Introduction

The Neves-Corvo mine located in the Iberian Pyrite Belt in southern Portugal (Fig. 1) is a world-class VMS deposit and the largest operating mine in the country. Seven massive sulphide bodies have so far been discovered (Fig. 1), of which 2 remain open at depth. The 150 Mt Lombador deposit is one of these with the current exploitation depth of about 1 km below the surface. To investigate the Lombador downdip extension (the lense has an approximate 45º dip), a 1D constrained inversion of time-domain ground loop electromagnetic data (TEM) followed by 3D forward modelling and 3D inversion of land gravity data have been performed in the same area. The deposit is hosted by a few geological formations embedded in the Volcanic-Sedimentary Complex (VSC) of Strunian age, topped by the Mértola Formation, comprising of greywackes and dark grey shales (Oliveira et al., 2004), and underlain by the Phyllite-Quartzite (PQ) basement Formation of Frasnian age (Oliveira et al., 2004). The autochthonous VSC is composed from top to bottom by the Brancanes Formation (black shales with disseminated pyrite), Godinho Formation (tuffites and grey siliceous shales), “Borra de Vinho” Formation (purple and green shales), Grandaços Formation (black shales with carbonated lenses and nodules), Graça Formation (black graphitic shales and grey siliceous shales), basic intrusive rocks and felsic volcanic rocks interbedded with Graça Formation (Upper VSC), jasper and carbonate unit (ore immediate hanging wall), as well as Neves and Corvo Formation (black pyritic shales) from Lower VSC and the basement, constituted by the PQ Formation. The area is marked by southwest verging thrust sheets and Late Hercynian Variscan vertical strike-slip faults. One major thrust tectonic panel, known to exist in the whole Neves-Corvo area, also affects the Lombador sub-area, below which lies the main ore-bearing horizon lying in the thrust footwall.

Figure 1 Geological map of the Neves-Corvo region (after Oliveira et al., 2016) showing the approximate location of the 3D gravimetric inversion and 3D EM forward modelling (green rectangle). Yellow lines represent the surface projection outline of the seven known deposits. Lombador EM loops are shown as red lines.

Ground TEM data modelling

The AMIRA p223 codes (Raiche et al., 2007; Wilson et al., 2006) were used for the TEM modelling. To investigate the electrical response of each geological formation, present in the region and prepare the 3D forward modelling, 1D inversion of ground TEM data was first carried out using Beowulf software (Raiche et al., 2007) and (EMIT’s) commercial Maxwell software. Each transmitter loop had a size of 1000 m x 1000 m with an approximate 13 Amp of current. A total of 60 stations 100 m apart
along 3 lines each 2 km long, with 300 m line spacing, were inverted using vertical component secondary field data. The inversion was constrained by information from approximately 300 drill-holes, which helped the identification of the signature of each geological formation. Only the drill-holes closer than 50 m to the TEM lines were considered, due to the strong lateral lithological variations present in the study area. 2D resistivity cross-sections were built by interpolation between the stations for each TEM line. An example is shown in Figure 2.

**Figure 2** Left: location of the TEM line 100 (yellow line) and other TEM lines and loops (black lines) superimposed on the Bouguer anomaly map of the study area. Some of the ore lenses are shown using red regions. Right: 1D inversion result along the TEM line 100, obtained using a stack of 1D models, overlaid with the existing drill-holes (within a 25 m corridor on each side of the TEM line).

After the 1D constrained inversion, Amira code Loki (Raiche et al., 2007) was used to carry out the 3D forward modelling of study area. A vast number of drill-holes available in the region were used to build the 3D starting model. Results from the 1D inversion were employed to interpolate electrical resistivity between the drill-holes and obtain resistivity values, allowing us to build a detailed geological model with 9 layers, where the average resistivity value of each layer agreed with the conductivity database of the study area. The layers of the model are, from top to bottom: (1)- Upper Mértola formation, (2)- Brancanes Formation and Tuffites (Godinho Formation), (3)- Shales (Godinho Formation), Purple and Green Shales and Grandaços Formation, (4)- thrust fault zone plus Graça Formation, (5)- Mértola 2 (Lower Mértola Fm) plus felsic volcanics, (6)- Black shales conductive layer, (7)- Neves Formation black shales and main ore horizon, (8)- transitional PQ layer, and finally (9)- PQ basement.

The calculated model response shows a good agreement with the observed data (Fig. 3), and confirms the results of the 1D inversion that the highly conductive layer of the Neves Formation black shales and massive ore (layer 7 of the input model), extends to 1 km depth and likely deeper. However, since both ore and black pyritic and graphitic shales have a high conductivity, it is not possible with the TEM data alone to infer if this highly conductive zone extending to 1.5 km depth is from the mineralization or other units.

**3D gravimetric inversion**

To better understand the geological cause of the high-conductivity region in the down-dip extension of the known mineralization, and taking into consideration that according to the density database the black shales have an average density of 2.8 g/cm³ whereas massive sulphides have an average density of 4.5 g/cm³, 3D gravimetric inversion was carried out covering the same model area as the TEM modelling.

The Bouguer anomaly data result from the levelling of several surveys acquired from the 1950’s until the 1990’s (Marques et al., 2019) and although the original surveys were acquired mostly with 50 m
regular spacing, the levelled grid has a 100 m grid spacing. The starting model for the gravimetric inversion was the same 9-layer model used in the 3D TEM forward modelling work (Fig. 3) plus the layer of the known Lombador deposit. The average densities for each layer were obtained from the 30,000 measurements database. The inversion voxel has 50 m x 50 m x 50 m dimension cell-size. The model geometry was fixed and constraints were set to the density values according to the end values of the density database. Layer 7 density, which may be mineralized, was left unconstrained.

The preliminary inversion result (not shown here) shows that a high-density layer 7, with a contrast of around 0.25 g/cm³ relative the average density of surrounding rocks, explains the observed gravity field. This density contrast corresponds, according to our density database, to the density of stockwork (3.06 g/cm³) and is well above the density of the PQ basement (2.79 g/cm³). The black shales/mineralization layer 7 extends down to 1.55 km depth below the surface (about 1.3 km m.s.l.) and matches a strong seismic reflection observed in reprocessed 2D seismic data from the study area (Donoso et al., 2020).

**Figure 3** Top: 3D model of the study area (Loop 70 and 69) built for the modelling work. See text for legend. Bottom: Example of misfit between the observed and calculated decay curves from the 3D modelling of line Lombador N 400, station 5800 for a resistivity of 100 ohm/m (A) and 10 ohm/m (B) for layer 7 (massive sulphide mineralization and black shales), demonstrating the presence of a conductive layer at Lombador down to 1.6 km depth.
Conclusions

The tier-1 Lombador deposit is likely open in the downdip direction and it is important to assess how deep the mineralization extends beyond the present-day exploitation depth (1 km). Processing and interpretation of TEM and gravimetric data, constrained by about 300 drill-holes, strongly suggests presence of a conductive and high-density layer down to 1.5-1.6 km depth. If the layer conductivity can also be attributed to black pyritic (and graphitic) shales, the high-density layer can be better explained by the presence of mineralization. With the present voxel cell-size and thickness of the conductive/high-density layer, the inversion results points to the presence of mineralization of the stockwork type. However, further studies currently underway using a thinner vertical voxel cell-size and a separation of layer 7 into a black pyritic shales layer (with 2.8 g/cm³ average density) and a mineralization layer (with density above 3.06 g/cm³), may allow to infer the presence (or not) of massive mineralization.

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References


