Brownfields and Beyond - Undercover at Neves Corvo, Portugal

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INTRODUCTION

The Iberian Pyrite Belt (IPB) in Spain and Portugal is a world-class volcanogenic massive sulfide terrain that hosts one of the world’s largest accumulations of massive sulfides and stockwork mineralization (>1700 Mt total reserves (Tornos et al, 1999) within 90 deposits). One of the largest deposits is the Neves Corvo Cu-Zn-Pb deposit which is in southern Portugal and was discovered in 1977 because of drill testing a gravity anomaly. Within a two-year period of that discovery, four of the six known ore bodies had been found within this VMS complex. The rate of discovery slowed significantly after that initial success due to the complexity of the thrusted geology and the significant depth of the ore bodies. A variety of exploration methods have been tried within the Neves Corvo complex and the belt, encouraged by the disparity in discoveries between the Spanish and Portuguese sides of the belt. The most recent discovery at Neves Corvo was the Semblana deposit in 2010 at a depth of approximately 830 m because of persistent and innovative exploration in the shadow of the Neves Corvo headframe.

During the first twenty years after the discovery of Neves, gravity was the primary tool with electromagnetic and electrical ground surveys used in combination with airborne transient electromagnetics (TEM) and magnetic surveys to increasingly probe deeper depths and larger areas around Neves Corvo. Geologic models for the deposits and structures improved significantly during this time also, but discovery was elusive. After 2006, deeper probing TEM, airborne gravity and ZTEM were conducted and integrated with the historical data to cover larger areas faster to focus efforts on the most prospective areas within the existing tenements. Drill testing was followed by borehole TEM to increase the effective radius of the boreholes. A brownfields 3D seismic survey was contracted over Neves Corvo while the Semblana deposit was discovered and proved to be the most effective geophysical method in detailing the extent of the Lombador and Semblana massive sulfide lenses as well as identifying detailed structures and helping to improve the geologic model between drill holes in the area. Wireline logging of drill holes was done to determine the petrophysical attributes to improve the velocity model and to better understand the seismic impedance across bedding and faults, and between the massive sulfides and host.

This review provides insight into the effectiveness of the individual geophysical methodologies used for mapping massive sulfides and structures at depth as well as the benefits of integration and 3D visualization of all existing data sets. Exploration is very challenging in areas of complex geology and at great depths, but the Neves Corvo example confirms the common knowledge that a combination of integration, best methods and team work increases the chances of discovery. This review also highlights the observation that 3D reflection seismology is the best exploration tool for exploring deeply within this belt.

GEOLOGIC SUMMARY

The IPB is approximately 250 km long and it varies from 25 to 70 km wide as it extends along a broad arc from Grandola, Portugal to Seville, Spain (Figure 1). The belt is the main part of the South Portuguese Zone (SPZ) which is part of the Variscan Fold Belt and it contains one of the world’s largest accumulations of massive sulfides and stockwork mineralization (>1700 Mt total reserves (Tornos et al, 1999) within 90 deposits) which include giant deposits such as Rio Tinto, Neves Corvo, La Zarza, Aljustrel and Tharsis. See Figure 1 showing the general...
geology of the region as well as the known sulfide deposits in the belt. Mining of massive sulfides in the IPB has a long history that began over 5,000 years ago (Tornos et al, 2006) but which declined after the fall of the Roman Empire and did not revive until the 19th century.

The SPZ is an exotic terrain that collided with the Iberian Terrane (Ossa-Morena) during Variscan times and transtensional forces within the SPZ basin produced graben to half-graben and pull-apart basins. Within these basins, bimodal magmatism, hydrothermal circulation and ore deposition occurred as noted by Leistel et al (1998). The area was subsequently covered by a thick sequence of turbidites. Transpressional forces compressed the terrane and created a fold and thrust belt that decreased in intensity to the south. There are three main formations within the IPB listed from oldest to youngest (see Figures 1 and 2): the Phyllitic Quartzite (PQ); Volcano-sedimentary Complex (VSC) and the Culm facies (also called the Baixo Alentejo flysch).

The PQ is late Devonian in age and consists of quartz sandstones, shales and rare conglomerates deposited in a possible shallow water environment. These are capped by thin carbonate shelf deposits and the formation is only exposed at the core of two major antiforms within the eastern portion of the SPZ (Mantero et al, 2011). The VSC is late Devonian to early Carboniferous in age and consists of subvolcanic intrusions, lava flows, pyroclastics and shales. Both felsic and basic volcanics are noted in the belt. The thickness of the complex generally varies from 100 to 600 m but locally at Neves Corvo it is up to 700 m thick (Tornos, 2006). The VMS deposits generally lie within the black shales or less commonly atop the rhyolites of the VSC and the sequence underwent extensive hydrothermal alteration in conjunction with the intrusive activity (circa 350–330 My during the Early Carboniferous). The Culm is a thick turbidite sequence composed of greywackes and shales that are synorogenic and are related to the collision of the SPZ with the Iberian Terrane. The sediments filled the resulting foreland basin.

The SPZ can be divided into three domains with only the two southern domains of interest for mineral exploration since those are the two containing the VSC (Mantero et al, 2011). The northern domain is referred to as the Aljustrel-Mertola-Rio Tinto Thrust Belt where thrust faulting and bedding has been rotated to high angles; the second domain is the Major Fault-Propagation Fold Region in which the thrust faults are at lower angle and large scale folding is more observable. Neves Corvo lies in the second zone, at the end of the Rosário-Neves Corvo Anticline (Figure 1). There is a major thrust fault that cuts the stratigraphy at Neves Corvo (see Figure 2) and it lies just above the massive sulfide deposits. Locally this fault is referred to as the Neves Corvo thrust fault. The Culm is locally referred to as the Mertola Formation and it contains a dark shale unit which generally is modestly conductive versus the more resistive greywackes.

The mineralization of the IPB is impressive with ore grades generally between 0.5% and 1.5% Cu, although reports of 6% Cu have been noted (Leistel et al, 1998). Higher copper grades exist as evidenced by the original copper head grade at Neves Corvo of 7% to 9%, but grades have reduced over time to the current value of 3% (Owen and Meyer, 2013). At Neves Corvo the mineral deposits lie on both flanks of the anticline and occurs as three main types of ore: massive sulfide, stockwork...
within the feeder zones and Rubané. Massive sulfide is the most common mineralization at Neves Corvo and it can be either pyrite-rich and barren or rich in copper and/or zinc. Tin grades are unusually high compared to other massive sulfide deposits, and the highest grades of tin (up to 8%) are associated with high copper concentrations. Main minerals are pyrite, chalcopyrite, sphalerite, tetrahedrite-tennantite and to a lesser degree cassiterite. The stockwork mineralization appears in the footwall and is part of the feeder system to the massive sulfide lense. The main minerals are pyrite, chalcopyrite and to a lesser extent sphalerite and cassiterite. Rubané ore is stockwork mineralization that is sheared by thrust faulting on top of the massive sulfides and occurs as thin bands of shales and acidic volcanics that alternate with massive sulfides. Chalcopyrite, sphalerite and cassiterite are common minerals found within the ore. In general, the copper-rich sulfides are at the base of deposits and if the zinc is present it will overly it (refer to Pacheco and Ferreira (1999) for details). The mineralized lenses lie at depths that vary from 230 to 1300 m below the surface (Owen and Meyer, 2013).

**HISTORICAL EXPLORATION**

Indigenous miners had exploited surface and shallow mineralization in the IPB for millennia but the Phoenicians were the first to open the area to significant international trading of tin and copper (Anderson et al, 1994) between 1000 to 500 BC. The Romans were the first to extensively extract copper, zinc, lead, gold and silver from the outcropping oxidized zones (gossans), for example at Aljustrel, and later exploited polymetallic veins. No significant mining was done until the 19th century when Aljustrel and Sao Domingos were mined for their pyrite as a source of sulfur. In the Portuguese portion of the IPB (PPB), base metal exploration boomed from the 1950s to the 1980s with seven deposits and deposit complexes discovered (LNEG, 1998) during that period: Moinho (1955), Feitaís (1963), Estação (1968), Gavião (1970), Salgadinho (1974), Neves (1977; followed by Corvo in 1977 and Graça and Zambujal in 1978 and then Lombador in 1988; see Figure 3) and Lagoa Salgada (1992). Initially exploration was focussed on those areas in the SPZ that contained outcropping volcano-sedimentary complex (VSC) and massive sulfides or those adjacent areas where these two characteristics were expected to be within 300 m of the surface (Oliveira et al, 1997). By the 1960s those areas had been extensively explored to shallow depths and standard exploration methods were being employed to search for the VMS deposits (geologic mapping and geochemical, electrical, EM, magnetic and gravimetric surveys).

Exploration in the area of Neves Corvo began in 1969 and consisted of geology and geophysical surveys followed by drilling but with no success. A more detailed gravity survey (100 m grid) detected a 0.5 mGal anomaly near the village of Neves. An exploration consortium (SFM) took over exploration in 1970 and the Neves anomaly was one of 10 high-priority anomalies to follow-up based on the geologic setting and the anomaly character. The interpreted density anomaly was thought to be between 90 and 150 m below surface so a 180 m hole was drilled in 1973. The hole was stopped at 210 m when Culm greywacke was intersected below the VSC. The drilled geology did not explain the gravity anomaly, however, so a new, deeper drill hole was recommended with a termination at 350 m but the proposal was not accepted (Leca, 1990). Exploration continued in the surrounding area and a better understanding and appreciation of the complexity of the geology was achieved as well as valuable experience gained with geochemical and geophysical methods.

In 1976 the updated geologic model was applied to the Neves target and it was again concluded that a deeper drill hole was needed to test the gravity anomaly. Drill hole N2 was started in 1977 and intersected 53 m of massive sulfides starting at a depth of 350 m. This was one of the first blind discoveries of mineralization in the IPB. Subsequent drilling showed that the bedding and mineralization was not nearly as steep as expected (Leca, 1990). This is similar to many discovery stories in early stage exploration: the integration of several disciplines eventually leads to a discovery of hidden mineralization and the realization that the geology is more complex than expected. The Corvo gravity anomaly was drilled a few months later and intersected massive sulfides at 507 m (see Figure 3 for location map). A fascinating twist is that the Corvo gravity anomaly was interpreted to be shallower than the Neves target and it had been on the list to drill after the failed first Neves drill hole. Had SFM drilled Corvo before drill hole N2, they would have failed to intersect mineralization and they might have written gravity off as an exploration tool in this area and skipped drill hole N2.

The Neves discovery was a very important exploration milestone for Portugal and the IPB because the deposit was found at depth and the high copper and tin grades made it economical to seek such targets at a much greater depth than before. Neves Corvo has more contained copper than a medium sized porphyry copper deposit with much higher grades. In fact, the Neves Corvo Mine was to become the largest producer of copper and tin in Europe (LNEG, 1998). This change in economics coupled nicely with the continual improvement in the understanding of the structure of the belt, the generation of improved deposit models and the new developments in geophysical data acquisition systems (eg., magnetics,
EM including magnetotelluric and borehole EM) and geophysical modelling. Armed with these constantly improving tools, the 1980s witnessed significant exploration effort in the PPB, but this effort translated into only two new discoveries: Lombador in 1988 and Lagoa Salgada in 1992.

By the early 1980s several major international companies were also exploring the PPB (e.g., Rio Tinto, Billiton, Elf Aquitane). Regional airborne magnetic, radiometric and time domain EM surveys (INPUT) were flown over a large portion of the PPB in an attempt to gain new insights into the hidden geology and to generate areas of interest for further study and hopefully generate drill targets. Rio Tinto flew a large portion of the PPB and Billiton flew their concession holdings that consisted of a large polygon that contained the VSC outcrop from Neves Corvo northwest to and across the Messegana fault. So neither group at the time had the complete view of the variation in apparent susceptibility, but when the data sets are merged it is clear that the high susceptibility portions are the volcanics along the VSC which extend to the southeast but begin to weaken and broaden as one approaches Neves Corvo. The volcanics are interpreted to extend further to the southeast towards the Spanish border but clearly they are plunging downward under flysch. Neves Corvo is blotted by culture but there is a hint that Lombador is indicated by a more subdued magnetic anomaly that dips to the north. In the northern half of the belt the magnetics tracks the arcuate nature of the geology but there is only one strong, linear magnetic anomaly in the central portion of the belt and then another magnetic anomaly near the border at the Sao Domingos Mine. By itself, magnetics is not a reliable targeting tool due to the magnetite destruction inherent with extensive hydrothermal alteration associated with VMS deposits in the belt.

Geoterrex flew INPUT airborne transient electromagnetics (TEM) surveys for three major mining companies and the surveys covered much of the PPB. The surveys denoted hundreds of conductors along the lines but none proved to be an economic ore deposit. The depth of penetration of this 12-channel system was approximately 150 m (Smith and Annan, 1997). The conductor picks were useful when linked together into lineaments which paralleled the geology and indicated where moderate to steeply dipping faults, graphitic zones and the more conductive shale horizons were located. Gravity was still the best tool at that time for detecting large massive sulfide accumulations but the surveys were either regional in scope with very large station spacing or small in areal extent and focussed on a particular prospect or geologic concept. It took decades before a network of these individual gravity surveys covered much of the PPB.

Ground EM surveys transitioned from the frequency domain Turam method in the 1960s to time domain EM techniques in the 1980s to detect conductors that are associated with massive sulfides. In the eastern portion of the PPB where the depth of cover was not well known but expected to be deep, magnetotellurics was attempted to map the subsurface resistivity. No discoveries were forthcoming but it was an early attempt at mapping the subsurface geology using electromagnetics. Induced polarization was tried but again the depth limitation prevented the method from being effective except for shallow mineralization. The graphitic shale horizons would also have been a source of geologic noise for the system. DC electrical soundings were attempted to gain better depth of penetration but time domain EM surveys eventually replaced that sounding method.

Geochemistry was also hampered by the depth of cover and where the VSC outcropped it struggled to differentiate between...
small pods of mineralization along faults or vein type mineralization and the large deposits at depth. The method showed that the VSC was prospective but could not effectively rank the myriad of targets. Widely spaced, intersecting, 2D seismic reflection lines were completed around Neves Corvo in 1991 and 1996. One of the lines extended across the Lombador deposit and a reflector appeared to correlate with the massive sulfides there, but no additional surveys were done and it apparently did not have a significant effect on exploration.

The most effective advancements in exploration were in the geologic models and structural geology of the belt which provided more effective conceptual targeting. When this was combined with geophysics (e.g., gravity) it did lead to the last PPB mineral deposit discovery in the 20th century at Lagoa Salgada (1992) which was a covered target that included variable thickness, lower-density, Tertiary sediments that covered the Culm and VSC.

During the years after the discovery of Neves Corvo different companies held interest in the deposit. In 2004 EuroZinc Mining acquired 100% interest of Somincor which had been the current owner of the mine. EuroZinc put a renewed focus on resource exploration at Neves Corvo, 16 years after the beginning of copper production. Over two hundred historical gravity survey data sets within the PPB were compiled, levelled to a common datum and gridded to create a regional data set (D. Woods, pers. comm., 2017) that covered 100% of the outcropping VSC and approximately 70% of the IPB. The denser VSC formation along the antiform and in the northern thrust belt show up well within the image. When the data is enhanced with a first vertical derivative or automatic gain control filter, Neves Corvo shows up as a ‘knot’ along a linear gravity high.

The geologic data, 2D seismic interpretation and drilling information were compiled together into a geologic model within GOCAD to provide a common platform and workspace to view the data sets. A constrained inversion of the gravity data, using Fullagar Geophysics VPmg 3D gravity inversion, was done using 6 layers to represent the geologic units with 3 of the layers given an unchanging density value while the other three layers (which included ore) were allowed to vary within a specified range of density to obtain the best fit between observed and calculated data. An anomalous density (+0.25 g/cc) was noted extending to the southeast from the Lombador density high over to the area of the undiscovered Semblana deposit. The anomaly was not given credence at the time since the existing drilling done in the area had not detected any significant mineralization. It was assumed that the anomaly was due to a formational increase in density and not mineralization.

**BROWNFIELDS AND REGIONAL EXPLORATION**

In 2006 Lundin Mining acquired 100% of EuroZinc Mining. The exploration group at this time had four different goals: Neves Corvo near mine exploration (Lombador focus), Aljustrel near mine exploration, Gaviao JV and PPB regional exploration of 3,511 km². The regional exploration had a time limit of 5 years with mandatory tenement reduction so it was important to cover the ground and denote the most prospective areas and drop the rest. The general 5-year goal was to add copper resources to the Neves Corvo Mine and to discover new economic copper mineralization somewhere within the belt. The challenges were obvious since this was a mature, mostly covered terrain with structurally complex geology with slivers of PQ masquerading as basement and potentially hiding prospective VSC beneath it. After a review of the data, it was assumed that the belt had been reasonably explored down to 500 m in the prospective areas but that economic mineralization could be found to a depth of 1000 m since the deposits tended to be large in size and grade.

As proven at Neves, an integrated exploration approach was needed using the best tools available that were fit to purpose. The first step was to review the data and physical properties of the rocks and then to organize all the data and append it into the existing 3D GOCAD geologic model. In that way, all geophysical and geological data could be easily imported and viewed and investigated using the software tools. Inherent in the review and organization of the data was the knowledge capture of what worked well and under what conditions in the belt. Physical properties for the regional rock package were known and density values for Neves Corvo had been refined during the modelling exercise. Additional resistivity and chargeability parameters were obtained from core measurements and later seismic velocity measurements would be done to complete the physical property inventory for the area. This would be used in geophysical modelling exercises to determine the effectiveness of different methods.

Integrating the geology and drilling information was the most tedious and time consuming task since it involved the rectification of drilling logs over a 30-year period. Fortunately, the ground gravity data had been merged and that allowed a gap analysis to be done to see where the holes in the coverage were. Although this data set was useful for depicting the regional gravity field over the PPB, it was apparent that there were numerous data quality issues which limited its use for detailed targeting. Particularly problematic was the fact that some of the worst quality data was over the Neves Corvo deposit area. In addition, 30% of the belt was not covered by ground gravity surveys. Airborne gravity gradiometer was chosen to fill in those gaps in a cost and time efficient manner. A test survey was done over Aljustrel and Neves Corvo Mines and the results were adequate to warrant flying the rest of the survey blocks. The boundaries of the airborne gravity gradiometer survey are shown on the regional gravity map in Figure 4. The focus of the survey was to fill the holes in coverage between the southern and northern VSC portions of the belt. The data was reviewed and ground surveys conducted over interesting responses but no surprises were noted in the areas covered by the greywackes (Culm).
Borehole TEM surveys were being conducted at Lombador during the resource drilling campaigns. Given the modestly conductive shale horizons in the areas of Culm outcrop and the desire to effectively explore between depths of 500 m to 1000 m, it was decided to use a hybrid ground TEM system which combined the depth of exploration of a large fixed loop with the versatility of a moving loop survey. A 1 km x 1 km square transmitter loop would be set up with three parallel lines extending through the loop and perpendicular to geologic strike; the middle line passed through the centre of the loop and the adjacent lines were 300 m from the central line. Station spacing was 100 m (10 stations inside the loop) with up to 6 stations outside the loop along the extension of the line. The stations outside the loop were only needed in areas where the bedding was greater than 50° so that proper coupling between the transmitter loop and the conductor could be achieved. Generally, only one of the three lines would be completed in a day; if an anomaly of interest was noted on the line then the other lines could be surveyed as infill the next day, otherwise the crew would move to the next loop. A layout crew would be laying out three loop segments of the next adjacent loop, using the front segment of the first loop as the back segment of the next loop. Once all desired stations in the first loop were completed, the receiver crew would move to this next loop and repeat the process until all lines/loops were completed. In this way, long lines of TEM data were quickly taken over areas of interest in a grid fashion (minimum 100 m x 1 km station grid). This array, referred to as a Moving-Fixed Loop, was trialed at Lombador with very good results so the survey was extended around the mine complex in search of any other potential deposits. A Superconducting Quantum Interference Device (SQUID) magnetic field sensor (LandTEM) was used initially as a low-noise B-field sensor to provide a deeper depth of exploration than provided by coil sensors (Le Roux and Macnae, 2007). However, developments in B-field sensor noise reduction allowed contractors to begin using compact, non-cryogenic sensors for the field surveys. The field crew conducted borehole TEM surveys as a primary objective and did the Moving-Fixed Loop surveys when not engaged in that pursuit. Twenty-one square kilometers could be covered on average each month by a single crew and the depth of exploration exceeded 1200 m in areas not covered by conductive Tertiary sediments, which is the normal condition southeast of the Messejana fault. Once that was done the crew was sent out into the PPB to explore all the prospective areas outlined by the combined geologic model and gravity anomalies. The loops used for the regional exploration of the belt can be seen in Figure 4 (see black squares); not all loops were completed but the majority were done.

A key element to this approach was to quantitatively model the results each night so that infill lines could be done on any detected conductors before the loop wire was picked up the next day. Consequently, each night all the TEM data from the day would be inverted using a 1D TEM modelling program (initially
Fullagar Geophysics EMAX and later the UBC EM1DTM computer program) and then stitched together to form a geoelectric section along the line. In addition to the modelling, data quality control was done and feedback provided to the field crew. If a modelled conductor was observed, either one of two infill lines could be completed to better assess the possible target and a geologist would be sent out to investigate any geologic outcrop. An example of a 2D geoelectric section model over the Lombador deposit is shown in Figure 5. The dipping red “layer” in the section is the stitched 1D conductor that correlates very well with the red outline of the Lombador deposit which is hosted within a pyrite lens. The image is draped upon a slice from the 3D seismic survey of 2010 to compare the results between the 3D seismic survey and the Moving-Fixed Loop array results. Very good correlation between the Lombador reflector and the dipping conductor occurs down to a depth of approximately 1500 m. At that depth, the reflector flattens out while the modelled conductor continues downward before flattening out at 1800 m. The results are impressive and provided confidence that a large, sub-horizontal deposit at depth would be detected with the array. This would prove to be a key element in the discovery of the Semblana deposit.

The 2D seismic reflection data obtained over Lombador was retrieved from the government archives and was reprocessed using the latest technology to determine if the reflector character and signal-to-noise could be improved. The results were better than the original seismic sections and Lombador showed up as a strong reflector, but the rest of the line still lacked the coherent character that was expected given the sub-horizontal layering of Culm and VSC formations in the subsurface. However, the results were very encouraging and costs for a 3D seismic survey over the Neves Corvo complex were investigated the next year. Seismic reflection surveys had been done over other mineral deposits since the 1990s (Salisbury and Snyder, 2007) but it is still not a normal or routine mineral exploration tool largely due to the higher costs and lack of experience by explorationists. Unfortunately, the Great Recession of 2008 occurred, so in that uncertain climate it was decided not to fund an expensive seismic survey but rather continue with the existing program as initially designed using ground TEM. Many of the areas that were covered had seen exploration before, but with the deeper depth of penetration, a very large volume of the subsurface to 1000 m was being quantitatively evaluated. The seismic survey was not the only casualty of the recession, the Aljustrel mine was shut down and sold and the exploration around the mine and the Gavião JV was terminated. So, the focus was reduced to just the brownfields and regional greenfield exploration within the Lundin Mining exploration concessions in the PPB.

![Figure 5: Resistivity geoelectric section atop seismic section and the Lombador deposit.](image-url)
At that time the geologic model around Neves Corvo was revisited and refined by reviewing core and core logs from some of the older holes scattered through the belt. This improved model was a key step forward in the exploration around the mine since it provided a good reference for all new drill hole results and geophysical responses. The regional geophysical program was going well but the area to be screened for conductors was too large to complete in the time required. Airborne EM systems had lacked the depth of penetration needed to explore the deeper portions of the belt, but a captive technology became available for use in 2007 and had potential. This method, Z-axis Tipper Electromagnetic (ZTEM) technique (Legault, 2012), is a passive EM technique that had proved itself in several different terrains and deposit styles. In-phase and quadrature amplitudes were measured at six frequencies ranging from 25 Hz to 600 Hz which together provide information about the subsurface conductivity. A survey was contracted to cover nearly all the northern two concessions as well as a portion east of Neves Corvo (see Figure 6). The ZTEM results were inverted using an Occam 2D magnetotelluric algorithm modified for use with ZTEM (Sattel and Witherly, 2012). The system easily detected theformational conductors within the steeply dipping and thrusted bedding in the Aljustrel-Mertola-Rio Tinto thrust belt in the north portion of the block. The more promising and interesting discrete conductors were followed-up with Moving-Fixed Loop ground TEM. A comparison of geoelectric sections from the airborne and ground surveys are shown in Figure 6 with the more detailed and reliable ground TEM conductors drawn on top of the ZTEM conductors in the lower panel. In general, the comparison is good with a difference in dip of conductors being the biggest difference. The ZTEM system was able to detect conductors to a depth of 1 km in the area, but none of the higher-resolution and deeper-penetration ground follow-up TEM profiles detected VMS style conductors. The combined airborne and ground EM did achieve the aim of screening all the prospective ground by mid-2010 so that a decision could be made regarding the disposition of the large tenement holding.

**SEMBLANA DISCOVERY**

By 2010 metal prices had rebounded and the fiscal climate was now amenable to funding a 3D seismic reflection survey over Neves Corvo. A seismic contractor specializing in mineral exploration was contacted in July of that year and they began working on a proposal, which entailed visiting the site and determining velocity and density of drill core. At the same time drilling was being conducted in an area down-dip and northeast of the Zambujal deposit where the drilling density was low and gaps in coverage could easily hide an economic-sized ore deposit. This drilling was designed to test the "formational" density anomaly that had been delineated 4 years earlier during the constrained inversion of the gravity data. Three holes were
drilled, with borehole TEM surveys completed, but no interesting mineralization or alteration was intersected. The TEM results from two of the holes (PSM44 and PSQ46) were very significant and ultimately led to the deposit discovery. The holes were drilled 400 m apart and each had a strong off-hole anomaly in the direction of the other hole—indicating that the two holes had bracketed a compelling conductive body. The project geophysicist was adamant that a fourth hole should be drilled and hole SO48 was collared in between. The hole intersected 5.15 m of zinc bearing massive pyrite underlain by pyritic stockwork sulfides 825 m downhole (approximately 800 m depth below surface). This was the discovery hole for the Semblana Cu-Zn-Pb deposit. The Inferred Mineral Resource at Semblana in 2016 is 7.8 Mt @ 2.9% Cu, 25g/t Ag with a 1% cut-off for Cu (Lundin Mining, 2016). This new discovery confirmed the concept that more economic deposits lie within the PPB and can be found with persistent exploration, even after a 22-year hiatus in discovery.

Delineation drilling began immediately at Semblana and borehole TEM surveys were done to help test the limits of the deposit. Even though the sub-horizontal nature of the deposit was noted early-on in the drilling program, a follow-up, detailed Moving-Fixed Loop survey done over the discovery provided no definitive response from the massive sulfide lens. This was both perplexing and alarming given the favorable coupling between the mineralization and the TEM array and the favorable physical property contrast between host and the massive sulfides. During this activity, the design of the 3D seismic survey was completed. The survey did not start in earnest until March of 2011 and was completed a few months later in June. The survey block (see Figure 7) consisted of overlapping source and receiver grids that covered an area 6 km x 4 km (NW-SE x NE-SW) with a bin width of 7.5 m x 7.5 m. Some areas in the southeast corner were not surveyed due to access issues (see Figure 8) and the survey of the tailings management facility (Figures 7 and 3) was done with all sources outside of the tailings facility and limited geophones inside the facility along existing dikes. More details concerning the equipment and field logistics are noted in Appendix I. The mine infrastructure was a very challenging environment due to limited locations for sources and receivers and the significant cultural noise generated by the large trucks, trains, hoists and ore processing activity. After the survey was completed a rock study of the velocity and density characteristics of 150 pieces of core representing the different

![Figure 7: 3D reflection seismic survey block for the Neves Corvo Survey with Semblana deposit shown.](image)
lithologic units as well as the Semblana ore was completed (Greenwood, 2011). Once the survey was completed, a full waveform sonic log survey of two holes and a vertical seismic profiling (VSP) survey of two other holes at Semblana was completed to provide detailed information on P-wave and S-wave velocities and the acoustic impedance within the host and the deposit. Both the core analysis and the VSP indicated that the massive sulfides should be a very good target (e.g., have significant acoustic impedance contrast with host) for seismic reflection methods.

The first processing of the data was completed in August of 2010 and a review and geologic feedback of the results by the exploration team provided to the processor. The data was of good quality over most of the block and provided coherent reflectors beyond the 2 km depth of investigation that was defined in the scope of work for the survey. A preliminary targeting exercise was conducted using the 3D geoscientific data set with the new seismic data added in. Targets were generated and ranked for follow-up. The two strongest and most coherent reflectors within the seismic cube were the Lombador and Semblana deposits. All other reflectors of interest due to their location and apparent acoustic impedance strength were secondary or tertiary in nature because none were as strong as the two known deposits. Drill testing was done on the targets in hopes of making a new discovery and to learn more about the reflection responses in the real world. Surprisingly many of the secondary targets were silicified rhyolites which should not have been a good reflector in this environment. However, the imaging of the Semblana reflector in the 3D seismic cube was useful in aiding the completion of the drilling of the Semblana deposit and indicated the southern extent of the deposit which had not been tested at that time.

Figure 8 displays a depth slice from the 3D seismic reflection cube at a depth of approximately 850 m below surface. The Lombador deposit has attributes of a strong reflector (high color contrast) in the central northwest portion of the survey block. Because the deposit dips at nearly a 45° to the northeast, the reflector shows as an apparent cross-section of the massive sulfides. Several disruptions in the reflector are indicative of faults that cut through the deposit. Semblana on the other hand is sub-horizontal and it is represented as a north-northeast trending high amplitude (red) zone near the center of the image with a east-northeast trending dark zone indicative of a dipping edge of the massive sulfides and some rhyolites on either side of its north end. The horizontal orientation of the deposit makes it a perfect target for reflection seismology since the seismic energy sent down to the deposit will reflect upwards to the receivers at nearly the same angle of incidence, so no energy is reflected outside of the receiver array. A vertical slice through the seismic cube through the middle of the Semblana deposit (Figure 9) shows the sub-horizontal nature of the reflectors (massive sulfides) at a depth starting at approximately 800 m below surface. The VSP surveys were useful in providing an accurate velocity model in the area of the Semblana deposit which allows for more correct transformation of the time to depth in that area. The survey was deemed a huge success but two questions did remain: why did silicified rhyolites exhibit high apparent acoustic impedance, and how could the data be improved underneath the tailings dam facility which suffered from significant reduction of seismic fold due to the limited coverage of sources and receivers.

![Figure 8: 3D Seismic reflection depth slice of cube at approximately 850 m below surface with Lombador and Semblana reflectors denoted.](Image)
The 3D geologic model was used to improve (add coherency and geologic meaning) the reflectors in the seismic cube and then that was fed back into the 3D geologic model to improve the model between known drill holes. This was especially true in areas where the drilling was stopped in PQ but where the seismic indicated the thrusting of PQ over VSC. This was tested in one area and proved to be the correct interpretation which opened new areas for exploration, similar to what happened in 1977 at Neves. The improved models are compared to the potential field and TEM data to determine if any new ideas or possible new targets can be generated. This process of continual improvement occurs with each new drill hole which will test the veracity of the geologic model and seismic cube in that area. Additionally, the geologic information is used to refine the re-processing of the data when new techniques are developed that improve the resulting seismic cube that better represents the known geology or highlights zones of interest better.

The 3D seismic reflection data and sonic logs were provided to Synem Yavuz, a PhD student at Curtin University, to study and determine if a different processing approach could provide a more unique result that could better discriminate between the massive sulfides and other strong reflectors (e.g., rhyolites). A modelling study of reflectors using the sonic logs indicated that preservation of the relative reflector amplitudes should provide a better result. She took a subset of the 3D cube centered on Semblana and processed the data using a workflow that preserved the relative amplitudes and then calibrated the results with the known geology. By adjusting the processing parameters, she could achieve a Relative Amplitude seismic cube that provides a much better result than the original, standard seismic processing (Yavuz, 2015). The secondary and tertiary targets picked from the original data became weaker reflectors with the new processing. It is likely that one or two of these tertiary targets (reflectors) would have been drilled to determine their cause and then the rest would have been avoided had the relative amplitude cube been delivered first.

The gravity data was reviewed after the discovery and given the size of the deposit, the depth and the thickness, the synthetic gravity response from Semblana is approximately 0.16 mGal with a long wavelength (half-width equals 530 m). In the regional gravity data, a much larger and shallower dense body would likely have been modelled for the data set, so it is not clear if Semblana would have been drilled based on just that interpretation and it if had it would have failed due to drill target depth. Perhaps with a much better data set the proper interpretation might have been made. Reflection seismology is not a perfect tool either but it has much higher resolution than the EM and potential fields (shorter signal wavelength) and much greater depth of penetration. In the PPB, reflection seismology is the best exploration tool in the search for deeper VMS ore bodies. This is especially true when the method is combined with all available exploration data sets, best geologic model and when assisted with wireline physical property measurements scattered throughout a given survey block.

**DISCUSSION AND CONCLUSIONS**

Exploration in the Portuguese portion of the IPB has followed a typical path with exploration first starting with visual prospecting of outcrops during the Chalcolithic Period ( Muller and Soares, 2008), then progressing to following mineralization to depth in mine workings during exploitation of ore. More sophisticated geologic models and more sensitive geophysical and geochemical methods were increasingly used in the twentieth century to explore deeper. The pace of discovery did a step change in the 1950s and discoveries were made on average every four years during a 23-year period. Between 1979 and 1992, only two deposits were found and Semblana was the next discovery 22 years later. Even though exploration technology and geologic understanding significantly advanced since the 1980s, the number of significant VMS deposits on the Portuguese side of the IPB is paltry compared to Spain. Portugal offers some unique challenges with the thrusting and fold belt and the deepening of the VSC formation as one goes southeast from Neves Corvo to the Spanish border. Semblana was a discovery that might have happened earlier if the density anomaly over the Semblana area had been drilled in 2007 or had the 3D reflection seismic survey been completed in 2009. The discovery did happen because the expected prize was substantial, persistence was maintained, best practice in mineral exploration was being done (eg, 3D geologic modelling with all available data) and effective expansion of the drill hole radius was done by conducting borehole TEM surveys. The process was not a straight-line from concept to discovery; it was a path affected by economics, multiple changes in company management and technology. It would have been great for the mineral exploration industry had the discovery been made using the 3D seismic reflection survey since that would have provided additional impetus to improve the "shallow" technology for mineral exploration through innovation, which leads to more success and usage which results in lower unit costs. We are confident that the transition of reflection seismology from a boutique exploration tool to a standard tool of application in the right setting will happen by the next decennial meeting.

The extension of the Neves Corvo-Rosário Anticline under the deep cover has been interpreted to extend to the Spanish border based on limited drill holes and a 2D seismic reflection survey (Inverno et al, 2015). The survey consisted of six, deep-penetrating profiles acquired by Laboratorio Nacional de Energia e Geologia (LNEG) between Neves Corvo and the border. The team of researchers used the Neves Corvo 3D reflection seismic survey to create their own geologic model around the mine and then extended that geologic model to the south. Their model included the PQ, VSC and Mertola Formation with the thrust fault that overlies the VSC and the mine horizon at Neves Corvo. Identification of fault intersections, geochemistry, coincident magnetic and gravity anomalies and prospective geology (VSC) were used to identify areas of interest for future exploration. This type of conceptual thinking anchored in quantitative results is the necessary step to distill large tracts of land into manageable areas of interest that can be searched effectively with the geophysical tools available. Three-dimensional reflection seismology is the most effective tool for depths below 1000 m and the most reliable tool for depths between 500 and 1000 m in the PPB.
Figure 9: Vertical slice through the 3D seismic cube with the Semblana deposit represented by the strong, central reflector (view to north-northeast). Relative elevations grid equals true elevation plus 1000 m; surface is approximately 1200 m.

Exploration in the Aljustrel-Mertola-Rio Tinto thrust belt to the north will be more challenging since the compression of terranes has steeply stacked the thrust sheets. Reflection seismology works best with horizontal bedding but it is worth giving the method a try in this region to see what knowledge could be gained and if steeply dipping deposits could be detected. A Lombador-sized deposit has a good chance of being detected but a Semblana size deposit may not.

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APPENDIX I

3D SEISMIC REFLECTION SURVEY SPECIFICATIONS

The Neves Corvo 3D seismic survey consisted of receiver sites spaced 15 m apart along lines 90 m apart and with transmitter sites spaced 45 m along lines spaced 90 m apart. The transmitter lines and receiver lines are orthogonal to each other. Two seismic sources were used during the survey, a Vibroseis and an impact source. Most of the survey was completed with a Vibroseis Mertz M22-601 with a 138 kNewton (31,022 ft-lbs) P-wave actuator plate with a frequency range of 10 to 120 Hz. The last few survey patches near the village of Lombador were completed with a Hydrapulse accelerated weight drop system with an energy of 16 kJoules (11,800 ft-lbs) and mounted on a tractor. In both cases, two sources were used in a flip-flop manner so that while one source was being recorded the other source was moving into position in preparation for the next "shot". With the 7.5 m bin width, the expected fold density within the central portion of the survey block is 100 which was deemed sufficient to provide good signal-to-noise to depths greater than 2 km (see Figure 9). Receiver density is 634 geophones per km² and the source density is 368 km². The number of channels recorded for each source transmission was 1,188. Twenty-eight patches were used to cover the survey block with each patch consisting of 11 receiver lines (1605 m long) and 10 source lines (1620 m long). When moving to the next adjacent patch, no sources were repeated but the leading geophones on the last patch became the lagging geophones on the next patch in order to provide continuous cover over the area.