The role of land gravity data in the Neves-Corvo mine discovery and its use in present-day exploration and new target generation

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Introduction

Several blind massive sulphide deposits associated with the Iberian Pyrite Belt (IPB) Volcano-Sedimentary Complex (VSC) (Figure 1) were discovered in SW Iberia using joint interpretation of geological and geophysical models, such as Neves-Corvo (Albouy et al., 1981; Leca et al., 1983) and Lagoa Salgada (Oliveira et al., 1998) in Portugal, and Valverde and Las Cruces in Spain. In the IPB Portuguese sector, the former government agencies Serviço de Fomento Mineiro (SFM) and Instituto Geológico e Mineiro (IGM), as well as LNEG, fostered the acquisition of systematic geophysical surveys, in particular gravimetry, in the region during the second half of the 20th century.

Since the 1960s, the former SFM carried out detailed ground surveys over N-S for E-W grids with distances between survey stations of 200, 100 and 50 m grid size (Oliveira et al., 1998). This enabled the identification of several potential targets which attracted the interest of important international investors and led to a continuous investment in geophysical research, based on ground and airborne surveys (Matos et al., 2019).

The discovery of several massive sulphide deposits, including the world-class Neves-Corvo Cu-Zn-Sn deposit in 1977 (see location in Figure 1, Albouy et al., 1981; Carvalho et al., 1996; Carvalho et al., 1999; Oliveira et al., 2013) was a direct result of joint efforts of mining companies (a consortium formed by the Soc. Mineira e Metalúrgica de Peñarroya Portuguesa, Soc. Mineira de Santiago/Emp. Mineira e Metalúrgica do Alentejo and Societé d’Études de Recherches et d’Exploitations Minières), and former SFM exploration surveys (Albouy et al., 1981; Leca et al., 1983; Carvalho et al., 1999; Matos et al., 2019). The consortium invested significantly in exploration (Albouy, et al., 1981), namely: processing of the SFM-acquired gravity data (covering an area of 300 km²), collection of new gravity surveys (190 km²), more than 200 km of electric resistivity and magnetic profiles, as well as very-low-frequency (VLF) studies on several drill holes.

The Neves-Corvo deposits occur along a NW trend, with seven deposits dispersed in a large complex antiform structure (Carvalho et al., 1996; Araújo and Castelo Branco, 2010; Oliveira et al., 2013). Understanding the geometry of subsurface orebodies requires accurate geological mapping based on surface surveys and/or borehole logging (Matos et al., 2019). The accuracy of the conceived model for geology and ore deposit at Neves Corvo, however, is limited by the sparse geologic outcrops and a biased distribution of drill holes. This has driven an impetus towards...
acquisition of geophysical data which can be more uniformly sampled and is typically less expensive to collect.

Among the different geophysical methods employed, a strong response is expressed within the gravity data. This is the result of the large physical property contrast between high density, massive sulphide deposits and the volcano-sedimentary host rock lithologies (Neves, Corvo, Graça and Zambujal). The uppermost lenses are located in the NE flank of a gently dipping structure (10º-40º NE), at depths between 230 m (Corvo) and 350 m (Neves) (Albouy et al., 1981; Carvalho et al. 1996; Matos et al., 2019).

These were therefore the first four orebodies to be discovered, while the gravitational response of the deeper Neves-Corvo massive sulphide lenses were weaker and more difficult to recognize. With less obvious gravitational anomalies to guide exploration at such depths, rock density studies become a key issue in the geophysical characterization of Neves Corvo. In the case of the Semblana deposit (2010, ~800 m depth), ground electromagnetic surveys and extrapolation of favourable geology down dip from the Zambujal area were utilized for exploration in addition to the gravity data (Araujo and Castelo Branco, 2010).

The use of gravity for direct detection of massive sulphides in the IPB has limitations. In areas covered by thick Flysch sediments (locally >1 km) where the VSC occurs at greater depths, the gravitational response is weak and more so a function of regional geologic elements. Localized variations in density, such as those caused by high density basic rocks or black shales with disseminated pyrite, are common within the VSC sequences. Intense rock weathering, low density siliceous shales or volcanogenic sandstones also contribute to a complex and multi-layered gravity profile.

The elevated copper grades of the Neves-Corvo deposits justified more investment in exploration. The possibility of new discoveries with high metal content warranted an extension of exploration research, to explore deeper structures in the area (>>500 m depth).

Considerable efforts were exerted in areas such as the Neves-Corvo-Corte Gafo, a 600 km² polygon located NE of the mine site (Carvalho et al., 1996; Matos et al., 2019). With technical support of the former SFM gravity team, Somincor/Lundin implemented a multidisciplinary programme of gravity and magnetic surveys (9015 points covering an area of 314.5 km², as well several profiles of transient electromagnetics (TEM, 215.5 km), magnetotellurics (27.0 km) and reflection seismic data (24.0 km).

At a regional scale, a multitude of geophysical methods were deployed to characterize specific exploration targets throughout the IPB. These included: deep seismic reflection, electrical resistivity induced polarization, electromagnetic EM 37, pulse electromagnetic, transient electromagnetic, vertical transient electromagnetic, vertical electrical soundings and magnetotellurics. In structurally complex zones, such as the Semblana area (Araujo and Castelo Branco, 2010), down-hole electromagnetic surveys were essential in the identification and delineation of the primary mineralized trends. In the Neves-Corvo region, seismic profiles were used by Lundin/Somincor to define key tectonic structures (Araújo and Castelo Branco, 2010; Inverno et al., 2015; Matos et al., 2019).

The importance of gravimetric data in the search for new exploration targets

Despite the above mentioned challenges and localized exceptions, gravity continues to be one of the primary geophysical methods for massive sulphide exploration in the IPB. The effectiveness of the gravity method is related to the density contrast between the sulphide deposits (d>4 g/cm³ in massive sulphides and d=2.9-3.9 g/cm³ in stockwork veins, see Table 1) and the surrounding host rocks, e.g. felsic volcanic rocks, black shales of the VSC and shales and quartzites of the PQ Formation, which commonly present densities below 2.9 g/cm³. At a local scale, sulphide stockwork and vein type structures can be identified. This, however, typically requires a reasonable degree of thickness (>50 m) and a near-surface depth (<300 m). After the gravity-assisted

<table>
<thead>
<tr>
<th>Formation/Unit</th>
<th>Rock Type</th>
<th>N</th>
<th>Observed density</th>
<th>Density average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mértola</td>
<td>Shales and greywackes</td>
<td>1858</td>
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<tr>
<td>Brancanes</td>
<td>Pyritic black shales</td>
<td>231</td>
<td>2.57 - 2.99</td>
<td>2.76</td>
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<tr>
<td>Godinho</td>
<td>Shales and volcanogenic sediments</td>
<td>477</td>
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<td>2.71</td>
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<tr>
<td>Xistos Borra de Vinho</td>
<td>Green/purple shales</td>
<td>178</td>
<td>2.4 - 2.85</td>
<td>2.75</td>
</tr>
<tr>
<td>Grandaços</td>
<td>Siliceous shales and volcanogenic sediments</td>
<td>799</td>
<td>2.58 - 3.01</td>
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</tr>
<tr>
<td>Graça</td>
<td>Black shales</td>
<td>11</td>
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<td>2.77</td>
</tr>
<tr>
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<td>1970</td>
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<td>Basalts</td>
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<tr>
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<td>Shales and quartzites</td>
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<tr>
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<td>3.08</td>
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</tbody>
</table>

Table 1 Measured rock densities from outcrops and drill core from exploration drilling in the Neves-Corvo region used for the gravity inversion carried out in this work. N: number of samples.
than ~388 000 gravity measurements have been collected in the IPB Portuguese sector. Depending on the survey parameters, the distance between points varied from 50 m to 500 m. The Portuguese Geological Survey, LNEG, was responsible for the storage and maintenance of this database. The data was compiled and levelled using common data points. It was then gridded, using a kriging algorithm to 500 m cells to achieve a uniformly distributed surface. The LNEG gravity database allowed for the production of the first regional IPB Portuguese sector Bouguer anomaly map (Represas et al., 2016). The regional Bouguer anomaly was determined using a crustal density of 2.6 g/cm³, which is similar to the one used in the IPB Spanish sector gravity surveys (García et al., 1998).

The gravity database. 3D inversion: still needed?

Although 3D geological models incorporating drillhole, underground and surface geological data have been built and used to constrain geophysical inversions at Neves-Corvo (e.g. Invemo et al., 2015), new data continues to be collected. Over several years, Somincor/Lundin performed surface TEM surveys over a large portion of their mineral claims. These have been inverted in 1D and stitched together to image the conductive layers/bodies to depths as great as 2 km. The majority of drillholes within the area do not exceed 2 km depth and most are well above that depth.
These anomalies are oriented parallel to the regional strike of the VSC host rocks (NW-SE to NNW-SSE) and correspond to the main areas of historic exploration (Carvalho, 1996; Matos et al., 2019).

From the regional gravity map for the IPB Portuguese sector, a grid was extracted for the Neves-Corvo region. The extracted, levelled grid was compared to the original overlapping datasets for quality assurance purposes and to assess the presence of any artefacts as a result of the levelling/gridding process. Some surveys, which were only available as paper maps, were digitized and the entire gravity survey releveled (Marques et al., 2019).

The resulting Bouguer anomaly map is shown in Figure 3, in a 3D perspective view. Beyond the main anomaly, directly related with the Neves-Corvo VMS deposit (massive and stockwork ores), other geological features can be correlated with elements of the gravity map including VSC/PQ, NW-SE lineament and tectonic structures.

The main thrust zones of the SW Neves-Corvo sector are represented by important gradients. Subvertical late-Variscan strike-slip faults of E-W, N-S and NE-SW orientations are also apparent with the residual anomaly map (e.g. N-S Lombador fault). In several areas, strong correlations exist between the gravity and seismic datasets. This is especially pronounced in the main NE-SW trending thrust fault zones.

To improve the 2D and 3D gravity modelling constraints, the existing density database (LNEG and Somincor/Lundin Mining data) was updated to more than 30,000 density measurements. The Lower VSC units have recently been the subject of focus as these were poorly sampled in the past. Table 1 presents rock densities, measured from drill core and outcrop in the Neves-Corvo region. These were the values used for the gravity inversion carried out in this study.

Rock density is affected by several factors such as porosity, fracturing, mineral distribution, weathering alteration and depth. Considering the same geological formation, the presence of metallic minerals (e.g. sulphide or magnetite veins/disseminations) will increase its average density, while low-density minerals (e.g. clays, silica, sericite, carbonates) will have the opposite effect.
gravity inversion. As the average densities obtained from Table 1, VSC host rocks and the PQ Fm. present similar densities and the major contrasts contributing to the gravity response are associated with the massive sulphides. This model and the constrained 3D inversion results are also shown in Figure 4 (middle and bottom images).

We can see using the massive sulphide lenses as an initial model leads to an inverted density model that better resembles the known lenses. However, this preliminary inversion also produces other high-density bodies, either beneath or to the side (marked A and B in Figure 4, respectively) of the known lenses. These were not a component of the constraint but are nevertheless required to satisfy the data. If substantiated by additional geophysical or geologic information, they may represent legitimate targets for future exploration. Presently, a new 3D geological model is being built to further constrain the inversion. This model will include the stratigraphic interface between Upper and Lower VSC refined by the interpretation of reprocessed 2D and 3D seismic reflection data, updated drill-hole data, a revised surface geologic map, (Donoso et al., 2018) and additional TEM data inverted in 1D.

Conclusions
In order to locate IPB VMS deposits different geophysical methods must be employed and integrated with geologic, geochemical and drill hole data. Vintage land gravity data, acquired by multiple private companies and government institutions in the second half of the 20th century led to the discovery of Neves-Corvo in 1977. Strong density contrasts between massive sulphides and their host rocks makes gravity one of the most useful tools for exploration in the Neves-Corvo IPB area. Ground gravity data played a significant role in the discovery of mineralization at Neves-Corvo (Neves, Corvo, Graça and Zambujal) and contributed to the overall geologic framework by which later exploration discoveries were based (Lombador and Semblana).

Drill hole data interpretation is of crucial importance in defining high-resolution local scale models of the geological structures, and should consider sulphide ore type and zonation, hydrothermal alteration events, geological units and overall tectonic setting. In this and petrophysically appropriate environments, gravity data, complemented with electromagnetic surveys, seismic reflection profiles and drill-hole logging can produce more realistic 3D geological models to constrain 3D gravimetric inversion models to help provide new targets to explore. In this work, gravity data was revisited, checked and a new Bouguer anomaly map was produced. From this data, both 3D gravimetric unconstrained inversion and a constrained inversion using a 3D drill hole-based geological model were undertaken. A new 3D gravity inversion using a more detailed 3D geological model is currently being carried out.

An iterative approach, incorporating new or reworked geologic and geophysical datasets as a constraint to the inversion process is the best solution to the problem of non-uniqueness. This is not only true of gravity, but all other potential fields geophysical datasets. Adopting this type of adaptive methodology will lead to the better results and the potential to reveal small and/or deeper orebodies previously undetected.

Preliminary results from 3D gravity inversion
After careful checking of the gravity database, generation of the revised Bouguer anomaly map and update of the density database, an unconstrained 3D gravity inversion was produced using commercial software (VOXI). This preliminary inversion is shown in Figure 4. The unconstrained inversion was unable to accurately locate the known orebodies, represented in the Figure 4 (middle image). As is typical with an unconstrained inversion, smoothly varying bodies are produced to most efficiently (and easily) satisfy the data.

To more accurately reflect the known distribution of the orebodies, a 3D geological model built from drill holes performed up to 2012 was used to constrain the 3D inversion. Although this model includes the base of the flysch/top of VSC contact, the base of the VSC/top of basement (PQ Fm.), only the massive sulphide lenses discovered up to date were used to constrain the gravity inversion. As the average densities obtained from Table 1, VSC host rocks and the PQ Fm. present similar densities and the major contrasts contributing to the gravity response are associated with the massive sulphides. This model and the constrained 3D inversion results are also shown in Figure 4 (middle and bottom images).
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