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ORIGINAL ARTICLE

Generalized physical-geological modeling for polymetallic deposits in northwest of Pinar del Río province, Cuba

Modelo físico-geológico generalizado para depósitos polimetálicos del noroeste de la provincia de Pinar del Río, Cuba

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Abstract

The northwest of Pinar del Río province is a well-known mining region, rich in copper and polymetallic sulfides hosted in a sedimentary basin, basically represented by San Cayetano and Esperanza formations. It is difficult to substantiate the rational complex of geophysical methods for prospecting, since a physical-geological model of the entire northwestern area of the province is not available for these deposits, which is the reason this research was aimed at obtaining such a model. First, the geological modeling was elaborated based on previous models collected in the literature; likewise, to elaborate the petro physical modeling, physical properties contained in project reports were collected and processed. The corresponding physical fields were calculated and generalized physical-geological modeling for the entire study area was formed. The model managed to systematize the information scattered in different sources and to generate an identifying pattern for this type of deposits, as well as determining the rational complex of geophysical methods for prospecting.

Keywords: polymetallic deposit, geophysical methods, physical-geological model, geological model, petro physical modeling

Resumen

El noroeste de la provincia Pinar del Río es una conocida región minera, rica en sulfuros de cobre y polimetálicos hospedados en una cuenca sedimentaria, representada básicamente por las formaciones San Cayetano y Esperanza. Al no disponerse de un modelo físico-geológico de toda la zona noroeste de la provincia para estos depósitos, se dificulta la fundamentación del complejo racional de métodos geofísicos para la prospección, razón por la cual esta investigación tuvo el propósito de obtener tal modelo. Se elaboró primeramente el modelo geológico, a partir de modelos precedentes recogidos en la literatura; igualmente, para elaborar el modelo petrofísico, se recopilaron y procesaron las propiedades físicas contenidas en informes de proyectos. Se calcularon los campos físicos correspondientes y se conformó el modelo físico-geológico generalizado para toda la zona de estudio. El modelo consiguió sistematizar la información dispersa en distintas fuentes y generar un patrón identificativo para este tipo de depósitos, así como determinar el complejo racional de métodos geofísicos para la prospección.

Palabras clave: depósito polimetálico, métodos geofísicos, modelo físico-geológico, modelo geológico, modelo petrofísico

1. INTRODUCTION

The northwestern part of Pinar del Río Province is a well-known mining region, rich in copper and polymetallic sulfides hosted within a sedimentary basin, represented primarily by the San Cayetano and Esperanza formations.

The resources contained in the copper, lead, and zinc sulfide deposits and occurrences located northwest of the Alturas de Pizarras del Norte (Northern Slate Highlands) have not yet been sufficiently studied. This region comprises two metallogenic provinces: a Cu-Co province, represented by volcanogenic massive sulfide (VMS) deposits of the Besshi-type in the westernmost part, and a Zn-Pb-Cu province with SEDEX-type deposits in the eastern part. These correspond to the Juan Manuel-Hierro Mantua (Cu-Co) and the Santa Lucía-Matahambre and Dora-Francisco (Zn-Pb-Cu) mining districts (Figure 1).

The insufficient level of study of the aforementioned resources necessitates the creation of physical-geological models (PGMs). PGMs describe the nature of physical fields in the upper and lower half-spaces of geological objects of interest by integrating geological, petrophysical, and geophysical information. A PGM results from the integration of three sub-models: the geological model, the petrophysical model, and the geophysical model; the latter being the product of solving the forward problem for the assumed geological model, incorporating the data provided by the corresponding petrophysical model.

The development of a PGM optimizes and reduces the cost of geological exploration for polymetallic deposits, primarily because it achieves a representation very close to reality based on comprehensive bibliographic research and the calculation of physical fields.

The first PGM reported in Cuba for the polymetallic deposits in northwestern Pinar del Río Province dates back to 1982 (Díaz-Duque, 1982a) and was presented to researchers in this field during the First Scientific Conference of the University Center of the province (1982b). A limitation of this model is that it only covers a portion of the northwestern region of Pinar del Río Province.

The absence of a generalized PGM for the polymetallic deposits throughout the entire northwestern zone of Pinar del Río Province hinders the justification for a rational suite of geophysical methods for the exploration of this type of deposit. Therefore, the development of such a model constitutes the main objective of the present work.

2. MATERIALS AND METHODS

2.1. Description of the Study Area

The study area (Figure 1) is located in northwestern Pinar del Río, encompassing the municipalities of Guane, Mantua, Minas de Matahambre, Viñales, and La Palma. It covers a total area of 3,839.7 km², which includes the main orographic feature, the Guaniguanico mountain range, of which the Viñales Valley is a part.

In the western sector of the Mantua-Minas de Matahambre region (Figure 1), the Lower-Middle Jurassic San Cayetano Formation is primarily developed. The lithology of this formation consists mainly of black shales and lutites, together with quartzose and polymictic sandstones. The black shales are composed of hardened clays with a low grade of metamorphism; their dark color is due to a high content of organic carbon, and they contain fine disseminations of authigenic pyrite precipitated by sulfate-reducing bacteria in the mud. The sandstones are primarily composed of consolidated quartz sands deposited after transport. The territory is tectonically complex, characterized by thrust and imbricate folding with reverse faults, conditioned by Alpine tectonics (Carballo-Otero, 2021).

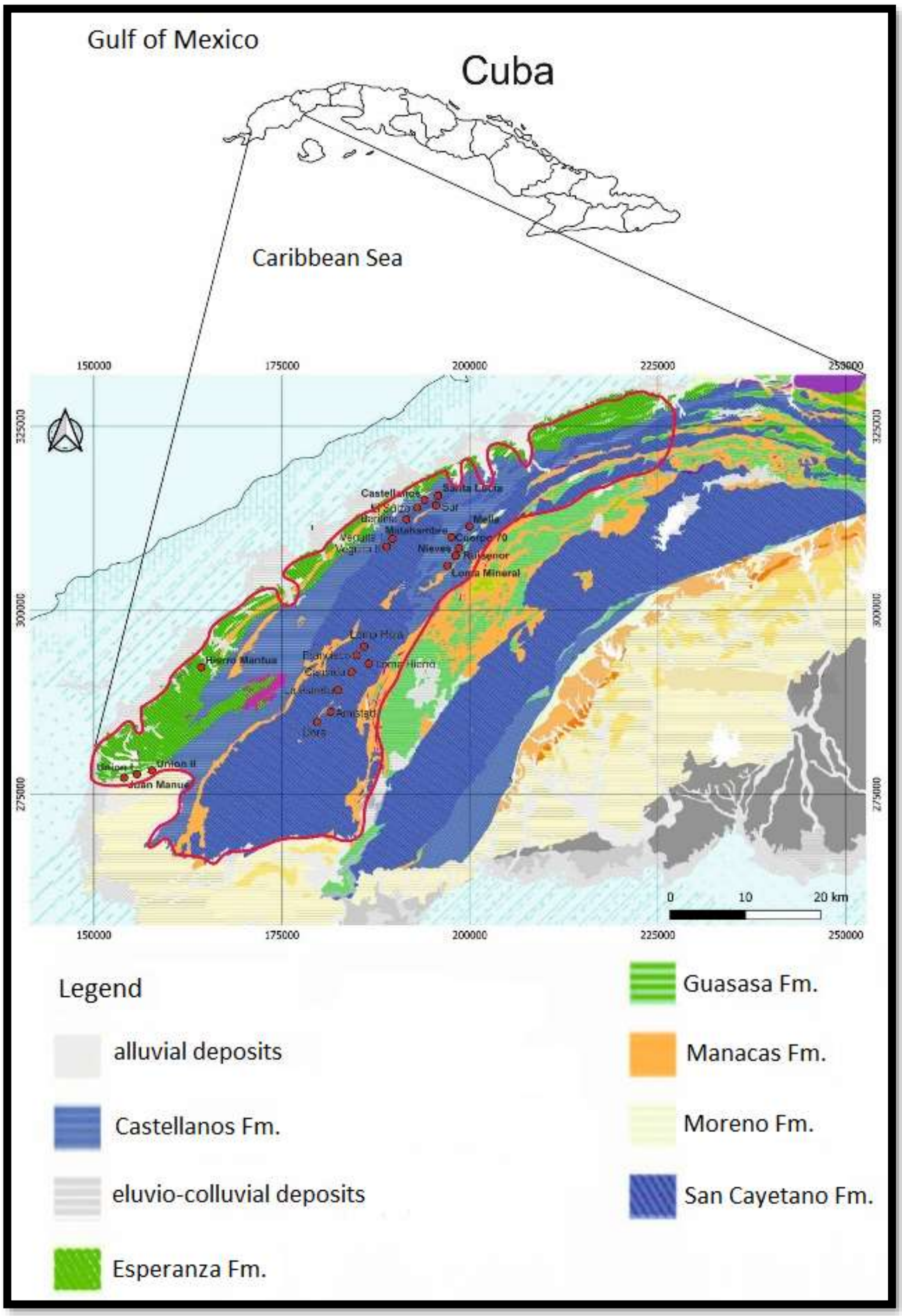

Figure 1. Location map showing the geological setting of Pinar del Río Province. The study area is outlined in red. The map also depicts the Zn-Cu-Pb and Cu-Co metallogenic provinces in the northwestern part of the province, showing the deposits of the three mining districts: Juan Manuel-Mantua in the southwest, Dora-Francisco in the center, and Santa Lucía-Matahambre in the northwest (modified from the geological map of Cuba, scale 1:100,000. IGP/SGC).

In the eastern sector (Viñales-La Palma), the area is predominantly underlain by sedimentary rocks, with subordinate igneous and metamorphic rocks.

Their age ranges from the Jurassic to the early-middle Eocene (Astajov et al., 1982).

Other significant formations identified within the study area include:

- **Castellanos Formation:** This formation occurs as elongated, folded bands within the tectonic units. It consists of interbedded carbonaceous argillaceous schists, siltstones, silty sandstones, and sandstones, with fine-grained rocks always predominating. It hosts SEDEX-type deposits.
- **Esperanza Formation:** Its stratigraphic column can be divided into two parts: a lower, carbonate-terrigenous sequence and an upper, terrigenous-carbonate sequence. Its age is Late Jurassic (Tithonian) to Early Cretaceous (Valanginian). This formation hosts Besshi-type volcanogenic massive sulfide (VMS) deposits.
- **Guasasa Formation:** Composed of massive, frequently laminated micritic limestones, sometimes dolomitized. Its age is Late Jurassic (Upper Oxfordian) to Early Cretaceous (Valanginian).
- **Manacas Formation:** Consists of polymictic sandstones, siltstones, argillites, calcarenites, cherts, limestones, and polymict, polycomponent chaotic deposits of terrigenous matrix, with intercalations of volcanomict sandstones and siliceous rocks. Its age ranges from the Early Eocene to the lower part of the Middle Eocene.
- **Moreno Formation:** The lower part of the section is composed of micritic and detrital limestones, ranging from sandy calcarenites to calcilutites, sometimes with gradational bedding. Terrigenous rocks are the predominant elements in the upper part. Age is Late Cretaceous (Santonian-Campanian).

The deposits of the Dora-Francisco and Santa Lucía-Matahambre metallogenic districts have been well-studied, and their genesis is considered to be of sedimentary-exhalative (SEDEX) type (Valdés-Nodarse, 1997; Lastra-Rivero, 2001; Pérez-Vázquez et al., 2017). This classification is confirmed by the integration of the region's geological characteristics, the mineralogical and geochemical features of the sulfide mineralization, the distribution of regional geochemical anomalies, and the inherent characteristics of the chemical composition, spatial distribution, and intensities of local geochemical anomalies. This evidence confirms the development of SEDEX-type deposits and demonstrates the unity of the processes that gave rise to the different mineral deposits (Pérez-Vázquez et al., 2015; Pérez-Vázquez et al., 2017).

Regarding the Juan Manuel-Mantua metallogenic district, some researchers (Cazañas et al., 2017; Torres-Zafra et al., 2017; Cobas-Torres and Torres-La

Rosa, 2023), based on structural particularities, mineralogical composition, spatial relationship with dolerite and gabbrodolerite bodies, as well as hydrothermal alteration processes in the surrounding rocks (silicification, propylitization with carbonatization, and to a lesser extent, chloritization and sericitization), descriptively classify it as a mafic-siliciclastic, Besshi-type volcanogenic massive sulfide (VMS) deposit.

2.2. Methodology

The research underpinning this work was conducted using the methodology proposed by Díaz-Duque (2022). This methodology is based on the integration of three informational sources to construct the PGM:

- Geological information about the object under investigation, in this case, the polymetallic deposits of northwestern Pinar del Río Province.
- Petrophysical information from the same object and its surrounding environment.
- Information on the expected behavior of potential geophysical fields that should be observed during the data acquisition stage.

These three sources are synthesized into three types of models, the integration of which constitutes the PGM for the polymetallic deposit.

Geological Model

To develop the geological model of the polymetallic deposits in northwestern Pinar del Río, the 1:100,000 geological map (Institute of Geology and Paleontology/Geological Survey of Cuba, IGP/SGC, 2017) was utilized, along with a body of geological and geophysical reports from the study area (Astajov et al., 1982; Pérez-Vázquez et al., 2017; Carballo-Otero, 2021). Furthermore, a generalization was made of the geological models previously presented by various authors (Díaz-Duque, 1982b; Pérez-Vázquez, 1998; Carballo-Otero, 2021), all pertaining to polymetallic deposits located in the northwestern zone of Pinar del Río Province.

Petrophysical Model

To obtain the petrophysical model for the polymetallic deposits of Pinar del Río Province, and in light of the scarcity of sufficient petrophysical studies on the specific object of study, the Principle of Analogy was applied. Data from investigations by several authors conducted in the study area were generalized (Sedov et al., 1971; Díaz-Duque, 1982a; Carballo-Otero, 2021; Fuentes, 2021). The physical properties considered were: density, magnetic susceptibility, electrical chargeability, electrical resistivity, and gamma-ray intensity.

Geophysical Model

Based on the generalized geological and petrophysical models, the mathematical determination of the behavior of the physical fields related to the properties exhibiting the greatest contrast was carried out, leading to the derivation of the geophysical model. For this purpose, the software systems Oasis Montaj (for density and magnetic susceptibility data) and Res2DMod (for electrical resistivity and chargeability data) were used.

3. RESULTS AND DISCUSSION

The geological model (Figure 2) is represented by a geometric schematic that adheres to the essential geological characteristics, with the aim of facilitating the solution of the forward problem.

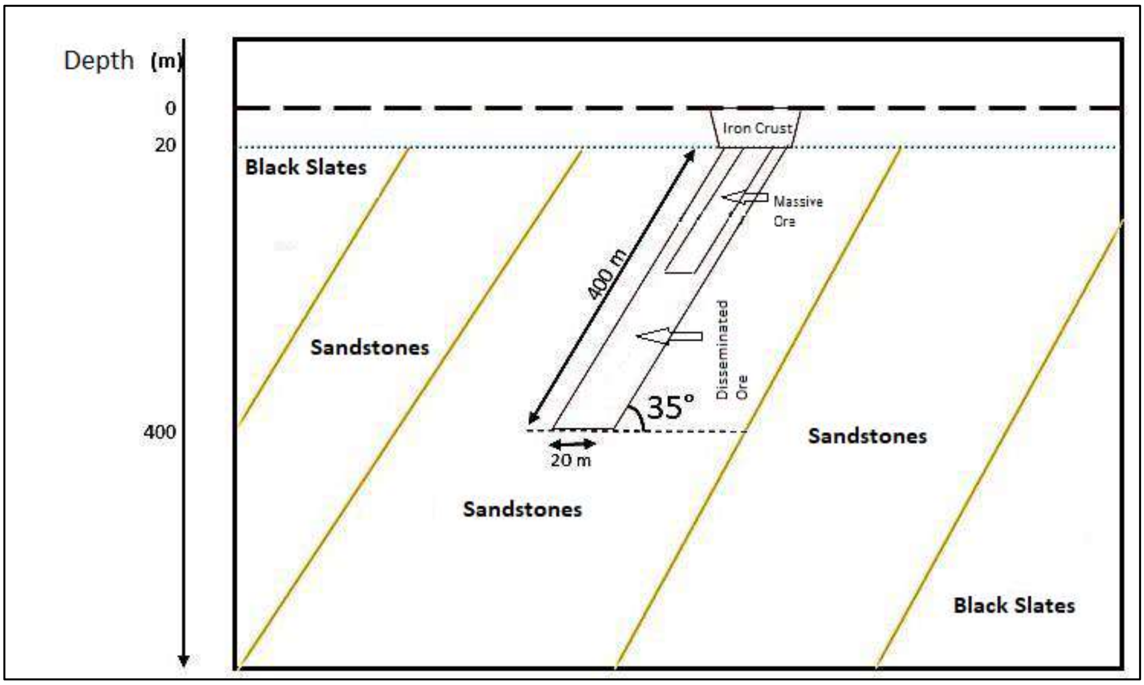

Figure 2. Generalized geological model for polymetallic deposits in the northwestern part of Pinar del Río Province.

The model identifies the polymetallic body as having an approximate extent of 400 m down-dip and 600 m along-strike, with an average thickness of 15 m and a dip of 35° from the horizontal. The graphical representation is a 2D cross-section where the body's strike is not visible but ranges between 310° and 320° NW. These bodies typically outcrop at the surface as an oxidation zone, known as a gossan or "iron hat," whose thickness and extent are highly variable, depending on topographic conditions, the erosion level, and the depth of the water table in the area (approximately 20 m).

The polymetallic body, which is tabular or lenticular in form, is characterized by a zone of massive mineralization accompanied by disseminated mineralization that extends at depth. Its immediate surrounding medium consists of concordant sandstone strata, which may be accompanied by intercalations of schists, lutites, disseminated ore, black shales, or other lithological types characteristic of the San Cayetano Formation, dated to the Lower to Middle Jurassic (J_1 - J_2).

The petrophysical model is presented in tabular form, indicating the rock type and the mean values for each property (Table 1), which were used for the forward problem calculation.

The greatest contrasts between the polymetallic ore and the surrounding rocks occur for the physical properties of density, magnetic susceptibility, electrical resistivity, and chargeability.

Table 1. Generalized petrophysical model for the polymetallic deposits in the northwestern part of Pinar del Río Province

Description	**Density (t/m3)**	**Magnetic susceptibility (SI*10-3)**	**Charge-ability (mV/V)**	**Electrical Resistivity (Ωm)**	**Gamma Intensity (μR/h)**
Black Slates	2,7	187,5	14,2	144,2	23,7
Sandstones	2,8	3,30	13,7	226,5	17,6
Iron Crust	2,4	1728,3	2,3	85,0	21,8
Disemined polimetallic ore	3,1	324,5	30,5	109,0	13,5
Massive polimetallic ore	3,9	650,3	44,3	101,0	9,4

Figure 3 response of the gravitational and magnetic fields over the geological model, incorporating density (D) and magnetic susceptibility (S) data for the polymetallic ore body and the surrounding rocks.

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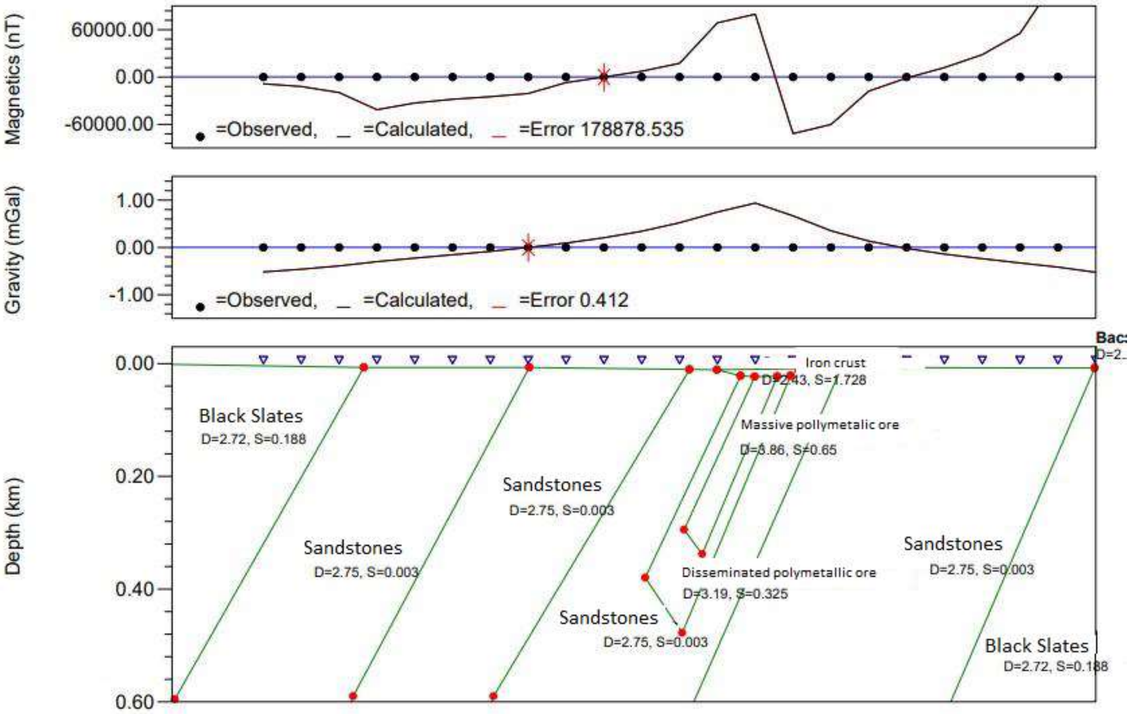

Figure 3. Generalized geophysical model for polymetallic deposits in the northwestern part of Pinar del Río Province, showing the response of the gravitational and magnetic fields.

In both cases, anomalies are observed over the surface projection of the top of the ore body, which corresponds to the contrast levels of the physical properties—density and magnetic susceptibility—between the polymetallic ore and the surrounding rocks.

The magnetometry curve shows a notable inflection associated with the contrast between the polymetallic body and the sandstones, providing an approximation of the body's extent. The curve's behavior, exhibiting a magnetic anomaly high and a low, reaffirms the presence of the gossan and the surrounding sandstones.

In the case of the gravity data, the major peak corresponds to the presence of the polymetallic body, composed of massive and disseminated polymetallic ores, and a gossan at the body's roof, which contrasts markedly with the adjacent sandstone rocks. Due to their mineralogical composition, the sandstones correspond to lower density values.

The remaining geophysical models for the polymetallic deposits were obtained using the Res2DMod software system, which enables the modeling of field behavior over a geological section based on the values of the physical properties of electrical resistivity and chargeability.

Figure 4 shows the distribution of apparent electrical resistivity values in a depth section, centered on the axis of the polymetallic body. The values are distinguished by color, with the lowest values in dark blue tones (minimum of 100 Ω·m) and the highest values in dark red tones (maximum up to 220 Ω·m). The zones with the highest values correspond to sandstone strata with quartz content and small amounts of feldspar and mica.

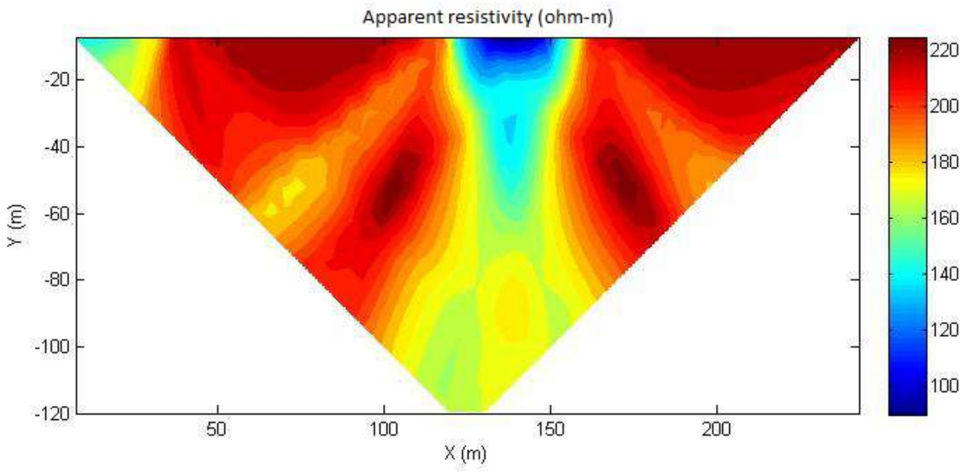

Figure 4. Generalized geophysical model of apparent resistivity for a polymetallic deposit in the northwestern part of Pinar del Río Province.

At the center of the section, an area with intermediate apparent resistivity values ranging between 140 Ω·m and 170 Ω·m is observed, identified by light blue, green, and yellow colors. This zone is associated with the presence of the polymetallic mineral body, composed of massive and disseminated ores that are more conductive than the surrounding layers. At the top of the body, coinciding with the gossan ("iron hat"), the minimum apparent resistivity value of approximately 100 Ω·m is noted.

Similarly, for the chargeability property, the *Res2DMod* system was used to obtain the depth section corresponding to the geophysical model for this physical property. The behavior of the apparent chargeability shows intermediate values (greater than 1008 mV/V) at the center of the profile, identifying the mineral body, while lower values indicate the presence of weakly polarized rocks.

Through the integration of the three model types (geological, petrophysical, and geophysical) presented, the resulting generalized PGM schematic was obtained by the superimposed integration of all its elements (Figure 5).

Within Figure 5, the values identifying the most contrasting physical properties for the different lithologies present in the geological model are represented inside a rectangle, in correspondence with the petrophysical model presented in Table 1. These properties are: magnetic susceptibility (χ), chargeability (η), electrical resistivity (ρ), and density (σ).

Considering all available information and based on the generalized PGM for the polymetallic deposits of northwestern Pinar del Río Province, the rational suite of geophysical methods for prospecting these deposit types was determined.

The rational suite for the prospection and exploration of polymetallic deposits in the northwestern zone of Pinar del Río Province would be integrated by magnetic, gravimetric, electrical resistivity, and induced polarization methods. In all cases, prospecting will be conducted at a 1:10,000 scale. Survey lines will be positioned perpendicular to the estimated strike of the bodies (i.e., N40°E), with line spacings of 100 m and station intervals of 10 m, ensuring the required precision and accuracy. The stations for the potential field methods (gravimetric and magnetic) will be the same, and the required corrections will be applied in each case.

For the electrical resistivity and time-domain induced polarization methods, the use of electrical tomography on the same lines as the potential field methods is recommended. This should employ two bilateral arrays of 24 electrodes each, with a 10 m spacing between electrodes, using the Wenner-Schlumberger configuration with ten acquisition levels. This array ensures good sensitivity to both horizontal and vertical variations in electrical resistivity and chargeability and achieves intermediate coverage, although it has a limited investigation depth. This limitation can be compensated for by performing several Vertical Electrical Soundings with Induced Polarization (VES-IP) at selected points within the observation network, with AB/2 = 1000 m to guarantee an investigation depth of at least 400 m.

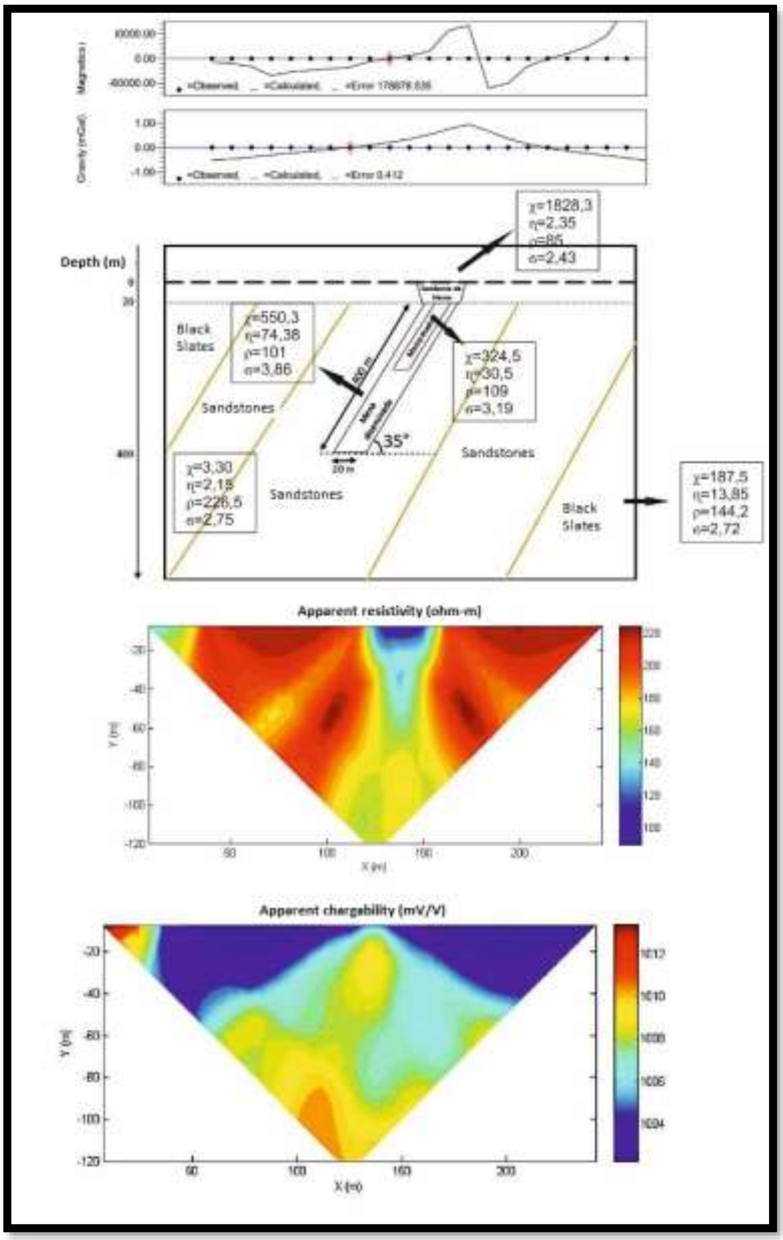

Figure 5. Generalized physical-geological model (PGM) of the polymetallic deposits in the northwestern part of Pinar del Río Province, integrating the geological model, the petrophysical model, and the models of the gravimetric, magnetic, electrical resistivity, and chargeability physical fields.

For the interpretation of the acquired data, the use of the following software systems is recommended:

a) Oasis Montaj for gravimetry and magnetometry data.

b) Res2DInv for electrical tomography data.

c) IPI2Win for VES-IP data.

4. CONCLUSIONS

- The methodology used to obtain the generalized PGM for the polymetallic deposits in northwestern Pinar del Río Province enables the systematization of geological and petrophysical information and the calculation of physical fields for which there is an effective contrast in the identified physical properties. This model provides an identifiable pattern for the prospecting of this type of deposit.

- The resulting PGM allows for the determination of a rational suite of geophysical methods, comprising magnetic, gravimetric, electrical resistivity, and induced polarization methods. This suite is intended for subsequent geological research aimed at identifying new resources in the northwestern region of Pinar del Río Province, and potentially in other regions with similar characteristics.

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Additional Information

Conflict of Interest

The authors declare no conflicts of interest.

Author Contributions

JADD: Research coordination, oversight, and direction; theoretical and methodological framework; literature review; PGM development; proposal of the rational geophysical methods suite; writing and revision of the final manuscript. **ANL**: Research design; data sourcing and processing for the petrophysical model; calculation of physical fields over the geological model; literature review; writing of the original draft. **OFCO:** Research design; development of the reference framework; review of data processing; PGM development; integration of the rational geophysical methods suite; writing of the original draft. **RGPV**: Research design; literature review; development of the geological model; reconciliation of petrophysical and geophysical models for integration into the PGM; review and final editing of the original draft. All authors approved the final version of the manuscript.

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