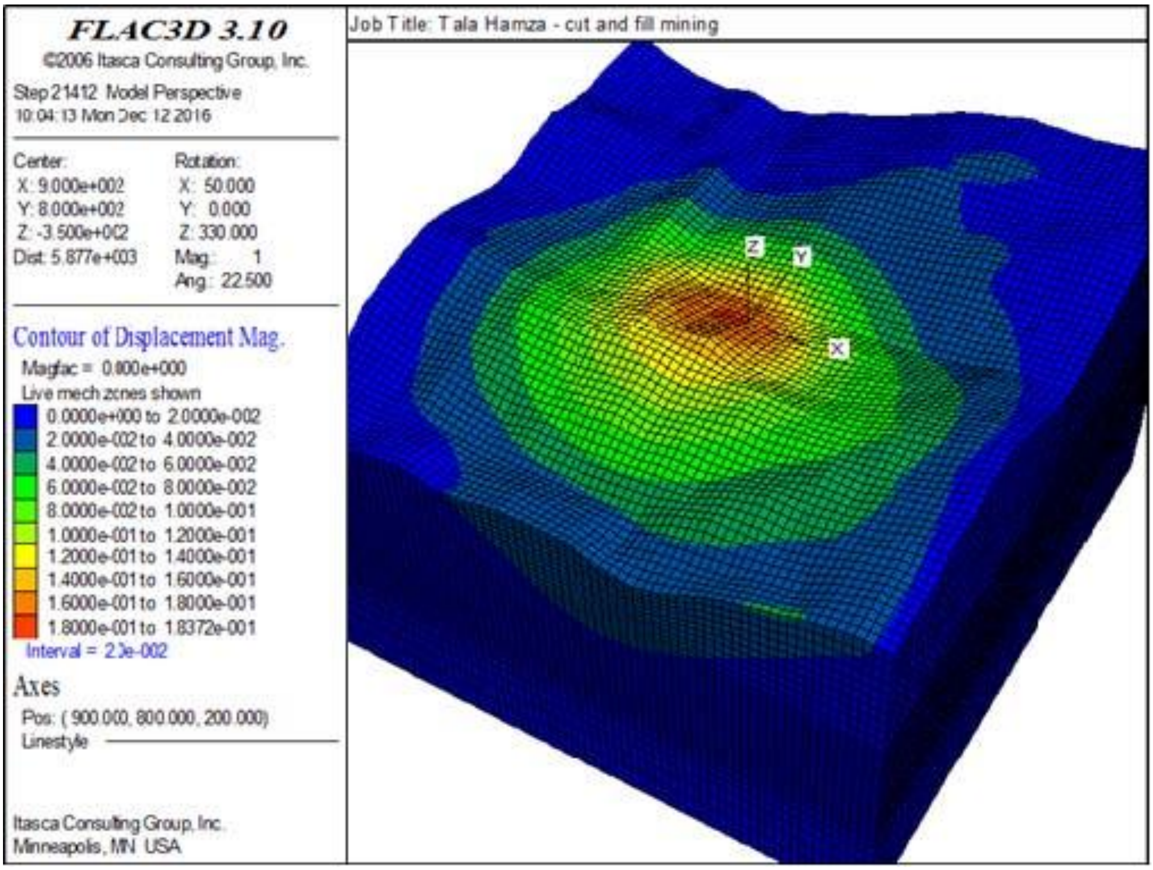

Figure 9. : FLAC3D modelling of potential surface subsidence using the DBC Mining method.

4.5. Technical Constraints and Challenges

Despite its potential, the exploitation of Tala Hamza-Oued Amizour presents several technical challenges. Lithological and structural variability complicates geological modelling and requires continuous geotechnical monitoring. In addition, the relatively moderate grade of the deposit requires optimisation of the metallurgical process in order to maximise zinc and lead recovery. Finally, local hydrogeological conditions, highlighted during field tests, require rigorous groundwater management to limit the risks of instability and flooding.

4.6. Geomatics Prospects for Exploration and Mining

The integration of remote sensing tools and geographic information systems (GIS) is a major prospect for complementing the geological, geotechnical and mining approach presented in this study. During the exploration phase, multispectral and hyperspectral images from sensors such as ASTER, Landsat 8 and Sentinel-2 can be used to detect hydrothermal alterations (clays, iron oxides, carbonates) associated with Zn-Pb mineralisation, which serve as a guide or metallotect for the detection of other mineralised bodies. This approach has been widely used around the world to guide mineral exploration and map favourable structures (Rajesh, 2004; Van der Meer et al., 2012; Chaabane et al., 2024).

GIS provides a powerful framework for integrating drilling data, geological observations and spectral anomalies to produce predictive maps of mineral potential. Previous work has demonstrated the effectiveness of combining geochemical, geophysical and remote sensing data in a GIS environment to optimise mineral exploration (Carranza, 2009; Lamine et al., 2018, 2019, 2024; Fernanda Da Silva Fuzzo et al., 2025).

During the exploitation phase, satellite interferometric radar techniques (InSAR, e.g. Sentinel-1) enable near real-time monitoring of ground deformation and, where applicable, subsidence induced by underground works (Herrera et al., 2013). This data, integrated into a GIS, reinforces geotechnical and environmental monitoring measures and contributes to safer and more sustainable operations.

Thus, combining geological and mining data, such as those presented in this study, with GIS and remote sensing tools opens up new perspectives, particularly for optimising the exploration of deposit extensions, improving geotechnical risk management and monitoring medium- and long-term environmental impacts.

6. Conclusions

The Tala Hamza zinc–lead deposit, located in the Amizour region (Bejaia, northern Algeria), represents one of the most significant base metal resources in the Maghreb. The results obtained from this integrated investigation provide a comprehensive understanding of its geological, geostatistical, geotechnical, and metallurgical characteristics.

Geologically, the deposit is composed mainly of sphalerite and galena mineralisation hosted within sedimentary formations affected by compressive tectonics. The resource inventory, exceeding several tens of millions of tonnes, displays average grades of approximately 5.3 % Zn and 1.3 % Pb. From a geostatistical perspective, spatial modelling of assay data revealed moderate to strong grade continuity, with variogram ranges of 120–200 m along the principal structural trends. Kriged grade maps confirmed the anisotropic distribution of mineralisation, consistent with the regional tectonic framework, while conditional simulations identified higher uncertainty along fault zones and deposit margins—areas that merit future infill drilling.

Geotechnical investigations, including laboratory testing and FLAC3D numerical simulations, indicated that the rock mass is of moderate to poor quality according to the RMR classification, requiring systematic support and backfilling. The integration of geostatistical results with geotechnical modelling validates the choice of the Descending Backfilled Chamber (DBC) mining method. This combined geostatistical–geotechnical assessment demonstrates that the DBC approach provides optimal conditions for maintaining stability, minimising dilution, and maximising ore recovery under the specific mechanical and spatial conditions of the Tala Hamza deposit.

From a processing standpoint, flotation tests confirmed high recovery rates exceeding 85 % for zinc and approximately 75 % for lead, confirming the technical feasibility of the beneficiation process. Cemented backfill and controlled surface storage of tailings contribute to both underground stability and the reduction of environmental impact. Furthermore, recent drilling campaigns to the east and southeast suggest the potential for resource expansion and improved confidence in the deposit's continuity.

Beyond these technical results, this study underscores the scientific and operational value of integrating geostatistical, geotechnical, and geomatics-based approaches in mineral resource evaluation. Future incorporation of remote sensing and GIS techniques will further enhance exploration targeting, geological modelling, and environmental monitoring. Collectively, these integrated methodologies provide a robust framework for sustainable and technically sound mining development at Tala Hamza and for similar deposits across Algeria.

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