Re-Discovering Semblana: what if we could find it again?

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BIOGRAPHY

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SUMMARY

Discovered in 2010, a full 22 years after the previous discovery at Lombador, Semblana is the sixth of seven known deposits within the greater Neves-Corvo mining concession. Located in a mature terrain less than 3 km from the operation's headframe, the lengthy time it took to discover Semblana was affected by macroeconomics, multiple changes in company management, and technological advances in equipment, inversion methods and visualisation tools. The fact that Semblana lies 800 m below surface and has neither a strong gravity anomaly nor a stellar EM response didn't help.

Exploration is always challenging in areas of complex geology and at great depths. The discovery happened because the expected prize was substantial, persistence was maintained, teamwork was emphasised and best practice was expected, and because people were given the time to think.

West and Penney (2017) first presented the story of Semblana at Exploration '17 in Toronto: a +0.25 g/cm^3 relative-density iso-shell coincident with a weak-to-moderate 1D TEM conductor (now known to be spurious), three barren drill holes, but… two weak yet significant late-time BHEM responses that pointed towards an off-hole conductor. In retrospect, had 3D seismic or airborne gravity gradiometer (AGG) data been available earlier, history would likely be different. The story of Semblana is therefore worth upgrading and repeating, not to re-write history, but to re-run the discovery playbook using newer data and modern inversion methods.

We thus intend to present two stories: Semblana as it happened, and Semblana as it might be discovered today.

Key words: Iberian Pyrite Belt, VMS, TEM, BHEM, AGG, 3D Seismics, Visualisation, SimPEG, Inversion.

INTRODUCTION

The Neves-Corvo deposit lies in the globally important Iberian Pyrite Belt (IPB), one of the largest accumulations of massive sulphide in the world. With over 250 known deposits, the IPB hosts and has hosted multiple supergiant deposits like Neves-Corvo, Aljustrel, and Rio Tinto. Mining in the IPB began over 5000 years ago, first by Tartessians and then discontinuously by Phoenicians, Romans, Arabs, Scots and Brits in the 18th century, and now Spaniards and Portuguese. Past production is estimated at >2 Bt with another 400 Mt still to exploit (Almodovar et al., 2019). In terms of both size and longevity, the IPB is therefore one of the world's preeminent volcanogenic massive sulphide (VMS) provinces.

The Neves-Corvo Cu-Zn-Pb camp itself, of which Semblana is part, was discovered in 1977 after drill testing a (mis-interpreted!) gravity anomaly. Within two years, the first four of the seven known ore bodies had been found: Neves, Corvo, Graça, and Zambujal. Lombador came 10 years later in 1988, then Semblana in 2010, and finally Monte Branco in 2012. The fact that rate of discovery slowed significantly after those initial successes is due to the complexity of the thrusted geology and the significant depth of the ore bodies, and hence their weak geophysical signal (West and Penney, 2017).

REGIONAL SETTING

Approximately 250 km long and 25 – 70 km wide, the IPB is the main unit of the South Portuguese Zone (SPZ), itself part of Iberia's Variscan Fold Belt. Decompressive trans-tensional regimes within the SPZ produced grabens, half-grabens, and pull-apart basins that triggered bimodal magmatism and the geothermal gradients necessary for hydrothermal circulation and ore deposition (Leistel et al., 1998).

The simplified regional stratigraphy consists of three major units, from oldest to youngest being: the Phyllite Quartzite Group (PQ), the late Famennian to early-late Visean age Volcano-Sedimentary Complex (VSC), and the Baixo Alentejo Flysch Group (BAFG). Within the IPB, over 90 VMS deposits are known lie within the black shales or on top of the rhyolites of the VSC (Oliveira et al., 2004). All the deposits across the entire belt have similar characteristics and all are represented at Neves-Corvo.

The late-Devonian-to-Carboniferous collision-related compressive deformation produced both tectonic disruption and inversion of the IPB stratigraphy, forming a SSW-verging thin-skinned foreland fold and thrust-sheeted belt (Quesada, 1998). This tectonic style was responsible for generating blind VMS deposits, like Neves-Corvo, and several others in the belt.

LOCAL TECTONO-STRATIGRAPHY

The structural architecture of the Neves-Corvo mine area is characterized by a stacked pile of thrust sheets as described above. The local stratigraphic sequence is divided into two main tectono-stratigraphic units, one autochthonous and the other allochthonous, separated by the "Neves-Corvo Main Thrust" (Figure 1). A brief description of the stratigraphy follows, as modified from Pacheco and Ferreira (1999):

- PQ: the known basement of the IPB, it is composed of dark shales (P) with interbedded thin siltstones and quartzites (Q) and topped with minor conglomerates and limestones.
- Lower VSC: this lower autochtonous unit consists of a 300m thick sequence of mafic volcanics, felsic volcanics (mainly rhyolites), intercalations of black shales, siliceous shales with carbonate nodules and volcaniclastics (Corvo Formation) and dark shales (Neves Formation). The massive sulphides at Neves-Corvo are typically hosted in the upper parts of the Lower VSC.
- Upper VSC: the upper allochthonous sequence comprises a suite of shale-based formations with dark, pyritic purple/green shales, volcanogenic sediments and occasional felsic volcanics and mafic intrusions. The base of the unit often includes pyritic and conductive shales (Graça Formation) that can significantly affect some kinds of geophysical data.
- BAFG: forms the uppermost turbidite succession of the regional Mértola Formation and is composed of shales and greywackes. The thickness in the mine area is more than 700 m.

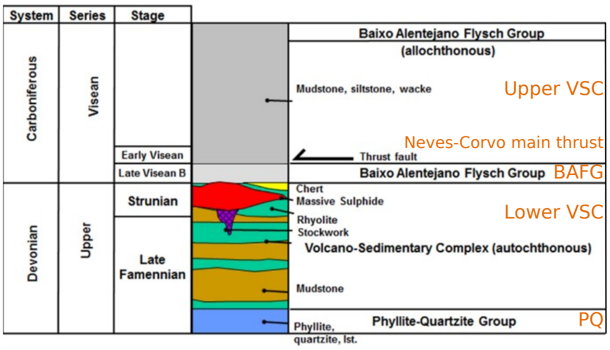

Figure 1: Simplified tectono-stratigraphic section.

MINERALISATION

Neves-Corvo is unique due to its large size and unusually high Cu and Sn grades. Covering an area of approximately 4 km × 2.5 km, the VMS complex comprises seven known massive sulphide orebodies (Neves, Corvo, Graça, Zambujal, Lombador, Semblana, and Monte Branco) with related and sometimes interconnected stringer-style stockwork feeder zones. It originally contained more than 300 Mt of sulphides, of which 138 Mt graded 3.5% Cu and 83 Mt graded 7% Zn (Somincor internal sources: data from 2019, including production records from 1989 until June 2019). The massive sulphide lenses occur at the top of the Lower VSC sequence, either in felsic volcanics (implying the ore-forming hydrothermal activity occurred at a late stage of effusive/intrusive rhyolitic magmatism and a corresponding strong genetic relationship between ore-forming processes and the volcanic activity), or intercalated/interfingered with the black shales of the Late Strunian-age Neves Formation.

GEOPHYSICAL METHODS

A variety of exploration methods have been used at Neves-Corvo as encouraged by discoveries on both the Spanish and Portuguese sides of the IPB.

Gravity was the primary geophysical tool leading up to and after the discovery of Neves in 1977 along with electrical and transient electromagnetic (TEM) ground surveys, complemented with airborne magnetics and eventually airborne EM methods as that technology improved. Given the conductive nature of VMS deposits and the depth of the deposits at Neves-Corvo, borehole electromagnetics (BHEM) has also been a staple of the exploration program. After Lundin Mining's acquisition of Somincor in 2006, progressively more advanced geophysical methods were undertaken, including 3D seismics, Airborne Gravity Gradiometry (AGG), and airborne Audio-Frequency Magnetics (AFMAG). Lastly, although not routinely acquired, what borehole physical property data that was collected has played an important role in understanding the geophysical responses (Table 1). For example, from this table it can be concluded that, on a gross scale, the sediments all behave alike.

Table 1: Petrophysical properties at Semblana (after Strauss et al., 1977 with internal data). Note that the wide range in the VSC unit includes both its sediment and volcanic sub-members.

	Density g/cm^3	MagSus SI $\times 10^{-3}$	Resistivity Ωm	Acoustic Impedance
BAF	2.5-2.8	<5	150-300	mod
Upper VSC	2.5-2.9	<5 - 100	150-2k	mod
Massive Ore	3.5-5.0	<5 - 50	<0.05-100	high
Lower VSC	2.5-2.9	<5	150-2k	low
PQ	2.5-2.8	<5	250-1k	low

THE DISCOVERY OF SEMBLANA

Upon assuming control of the exploration program at Neves-Corvo, Lundin's exploration team embarked on a three-pronged exploration strategy. Firstly, they continued to collect property-scale TEM data using a Moving-Fixed Loop setup (as explained in West and Penny, 2017) that deployed a low-noise SQUID B-field "LandTEM" sensor (Le Roux and Macnae, 2007) with a low frequency, 5 Hz waveform to explore for deeper and longer time-constant (c.f. higher quality) conductors. All

TEM data were inverted in-house using UBC's EM1DTM code (Farquharson and Oldenburg, 2004).

The second prong acknowledged the significant role played by gravity in the discovery of Neves-Corvo (Marques et al., 2019). In parallel with the TEM work, they contracted the creation of a constrained density-inversion model from a ground-gravity dataset compiled from multiple (and historical) surveys. The study optimised and removed the effects of the "known" non-mineralised formations using the homogeneous inversion method in VPmg (Fullagar and Pears, 2007) and then forced any remaining residual gravity anomalies to be accounted for by density variations in the prospective Lower VSC. An excellent description of this inversion technique can be found in Pears et al. (2017).

Finally, the third part of the strategy relied on viewing all geoscientific data in 3D. Today this is routine, but 14 years ago it was cutting edge, with Lundin's team being an early adopter of this best-practice technology. The "known" geological model was built in GoCAD using drill logs and then imported into VPmg. After inversion, the density iso-shells and 1D TEM sections were imported back into GoCAD and viewed alongside the geological model. This identified a new target area downdip and northeast of Zambujal with coincident anomalies within a region of sparse-to-no drilling. Three holes were allocated to test this new target.

Disappointingly, the three holes returned neither mineralisation nor interesting alteration. However, again with best practice in mind, the program's budget included costs for surveying each hole with BHEM. The first hole showed no anomalous response, but PSM44 and PSQ46, drilled 400m apart, each showed late-time off-hole responses at depth that indicated a conductor between the holes.

The next step after the negative drill results was fiercely debated, but this insightful BHEM interpretation led to the discovery of the Semblana Cu-Zn-Pb deposit with the fourth hole, SO48, intersecting 5.15 m of zinc-bearing massive pyrite underlain by pyritic stockwork sulfides at 825 m downhole (~800 m below surface). The Inferred Mineral Resource at Semblana in 2016 was 7.8 Mt @ 2.9% Cu, 25g/t Ag using a 1% Cu cut-off (Lundin Mining, 2016). This new discovery confirmed the ongoing belief that more economic deposits lie within the IPB and can be found with persistent exploration, even after a 22-year hiatus in discovery.

In retrospect, and as will be elaborated on further in the section on 3D TEM inversion, the 1D TEM anomaly seen over Semblana is now considered to be an artefact of the nearby, and much shallower, Zambujal orebody. This will likely not be the last time that a misunderstood signal plays a role in an exploration success.

SUBSEQUENT WORK

Delineation drilling began immediately thereafter, as did other geophysical surveys and inversions to better delineate and define Semblana's extents. Their "historically revised" impact is discussed below.

1. **3D seismic reflection** (after West and Penney, 2017)

A 3D hard-rock seismic survey was first conceived shortly after Lundin's acquisition of Neves-Corvo but given the lengthy lead time required to plan a survey of this scale it became a casualty of the Global Financial Crisis of 2008. However, the idea remained active, and a four-month survey was eventually completed in June 2011. The 6 km × 4 km survey block consisted of orthogonal source and receiver lines and a square 7.5 m bin size with >100 fold in the centre of the grid. Mine infrastructure posed huge challenges by limiting locations for sources and receivers, in addition to the noise generated by the trucks, trains, hoist and mill.

To aid in the processing and interpretation of the data, 150 core samples representing the different lithological and ore units at Semblana were analysed for density velocity. Borehole full-waveform sonic (FWS) data were also collected in two holes and vertical seismic profiling (VSP) surveys acquired in two other holes. Combined, those surveys provided detailed information on P-wave and S-wave velocities and the acoustic impedance within the host and the deposit. Unsurprisingly, the core analysis, FWS and VSP data all predicted a significant acoustic impedance contrast between the massive sulfide ore and the host rocks.

Semblana's sub-horizontal orientation made it a perfect target for reflection seismology as borne out in the first processed results delivered in August 2011. Figure 2 shows a SSW-NNE vertical slice through the seismic cube and crossing through the middle of Semblana. The accurate depth of 800 m was helped by the velocity model provided by the VSP surveys. The existence of the strong reflector in the 3D seismic cube was very useful in completing the delineation drilling of the deposit in general, and specifically of its southern extent of the deposit which had not been tested at that time.

Regionally, the new seismic data were added to the existing Neves-Corvo 3D geology model, which generated a plethora of secondary and tertiary targets for follow-up. The 3D geologic model was in turn used to add coherency and geologic meaning to the reflectors in the seismic cube that in turn fed back into the 3D geologic model in an iterative way, resulting in a vastly improved geological model between drill holes. This was especially true in areas where the drilling had stopped in PQ but where the seismic data indicated the thrusting of PQ over VSC. This was tested in one area and proved to be the correct interpretation, which in turn opened new exploration areas, like what happened with the original

1977 discovery of Neves where "conventional wisdom" interpreted the gravity anomaly to be much shallower than it truly was.

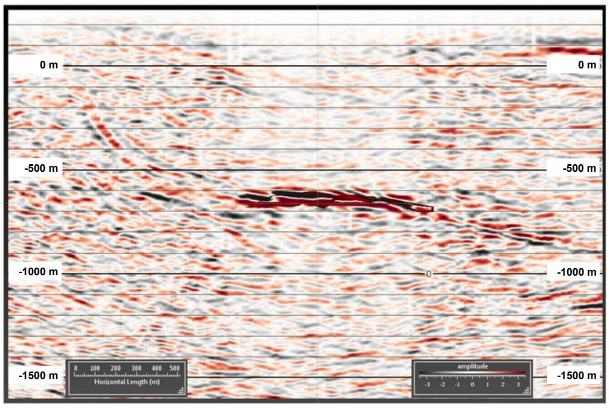

Figure 2: Vertical slice through the 3D seismic cube with the Semblana deposit represented by the strong, central reflector.

2. Airborne Gravity Gradiometry (AGG)

That gravity data has played and will continue to play an important role at Neves-Corvo is well established. However, the reality with gravity data in many long-lived exploration camps like Neves-Corvo, or Red Dog in Alaska, is that surveying errors exist in the historical data. Multiple contractors, survey technicians, field methods, and the use of different base stations and terrain correction methods, to name the obvious, all conspire to add errors to the data set without any malintent – mistakes happen! But years later, especially when the original field data were only recorded in a long-lost notebook, the inconsistencies are almost impossible to unravel.

The "fierce debate" mentioned above was in part because some people on the team had doubts about the density iso-shells delivered by the consultant: was a "bust" in the data responsible for the anomaly? In fact, the consultant specifically addressed this concern in their report (Mira Geoscience, 2007; also, Dick West, pers. comm.).

AGG survey technology thus offers a clear solution to the problem by supplying internally consistent data sets, in addition to the improved geological mapping provided by the gradient channels. Lundin's gravity database contains almost 5000 data points and is the product of decades of surveying. The entire survey could now be collected from the air in a month.

With respect to Semblana, it is neither a discrete nor an obvious gravity anomaly. Its targeting was partially the result of a geologically constrained density inversion using a sparse geological model due to a lack of drilling and a gravity database that likely had levelling errors within it. Had the AGG data been available in 2007 at the time of the constrained inversion perhaps part of the debate would have been moot.

3. 3D TEM inversion

The 1D TEM conductor that coincided with the 0.25 g/cm^3 density iso-shell was the result of nine partially overlapping survey lines collected from five 1 km × 1 km loops, none of which covered more than a quarter of what is now known to be Semblana. As stated, the EM1DTM inversion model identified a conductive anomaly that, in hindsight, fortuitously overlapped the modelled density anomaly. However, recent 3D TEM modelling using SimPEG disagrees with the 1D model. In fact, the 3D model is unable to image Semblana at all. But why?

Plate modelling of the BHEM data suggests a target conductance of 150 S but given Semblana's 30 – 35 m thickness (that includes a large proportion of massive pyrite at the top of the deposit), its conductivity is only about 5 S/m, slightly higher than that of sea water. With an average host resistivity of 300 Ωm, the conductivity contrast is a respectable 1500, but at 800 m Semblana is also deep and it lies under some beds of pyritic and conductive shale in the Upper VSC that likely masked the response. Modelling shows this to be the case with the original 5 Hz data and even with the 0.5 Hz transmitter frequency that is now the norm at Neves-Corvo.

The new understanding strongly suggests the 1D inversion of the Moving-Fixed Loop data was instead modelling the far-field response of the shallow Zambujal deposit, 1500 m to the southwest in the line direction. 1D inversions are often touted as a good starting place for 3D modelling because they are quick to create, but sometimes they're more like quick and dirty – dirty because 1D models create a geo-electric section beneath the observation point without regard to the spatial geometry of the EM response. At Semblana, each of the five loops was able to energise Zambujal, whose secondary response was detected over Semblana, even though Semblana wasn't – its conductance is lost in the geological noise. However, forward modelling indicates it only needs a 10× increase in conductance to be detectable. This is not unreasonable, say, in settings with a higher metamorphic grade where some primary pyrite can alter into much higher conductivity pyrrhotite.

RE-DISCOVERING SEMBLANA

So, what would Semblana's discovery ideally look like today if we could do it again?

1. We'd collect AGG to provide a consistent gravity data set for both a fraction of the time and cost of acquiring ground data over the entire Neves-Corvo concession.
2. Because we'd have sparse drilling everywhere except over the known deposits, we'd collect 3D seismic reflection data to identify high-amplitude primary targets in areas of prospective geology mapped with AGG. With modern wireless nodes, a comparable survey's time and cost would both be less than before.
3. We'd then combine the drilling, gravity, and seismic data to create a better geological model.

4. In parallel, we'd continue to collect TEM data because the target is a conductor, but we'd eschew 1D for the 3D inversions that are now easily within our computing reach. (See Napier et al., 2023).

CONCLUSIONS

Any afficionado of science fiction understands the perils of traveling back in time, because changing the past can illicit broader reaching effects in the present, and Semblana's discovery was affected by many events outside the immediate scope of exploration. The factors of persistence, best practice, and teamwork that led to its success the first place will always apply, so the desire is to deliver discovery success more easily and quickly (and with less reliance on luck). To do so, this paper has argued for the collection of large, dense, and high-quality data sets that exploit the relevant physical-property contrasts, and whose results are integrated into a common 3D geological framework. Semblana's discovery was likely inevitable – doing it again we'd execute the technical aspects better, but what about managing the process?

FUTURE WORK

Assuming no further geophysical data is collected at Semblana, any remaining work that centres around (joint) inversion modelling, especially of the AGG and 3D seismic data sets, would be most enlightening.

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