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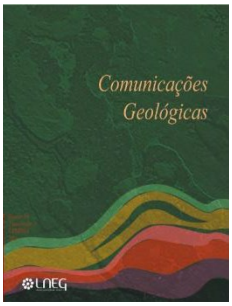
Opportunities and challenges in a world-class mining district, the Iberian Pyrite Belt

Oportunidades e desafios num distrito mineiro de classe mundial, a Faixa Piritosa Ibérica



J. M. Castelo Branco[1]*

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Abstract: A summary is made on the exploration work carried out in the Iberian Pyrite Belt (IPB) and an attempt is made to describe the evolution of the exploration methods and strategies applied in the field which led to the discovery of the main deposits. Finally, a reference is made to the good potential for new discoveries in the IPB, giving clues about new exploration models to be pursued. Being undoubtedly a world-class metallogenic province, the IPB naturally deserves a special mention regarding the mining history and on the evolution of the exploration techniques, adjusted to the new paradigms, namely in the need to search at ever greater depths. The most recent cases of successful new discoveries in the IPB are described, largely resulting from the refining of geological, geophysical and geochemical prospecting methodologies, and clues that are expected to lead to the discovery of new concealed deposits are equated.

Keywords: Volcanic Hosted Massive Sulphides, Iberian Pyrite Belt, South Portuguese Zone, Volcano-Sedimentary Complex, Mineral Exploration.

Resumo: Faz-se uma síntese dos trabalhos de prospeção realizados na Faixa Piritosa Ibérica (FPI) e procura-se descrever a evolução das metodologias e estratégias de exploração aplicadas no terreno que conduziram à descoberta dos principais jazigos. Por fim, é feita referência ao elevado potencial de novas descobertas no IPB, dando pistas sobre novos modelos e estratégias a desenvolver. Sendo inquestionavelmente uma província metalogénica de classe mundial, a FPI merece naturalmente uma referência especial no que respeita à história mineira e à evolução das técnicas de investigação, ajustadas aos novos paradigmas, nomeadamente na necessidade de prospeção a profundidades cada vez maiores. Discutem-se os casos mais recentes de novas descobertas bem sucedidas na IPB, resultantes, em grande parte, do refinamento de metodologias de prospeção geológica, geofísica e geoquímica, sendo traçadas novas pistas, que se espera, levem à descoberta de novos depósitos ocultos.

Palavras-chave: Sulfuretos Maciços Vulcanogénicos, Faixa Piritosa Ibérica, Zona Sul Portuguesa, Complexo Vulcano-Sedimentar, Prospeção Mineral.

1. Introduction

The Iberian Pyrite Belt (IPB) represents probably the most important metallogenetic province of massive polymetallic volcanogenic sulphide deposits in the world, both in size and in number of occurrences. The lithostratigraphic succession comprises three main units including, from the bottom to the top: i) Phyllite-Quartzite Group (PQ) consisting of detrital rocks from the Devonian (Givetian to Famennian); ii) Volcano-Sedimentary Complex with manifestations of bimodal, felsic and mafic volcanism and metasedimentary rocks, aged between the Famennian and the late Visean; iii) Baixo Alentejo Flysch Group, a turbidite late Visean to Muscovian sequence of, composed of fine clayey shales alternating with greywackes of varying grain size.

The IPB deposits, mined since the Neolithic period, had greater expression during the period of Roman occupation with large open pit exploitations that are still visitable today (Aljustrel, São Domingos and Caveira, in Portugal; Rio Tinto, La Zarza and Tharsis, in Spain). Significant mining operations in the mines of Aljustrel, São Domingos, Canal Caveira, Lousal and others of smaller dimensions have been reported since the late 19th / early 20th century. Aljustrel has been operating more continuously since 2010 following several intermittent production periods going back to the turn of the 19th century and Neves-Corvo mines have been active in Portugal uninterruptedly since 1989.

Exploration work using more sophisticated methodologies and techniques began in the 1950s, conducted in the IPB by the Portuguese state through its mining and exploration branch, the Serviço de Fomento Mineiro (SFM). Extensive geophysical surveys were carried out, namely gravimetry, magnetometry, electromagnetism (TURAM, among others) and electrical methods. In addition, detailed surveys of soil geochemistry and stream sediment surveys were also done. These works, together with reinterpretative geological studies, led to the discovery of two new massive sulphide lenses in the Aljustrel mining field along with the giant Neves Corvo deposit.

The evolution of exploration techniques has been essentially focused on the specialization of previous methodologies, and the introduction of airborne magnetic, radiometric, electromagnetic surveys (Input EM, VTEM, GEOTEM, HeliTEM, etc.) and more recently gravimetric (AirFTG).

The current focus is mainly on finding deposits at successively higher depths (> 400 - 500 m), given that the probability of new discoveries at shallow depths seems to us to be reduced and thus making it necessary to adjust the exploration strategy to the new paradigm. To face this challenge, the use of more appropriate

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[1] Geologia e Geotecnia Consultores Lda., Rua Cunha Júnior, 41-B, Sala 1.6, 4250-186, Porto, Portugal.

* Corresponding author / Autor correspondente: jmcb@ggconsult.com.pt

geophysical techniques becomes a priority, including the new TEM methodologies, in particular, combined with high-sensitivity sensors, namely SQUID, which can investigate depths greater than 1000 m, following diamond drilling on targets defined and, finally, downhole EM surveys to complement the information collected. This strategy had an unquestionable success, both in Portugal, with the discovery of the Semblana deposit in the Neves Corvo mining field, and in Spain, with the identification of the La Magdalena deposit to the east of the Aguas Teñidas mine.

Finally, it is also noteworthy to mention the high-resolution reflection seismic, a technique that came to produce surprising results at depths never investigated before, namely in the clear detection of the sulphide lenses of Lombador and Semblana within the Neves-Corvo mining concession (although these were found earlier by other methods, respectively Gravity in Lombador and a combination of EM and Gravity in Semblana). These results encourage in the future the use of this method more intensively in the IPB, naturally having to consider the high costs that its application may involve on a case-by-case basis.

2. Geological setting of the Iberian Pyrite Belt

The IPB represents an important metallogenetic province, integrated in the South Portuguese Zone, a major geotectonic unit located in the southernmost segment of the Variscan orogenic front in the Iberian Peninsula (Fig. 1). General references to the IPB include Strauss *et al.* (1977), Routhier *et al.* (1980), Carvalho (1979), Leca (1990), IGME (1982), Barriga (1990), Sáez *et al.* (1999), Leistel *et al.* (1998), Carvalho *et al.* (1999), Tornos (2006), Oliveira *et al.* (2011), Matos and Filipe (2013). Studies focused on the stratigraphy include Oliveira (1990), Pereira *et al.* (2007, 2008, 2012); on volcanism, Munhá (1983), Thiéblemont *et al.* (1998); on structure and regional metamorphism, Ribeiro *et al.* (1990, 2007), Munhá (1990), Silva *et al.* (1990), Boulter (1996), Quesada (1998), Simancas *et al.* (2003) and on the facies analysis and architecture of the volcano-sedimentary complex, Soriano and Martí (1999), Junta de Andalucía (1999), Rosa (2007), Rosa *et al.* (2008).

The oldest rocks present in the South Portuguese Zone are the metasediments of the Phyllite Quartzite Group (PQ), represented by rocks of Mid- to Upper Devonian age (Fig. 2). This basal group consists of a thick series of detrital sediments including fine clayey shales, siltstones and quartzites, deposited in a shallow marine platform environment (Oliveira *et al.*, 2004, 2013, 2020; Schermerhörn, 1971; Pereira *et al.*, 2007, 2008, 2012; González, 2005).

This sequence is superimposed by the Volcano-Sedimentary Complex (VSC), a unit that hosts the known mineralizations, including a bimodal, polyphasic volcanic sequence, interlayered and cutting metasediments and exhalites, dated from Late Famennian (Upper Devonian) until the beginning Upper Visean (Lower-Mid Carboniferous) (Oliveira *et al.*, 1984, 2004, 2013; Pereira *et al.*, 2008, 2012).

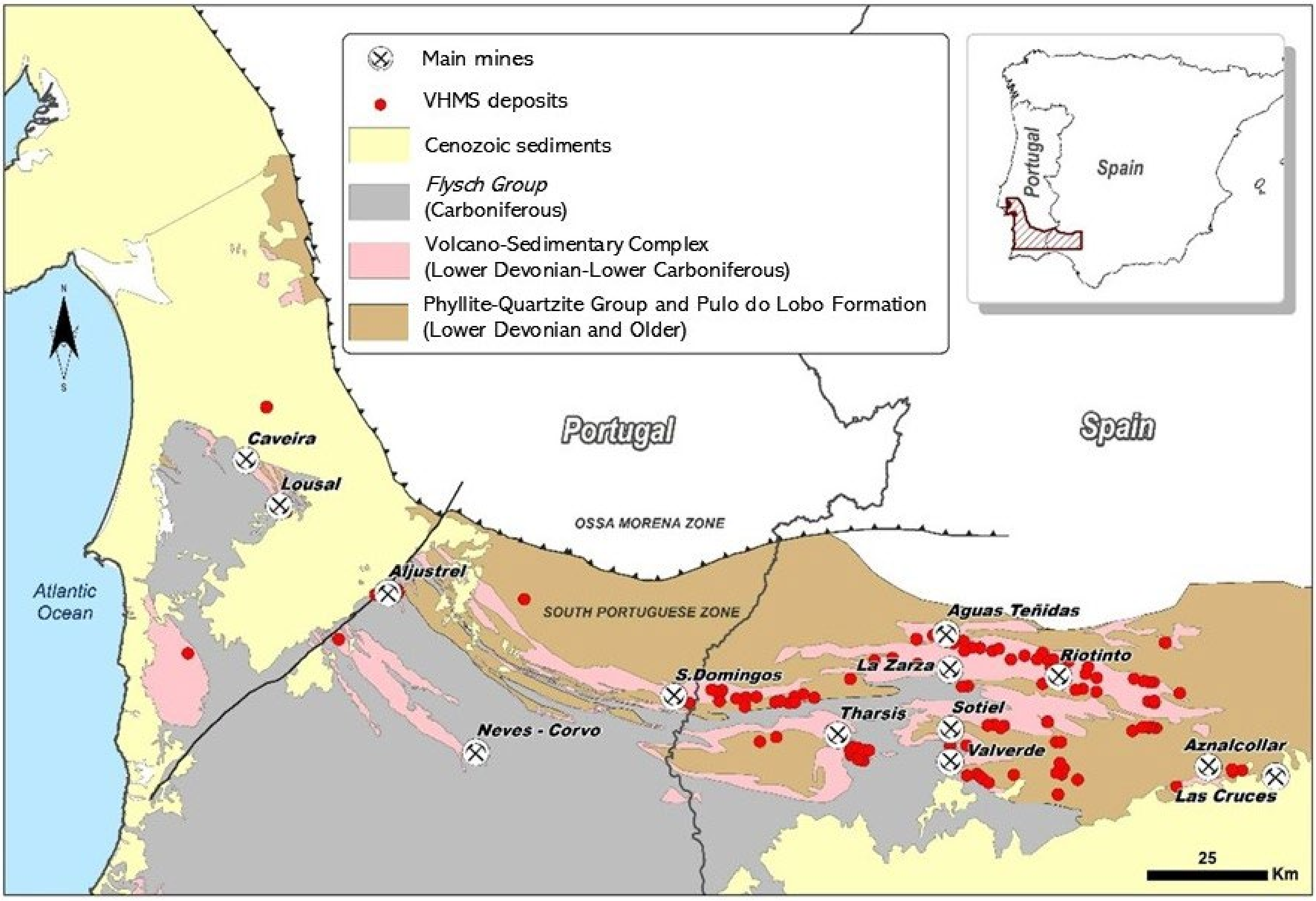

Figure 1. Simplified geological map of the South Portuguese Zone and location of the main massive sulphide deposits (geology adapted from LNEG and IGME maps, in Pereira *et al.*, 2021).

Figura 1. Mapa geológico simplificado da Zona Sul Portuguesa com a localização dos principais jazigos de sulfuretos (geologia adaptada dos mapas do LNEG e IGME, Pereira *et al.*, 2021).

Several cycles of felsic volcanism and two dominantly mafic are recognized. However, it is difficult, to accurately pinpoint all these events in the lithostratigraphy, due to the intrusive nature of some of the rocks, as well as the extreme facies variability, which, in fact, reflects the original complex architecture of volcanic piles. Additionally, this multiple thrusting and diachronism of the volcanic events, complicate an already complicated tectonostratigraphic history (Silva *et al*., 1990; Quesada, 1998).

The felsic rocks consist essentially of dacites, rhyodacites and rhyolites, representing domes or cryptodomes and, furthermore, dykes and sills intruding meta-sediments, both previous and contemporary (Martí Molist *et al.*, 1994; Soriano and Martí 1999; Junta de Andalucía, 1999; Rosa *et al.*, 2008). The mafic domain is represented by sills as well as basaltic and doleritic dykes, and by extensive basaltic lava flows, often with pillow lavas.

It is admitted that the mineralizing events of the massive sulphides (Sáez *et al*., 1999) coincided with the formation of deep basins or grabens, that were the *loci* of deposition of the volcanogenic deposits, separated by shallow marine platforms, in some cases materializing even a subaerial volcanism.

The VSC is superimposed by a thick turbidite sequence, the Baixo Alentejo Flysch Group (informally called *Culm*), consisting essentially of shales and greywackes and some conglomeratic layers, which locally may be greater than 3,000 m thick. The age of these formations is between the Upper Visean and the Upper Muscovian (Oliveira *et al.,* 1979; Silva *et al*., 1990; Pereira *et al*., 2008).

From a structural point of view, the IPB is made up of folds and overthrusts with a dominant NW-SE orientation, verging mainly to the SW in the Portuguese segment of IPB and to the S in the Spanish sector, in which it undergoes rotation. The deformational reactivation is materialised as Late-Variscan NE-SW and N-S faults with a significant horizontal displacement and more recent Alpine age, among them the great Messejana-Plasencia fault in Portugal and Spain (Ribeiro 1984; Schermerhörn *et al*., 1987; Oliveira and Araújo 1992; Quesada, 1998; Inverno *et al.*, 2015a, b).

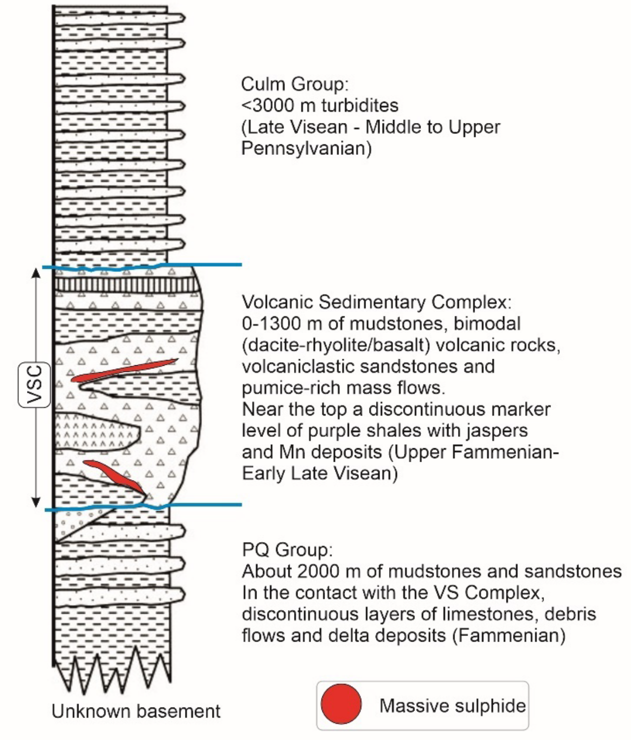

Figure 2. Simplified lithostratigraphic succession of the IPB (based on Tornos, 2006).

Figura 2. Litoestratigrafia simplificada da FPI (baseado em Tornos, 2006).

The Variscan metamorphism is low-grade, essentially greenschist facies. The geotectonic setting of the South Portuguese Zone has been subject to several interpretations, highlighting a model related to oblique strike-slip faulting in relation to the front of the orogen (Schermerhörn, 1971; Routhier *et al*., 1980), linked to intracontinental rifting in back-arc basins (Munhá, 1983) or pull-apart basin(s) related to sinistral faulting as a result of oblique plate collision (e.g., Silva *et al*., 1990; Oliveira and Quesada, 1998; Tornos *et al*., 2005). This predominantly transpressive regime gives rise to the formation of folds oriented from NW-SE to W-E, verging respectively to SW and S, accompanied by more intense thrusting in the S and SW limits of the IPB (Ribeiro, 1984; Schermerhörn *et al*., 1987; Oliveira and Araújo, 1992; Quesada, 1998).

3. Brief Mining History

The deposits in the IPB were first mined between the Neolithic and Chalcolithic (Gaspar, 1995; Mateus *et al.*, 2001) and, later, with much greater intensity and sophistication, during the period of Roman occupation of the Iberian Peninsula until the beginning of the 5th century. Mining was concentrated, essentially, in gossans, developed in most of the outcropping deposits (São Domingos, Aljustrel and Caveira in Portugal and Rio Tinto, Tharsis, La Zarza, in Spain), focused essentially on precious metals (gold and silver), but also on copper.

Although minor mining activity has been undertaken by the Tartessians, Visigoths and later by the Moors, it was only in the 16th and 17th century that the first mining records appeared (Duarte, 1995; Mateus *et al.,* 2001). Much later, in the 19th century, mining activity gained new impetus with modern operations both on the Spanish and Portuguese sides. Mining focused on the pyrite ore for the manufacture of sulfuric acid and on base metals, particularly copper. In addition to base metals, large-scale exploitation of the extensive gossan in the Rio Tinto gold mine was undertaken, which remained in production until 2002 (Bolaños, 2011), having produced since 1937, a total of 106,647 kg (ca. 3.4 million oz) of gold and 1,745,010 kg (ca. 56.1 million oz) of silver.

There was a massive closure of numerous mines in the late 1980s, with the loss of competitiveness of pyrite as a source of sulfuric acid in the international markets, with only a few copper and zinc mines that remained open, namely Aljustrel in the Portuguese territory which was also interrupted by periods of partial closure/maintenance in the last four decades.

4. Main sulphide deposits

About 90 volcanogenic massive sulfide (VMS) deposits are known in the IPB, with very variable contents in copper, zinc, lead, silver, gold and tin and sizes ranging from a few hundred thousand to several hundred million tons of pyritic ore.

In this latter category, the Neves-Corvo and Aljustrel mines stand-up in Portugal while in Spain, Rio Tinto, Tharsis, La Zarza, Aznalcollar-Los Frailles, Sotiel and Masa Valverde are the best-known examples. In Portugal, in addition to the Neves-Corvo and Aljustrel mines in production, deposits with > 20 million tons, include São Domingos, and Lousal (already exhausted), and both Lagoa Salgada and Gavião, still to be developed.

the Spanish side, this group includes Las Cruces mine, Aguas Teñidas, Sotiel-Migollas and the Rio Tinto project, all in production, and the new La Magdalena discovery made in 2013, located about 8 km east of Aguas Teñidas, which is currently in the start-up phase. The deposits of La Romanera and Concepción which also fall in this category are exhausted.

It is estimated that, in total, the pre-erosion concentration of mineralised material in the IPB would amount to more than 1600 million tons of massive sulphides and 2500 million tons of the stockwork or semi-massive types (Tornos, 2006; Tab. 1). The estimated total average grades for all massive sulphides in the IPB are in the order of 45% S, 40% Fe, 1.3% Cu, 2.0% Zn, 0.7% Pb, 26 g / t Ag and 0.5 g / t Au, with only 20% of the massive ore having been mined and between 10 and 15% having been lost due to erosion (Carvalho *et al.*, 1999).

The massive sulphide deposits generally occur in lenticular bodies, with thicknesses ranging from < 1 m to several tens of meters, occasionally exceeding a hundred, and may extend over several kilometres along strike. With some exceptions, namely São Domingos and Las Cruces, the deposits usually appear in groups, particularly in the large mining fields, namely Neves-Corvo and Aljustrel in Portugal and in Rio Tinto, Tharsis, La Zarza, among others in Spain.

In addition to these other smaller prospects mention is also made to the Chança mine, (6 km N of the São Domingos mine), Montinho mine (14 km SE of Aljustrel mine camp) and the Salgadinho stockwork (6 km S of the town of Cercal). The latter along with base-metals also shows gold potential.

The hydrothermal feeder system of these deposits is materialized by a stockwork made up of a dense network of quartz-chlorite-sulphide stringers, or, moreover, by families of oriented, more or less deformed vein swarms. The stockwork or the vein swarms include a typical zonation for these hydrothermal systems, including a central zone with strong chloritic and silica alteration, passing to a peripheral zone which is characterized by sericitic alteration and, more marginally, paragonitic, as described among others for the Gavião (Relvas, 1991), Aljustrel (Inverno *et al.*, 2008) and Neves-Corvo deposits (Barriga *et al.*, 1997; Relvas *et al.*, 2006).

The sulphide lenses are often deformed. However, there is good preservation of the primary structures, even more so in the central part of the bodies where the deformation was less intense. These are frequently affected, sometimes truncated, by thrusts and reverse faults, verging to the south and southeast, which often result in a significant tectonic stacking (Barriga *et al.*, 1997; Carvalho *et al.,*1999) as for the case of all the Neves-Corvo deposit where part of the hanging wall is made up of thrusted over stockwork over the massive sulphides and in Semblana where its actual shallow-dipping morphology is a consequence of this phenomena (B. Marten, pers. comm., 2012).

5. State-of-the-art methodology for exploration in the IPB

The beginning of modern exploration work in the Portuguese sector of IPB, started with the initiation of extensive surveys in the most prospective areas during the early fifties in the 20th century. These pioneering works were carried out by the then Serviço de Fomento Mineiro, now LNEG (Laboratório Nacional de Energia e Geologia), having started with systematic gravimetric surveys, at the time considered as a highly innovative technology.

The surveys carried out at that time were focused on the most potential areas of the IPB, in areas of outcropping volcanic belts (VSC), followed by a more strategic coverage of the zones dominated by the Carboniferous formations of the Baixo Alentejo Flysch Group and the Cenozoic sediments. This strategy was set up to identify hidden sulphide deposits, with an increasingly intense involvement of private, multinational mining companies along with the national state-owned bodies including the LNEG and EDM (Empresa de Desenvolvimento Mineiro).

It did not take long until the first discoveries were made, including the Moinho deposit in 1955, Feitais in 1963, Estação in 1968, all in the Aljustrel Mining camp, Gavião in 1970 and the world-class deposit of Neves-Corvo in 1977. The Lagoa Salgada deposit was discovered in 1992, under Cenozoic sedimentary formations, while the important Las Cruces deposit in Spain was intercepted, in very similar circumstances. Also noteworthy is the most recent discovery, in 2010, of the Semblana lense in the Neves-Corvo Mining Camp and the Sesmarias VMS system, in 2014, still under evaluation.

Extensive ground magnetic surveys were carried out concomitantly, a technique that continues to be used systematically today. From the beginning of the nineties, vast strategic airborne surveys followed, which proved to be highly valuable in the detection of hidden structures, as well as a reliable tool in mapping, in areas of little outcrop, or concealed both under more recent cover sediments and rocks of the Carboniferous Baixo Alentejo Flysch Group.

The most important airborne surveys were carried out by Rio Tinto and Anglo American, both in 1991, which at the time represented a significant technical advance in the understanding of the geology of the IPB. Some of these surveys were accompanied by four channel (U, Th, K and Total Count) radiometric surveys.

In addition to these methodologies, geophysical exploration work included the extensive use of electromagnetic (EM) methods, initially the Turam system which played a key role in identifying the masses of Carrasco and Moinho, in the Aljustrel mine camp. This was followed on a large scale, by other EM techniques, since the early eighties to the present, namely the Crone Geophysics Pulse-EM, the Magnetoteluric method, Zonge GDP, among many others.

From a very early stage, electrical methods were also used with some success, namely electrical resistivities, induced polarization and *Mise-à-la-Masse*. The latter was particularly useful in identifying the extensions of the Lagoa Salgada sulphide lens, right after the discovery that was successfully used to support the follow-up drilling of the NW extensions of the deposit (Castelo Branco, 1996; Oliveira *et al.*, 1998).

Reflection seismic surveys were first attempted by Somincor in 1991 and 1996 including the coverage of long 2D profiles of the exploration license area then held by the company. As a result of these surveys, deep drilling was carried out which, despite not intersecting massive sulphides, it gave a strong impetus for the local geological interpretation (West and Penney, 2017; Matos *et al.*, 2020; Donoso *et al.*, 2021).

This work served as the basis for two large, high-resolution, 3D and 2D reflection seismic surveys, in 2011 and 2012 in the areas surrounding Neves-Corvo (Donoso *et al.*, 2021; Araújo and Castelo Branco, 2010; Castelo Branco, 2014; West and Penney, 2017) and in the investigation of regional targets in the W and NW, in the alignment of the VSC rocks of the Rosário antiform (see geological setting in Oliveira *et al.*, 2016; Matos *et al.*, 2020). This led to the identification of several dozens of reflectors, two of which are attributable to the massive sulphide lenses of Lombador and Semblana in the Neves-Corvo mine. The remaining reflectors identified seem to be related to the signature of the top of heavily silicified rhyolitic domes. It is also worth mentioning the 2D seismic survey carried out in partnership between LNEG and Lundin in 2012, within the scope of the European project PROMINE (Inverno *et al.*, 2015b), which came to produce aluable

Table 1. Inventory of the main IPB deposits with indication of resources and tonnages (developed and updated from Tornos, 2006).

Tabela 1. Inventário simplificado dos principais jazigos da FPI com a indicação dos recursos e tonelagens (desenvolvida e adaptada de Tornos, 2006).

Name of deposit	M ton	% Cu	% Pb	% Zn	ppm Ag	ppm Au	% Sn	Source
Aguas Teñidas	0.4	5.7						Pinedo (1963)
Aguas Teñidas Este	41.0	1.5	0.9	3.5	40	0.50		Hidalgo (pers. comm., 2002)
Stockwork	5.5	1.5	0.1	0.3				
Pyritic	41.0	1.0	2.0	3.0				
Cupriferous	12.3	2.3	0.3	0.7	24	0.40		
Polimetallic	16.0	1.1	1.7	6.4	60	0.70		
La Magdalena	25.4	2.2	0.8	2.5	37.5			SANDFIRE (2024)
Monte Romero	0.8	2.0	2.5	5.0				IGME (1982)
Vuelta Falsa	1.0	1.3	8.8	20.7	307	9.00		IGME (1982)
Sierrecilla	1.0	1.5	5.0	12.0	500			Leistel *et al.* (1998b)
San Miguel	1.3	3.0						Pinedo (1962)
San Platón	2.5	1.5	0.2	5.6	31	0.90		
Pyritic								
Polimetallic								
Lomero–Poyatos (OP+UG)(b)	11.2	0.5	0.5	1.1	24	2.14		Denarius Metals (2023)
Lagoa Salgada								
North Zone	8.9 (b)	0.3	2.6	2.5	64.4	0.75	0.16	Ascendant Resources (2023)
Zonas Central e Sul	10 (b)	0.4	0.7	1.2	15	0.06		
San Telmo	4.0	1.2	0.4	12.0	60	0.80		IGME (1982)
Pyritic	1.0	1.2						
Polimetallic	3.0	1.2	0.4	12.0				
Cueva de La Mora	4.2	1.5	0.3	0.7				Pinedo (1963)
Herrerias	5.0	0.9	0.5	0.4				IGME (1982)
São Domingos	30.0	1.2		3.0				
La Romanera	34.0	0.4	1.2	2.3	44	0.80		
Pyritic	22.8	0.4	0.5	0.7				
Polimetallic	1.2	0.4	2.5	5.6	64	1.00		
Las Cruces	42.7	3.0	1.2	2.1	28	0.50		Doyle *et al.* (2003)
Cupriferous	4.5	3.3	0.3	1.0	18	0.30		
Polimetallic	20.7	0.8	2.0	4.2	42	0.40		
Supergene enrich.	15.5	6.1						
Gossan	2.0	0.3	4.5	0.0	115	5.10		
Lousal	50.0	0.7	0.8	1.4				Leistel *et al.* (1998b)
Stockwork		0.7	0.1	0.6				
Concepción	55.9	0.6	0.2	0.5	7	0.20		Leistel *et al.* (1998b)
Pyritic	32.1	0.1	0.0	0.1				
Cupriferous	20.7	1.3	0.1	0.3	9	0.30		
Polimetallic	3.0	0.7	2.2	5.7	34	0.50		
Valverde	92.3	0.4	1.9			0.20		Ruiz *et al.* (2001)
Pyritic	80.0	0.4	1.5 (a)			0.10		
Cupriferous	1.3	1.9	1.7 (a)			0.10		
Polimetallic	11.0	0.5	5.0 (a)			0.80		
Tharsis	115.0	0.5	0.6	2.7	22	0.70		Tornos *et al.* (1998)
Filón Norte	20.0	0.7	0.8	1.8				
San Guillermo	55.0	0.7	0.8	1.8				
Sierra Bullones	13.0	0.7	0.8	1.8				
Filón Centro	3.0	0.7	0.8	1.8				
Filón Sur	0.4							
Filón Sur(Gossan)	5.3				37	3.00		
Esperanza	4.3	0.7						
Others	18.3				37			
Sotiel-Migollas	132.8	0.7	1.2	2.8	14	0.10		IGME (1982); Santos et al.(1996)
Sotiel	75.2	0.6	1.3	3.2	24	0.20		
Migollas	57.6	0.9	1.1	2.2				
Aznalcollar	161.0	0.4	1.4	2.7	47	0.40		Pons et al. (1996); Fernández (2001)
Massive sulphides	43.0	0.4	1.8	3.3	67	1.00		
Stockwork	47.0	0.6		0.4	10			
Los Frailles								
Massive sulphides	70.0	0.3	2.1	3.8	60	0.40	0.01	Pons *et al.* (1996); Fernández (2001)
La Zarza	171.6	1.2	1.0	2.4	45	1.70		Castillo (pers. comm.)
Aljustrel	300.0 (c)							Dawson and Caessa (2003)
Zinc min.	23.6 (d)	0.2	5.7	1.8	60.79			Lundin Mining (2023)
Copper min. (f)	6.9 (e)	2.1	1.1	0.4	17.19			
Gavião	21.6	1.5	1.0	3.0	35	0.80		Dawson and Caessa (2003)
Neves-Corvo	219.3	1.9		3.1			0.13	Relvas (2000); Ferreira (pers. comm., 2002)
Copper min. (f)	56.0	2.2	0.3	0.8	44			Lundin Mining (2023)
Zinc min.o (f)	65.1	0.3	6.8	1.4	61			
Proj Semblana (g)	7.8	2.9			25			
Rio Tinto (h)	513.0	1.4						Pinedo (1963), Escobar (pers. comm., 2002), data from Mina de Rio Tinto SAL
Filón Sur (incl. San Dionisio)	268.0	2.0	0.7	1.4				
Filón Norte	25.7	1.5						
Cerro Colorado Stockwork (i)	200.0	0.4	0.1	0.2	7	0.10		
Planes-San Antonio	19.5	1.4	0.9	1.6				
Gossan	100.0	1.2	56.0	2.2				

a) Zn+Pb

b) Inferred+Indicated Resources

c) Probable tonnage of primary pyritic ore

d) Indicated+measured resources for the ore lenses of Feitais, Moinho e Estação

e) Indicated+measured resources for the ore lenses of Feitais and Moinho

f) Indicated+measured resources for Neves-Corvo

g) Inferred resources for Semblana

h) Only primary ore

i) The total tonnage of the sub-economic Cerro Colorado stocwork is 1900–2000 Mt grading 0.15%Cu and 0.07 g/t Au.

information on the progress of the structures in depth, namely in potential areas, hidden under the thick Flysch cover to the SE of Neves-Corvo (Fig. 3) (Matos *et al*., 2020).

Almost simultaneously with the gravimetric surveys initiated in the fifties, LNEG has also positioned itself at the forefront of IPB geochemical prospecting, with updates on methods and technologies, from that date to present (Batista *et al*., 2020). These geochemical sampling programs, of which LNEG has a vast database, included strategic stream sediment surveys, detailed soil geochemistry grids, partly coordinated with gravimetric surveys.

The assay methods used included cold extraction by chlorimetry (now outdated, but still usable), followed by atomic absorption and, more recently, various multielement Induced Coupled Plasma (ICP) methods. Meanwhile, other analytical techniques have been developed in soil geochemistry, namely the Mobile Metal Ions technology and others, based on the information produced by the partial extraction of specific combinations of metal ligands, transported *per ascensum* from hidden mineralizations at depth. Tests were carried out, with partially positive results on the deposits of Lagoa Salgada by Rio Tinto, Lombador by Lundin and Gavião by EDM (*e.g*., Matos *et al*., 2020).

In addition to the range of tools used, absolute and relative dating played an important role as ore finder, the first performed on volcanic and volcaniclastic rocks (isotopic dates), the second in metasediments (palynology). These methods have undergone a significant evolution in the last two decades, enabling new structural, paleogeographic, stratigraphic and geodynamic interpretations impossible until then, based on the identification and dating of some of the known ore/guide horizons, related to mineralizing events (Oliveira *et al*., 2013; Pereira *et al*., 2021, 2023).

Finally, the fundamental contribution of core drilling in the understanding of the geology of the IPB, as well as in the identification and evaluation of new deposits. Drilling is called with humour the best "geophysical method", being ultimately responsible for the discovery of concealed deposits, which corresponds to the totality of new discoveries in the IPB today. It is estimated, based on provisional data, that, from 1953 to 2016, approximately 1136 holes have been drilled, which made a total of 405,402 m (J. Matos, pers. comm., 2019). These figures do not include all surface and underground evaluation drilling carried out in Aljustrel, Neves-Corvo and Gavião during the last decades.

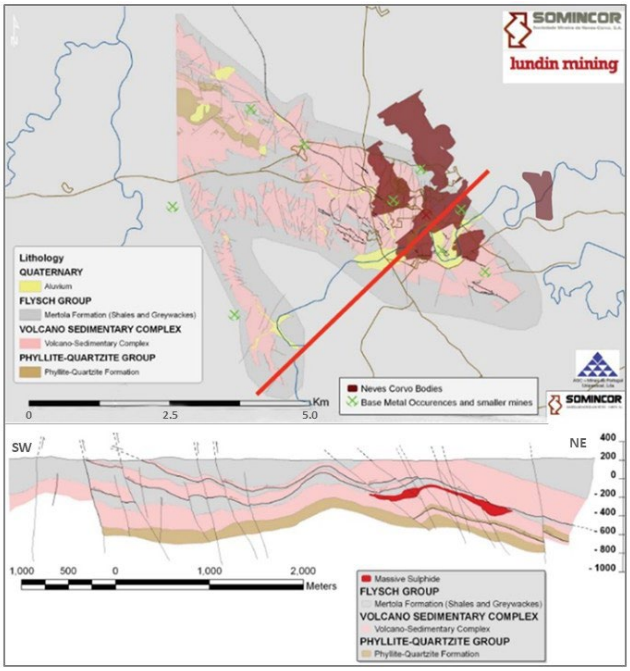

Figure 3. Simplified geology map (above) and interpretative geological section (below) of the Neves-Corvo area (B. Marten, pers. comm., 2012).

Figura 3. Carta geológica (acima) e secção geológica interpretativa (abaixo) da zona de Neves-Corvo (B. Marten, pers. comm., 2012).

6. Current exploration strategy and cutting-edge methods

Based on the current understanding of the IPB, it seems somewhat consensual among the technical and scientific community that the potential for discovery of new deposits lies essentially at depths greater than 400-500 m. Up to these depths, the probability of discovering new deposits is therefore considered to be lower, based on the results available from geophysical surveys and drilling. Therefore, it is anticipated that this more superficial fringe will be somewhat better recognized, and for this reason largely sterilized.

It should be noted that this interpretation must, however, be taken with due reservations, since exceptions to the rule are always liable to occur, using, among others, the example of the recent discovery in Spain, of the new upper mass from La Magdalena intercepted by the MATSA team at 200 m depth (Granda *et al*., 2016). The body initially identified coincides with an airborne VTEM anomaly (electromagnetic) in an area previously covered by other geophysical methods, namely gravity and TEM, without having previously identified any significant targets.

In recent years there has been a progressive sophistication on the exploration approach, both in terms of data processing and in the methodologies used, to face the challenge of the assumption that new discoveries of polymetallic sulphides will occur at greater depths.

The current understanding of the way forward involves a homogenization of multiple databases (analogue and digital) and fusion of the whole, ideally into a single regional dataset, followed by the production of 3D geological models with more advanced software and, finally, the integrated interpretation of the data as a whole, with a view to defining new targets to investigate.

Exploration strategy has been increasingly supported by a multidisciplinary geological and geochemical input combined with gravimetric and magnetic inversions / models, on a regional scale (Marques *et al*., 2019; Matos *et al*., 2020), almost always supported by airborne surveys (VTEM, ZTEM, magnetic, Radiometric, etc.).

This will be followed using EM methodologies with greater penetration and definition, with emphasis on the TEM method with the high-resolution sensor, known by the acronym *SQUID* (Superconducting Quantum Interference Devices), which reaches depths greater than 1000 m in the IPB's terranes. When drilled, the targets thus identified should then be investigated using downhole EM techniques (*e.g*., Figs. 4 and 5), whenever possible, to investigate, on the one hand, the presence of electrical conductors in the vicinity of the drill hole trajectory and, on the other hand, the orientation and magnitude of these conductors.

This strategy, in addition to the success demonstrated in the discovery of Semblana in the Neves-Corvo mining field, (Fig. 5), played a crucial role in Spain in the discovery of the La Magdalena deposit, intercepted about 8 km to the east of the Aguas Teñidas deposit. The ore lens *Masa 1* (about 6 Mt) was detected by a drill hole checking an electric conductor identified through a VTEM survey at a depth of 225 m. Follow-up deeper drilling was accompanied by down-hole EM. This led to the identification of a strong off-section electrical conductor which

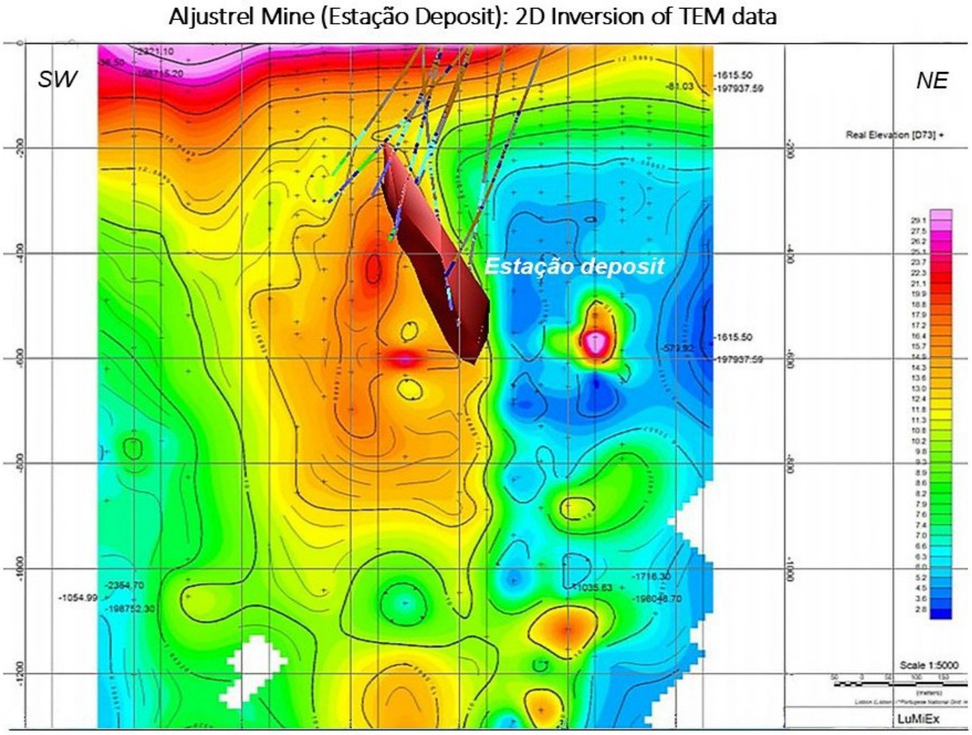

Figure 4. Estação deposit, Aljustrel mine. Cross-section with drilling and 2D SW-NE inverted TEM pseudosection (Casstelo Branco, 2014).

Figura 4. Depósito da Estação, mina de Aljustrel. Secção geológica e pseudosecção 2D com inversão dos dados de TEM (Castelo Branco, 2014).

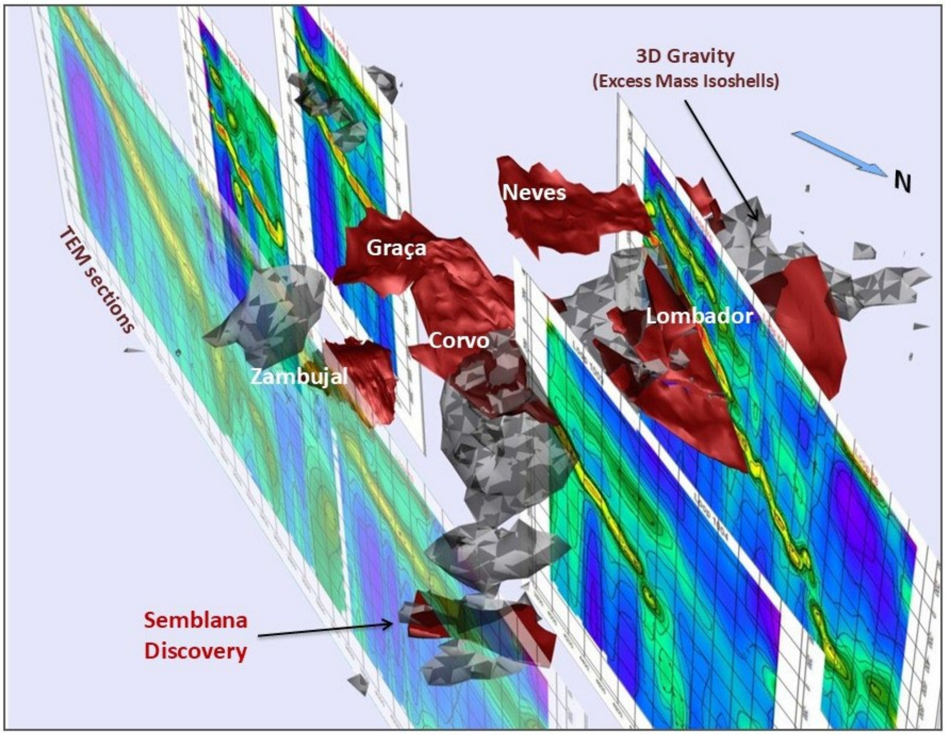

Figure 5. 3D modelling of the Neves-Corvo lenses with TEM and gravimetry which led to the discovery of the Semblana (Araújo and Castelo Branco, 2010; Casstelo Branco, 2014).
Figura 5. Modelação 3D das massas de Neves-Corvo com a integração dos dados de TEM e gravimetria os quais levaram à dscoberta do jazigo da Semblana (Araújo e Castelo Branco, 2010; Casstelo Branco, 2014).

was later drilled, having successfully intercepted a new large-size sulphide body, from about 349 m deep, the *Masa 2* ore lens (about 44 Mt).

The potential of the high-resolution seismic reflection methods is also highlighted as a valid exploration tool, and although being still quite expensive, it has gradually been included in the list of options for increasingly deeper targets (Brodic *et al*., 2021; Matos *et al*., 2020). Finally, mention should be made to the growing sophistication of the technologies used in current drilling (equipment, muds, additives, etc.) as well as the use of directional drilling techniques namely Devico, (now part of IMDEX) that was extensively used in recent times in the Neves-Corvo mine, but also Boart Longyear, Geodrill, International Directional Services (IDS) among many others.

7. Challenges and discovery potential of new VHMS deposits in Portugal

From the most recent discoveries throughout the IPB, the one that stands out most is, of course, Neves-Corvo (1977), both in size and high metal content, including massive copper, lead, zinc, silver and tin ores and footwall black shales (Fig. 6a). Meanwhile, the Lombador orebody was identified 11 years later and, more recently, Semblana in 2010 (Fig. 6b), and in 2012 the Monte Branco cupriferous *stockwork*, still under evaluation, all within the Neves-Corvo Mine lease (Lundin NI 43-101Tech. rep. 2023). Elsewhere in the Iberian Pyrite Belt recent discoveries include Lagoa Salgada in 1992 (Gaspar *et al*., 1993; Oliveira *et al*., 1998; Matos *et al*., 2000, 2020; Oliveira *et al*., 2011; Ascendant Resources, 2019, 2021, 2023) and Sesmarias in 2014 (Matos *et al*., 2020) that are both under evaluation.

This constitutes strong evidence of the enormous potential for the discovery of new deposits, either in the vicinity of those already known or in new areas, as in the case of the discovery of the Lagoa Salgada massive sulphides hidden under about 128 m of Cenozoic and Quaternary sediment cover (Oliveira *et al*., 1998). In the Spanish sector, the Las Cruces deposit located near Seville, which was discovered almost simultaneously with Lagoa Salgada, on a very similar setting, is now in the process of advancing with an underground operation after mining the supergene high-grade section of the deposit by open pit methods.

Lack of continuity of VSC outcrops by more recent Cenozoic sediments and the masking produced by hydrothermal alterations, imply that the nature and the complex architecture of the volcanic packages represent, on one hand, a challenge to overcome and, on the other, a favourable factor for the discovery of new deposits. This can be facilitated by a combination of geochemistry from trace and major elements, textural/facies analysis to help target definition (Matos *et al*., 2000, 2020; Batista *et al*., 2020).

As previously stated, the VSC does not occur on continuous outcrop and thus only represents about 25% of the total area of exposure in the South Portuguese Zone, and in Portugal this percentage is much lower, perhaps in the order of 5%. This discrepancy may explain the much higher number of known deposits in the Spanish side when compared to the Portuguese sector. Furthermore, the larger areal extent of the late Carboniferous Flysch sediments may also contribute to the significant difference in number of deposits cropping out or subcropping in the Portuguese sector. This although representing a challenge to exploration may also be a positive factor for the revelation of new, hidden deposits as new innovative technologies and exploration approaches are being developed, like 2D/3D seismics combined with TEM/DHEM, geochemistry and fine stratigraphy (Inverno *et al*., 2015b; West and Penney, 2017; Matos *et al*., 2020).

A metaphor used commonly on the mineral resources sector is that large deposits are often referred to as elephants. Like “elephants”, these deposits are not common, but when they occur, they almost always appear in “herds”. The analogy of the IPB and an *Elephant Country*, outlines an attractive exploration target given the high reward in case of success which the most recent discoveries in Portugal and Spain are unquestionable proof.

8. Conclusions

The large size of the volcanogenic massive sulphide deposits mined to date, undoubtedly enhances the high economic interest played by the IPB from the pre-Roman period to the present as in the case of the recent discoveries namely Semblana, Monte Branco and Sesmarias in Portugal and La Magdalena along with the Majadales adjacent to the Masa Valverde in Spain. These

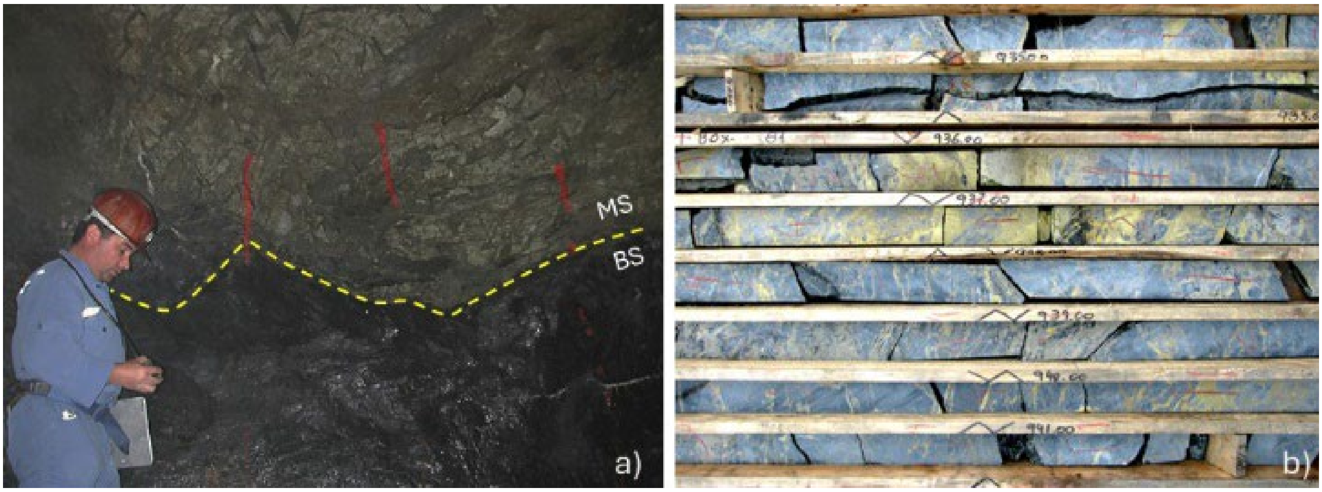

Figure 6. a) Stope face at Graça body in Neves Corvo deposit (photo of N. Pacheco, Somincor). MS – Massive Sulphide; BS – Footwall black shales. b) Cupriferous stockwork core intercept from the Semblana deposit.

Figura 6. a) Frente de desmonte no corpo da Graça no jazigo de Neves-Corvo (foto de N. Pacheco, Somincor). MS-Sulfureto Maciço; BS-Xistos Negros a muro. b) Interceção de sondagem de *stockwork* cuprífero do jazigo da Semblana.

discoveries are a result of an increased exploration effort and puts in perspective an enormous potential for the discovery of new deposits.

In the case of the IPB segment in Portugal, the discovery potential is particularly evident, due to the large areal extent of the Cenozoic sediments covering the volcanic structures, which host the base-metal mineralization, by sediments of the Flysch group in some areas and, by Cenozoic sediments, in others.

Based on this assumption, it is therefore necessary to adopt an exploration strategy tailored to the investigation of the aforementioned models, which will necessarily involve the use of powerful detection techniques, namely geophysics, and systematic palynology, a good geological control, supported naturally by deep diamond drilling.

In addition to the covered areas mentioned above, it is also necessary to investigate a whole set of deep targets that may be identified based on geophysical surveys (TEM, Seismic, Gravimetry, among others), potentially masked by the stacking of tectonic slices which would otherwise be impossible to identify.

In order to further advance along this path, it is necessary to clearly assess the present technical challenges, namely the greater depths of the targets, their structural complexity and, based on this, design compatible exploration programs.

Due to the substantial means that these programs involve, it is anticipated that the IPB is more tailored for companies with a strong financial capacity or easy financing, as they involve considerable investments, which is a difficult task for junior groups. Work programs must be well designed, disciplined and supported by compatible budgets. Time and resilience are keys to success.

It will be necessary to use new concepts and technologies, to reassess and prioritize in a dynamic way for target selection and testing. It will be imperative to invest courageously on aggressive drilling campaigns, focused on deep, high-ranking targets.

To do this we must add a certain dose of serendipity, a term created by the British writer, Horace Walpole, to describe something unexpected, the result of luck, but based on an attitude of wit and persistence!

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