

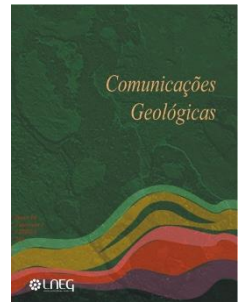
Geophysical surveys in the Portuguese sector of the Iberian Pyrite Belt: a global overview focused on the massive sulphide exploration and geologic interpretation

Levantamentos geofísicos no setor português da Faixa Piritosa Ibérica: perspetiva global da sua importância em prospeção de sulfuretos maciços e interpretação geológica

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Abstract: The application of geophysical techniques to massive sulphide deposits exploration has proven to be a success in the Iberian Pyrite Belt (IPB) metallogenic province, both in Portugal and in Spain. Several hidden deposits were discovered through the interpretation of geological models, supported by geophysical data collected in land and airborne surveys, as well as applied using down hole techniques in selected drill holes. This paper presents an overview of the methodologies applied in Portugal in the South Portuguese Zone (SPZ) geological domain, where the IPB is included, mostly by the LNEG and mining companies, with emphasis on the interpretation of the regional gravity, magnetometry and radiometry surveys, published in 1/400 000 scale by the EXPLORA/Alentejo2020 Project. In this regional mapping program, the large volume of data collected by LNEG and mining companies since the 1960's was compiled and processed. The integrated interpretation and correlation between these methods will enable a better planning of new IPB exploration investments. IPB Volcano-Sedimentary Complex (VSC, Famennian to Late Viséan age) lineaments are well defined in the gravity and magnetic fields along the IPB western region (*e.g.* Alcoutim/Neves-Corvo/Montinho/Sesmaria/Lousal/Caveira). Aeromagnetic data also reflect deep and large anomalies related with the SPZ basement. A rock density database is presented and used to interpret the gravity data. Radiometric map (Natural Radioactivity), based mostly in airborne radiometric surveys, show contrasts between rocks in Paleozoic, Mesozoic and Cenozoic formations and correlations with geological and hydrothermal mapping are highlighted. The use of geophysical techniques is particularly critical in areas where VSC is concealed by younger sediments (*e.g.* Baixo Alentejo Flysch Group and/or Cenozoic formations), allowing the selection of target areas. Case studies are discussed based on electromagnetics, seismic and magnetotelluric methods and on the high mineral potential of defined targets. Multilayered data correlation (geophysics including petrophysical data, geochemistry and stratigraphic high-resolution models) is a key prospecting methodology and is essential for the accurate modelling of ore horizons and geological structures. Considering the IPB potential for VMS deposits, including the possible discovery of new giant (> 200 Mt) deposits, an increase of investment in new geophysical methods can be predicted. LNEG development of R&D projects such as EXPLORA/Alentejo2020 and SmartExplorationTM/H2020 also contribute to a favourable setting in the province, both in near mining and green fields scenarios. Thus, new discoveries are expected, like others made in the recent times in the IPB Portuguese sector, such as Lagoa Salgada (SFM, 1992, SFM; Redcorp/EDM, 2011; Redcorp/Ascendant/EDM, 2017), Semblana (Somincor-AGC-Lundin Mining, 2010), Monte Branco (Somincor-Lundin Mining, 2012) and Sesmaria (Maepa/Avrupa, 2014). The importance of these data goes beyond the mineral exploration purpose.

Since some of them use rock and mineral physical properties that can be related with environmental contamination (*e.g.* radiometry and magnetics) they can also be used in geochemical background studies, acid mine drainage and metal dispersion. Therefore, they can also promote a deeper knowledge in other areas of research related with environment preservation.

Keywords: Iberian Pyrite Belt, South Portuguese Zone, massive sulphides, geophysics, mineral exploration.

Resumo: A aplicação de técnicas de prospeção geofísica na pesquisa de jazigos de sulfuretos maciços na Faixa Piritosa Ibérica (FPI) tem-se revelado um sucesso em Portugal e em Espanha. Vários jazigos ocultos foram descobertos a partir da interpretação de modelos geológicos, com o apoio de dados geofísicos recolhidos em levantamentos terrestres, aerotransportados ou em profundidade, em sondagens (diagrfias). Neste artigo, apresenta-se uma análise das metodologias aplicadas principalmente pelo LNEG e empresas mineiras em Portugal, na Zona Sul Portuguesa (ZSP), onde se insere a FPI. Destaca-se a interpretação dos levantamentos regionais, esc. 1/400 000, de gravimetria, magnetometria e radiometria (EXPLORA/Alentejo2020). Nestes programas, foi feito o processamento de um volume de informação significativo, a partir de dados obtidos desde a década de 1960. Neste contexto indicam-se diversos alinhamentos de gravimetria e de aeromagnetometria relativos a unidades geológicas com elevado potencial mineiro, como o Complexo Vulcano-Sedimentar (CVS, idade Famenniano a Viséano sup.), sobressaindo o eixo Alcoutim/Neves-Corvo/Montinho/Sesmaria/Lousal/Caveira. Os dados de aeromagnetismo refletem também anomalias com origens mais profundas e relacionadas com a estrutura basal da ZSP. A base de dados de densidades de rocha é utilizada na interpretação gravimétrica da FPI. O mapa radiométrico (Radioatividade Natural), baseado fundamentalmente em radiometria aeroportada (contagens totais) mostra o contraste à superfície de litologias das formações paleozoicas, mesozoicas e cenozoicas, sendo salientado, no primeiro caso, a sua correlação com a cartografia de alterações hidrotermais. Em áreas onde o CVS se encontra subjacente sob sedimentos mais recentes (*ex.* Grupo Flysch Baixo Alentejo e formações cenozoicas), o uso de técnicas geofísicas é fundamental para a seleção de alvos. São também descritos exemplos sobre a aplicação de métodos eletromagnéticos, sísmicos e magnetotéluricos na identificação e caracterização de estruturas geológicas. A análise integrada de diferentes métodos geofísicos, complementados com informação geológica e geoquímica, constitui a melhor metodologia de prospeção, sendo essencial para a pesquisa de horizontes de mineralização. Considerando a FPI como uma das

principais províncias metalogenéticas do mundo, é expectável que venham a ocorrer mais investimentos e assim serem identificados novos jazigos, inclusive com dimensão superior a 200 Mt. Através de projetos ID como o EXPLORA/Alentejo2020 e SmartExploration™/H2020 o LNEG contribui para um melhor conhecimento na FPI em cenários de prospeção *near mining* e *green fields*. Nesta perspectiva, são esperadas novas descobertas de jazigos à semelhança do que tem acontecido em Portugal, como por exemplo Lagoa Salgada (SFM-1992, Redcorp/EDM-2011, Redcorp/Ascendant/EDM-2017), Semblana (Somincor-AGC-Lundin Mining, 2010), Monte Branco (Somincor-Lundin Mining, 2012) e Sesmarias (Maepa/Avrupa, 2014). A importância destes dados vai muito para além da prospeção mineira. Uma vez que alguns métodos utilizam propriedades físicas que podem ser relacionadas com contaminações ambientais. Certos métodos geofísicos como radiometria e magnetometria, resistividade e métodos elétricos em geral, podem ser utilizados também em trabalhos de investigação sobre background geoquímico, drenagem ácida de mina e dispersão de metais. Desta forma, a aplicação destes métodos promove também um conhecimento mais aprofundado noutras áreas de investigação relacionadas com a preservação do ambiente.

Palavras-chave: Faixa Piritosa Ibérica, Zona Sul Portuguesa, sulfuretos maciços, geofísica, prospeção mineral.

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1. Introduction

The Iberian Pyrite Belt (IPB) is one of the main world provinces of massive sulphide deposits and considered a key mining region in Europe. The IPB is shared by the Alentejo (Portugal) and Andalusia (Spain) provinces and is characterized by more than 90 VMS deposits (Barriga *et al.*, 1997; Leistel *et al.*, 1998; Carvalho *et al.*, 1999; Saez *et al.*, 1999; Tornos, 2006; Almodovar *et al.*, 2019) associated with the Volcano-Sedimentary Complex (Famennian-Late Visean age) and Phyllite-Quartzite Group (Givetian-Strunian age) (Pereira *et al.*, 2008; Oliveira *et al.*, 2013, 2019), (see Fig. 1). The use of geophysical prospecting methods has always been recognised as a powerful tool in mineral resources exploration. Taking advantage of rock contrast physical properties, a set of methods can be applied, and each survey can be carefully planned according with target characteristics, host rock and geological setting. The goal of this paper is to review the geophysical methods applied in VMS deposit exploration in the IPB Portuguese sector. Exploration criteria, case studies and type of surveys carried out at regional and local scales are presented and discussed. The gravimetric, magnetic and radiometric 1/400 000 scale maps (LNEG/EXPLORA edition, Represas *et al.*, 2016a, b; Batista *et al.*, 2016b), are also presented and discussed. Considering the present knowledge, multidisciplinary exploration vectors are defined, related with primary sulphide mineralizations occurrence and later mineralization stages related with syn-tectonic ore forming events, late variscan faults and development of supergene alteration zones related with Paleozoic basement erosion. The exploration overview is focused on the IPB Portuguese sector experiences since the 1960s. Geophysical surveys have been used to identify AMD groundwater, using electromagnetics Geonics EM31, EM 34, Self-Potential (SP) (*e.g.* Custis, 1994). Groundwater quality parameters include an increase in mineralization that can be detected through electromagnetic and electrical methods (*e.g.* Custis, 1994; Shemang *et al.*, 2003; Moreira *et al.*, 2020). Magnetic, gravimetric and radiometric data can also be used to identify

faults and conductive structures that locally can show not only paths on mineral deposits existence but also the electrical and electromagnetic methods can be used in the study of contamination sites, as a result of mining activity. Nonetheless, the same methods used to identify potential mineral deposits can also be used to diagnose situations caused by their exploration that can potentially be an environmental problem. Radiometry can be an accurate methodology to be applied in geochemical background, AMD and metal dispersion studies. Magnetometry can also be useful in these scenarios. However, this issue does not belong to the aim of this volume, whose target is IPB as a valuable province to exploit and enhance.

Although this paper does not also have the goal of describing and explaining the geophysical methods herein referred, table 1 shows the following mentioned geophysical methods and the physical properties they study. A comprehensive approach of the geophysical methods applied to mineral prospecting can be found in many publications and specific textbooks (*e.g.* Milsom, 2003; Telford *et al.*, 2012) or related with environmental protection (Reynolds, 1997; Sharma, 1997).

Table 1. Geophysical methods referred in this paper applied to mineral exploration and the rock physical properties they study.

Tabela 1. Métodos geofísicos referidos neste trabalho aplicados em prospeção mineral e as propriedades físicas das rochas que eles estudam.

| Geophysical method | Physical property | Units | Usual mapping units | 2D modelling | 3D modelling |
|---|---|--------------------------|--------------------------|---|---|
| Gravimetry | Density | gcm ⁻³ | mGal | Yes | Yes |
| Magnetometry | Magnetic susceptibility | SI | nT | Yes | Yes |
| Radiometry | Natural gamma radiation | ppm, %, cps | nGyh ⁻¹ | No or yes (if there is a number enough of natural gamma ray logs) | No or yes (if there is a number enough of natural gamma ray logs) |
| Electrical Resistivity | Electrical resistivity | ohm.m | ohm.m | Yes | Yes |
| Induced Polarization | Chargeability | ms | ms | Yes | Yes |
| Electromagnetics, EM (time and frequency domains) | Electrical conductivity/ electrical resistivity | mSm ⁻¹ /ohm.m | mSm ⁻¹ /ohm.m | Yes | Yes |
| Geophysical logging | Several parameters, depending on the chosen logging programme | na* | na* | Yes (if there is a suitable number of geophysical logs) | Yes (if there is a suitable number of geophysical logs) |
| Seismics | Velocity of P waves; velocity of S waves | ms ⁻¹ | ms ⁻¹ | Yes | Yes |

*na – non applicable.

2. VMS deposits exploration in the IPB

The application of geophysical techniques in massive sulphides deposits exploration has been a success in the Iberian Pyrite Belt province (IPB), both in Portugal and in Spain. Several non-outcropping massive sulphide deposits associated to the IPB Volcano-Sedimentary Complex (VSC) (Famennian-Late Visean age, Pereira *et al.*, 2008; Oliveira *et al.*, 2013, 2019) were discovered in SW Iberia using interactive interpretation of geological and geophysical models, such as Feitais and Gavião (Aljustrel) (Andrade and Schermerhorn, 1971); Neves-Corvo (Albouby *et al.*, 1981; Carvalho, 1982; Leca *et al.*, 1983), Lagoa Salgada (Oliveira *et al.*, 1993, 1998a, b; Matos *et al.*, 2000;

Daigle, 2018; Murahwi and Gowans, 2019) and Sesmarias (Kuhn, 2017; Coder and Kuhn, 2020) in Portugal (Fig. 1 and Tab. 2) and Valverde (Castroviejo *et al.*, 1996; Gable *et al.*, 1998), Las Cruces (Doyle, 1996), La Magdalena (Sáenz de Sicilia, 2013) and Elvira (discovered by Matsa in 2018, Gisbert *et al.*, 2019) in Spain (see Fig. 1). Over the last decade *stockwork* mineralization (sulphide veins network) become an important mining resource considering the decrease of the copper cut off and stockwork minor content in penalty elements compared to massive ore. The economic demand for this type of mineralization is reflected in an increasing interest over host rocks study. Commonly, IPB

stockwork networks are hosted by VSC felsic volcanic rocks and black shales (Leistel, 1998; Tornos, 2006; Relvas, 2006; Matos *et al.*, 2011) that exist close to the massive ore or nearby. These sulphide networks can also be present in the Phyllite-Quartzite Formation (PQ) (Givetian-Strunian, Pereira *et al.*, 2008; Matos *et al.*, 2014; Mendes *et al.*, 2020b) considered the VSC basement. Currently massive and *stockwork* mineralizations are exploration main targets and must be considered in research and geological, geophysical and geochemistry modelling (see current exploration methods and techniques in table 3).

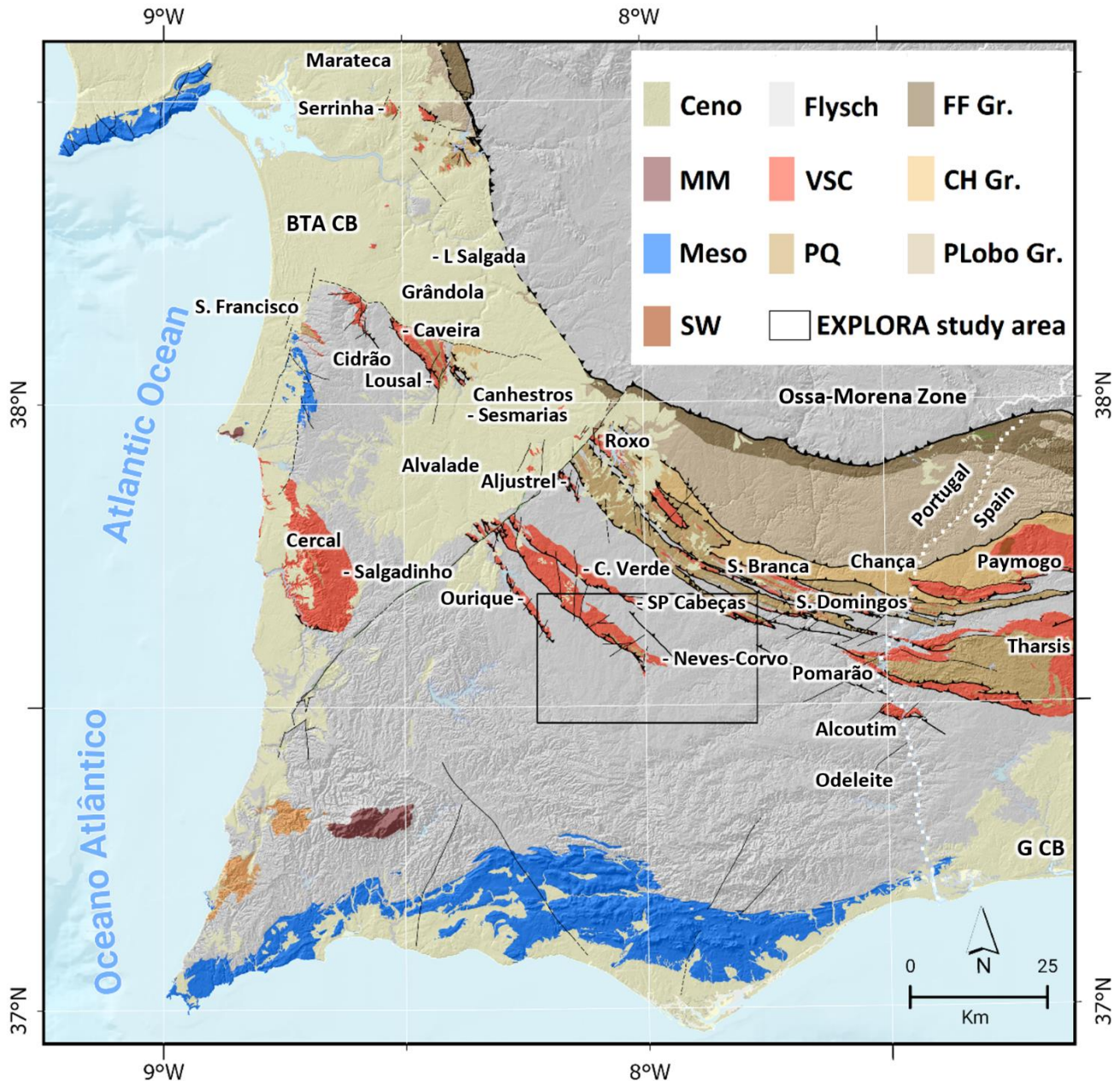


Figure 1. South Portuguese Zone in Portugal and western sector of Iberian Pyrite Belt. Ceno - Cenozoic Basins: Baixo Tejo - Alvalade (BTA CB) and Guadalquivir (G CB); MM - Sines and Monchique mesozoic massifs; Meso - Mesozoic sequences; SW - SW Sector; Flysch - Baixo Alentejo Flysch Group; Iberian Pyrite Belt: VSC - Volcano-Sedimentary Complex; PQ - Phyllite-Quartzite Group; Pulo do Lobo Domain: FF Gr. - Ferreira-Ficalho Group; CH Gr. - Chança Group; PLobo Gr. - Pulo do Lobo Group including basic volcanic rocks. Rectangle: EXPLORA Neves-Corvo/S. Pedro das Cabeças study área, see gravity map. Geology: LNEG-IGME 1/400 000 GEO-FPI Project Map.

Figura 1. Zona Sul Portuguesa em Portugal e setor oeste da Faixa Piritosa Ibérica. Ceno - Bacias Cenozoicas: Baixo Tejo-Alvalade (BTA CB) e Guadalquivir (G CB); MM - maciços mesozoicos de Sines e Monchique; Meso - sequências mesozoicas; SW - Setor SW; Flysch - Grupo Flysch Baixo Alentejo; Faixa Piritosa Ibérica: VSC - Complexo Vulcano-Sedimentar; PQ - Grupo Filito-Quartzítico; Domínio Pulo do Lobo: FF Gr. - Grupo Ferreira-Ficalho; CH Gr. - Grupo Chança; PLobo Gr. - Grupo Pulo do Lobo incluindo rochas vulcânicas básicas. Retângulo: área de estudo EXPLORA Neves-Corvo/S. Pedro das Cabeças, ver mapa gravimétrico. Geologia: Mapa LNEG-IGME 1/400 000 Projeto GEO-FPI.

In the IPB Portuguese sector, an important initial work was enhanced by the regional and systematic surveys developed and improved by the former government agencies Serviço de Fomento Mineiro (SFM)/Instituto Geológico e Mineiro (IGM), presently LNEG (Carvalho, 1982; Queiroz *et al.*, 1990; Oliveira *et al.*, 1993, 1998a, b, c; Matos and Sousa, 2008; Matos *et al.*, 2009). This public investment and other surveys promoted by exploration companies, allowed the development of large databases that increased along time, especially in methods like gravimetry, magnetometry, geoelectrical and electromagnetics. This paper presents an overview of the geophysical techniques, with emphasis on gravity, magnetic and radiometric surveys, considering a regional approach to the IPB Portuguese sector. A key European mining region where since the 1950s, 46 companies and Geological Surveys (LNEG/IGM/SFM) conducted dozens of exploration projects.

The following IPB regions can be considered in Portugal, from NW to SE (see geology characteristics on Tab. 4 and Fig. 1): Grândola/Marateca; São Francisco/Cidrão; Lousal/Caveira; Alvalade/Canhestros; Cercal/Odemira; Ourique; Montinho/Rosário/Neves-Corvo; Castro Verde/Casével; Aljustrel; Roxo/Albernôa-S.Branca-São Domingos-Chança; Pomarão and Martinlongo-Alcoutim-Odeleite. As expected, regions with large outcrop areas of VSC volcanic felsic rocks are the most selected for investment, like Lousal-Caveira, Rosário-Neves-Corvo, Aljustrel and Serra Branca-São Domingos. Local case studies are also important, and are presented, focusing on geological structures and ore deposits characterization, using gravity, magnetic, electromagnetic, seismic and magnetotelluric methods, correlated with geological data from surface mapping and exploration drill holes. A correlation between regional gravity, magnetic and radiometric maps (1/400 000 scale, Batista *et al.*, 2016b; Represas *et al.*, 2016a, b) is proposed, considering the IPB western region geological setting and possible VMS deposits scenarios.

The integrated approach to the IPB ores (massive sulphides, *stockwork* and disseminated veins) and geological ore horizons is an important key for a successful exploration planning. The LNEG development of R&D projects, such as EXPLORA/Alentejo2020 and SmartExplorationTM/H2020, also contribute to the enhancement of this integrated approach, both in near mining and green fields scenarios. In both cases, geophysics provides useful information allowing to correlate geological surface mapping and known stratigraphic sequences with deep geological structures. In unknown areas, new scenarios favourable to ore horizons can be predicted and indicated by geological-geophysical interactive modelling.

3. Exploration surveys at regional and local scale in the IPB Portuguese sector

Geophysical methods have been widely used in the IPB since the early 1940s. As part of a national prospecting plan lead by the former SFM (Carvalho, 1982; Queiroz *et al.*, 1990) and IGM (Oliveira *et al.*, 1993), both of them Governmental Institutions dedicated to the mining industry, several surveys were conducted between the 1950s and the 1990s. Up to the present day, dozens of surveys were carried out (Tab. 4), carried out by the SFM/IGM activity, and LNEG RD projects like EXPLORA, leading to easy data access and to the discovery of several massive sulphide deposits, including the giant Neves-Corvo Cu-Zn-Sn world class deposit (Tab. 2, Fig. 1) (Albouy *et al.*, 1981; Carvalho, 1982; Carvalho *et al.*, 1996; Pacheco *et al.*, 1998; Carvalho *et al.*, 1999; Relvas *et al.*, 2006; Matos and Sousa, 2008).

Moreover, international investors like Amax, Anglo American (Minaport), Antofagasta, Asarco, Ascendant, Atlantic Copper, Avrupa, Billiton, BP Minerals, Colt Resources, Conasa, Elf Aquitaine, Ferragudo Mining, Lundin Mining (Somincor/AGC Minas de Portugal), Northern Lion Gold Oy, Redcorp, Redfern, Rio Tinto (Riofinex, Soc. Mineira Rio Artezia), Utah and the consortiums SPE/SEREM/EDMA and SMS/SEREM/SMMPP, lead to a continuous investment in geophysical research, based on ground and airborne surveys.

In some areas, the technical support was provided by the SFM, IGM and LNEG teams (Matzke, 1971; Albouy *et al.*, 1981; Leca *et al.*, 1983; Leca, 1990; Castelo Branco, 1995; La Fuente, 1995; Carvalho *et al.*, 1996; Castelo Branco, 1996; Palomero and Mora, 1996; Castelo Branco and Sá, 1997; Palomero, 1999; Mora, 2002; Faria, 2007; Matos *et al.*, 2009a, b; Araujo and Castelo Branco, 2010; Carvalho *et al.*, 2011), which resulted in a scientific interchange between mining companies and the Portuguese government. National companies like the Emp. de Desenvolvimento Mineiro (EDM), Emp. Desenvolvimento Mineiro do Alentejo (EDMA), Emp. Mineira e Metalúrgica do Alentejo (EMMA), Emp. Mineira Serra do Cercal (EMSC), MAEPA, Portuglobal, Pirites Alentejanas and Somincor also invested in different geophysical surveys.

A significant volume of exploration work was conducted by junior mining companies, investing in the characterization of drill targets defined in the geological structures with high mining potential. Relog of old exploration drill holes was commonly being supported by LNEG drill core shead (*e.g.* Avrupa/Maepa 50 km relog in 2012-2013, before the discovery of the Sesmarias ore lens in 2014, Khun, 2017). Meantime, specialized consulting companies worked at IPB, to improve data processing and interpretation techniques *e.g.* A.B. Elektrisk Malmteining, Adaro, Anglo American (Minaport) prospecting services, Bundesanstalt für Geowissenschaften und Rohstoffe, Condor Consulting, Compagnie Générale de Géophysique, Crone Geophysics, Geoconsult, Geoterrex, Institut für Geophysik TU Clausthal, International Geophysical Technology, International Geotech Airborne, La Montagne SAP, Lea Cross Geophysics, Lab. Geophysique Appliqué et Structural, Mac Phar, University of Nancy, Soc. Mineira Rio Artezia/Rio Tinto Zinc, Sanders Geophysics and Urganhart-Dvorak. The SFM, IGM and LNEG teams worked for various mining companies as geophysical consultants (gravity, magnetic, seismic, electric and electromagnetic surveys), and the collaborations with MAEPA, Northern Lion Oy, Somincor and Soc. Mineira Rio Artezia are good and recent examples of this effort (Faria, 2007; Matos *et al.*, 2009a, b; Ramalho and Matos, 2009; Carvalho *et al.*, 2011).

The first geophysical method used in the Portuguese sector of the IPB was the electromagnetic Turam technique, with some initial essays in the early 1940s (Gomes, 1955; Queiroz *et al.*, 1990). However, the comprehensive geophysical prospecting activity only started in the early 1950s with the continuous work of the SFM teams, especially near the active main mining areas of Aljustrel and São Domingos, respectively operated by Mines d'Aljustrel (Matzke and Schermerhorn, 1971; Leitão, 1998; Martins *et al.*, 2003) and Mason and Barry companies (Webb 1958; Palmer, 1961; Carvalho, 1982; Matos *et al.*, 2006).

The discovery, in 1953, of the near surface section of the Aljustrel Moinho sub vertical massive sulphide orebody (Andrade, 1953; Carvalho, 1982; Leitão, 1998, 2009), named Carrasco, is the first successful application of the Turam method in the Portuguese IPB. This positive result promoted the SFM regional surveys dedicated to the exploration study of areas where the VSC and PQ formations outcrop (Fig. 1).

Table 2. Massive sulphide and *stockwork* mineralization discoveries in IPB Portuguese sector since the 1950s.Tabela 2. Mineralizações de sulfuretos maciços e *stockwork* no sector português da FPI, desde a década de 1950.

| Ore deposit/region | Year | Institution | Exploration methodology | Status | Drill hole | Depth* | References |
|---|------|----------------------------|---|-------------------|----------------|---------|--|
| Cerro do Carrasco/Aljustrel | 1953 | SFM-Mines d'Aljustrel | EM Turam, geology | NME | Mine shaft | 14 m | Andrade, 1953; Carvalho, 1982 |
| Moinho/Aljustrel | 1955 | SFM-Mines d'Aljustrel | EM Turam, geology | Mining (Almina) | | 50 m | Gomes and Silva, 1955; Andrade and Schermerhorn, 1971; Carvalho, 1982 |
| Feitais/Aljustrel | 1963 | Mines d' Aljustrel | Gravimetry, geology | Mining (Almina) | LC1 | 156 m | Mines D'Aljustrel, 1964; Andrade and Schermerhorn, 1971 |
| António/Lousal | 1966 | Mines et Industries | Geology | NME | | | Silva, 1968; Matzke, 1971; Carvalho, 1982 |
| Estação/Aljustrel | 1968 | SFM | Gravimetry | NME | S1 | 320 m | Oliveira, 1968; Andrade and Schermerhorn, 1971; Carvalho, 1982 |
| Gavião/Aljustrel | 1970 | SMS | Gravimetry, geology | Exploration ** | SA1 | 162 m | Soc. Mineira de Santiago, 1970; Andrade and Schermerhorn, 1971 |
| José and Fernando/Lousal | 1974 | Mines et Industries-SFM | Underground resistivity and gravimetry, geology | Exploration | | | Matzke, 1974; Carvalho, 1982 |
| Salgadoinho/Cercal | 1974 | SFM | Gravimetry, geology | Exploration | SL1 | | Carvalho <i>et al.</i> 1974; Carvalho, 1982 |
| Neves/Neves-Corvo | 1977 | SPE-SEREM-SMMPP | Gravimetry | Mining (Somincor) | NA-1(N2) | 350 m | Albouy <i>et al.</i> , 1981; Leca <i>et al.</i> , 1983; Leca, 1990; Relvas <i>et al.</i> , 2002 |
| Lombador/Neves-Corvo | 1988 | Somincor | Gravimetry, geology | Mining (Somincor) | NC20/NC20-1 | 696 m | Nelson Pacheco, written communication |
| Lagoa Salgada SW + Central <i>stockwork</i> /Grândola | 1992 | SFM-IGM | Gravimetry, magnetotellurics, vertical electrical sounding, geology | Exploration | SD.LS4, SD.LS1 | 128 m | Oliveira <i>et al.</i> , 1993, 1998 |
| Rio de Moinhos <i>stockwork</i> /São Mamede do Sadão | 1995 | IGM | Gravimetry, magnetometry, vertical electrical soundings | Exploration | SD.RM2 | 482 m | Oliveira <i>et al.</i> , 1996; |
| Chança <i>stockwork</i> /Corte Pinto | 1994 | CONASA | Gravimetry, geology | Exploration | S-6652 | 230 m | Mora, 1994 |
| Montinho <i>stockwork</i> /Panoias | 2001 | Atlantic Copper | Gravimetry, geology | Exploration | MMO-1 | 215 m | Mora, 2002b |
| Caveira East <i>stockwork</i> /Caveira | 2002 | Atlantic Copper | Gravimetry, soil geochemistry, geology | Exploration | CAV2 | 126 m | Malavé, 2002; Pereira <i>et al.</i> , 2008; Pereira <i>et al.</i> , 2012; Matos <i>et al.</i> , 2014 |
| Lousal <i>stockwork</i> /Lousal | 2008 | Pirites Alentejanas/AGC | Gravimetry | Exploration | LS08001-2 | 656 m | Castelo Branco <i>et al.</i> , 2009; Oliveira <i>et al.</i> , 2013; Matos <i>et al.</i> , 2014 |
| São Domingos <i>stockwork</i> /Mértola | 2010 | AGC | Geology, gravimetry | Exploration | SD1002 | 528 m | Castelo Branco <i>et al.</i> , 2010 |
| Semblana/Neves-Corvo | 2010 | Somincor-AGC-Lundin Mining | Surface and borehole, electromagnetics, constrained gravity inversion and seismic | NME | PSO48 | 790 m | Castelo Branco <i>et al.</i> , 2010; Owen <i>et al.</i> , 2013; Newall <i>et al.</i> , 2017 |
| Lagoa Salgada NE/Grândola | 2011 | Redcorp-Portex | Gravimetry, downhole EM, geology | Exploration | PX08 | 151 m | Barros and Alverca, 2011; Matos, 2011 |
| Mte Bela Vista <i>stockwork</i> /Lousal NW | 2012 | Maepa | Gravimetry, EM Turam, soil geochemistry | Exploration | MBV1 | 0-120 m | Dawborn, S. and Cunha, C., 2012 |
| Monte Branco/Neves-Corvo | 2012 | Somincor-AGC-Lundin Mining | Gravimetry | NME | SCA26 | 480 m | Castelo Branco <i>et al.</i> , 2012; Newall <i>et al.</i> , 2017 |
| Sesmarias/Azinheira de Barros | 2014 | Maepa/Avrupa | Downhole EM, drill hole relog, soil geochemistry | Exploration | SES002 | 150 m | Kuhn, 2017; Coder and Kuhn, 2020 |
| Lagoa Salgada South | 2017 | Redcorp/EDM/Ascendant | Downhole EM | Exploration | LS_ST02 | 150 m | Daigle, 2018; Murahwi and Gowans, 2019 |

Notes: * Length in the case of drill hole data. ** Experimental exploitation permit by EDM company. Institutions: IGM – Instituto Geológico e Mineiro; SFM – Serviço de Fomento Mineiro; SMMPP – Soc. Mineira Peñarroya; SMS – Soc. Mineira Santiago; SPE – Soc. Portuguesa de Empreendimentos; SEREM – Société d'Études et de Recherches et d'Exploitations Minières (Bureau de Recherches Géologiques et Minières). Status: NME – near mining exploration; E – exploration.

Notas: * Comprimento no caso de dados de sondagem. ** Concessão de Exploração Experimental (companhia EDM). Instituições/entidades: IGM – Instituto Geológico e Mineiro; SFM – Serviço de Fomento Mineiro; SMMPP – Soc. Mineira Peñarroya; SMS – Soc. Mineira Santiago; SPE – Soc. Portuguesa de Empreendimentos; SEREM – Société d'Études et de Recherches et d'Exploitations Minières (Bureau de Recherches Géologiques et Minières). Estado: NME – prospeção próximo ou em área mineira; E – prospeção.

Table 3. Exploration methods and techniques applied in the Iberian Pyrite Belt Portuguese sector.

Tabela 3. Métodos e técnicas de prospeção aplicadas no setor português da Faixa Piritosa Ibérica.

| IPB exploration | Geology | Geophysics | Geochemistry | Modelling |
|--|---|---|---|---|
| Regional scale: 1/400 000, 1/200 000, 1/100 000, 1/50 000, 1/25 000 | Geological mapping Regional stratigraphy based on rock dating Variscan and late Variscan tectonic studies Regional drill hole program (e.g. Paleozoic basement study in Cenozoic Basin areas) | Gravimetry Magnetometry Radiometry (U, Th, K, Total Count) Electromagnetics 2D Seismic profiles Airborne multi/hyperspectral Remote sensing | Soils (grid) Stream sediments Geochemistry fingerprints of VMS deposits related volcanic and sedimentary rocks XRF studies XRD studies SWIR spectrometer studies | Regional mapping and stratigraphic correlation Definition of VSC/PQ structures 3D data integration Target selection and ranking Deep and near surface anomalies studies Machine learning applied to ore horizons |
| Local scale: 1/10 000, 1/5 000, 1/2 500, 1/1 000 | Geological mapping Geological sections supported by rock dating (palynology and U/Pb geochronology) High resolution stratigraphy Drill hole correlations Trenches Underground surveys Gossan detail studies Hydrothermal alteration zonation Volcanic rocks and sediments dating (geochronology and palynology) | Electromagnetics: ground survey (TEM, TDEM - EM37, UTEM, CRONE PEM) profiles and loops/grids; airborne survey (VTEM, ZTEM) Induced polarization (electrical resistivity/chargeability) Vertical electrical sounding Electrical Resistivity Tomography (ERT) Very-low-frequency (VLF) 2D and 3D seismics Magnetotellurics Mise-à-La Masse Down hole EM surveys Other geophysical logging Petrophysical measurements in drill cores and samples (e.g. rock density, magnetic susceptibility) Airborne multi/hyperspectral Remote sensing LIDAR topographic surveys | Soil (profiles and narrow grids) with conventional soil geochemistry; Mobile Ionic Leach (MIL); Soil Gas; Halogens Outcrop profile sampling Litho-geochemistry (ore, volcanic and sedimentary rocks) in drill cores, outcrops and mining galleries XRF studies XRD studies SWIR spectrometer studies | 2D geological section modelling integrated with geophysical and geochemistry methods 3D models (geological, geophysical, geochemistry) Drill hole correlation Data inversion models Prediction models, machine learning |
| Near mining | Detail surface and underground mapping + drill hole grids Hydrothermal and supergene alteration zonation High resolution stratigraphic studies Tectonic studies | Local scale surface and underground geophysics (e.g. gravity, seismics) Down hole EM surveys Other geophysical logging | Local scale geochemistry including underground surveys and drill core characterization | Same as above Mine planning considering ore horizons and near mining targets and future resource exploitation Exploration galleries 3D modelling |

Notes: Electromagnetic methods (EM): TEM – transient; TDEM – time-domain; VTEM – versatile time-domain; PEM – pulse. XRF – X-ray fluorescence. XRD – X-ray powder diffraction; SWIR – short-wave infrared.

Notas: Métodos eletromagnéticos (EM): TEM – transiente; TDEM – domínio do tempo; VTEM – domínio do tempo versátil; PEM – impulso. XRF – fluorescência de raios X; XRD – difração raios X. SWIR – infravermelho de ondas curtas.

Table 4. Exploration projects in Iberian Pyrite Belt Portuguese regions, since 1950s.

Tabela 4. Projetos de prospeção na Faixa Piritosa Ibérica em Portugal, desde os anos 1950, por região.

| Portuguese IPB region | | Grândola / Marateca | São Francisco / Cidrao | Lousal / Caveira | Alvalade / Canhestros | Cercal / Odemira | Ourique | Montinho / Rosário / Neves-Corvo | Castro Verde / Casével | Ajustrel | Roxo / Alameda-S. Branca-S. Domingos-Chança | Pomarão | Martimlongo-Alcoutim-Odeleite |
|---|-------------------------------|---------------------|------------------------|------------------|-----------------------|------------------|---------|----------------------------------|------------------------|----------|---|---------|-------------------------------|
| Geology | Cenozoic | | | | | | | | | | | | |
| | Baixo Alentejo Flysch Group | | | | | | | | | | | | |
| | Volcano-Sedimentary Complex | | | | | | | | | | | | |
| | Phyllite-Quartzite Group | | | | | | | | | | | | |
| | Pulo do Lobo Domain | | | | | | | | | | | | |
| Geological Survey | LNEG – RD Projects* | LS | | | | | | | | | | | |
| | Instituto Geológico e Mineiro | LS/R | | | | | | | | | | | |
| | Serviço Fomento Mineiro | LS | | | | SAL | | | | EST | | | |
| AGC/Lundin Mining | | | | | | | SMB | | | | | | |
| Almina | | | | | | | | | | | | | |
| Amax | | | | | | | | | | | | | |
| Asarco | | | | | | | | | | | | | |
| Atlantic Copper/RTZ | | | | | | | | | | | CHA | | |
| Auroch/Bolt | | | | | | | | | | | | | |
| Avrupa/Antofagasta/Matsa | | | | | | | | | | | | | |
| Billinton Portuguesa | | | | | | | | | | | | | |
| Billinton-Minaport | | | | | | | | | | | | | |
| BP | | | | | | | | | | | | | |
| Colt Resources/Eurocolt | | | | | | | | | | | | | |
| Conasa | | | | | | | | | | | | | |
| Emp. Desenvolvimento Mineiro (EDM) | | | | | | | | | | | | | |
| EDM/Esanmet | | | | | | | | | | | | | |
| EDM/Portuglobal | | | | | | | | | | | | | |
| Emp. Desenvolvimento Mineiro do Alentejo (EDMA) | | | | | | | | | | | | | |
| Elf Aquitaine | | | | | | | | | | | | | |
| Emp. Exploradora de Minas | | | | | | | | | | | | | |
| Emp. Mineira Serra Cercal | | | | | | | | | | | | | |
| Epos | | | | | | | | | | | | | |
| Esanmet | | | | | | | | | | | | | |
| Ferragudo Mining | | | | | | | | | | | | | |
| Iberian Resources | | | | | | | | | | | | | |
| Maepa/Avrupa | | | | | SE/V | | | | | | | | |
| Mason and Barry | | | | | | | | | | | | | |
| Minaport/EDM | | | | | | | | | | | | | |
| Mines d' Ajustrel | | | | | | | | | | | | | |
| Mines et Industries | | | | | | | | | | | | | |
| Mining Explorations | | | | | | | | | | | | | |
| Northern Lion Gold Oy | | | | | | | | | | | | | |
| Pirites Alentejanas | | | | | | | | | | | | | |
| Pirites Alentejanas/Eurozinc | | | | | | | | | | | | | |
| Portuglobal/Exmin (EDM) | | | | | | | | | | | | | |
| Redcorp/EDM/Ascendant | | LS/R | | | | | | | | | | | |
| Redfern Resources | | | | | | | | | | | | | |
| Riofinex | | | | | | | | | | | | | |
| Soc. Mineira Rio Artésia | | | | | | | | | | | | | |
| Soc. Mineira Rio Artésia/EDM | | | | | | | | | | | | | |
| Soc. Mineira Santiago | | | | | | | | | | GAV | | | |
| Soc. Mineira Santiago/SEREM/SMPP | | | | | | | NC 1 | | | | | | |
| Somincor | | | | | | | NC 2 | | | | | | |
| Soc. Portuguesa Empreendimentos/SEREM/EDMA | | | | | | | | | | | | | |
| tah | | | | | | | | | | | | | |

Notes/Notas

Massive sulphide mineralizations discovered/mineralizações de sulfuretos maciços descobertas: CHA – Chança N; EST – Estação (Ajustrel); F/MO – Feitais; Moinho (Ajustrel); GAV – Gavião (Ajustrel SW); LS – Lagoa Salgada; NC 1 – Neves-Corvo (Neves, Graça, Corvo, Zambujal); NC 2 – Neves-Corvo (Lombador, Semblana, Monte Branco); RM – Rio Moinhos *stockwork*; SAL – Salgado; SE/V – Sesmarias and Monte Bela Vista *stockwork*.

* LNEG: Research Projects applied to mineral exploration/projetos de investigação aplicados a prospeção mineral.

Companies/Empresas: SEREM – Societé d'Études et de Recherches et d'Exploitations Minières (Bureau de Recherches Géologiques et Minières); SMMPP – Soc. Mineira e Metalúrgica de Peñarroya Portuguesa.

The methodology consisted of dozens of NE-SW parallel Turam profiles (*e.g.* Almodôvar region, Gomes and Silva, 1955; Silva and Gaspar, 1955), parallel to the VSC and PQ geologic structures (see Forno da Cal and Brancanes sectors located WNW Neves-Corvo in Fig. 2).

Also, in the 1950s, the magnetic method began to be successfully used, complementing the acquisition of Turam data. However, after the initial use of Turam and large magnetic surveys, the gravimetric method became the main tool to detect new sulphide masses in the IPB, due to its sensitivity to density variations. Until the 1960s, the role of the SFM was therefore singular, based on detailed gravimetric ground surveys carried out over N-S, E-W grids with distance between points of 200 m, 100 m and 50 m (Queiroz *et al.*, 1990; Oliveira *et al.*, 1993). The discovery of the Aljustrel Feitais orebody in 1964 (Leitão, 1998; Martins *et al.*, 2003) by Mines d'Aljustrel, using gravimetric surveys, demonstrates the proficiency of this method. Later, the introduction of geoelectrical methods using Vertical Electrical Soundings (VES), with different arrays like Schlumberger, dipole-dipole, pole-dipole, Wenner or rectangle (Telford *et al.*, 2012) improved the quality of the geoelectrical models inferred from electromagnetic data, since they provided deeper and more reliable information than Turam. The discovery of the Neves-Corvo ores in 1977, as a direct result of the exploration work of mining companies (a consortium formed by the Soc. Mineira e Metalúrgica de Peñarroya Portuguesa, Soc. Mineira de Santiago/Emp. Mineira e Metalúrgica do Alentejo and Societé d'Études de Recherches et d'Exploitations Minières), as well as previews of SFM exploration surveys (Albouy *et al.*, 1981; Carvalho, 1982; Leca *et al.*, 1983; Carvalho *et al.*, 1999; Oliveira *et al.*, 2013), showed the advantages of an interactive model interpretation, as it included the study and interpretation of geological structures based on the simultaneous use of electrical resistivity and spontaneous potential, followed by magnetic and gravimetric surveys. Prior to the discovery of the giant Neves-Corvo deposit the companies' consortium made a large exploration investment (Albouy *et al.*, 1981), that is: processing of the SFM gravimetric data (covering an area of 300 km²), collection of new gravity surveys (190 km²), 95 km of electric resistivity profiles, 124 km of magnetic profiles, as well as Very Low Frequency (VLF) studies on 9 drill holes. The excellent response of the gravity method, due to the large density contrast between massive sulfides and host rocks, can also be associated with a favorable geological scenario, defined by the presence of four high density orebodies (Neves, Corvo, Graça and Zambujal) located in the NE flank of a gently sloping structure (10° to 40° NE), at relatively shallow depths between 230 m (Corvo) and 350 m (Neves) (Albouy *et al.*, 1981; Leca *et al.*, 1983; Pacheco *et al.*, 1998; Carvalho *et al.* 1996). The gravity response of the deeper Neves-Corvo ore lenses is not so well defined and is more ambiguous. In fact, in the case of the Lombador ore lens, discovered in 1988 at 696 m deep (Pacheco *et al.*, 1998), the use of geological drill hole data was essential, supported by complementary gravimetric data processing and interpretation especially by application of a 2nd derivate filter. In the case of the discovery of the Semblana orebody (2010, ~800 m depth) other geophysical methods were applied in addition to gravity, that is time domain ground electromagnetic (TDEM) and extrapolation of favorable geology down dip modelling from the Zambujal area (Araújo and Castelo Branco, 2010; Owen *et al.*, 2013). Geological criteria from drill hole data were essential to the discovery of the Monte Branco ore lens (2012, identified between 480 m and 790 m depth). The extreme copper grades of the Neves-Corvo deposit justified more investment in exploration (Carvalho, 1994). In fact, the possibility of new discoveries with

high metal content warranted an extension of the exploration research, including deep structures (> 500 m depth). Considerable efforts were developed in areas like the Neves-Corvo-Corte Gafo, a 600 km² polygon (Carvalho *et al.*, 1996), where Somincor developed a multidisciplinary program: gravimetric + magnetic surveys (9015 points covering an area of 314.5 km², with technical support of the SFM gravimetry team) and several profiles of transient electromagnetic (TEM, 215.5 km), magnetotelluric (27.0 km) and seismic reflection (24.0 km) data. Detailed works were conducted at Neves-Corvo, João Serra and Corte Gafo areas, including borehole geophysical logging: 2 000 m of electrical resistivity logs + sonic logs and 2500 m of TEM logs.

High logistic costs and the development of differential GPS topographic techniques lead, in the 1990s, to the change of ground gravity and magnetic surveys, from regular grids to random grids with ~300 m spacing. The Rio Tinto Company was the first to apply this layout in the region, after successful test programs developed in well-known areas like Águas Teñidas (Spain) (Rio Tinto, 1991; Castelo Branco, 1995, 1996; Braux *et al.*, 1996; Castelo Branco and Sá, 1997). Rio Tinto and other companies like Minaport (Anglo American), also promoted, during that decade, regional magnetic and radiometric airborne surveys (La Fuente, 1995; Castelo Branco, 1995; Castelo Branco and Sá, 1997; Torres and Carvalho, 1998). At a local scale, other geophysical methods were used to characterize gravity and geological targets. Aiming at specific goals in well-defined targets, methods such as deep seismic reflection, electrical resistivity, induced polarization, electromagnetic EM37, pulse electromagnetic, transient electromagnetic (TEM), vertical transient electromagnetic (VTM), VES and magnetotellurics (MT) (Reynolds, 1997; Telford *et al.*, 2012) have been applied. In massive sulphide mineralized structures, down-hole surveys (*e.g.* mise à la masse, TEM) were essential to follow the mineralization trends, like in the Lagoa Salgada (Oliveira *et al.*, 1993, 1998a) and Semblana (Araujo and Castelo Branco, 2010) sectors. *Stockwork* vein type mineralization was also identified using these methods, like the recent cases of the Serrinha (NW IPB sector, see Fig. 1) induced polarization profiles (Ramalho and Matos, 2009; Matos *et al.*, 2009a) or Chança, Montinho and Caveira massive sulphide orebodies detailed exploration studies conducted by Sociedade Mineira Rio Artezia (Mora, 2002) and Atlantic Copper (Palomero, 1999). At the Neves-Corvo region, seismic reflection profiles were used by Lundin/Somincor to define key tectonic structures (Araújo and Castelo Branco, 2010; Inverno *et al.*, 2013, 2015; Carvalho *et al.*, 2017; Donoso *et al.*, 2020).

After 70 years of exploration work, a large area of the IPB is already covered with several geophysical methods, most of them superimposed, creating a large amount of acquired data that is supervised and homogenised by LNEG. Current methodologies are presented considering geology, geophysics and geochemistry as key mineral exploration techniques (Tab. 4). Potential field methods (gravimetric and magnetics) have proven to be important exploration tools and are commonly used along the Portuguese IPB with significant success. These methods are ultimately responsible for the discovery of several massive sulphide orebodies, namely Neves-Corvo, Lagoa Salgada, Salgadinho, Estação and Gavião (Carvalho, 1979; Carvalho, 1982; Oliveira *et al.*, 1993; Carvalho *et al.*, 1996; Oliveira *et al.*, 1998a, b, c; Carvalho *et al.*, 1999; Matos and Sousa, 2008). As an example of ground gravity survey, see in figure 3 the distribution of the field stations in the northern IPB sector, between Albernôa and the Portuguese/Spanish border.

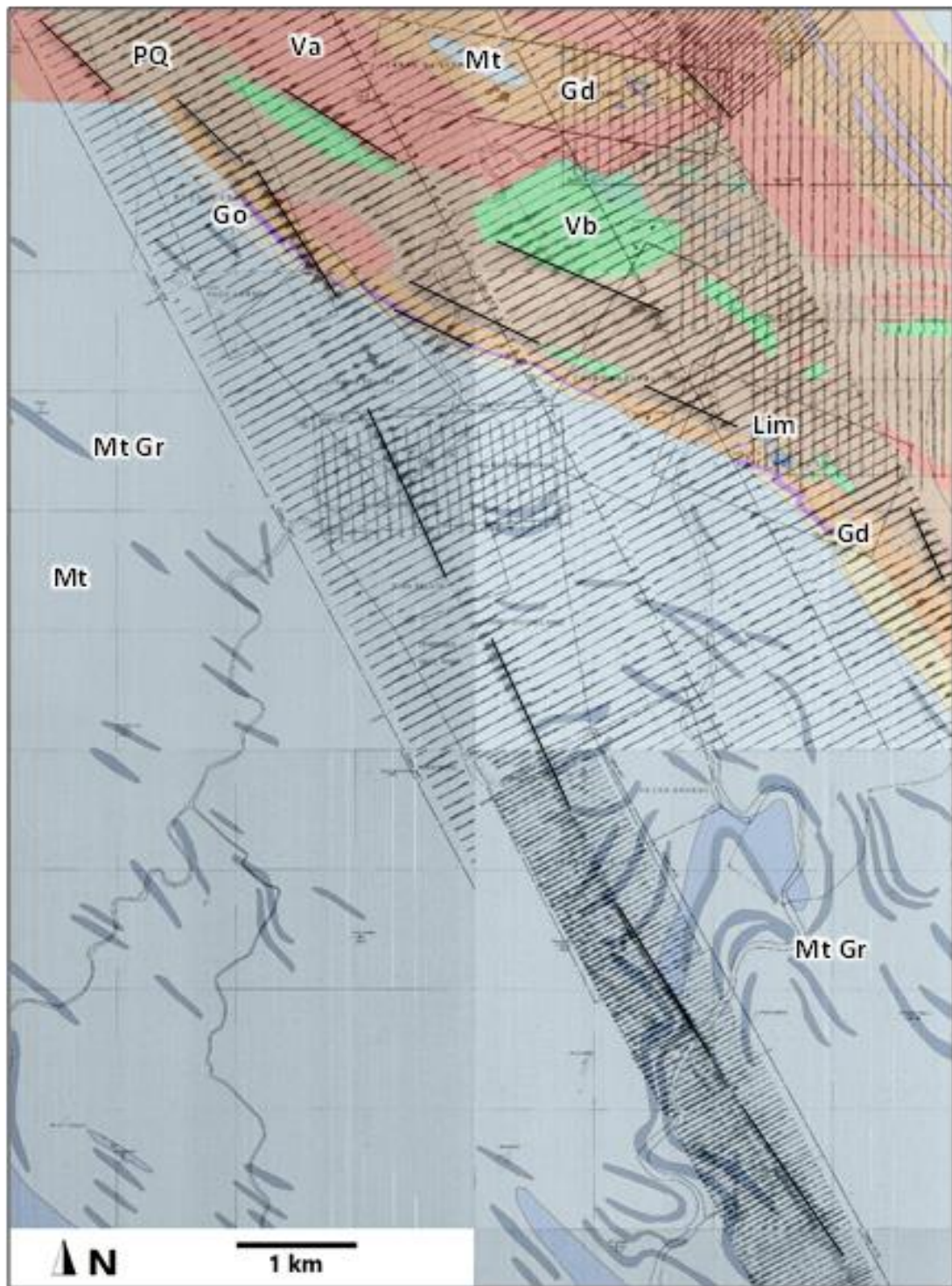


Figure 2. TURAM SFM profiles (grey fine lines) in the Neves-Corvo mine WNW sector and electromagnetic conductor zones (black lines) related with near surface thrust fault zones locally mineralized with sulphides and lithological contacts between sediments and volcanic rocks. Geology: Oliveira *et al.*, 2016, Sheet 46-C Almodôvar of Portugal Geological Map. PQ – Phyllite-Quartzite Formation (Givetian-Strunian); Lim – PQ Famennian age limestones; Volcano-Sedimentary Complex – Lower sequence: Va – felsic volcanic rocks (Famennian-Tournaisian), Upper sequence (Late Visean age); Gd – Grandaços Formation; Bv – Borra de Vinho Formation; Go – Godinho Formation. Baixo Alentejo Flysch Group: Mt – Mértola Formation turbidites (shales and greywackes) (Late Visean age); Mt Gr – Mértola Formation greywackes dominant sedimentary levels.

Figura 2. Perfis TURAM SFM (linhas finas a cinzento) situados no setor WNW da mina de Neves-Corvo e condutores eletromagnéticos (linhas a negro) relativos a zonas de cavalgamento situadas próximas da superfície, localmente mineralizadas com sulfuretos, e a contactos litológicos entre rochas sedimentares e vulcânicas. Geologia ad. de Oliveira *et al.*, 2016, Folha 46-C Almodôvar da Carta Geológica de Portugal. PQ – Formação Filito-Quartzítica (Givetiano-Estruniano); Lim – PQ Calcários de idade Famenniano; Complexo Vulcano-Sedimentar – Sequência Inferior: Va – rochas vulcânicas félsicas (Famenniano-Tournaisiano), Sequência Superior (Viseano superior); Gd – Formação Grandaços; Bv – Formação Borra de Vinho; Go – Formação Godinho. Grupo Flysch do Baixo Alentejo: Mt – Formação de Mértola, turbiditos (xistos e grauvaques) (Viseano superior); Mt Gr – Formação de Mértola, níveis sedimentares com predominância de grauvaques.

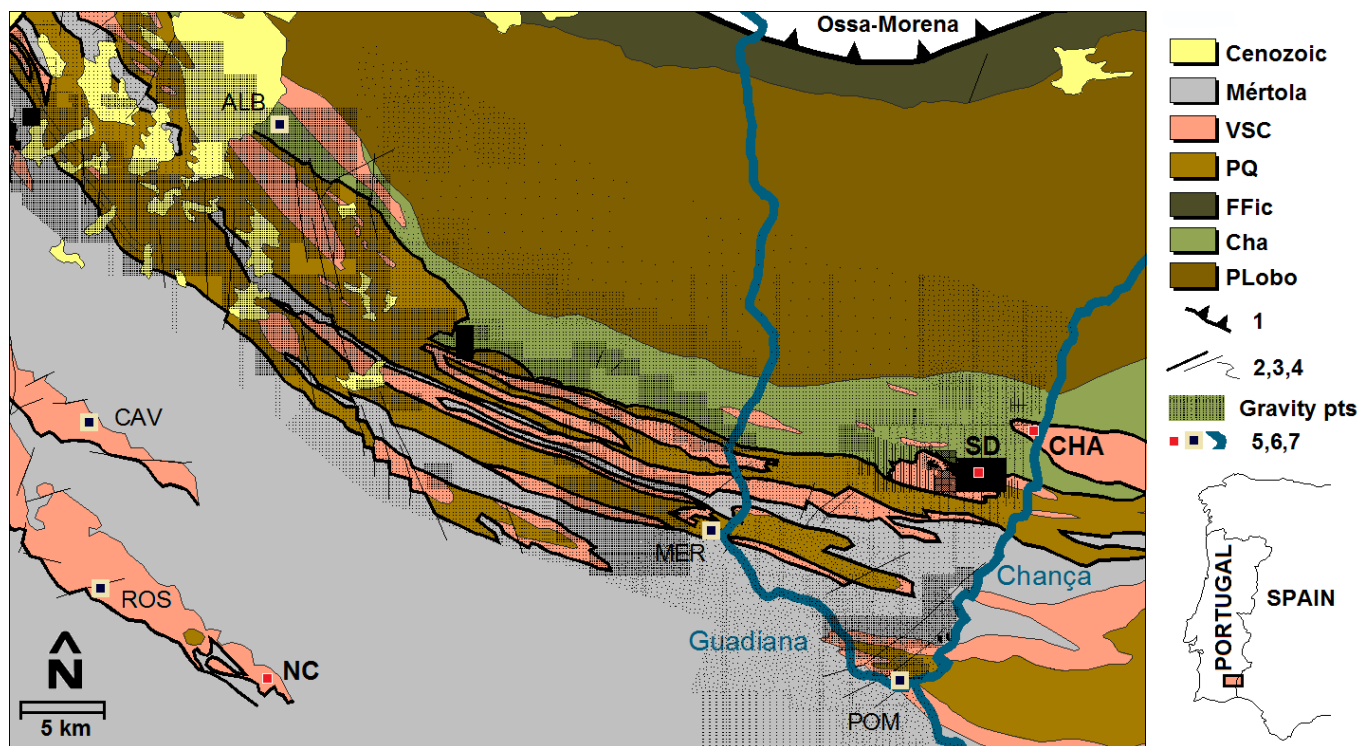


Figure 3. Gravity surveys performed in the northern IPB region, between Albernôa and the Portuguese/Spanish border (black dots, ~108 000 field stations, black rectangles: narrow grids, e.g. 100 m x 100 m and 50 m x 50 m). Geology: Sheet 8 of Portugal Geological Map 1/200 000 scale (Oliveira *et al.*, 1992). Ceno – Cenozoic sediments; Mértola – Mértola Fm. (Late Viséan); VSC – Volcano-Sedimentary Complex (Famennian-Late Viséan); PQ – Phyllite-Quartzite Group (Givetian-Strunian); FFic – Ferreira-Ficalho Group (Frasnian-Famennian); Cha – Chança Group (Famennian-older); PLobo – Pulo do Lobo Group (Frasnian-older); 1 – Ferreira-Ficalho thrust; 2 – thrust; 3 – fault; 4 – geological limit; 5 – massive sulphide deposits; NC – Neves-Corvo, SD – São Domingos, CHA – Chança; 6 – villages: ALB – Albernôa, CAV – Castro Verde, MER – Mértola, POM – Pomarão, ROS – Rosário, 7 – river.

Figura 3. Levantamentos gravimétricos efetuados na região norte da Faixa Piritosa Ibérica, entre Albernôa e a fronteira luso-espanhola (pontos a negro, ~108 000 estações de campo, retângulos a negro: malhas de pormenor, ex. 100 m x 100 m e 50 m x 50 m). Geologia: Folha 8 da Carta Geológica de Portugal, escala 1/200 000 (Oliveira *et al.*, 1992). Ceno – Sedimentos cenozoicos; Mértola – Fm. Mértola (Viséano sup.); VSC – Complexo Vulcano-Sedimentar (Famenniano-Viséano sup.); PQ – Grupo Filito-Quartzítico (Givetiano-Estruniano); FFic – Grupo Ferreira-Ficalho (Frasniano-Famenniano); Cha – Grupo Chança (Famenniano-mais antigo); PLobo – Grupo Pulo do Lobo (Frasniano-mais antigo); 1 – Cavaleamento Ferreira-Ficalho; 2 – cavaleamento; 3 – falha; 4 – limite geológico; 5 – jazigos de sulfuretos maciços; NC – Neves-Corvo, SD – São Domingos, CHA – Chança; 6 – povoações: ALB – Albernôa, CAV – Castro Verde, MER – Mértola, POM – Pomarão, ROS – Rosário, 7 – rio.

Another example can be shown in the Neves-Corvo area where different gravimetric surveys were conducted by SFM (1960s-1990s, grid 200 m x 200 m to 50 m x 50 m NS and EW grid), SAPA (1970s-1980s, 200 m spacing NE-SW profiles) and Asarco (1994-1995, 200 m x 100 m grid). Despite the heterogeneous database new gravity processing techniques can be applied and developed (Marques *et al.*, 2019, Fig. 4).

Complementary electromagnetic methods were useful in the discovery of the Semblana (Araújo and Castelo Branco, 2010; Owen *et al.*, 2013; Newall *et al.*, 2017) and Sesmarias massive sulphide ore lenses (Kuhn, 2017). Considering the IPB as an important base metals mineral province, the mineralization targets are defined by massive/semi-massive sulphide ore lenses, *stockwork* veins and disseminated mineralization with hydrothermal halos, present in VSC felsic volcanic rocks and shale units (Carvalho, 1979; Carvalho, 1982; Oliveira *et al.*, 1993; Matos and Sousa, 2008; Matos *et al.*, 2011). At local scale the definition of the local constraints of the geological structures is essential, like the presence of key geological horizons, e.g. cherts, jaspers and felsic volcanic rocks (Oliveira *et al.*, 1993; Carvalho *et al.*, 1999), Strunian age geological formations (Matos *et al.*, 2011), folding and fault systems (Variscan and late-Variscan). IPB vertical/sub-vertical ore lenses are defined in Portugal at Lagoa Salgada (Oliveira *et al.*, 1993; Matos *et al.*, 2000, 2017, 2019; De Oliveira *et al.*, 2011; Represas and Matos,

2012), Caveira W (Helena/Salvador sector, Matos *et al.*, 2015), Lousal (Matzke, 1971; Matos and Oliveira, 2003; Relvas *et al.*, 2012), Moinho and Algaes (Aljustrel) (Andrade and Schermerhorn, 1971; Leitão, 1998), Gavião (Relvas *et al.*, 2011) and São Domingos (Matos *et al.*, 2006). Mineralized structures deeping 40° to 60° to NE are defined at Salgadinho (Carvalho, 1979, 1982; Faria, 2007), Feitais and Estação (Aljustrel) (Leitão, 1998), Caveira E (Luísa sector, Matos *et al.*, 2014) and Chança areas (Palomero and Mora, 1996; Palomero, 1999). The Neves-Corvo deposit presents a slight inclination towards NE, with seven orebodies dispersed in a large complex antiform structure (Carvalho *et al.*, 1996; Relvas *et al.*, 2006; Araújo and Castelo Branco, 2010; Oliveira *et al.*, 2004, 2013). The correct understanding of the geometry of each study area implies a significant detail in the geological mapping based on surface surveys and/or drill hole logging (Tab. 4). The accuracy of the conceived model for the geology and ore deposit can be limited by a short number or heterogeneous geographical distribution of available drill holes. In areas where information is scarce, geophysical data can therefore be essential to the definition of consistent models to be tested. Geophysical IPB data integration with geological, geochemistry (Batista *et al.*, 2020) and remote sensing data (Quental *et al.*, 2020) data using 3D model software is essential to define target zones in future drilling surveys.

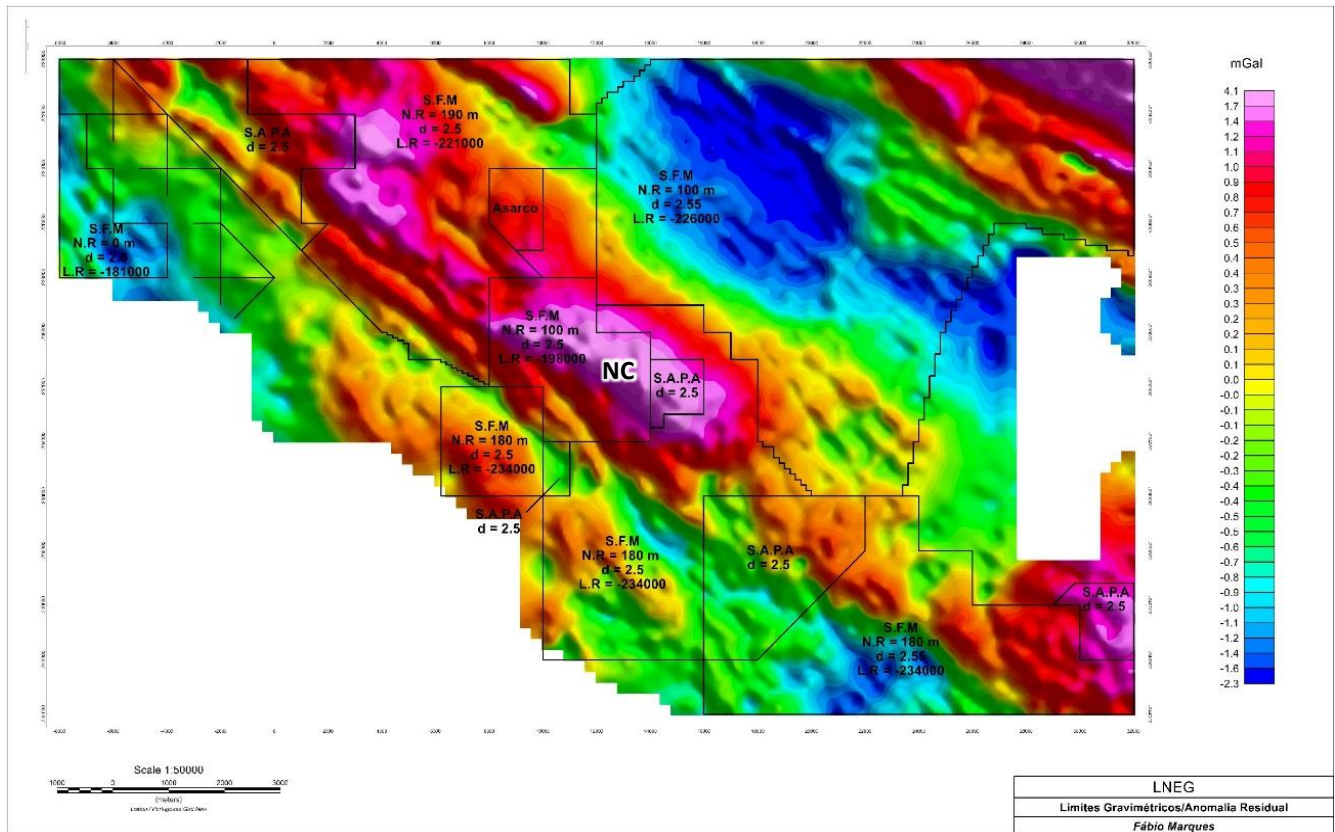


Figure 4. Gravimetric surveys in Neves-Corvo region (see location in Fig. 1). Data processing by the Project EXPLORA/LNEG, residual gravimetric anomaly $d = 2.6$ (Marques *et al.*, 2019). NC – gravimetric anomaly associated to the Neves-Corvo Ore.

Figura 4. Levantamentos de gravimetria na região de Neves-Corvo (ver localização na Fig. 1). Processamento de dados pelo Projeto EXPLORA/LNEG, anomalia gravimétrica residual $d = 2,6$ (Marques *et al.*, 2019). NC – anomalia gravimétrica associada ao jazigo de Neves-Corvo.

Recent powerful methodologies are being applied in another metallogenetic provinces using neural networks and machine learning to promote new approaches to multi source data (Hasti *et al.*, 2017; Li *et al.*, 2020). However, modelling and inversion is an ill-posed problem, and no unique solution exists. In structural complex areas this ambiguity is even higher, and the seismic reflection method is often used to provide structural information, thus reducing the ambiguity of potential field data modelling. This technique is being used with success by Lundin Mining in the IPB Neves-Corvo region, following existing massive sulphide ores (*e.g.* Lombador, Fig. 4) and defining new targets, as the recent Semblana and Monte Branco discoveries (Araújo and Castelo Branco, 2010; Owen *et al.*, 2013; Newall, *et al.*, 2017). Preliminary 3D models based on gravity and geological data are already defined for the IPB deposits of Neves-Corvo (Inverno *et al.*, 2013; Batista *et al.*, 2014; Granado *et al.*, 2014; Inverno *et al.*, 2015; Carvalho, 2020; Dias, 2020; Donoso, *et al.*, 2020), Caveira (Matos *et al.*, 2015), Lagoa Salgada (Represas and Matos, 2012) and Rio Tinto (Martin-Izard *et al.*, 2015). However, additional geophysical methods are still required in strategic locations as a satisfactory geophysical interpretation regarding mineral resources exploration can only be accomplished with geological, geochemical, borehole drilling and even hydrogeological support.

4. Gravimetry

In the early 1960s, the former SFM began to use the gravimetric method in the Portuguese IPB sector with considerable success.

This method is based on the detection of density contrasts and the reader can consult Milsom (2003) or Telford *et al.* (2012), for a more comprehensive approach of the gravimetric method. Because of its characteristics and favourable geological conditions, it has been the main geophysical method applied. Its use lead to the discovery of new polymetallic massive sulphides ore deposits like Neves-Corvo, Feitais, Estação and Gavião (Aljustrel, Fig. 5), Lagoa Salgada and Salgadinho (Andrade and Schermerhorn, 1971; Matzke, 1971; Carvalho, 1979; Albouy *et al.*, 1981; Carvalho, 1982; Leca *et al.*, 1983; Leca, 1990; Queiroz *et al.*, 1990; Oliveira *et al.*, 1993; Carvalho *et al.*, 1996; Leitão, 1998; Oliveira *et al.*, 1998a, b, c).

The same occurred in Spain, at Las Cruces and Valverde deposits (Doyle, 1996; Gable, 1996). At local scale sulphide *stockwork* and vein type structures can be identified in favourable geological settings by the gravity method if the mineralization vertical dimension is considerable (> 50 m in thickness). Important *stockwork* mineralization case studies are reported at Lagoa Salgada central area (Fig. 1, Oliveira *et al.* 1993, 1998a; Matos *et al.*, 2000), Rio de Moinhos (Oliveira *et al.*, 1998b, 2001) and Chança northern sector (Palomero and Mora, 1996; Palomero, 1999).

The major utility of the gravimetric method is related to the density contrast between the pyrite ores ($d > 4 \text{ g.cm}^{-3}$ in massive ores and $d = 2.9\text{-}3.9 \text{ g.cm}^{-3}$ in *stockwork* veins, see Tab. 5) and the surrounding host rocks, *e.g.* VSC acid volcanic rocks and black shales and PQ shales and quartzites, which present commonly densities lower than 2.9 g.cm^{-3} .

Table 5. Observed rock density in outcrops and exploration drill holes. Variations related with rock porosity along drill hole depth not considered.

Tabela 5. Densidade de rochas observada em afloramento e testemunhos de sondagens mineiras. Variações da porosidade das rochas em profundidade não consideradas.

| Unit | Rock type | IPB Portugal - drill holes | | | ITGE IPB Spain Outcrops g.cm ³ |
|-------------------------|--|----------------------------|----------------------------|---|---|
| | | g.cm ⁻³ min-max | g.cm ⁻³ average | Sectors | |
| Sulphide mineralization | Acid volcanics + veins + hydrothermal alteration | 2.63-2.96 | 2.82 | Lagoa Salgada ^{1,2} | |
| | Stockwork zones | 2.88-3.91 | 3.40 | Lagoa Salgada, Rio de Moinhos ^{1,2} | |
| | Semi-massive pyrite | 2.25-3.54 | 3.07 | Lagoa Salgada ^{1,2} | |
| | Massive pyrite | 4.29-5.03 | 4.71 | Lagoa Salgada ^{1,2} | |
| Cenozoic /weathering | Sandstones | 1.92-2.20 | 2.12 | Lagoa Salgada ^{1,2} | 2.00 |
| | Limestones | 2.32 | 2.32 | Lagoa Salgada ¹ | |
| | Conglomerates | 2.02-2.42 | 2.27 | Lagoa Salgada, Piugada, Fresta ^{1,2} | |
| | Weathered Paleozoic | 2.04-2.70 | 2.70 | Lagoa Salgada, Lameira, Piugada ^{1,2} | |
| | Gossan | 2.62-3.97 | 3.36 | Lagoa Salgada ^{1,2} | |
| Mértola Fm. | Shales and greywackes | 2.70-2.81 | 2.77 | Taralhão ¹ | 2.66-2.68 |
| VSC | Siliceous shales | 2.65-2.77 | 2.70 | Rio de Moinhos ¹ | 2.65 |
| | Green/purple shales | 2.58 | | Rio de Moinhos ¹ | |
| | Black shales | 2.81 | | Rio de Moinhos ^{1,2} | |
| | Jaspers and cherts + disseminated/veins magnetite* | 2.73-2.98 | 2.78 2.90 (mag) | Rio de Moinhos ¹ | 2.63-3.06 |
| | Basic volcanics | 2.73-2.89 | 2.84 | Lagoa Salgada ^{1,2} | 2.78-3.00 |
| | Acid volcanics | 2.58-2.90 | 2.79 | Lagoa Salgada ^{1,2} | 2.61-2.68 |
| PQ | Shales and quartzites | 2.58-2.67 | 2.63 | Chaparral, Lameira ¹ | 2.56-2.65 |
| | Dark grey shales | 2.62-2.84 | 2.78 | Chaparral, Lameira, Rio de Moinhos ¹ | |
| | Limestones | 2.79 | 2.79 | Rio de Moinhos ¹ | |

Data source: ¹ Instituto Geológico e Mineiro/Serviço de Fomento Mineiro; ² Sociedade Mineira Rio Artésia/EDM. ITGE data in García *et al.*, 1998 and Jiménez, 2013.

After the successful discovery of the Neves-Corvo deposit (Albouy *et al.*, 1981; Leca *et al.*, 1983) related with gravimetric data processing, rock density determination in drill hole cores become a common procedure in Portugal and Spain. Table 5 shows outcrop rock density (Spain, García *et al.*, 1998; Jimenez, 2013) and drill hole cores density from IPB Portuguese sectors (Oliveira *et al.*, 1993, 1998a; Castelo Branco, 1995, 1996; Castelo Branco and Sá, 1997). The last density measurements consider the weight of the rock cores and the weight of the equivalent water volume. Rock lithologies are shown according to the main geological formations: Cenozoic sediments, Mértola Formation (flysch sediments), VSC (sediments, volcanics and sulphide ores) and PQ (shales and quartzites). Differences between density data from the Portuguese data sources and Spanish data sources are related to different methodologies of density measurement, that is, in the Portuguese sector only drill cores were studied (outcrop samples are not considered due to their lower density related with rock alteration by weathering). The highest density values refer to massive and semi-massive sulphide ores, basic volcanic rocks and jaspers with disseminated magnetite. Cenozoic sediments show lower density values than Paleozoic basement rocks. PQ, VSC and Mértola Formation lithologies present a wide range of values. Rock density is affected by several factors like porosity, fracturing, mineral distribution, weathering alteration and depth. Considering the same geological formation, the presence of metallic minerals (*e.g.* sulphide or magnetite veins/disseminations) will increase its

average density, while low density minerals (*e.g.* clays, silica, sericite, carbonates) will have the opposite effect. Interstitial water content also affects density values, especially in poorly consolidated Cenozoic sediments and fault breccia zones.

Gravimetric data were acquired in ground surveys (*e.g.* northern IPB region, Fig. 3), as well as in airborne gravimetric surveys conducted by AGC/Lundin (Araujo and Castelo Branco, 2010; Nobre, 2013). Consulting LNEG's databases and 1/5 000 and 1/25 000 map libraries is essential in current IPB exploration planning. Despite the difference between gravity surveys over time (different grids) legacy data could be reprocessed with modern codes and reinterpreted. An example is the Gravity map 529 (1/25 000 scale, Fig. 5) of the Aljustrel area, produced by Minaport (T. Burvenich *in* La Fuente, 1992, 1994, 1995) using company and previous SFM data. Different multi sources gravimetric anomalies can be identified in the 529 Bouguer anomaly map (Fig. 5): i) massive sulphide ore lenses – Feitais (FE), Estação (ES), Moinho (MO), São João (SJ) and Gavião (GV) (Aljustrel area); ii) Paleozoic basement at the Messejana Fault SE block; iii) Paleozoic windows in the Alvalade Basin, locally with basic volcanic rocks; iv) graben structures (G) in the Alvalade Basin; v) thrust fault zones; vi) strike-slip faults zones defined by intense gradients, *e.g.* Represa (RF) and Farrôbo (FF); vii) pull-apart local grabens related with Messejana Fault (MF) cinematic – normal left movement and downlift of the NW block, *e.g.* Morgado Graben (MG) where -50 m Paleozoic basement downlift is indicated by exploration drill holes. In this complex

geological setting of the Aljustrel region (Schermerhorn *et al.*, 1987; Leitão, 1998, 2009; Matos *et al.*, 2010) the gravity field interpretation is essential to carry out consistent geological modelling and ore horizon research. In the Alvalade Basin drill hole profiles were performed by Minaport to constrain the depth of the Paleozoic basement and perform an accurate modelling of the Cenozoic/Paleozoic interface (La Fuente, 1995). Paleotopography and paleozoic basement structure modelling can be used to detect different anomaly sources (*e.g.* ore, structure, paleorelief).

The South Portuguese Zone (SPZ) Gravimetric map (Bouguer Anomaly) (1/400 000 scale, Represas *et al.*, 2016b) was produced based on a total of ~388 000 data points acquired during different exploration surveys conducted since the 1960s, by the Billiton, Emp. Mineira da Serra do Cercal, Minaport-EDM, SFM/IGM/LNEG, Soc. Mineira Rio Artezia and Somincor companies (Fig. 6 and Annex 1). These gravimetric surveys were carried out by Adaro, Geoconsult, Minaport, SAP, SFM/IGM/LNEG, SMRA/Rio Tinto Zinc teams. Depending on the survey methodology, the distance between acquisition data points varied from 50 m to 500 m. Bouguer correction requires the use of a unique density value, so that the obtained anomalies refer to a uniform background. In the SPZ gravity map, the Bouguer anomaly map was determined using a crustal density of 2.6 g.cm^{-3} . This value results from the knowledge acquired with

drill hole Paleozoic basement density measurements (see Tab. 5), and the taking into account the areas covered by Cenozoic sediments, *e.g.* Baixo Tejo-Alvalade Basin at Lagoa Salgada (Oliveira *et al.*, 1998), Lameira-Figueira de Cavaleiros (Carvalho *et al.*, 2010) and Milhouros (W Aljustrel) area (La Fuente, 1992, 1994, 1995), where densities are around 2.1 g.cm^{-3} . Also, similar densities are used in the Spanish IPB sector gravity mapping surveys (Torres *et al.*, 1998; Garcia *et al.*, 1998; Jimenez, 2013). The obtained Bouguer anomaly data was levelled and homogenized using common data points. Then, it was gridded to a 400 m spacing mesh, using the ordinary *kriging* interpolation method, with a spherical semivariogram model, and considering only points within a radius of 400 m, using a minimum of 8 and a maximum of 16 valid data points, to avoid mathematical artefacts produced by the interpolation method. Several tests with different parameters were conducted in the interpolation method; however, there was no significant difference among results. Keeping in mind the overall scale (1/400 000), the field is well sampled. The distance between data points limits the minimum size of the anomalies sampled by the data to the double of that distance, as derived from the Nyquist theorem (Clement, 1973). As such, the data spacing was set to the largest data spacing provided by the data to obtain a uniform and consistent anomaly map. Data processing and map production were made using Geosoft *software*.

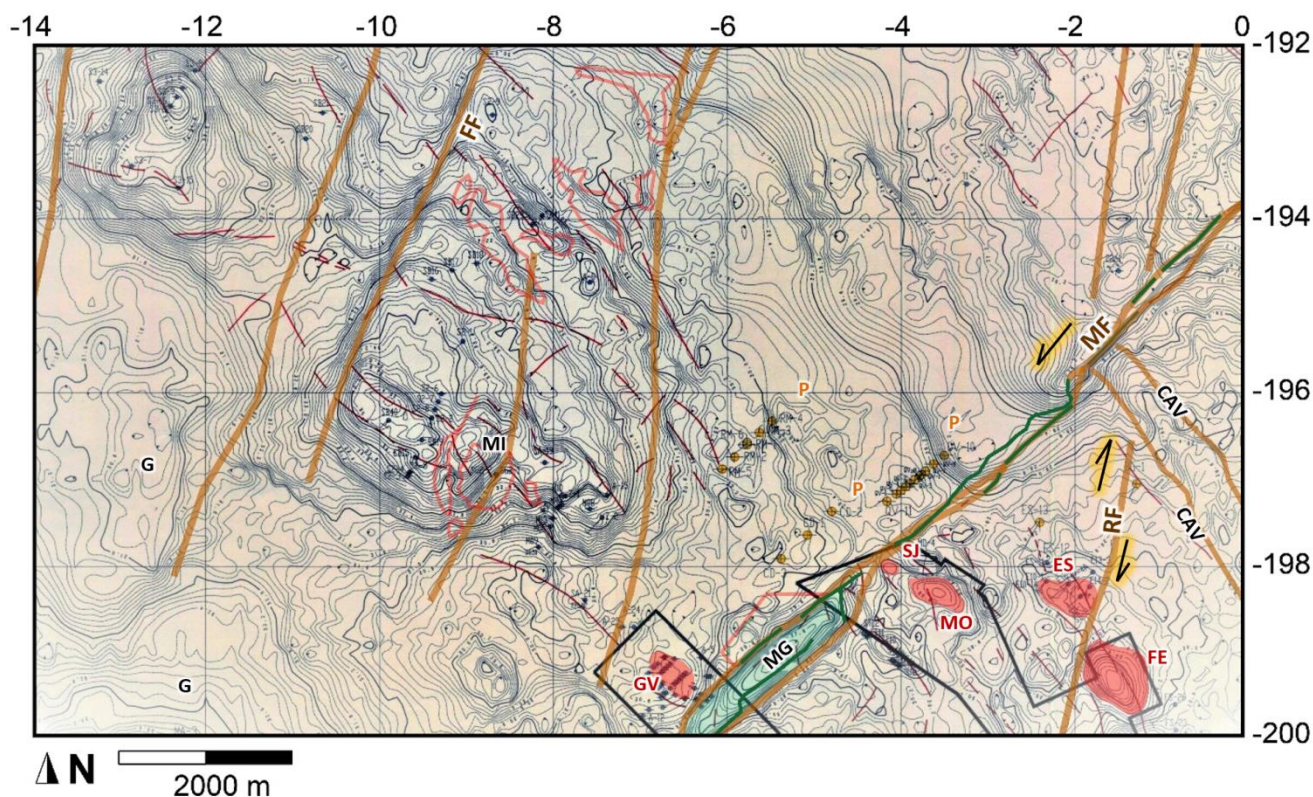


Figure 5. SE sector of the Gravity (Bouguer Anomaly, density 2.7 g.cm^{-3}) 529 map (LNEG Archive). Coord. Hayford-Gauss Lisbon IPCC in km. Massive sulphide ore lenses: Feitais (FE), Estação (ES), São João (SJ), Moinho (MO) and Gavião (GV); Paleozoic basement windows in the Alvalade Basin, locally with basic volcanic rocks – *e.g.* Milhouros horst (MI) see outcrop limits (red lines). Graben structures in the Alvalade Basin (G) and Morgado Graben (MG); CAV – thrust fault zones; strike-slip faults zones: Messejana (MF), Represa (RF), Farrôbo (FF). Green lines – Messejana Dolerite. Drill hole profiles – P.

Figura 5. Setor SE da Carta Gravimétrica (Anomalia Bouguer, densidade $2,7 \text{ g.cm}^{-3}$) nº 529 (Arquivo LNEG), Coord. Hayford-Gauss Lisboa IPCC em km. Jazigos de sulfuretos maciços: Feitais (FE), Estação (ES), São João (SJ), Moinho (MO) e Gavião (GV); janelas do soco Paleozoico na Bacia de Alvalade, localmente com rochas básicas - ex. Milhouros horst (MI). Limites dos afloramentos indicados por linhas vermelhas. Estruturas em *graben* na Bacia de Alvalade (G) e *Graben* Morgado (MG); CAV – cavalgamentos; falhas de tipo deslizeamento: Messejana (MF); Represa (RF); Farrôbo (FF). Linhas a verde – Dolerite da Messejana. Perfis de sondagens de prospeção – P.

The SPZ Bouguer anomaly map where the IPB western region is included shows a large regional south-eastwards and westwards trend (20, 17 and 12 in Fig. 6), related with regional variations of the gravity field due to deep and large-scale sources. Studies developed at Iberian scale (Portugal and Spain) define large E-W anomalies related with the geometry of Moho (Moraleda *et al.*, 2013) and with deep alkaline plutonic structures with a main W-E direction along the Algarve region (González-Castillo *et al.*, 2014). According to the large wavelength Bouguer anomalies observed in the SW of the Iberian Peninsula show important differences between the basements of the SPZ and Ossa-Morena Zone (OMZ). In the first geotectonic region the Earth, crust presents higher density, probably related with a thin upper crust and larger thickness of the middle and lower crust levels. Compared with SPZ, the OMZ presents a thick upper crust level and a thin middle and lower crust levels (Jiménez, 2013). In the northeast IPB sector, between Albernôa and Mértola, a regional NE-SW gravity gradient is observed, dipping to NW, probably related with geological changes in the SPZ deep setting. Unknown basement geological formations can be present in this region, below outcropping flysch sediments of the Gafo Formation (Famennian age, Pereira *et al.*, 2018, 2020) (GF1 – Corte Gafo and GF2 – Chança south anomalies in Fig. 6).

The overall values of the gravity anomaly drop considerably in areas where the Paleozoic basement is covered by Cenozoic sediments (*e.g.* Baixo Tejo/Alvalade Basin, ACB in Fig. 6) (Oliveira *et al.*, 1993; La Fuente, 1995; Oliveira *et al.*, 1998a, b, 2001; Matos *et al.*, 2009a, b; Carvalho *et al.*, 2011; Represas and Matos, 2012). The low gravity field areas reflect the lower density of the Cenozoic sediments in contrast with the higher density basement rocks (Flysch, VSC and PQ, Tab. 5). Strong gravity gradients can be observed in figure 6 delineating the main late Variscan subvertical fault zones, *e.g.* Messejana (MF), Farrôbo (FF), Corona (CoF) and Sado valley (SVF), Grândola (GF), Pedrogão-Valverde-Clérigos (PVF) and Cordoeira (CF) (Oliveira *et al.*, 1998; Oliveira *et al.*, 2001; Matos *et al.*, 2009a, b). The fault block displacement is confirmed in all cases by drill holes and locally by seismic profiles (*e.g.* Grândola Fault, Carvalho *et al.*, 2011). The NE-SW and NNE-SSW faults are clearly defined in the gravity maps, especially in 1/25 000 scale maps (Fig. 5 and 5, 8, 13 in Fig. 6). In the NW sector of the Messejana fault, changes in the gravity field are conditioned by local basement geology and Cenozoic sediments thickness, reflecting grabens and horst structures developed during the late Variscan and Alpine periods. The labelled anomalies, indicated in the map on figure 6, are correlated with the following structures, North to South (Andrade and Schermerhorn, 1971; Oliveira *et al.*, 1998a, b; Leitão, 1998; Oliveira *et al.*, 2001; Matos *et al.*, 2009a, 2018; Represas and Matos, 2012): Serrinha horst (1); Porto de Mel and Pedrogão horsts (2 and 3), Lagoa Salgada horst (LS), Batão graben (5), Garcia Menino/Vale Parreira horst (6); Milhouros horst (13) and the Morgado graben (G). Paleoreliefs must be also considered in the gravity data interpretation as referred by (Oliveira *et al.*, 1998; Represas and Matos, 2012). The best examples in the Baixo Tejo/Alvalade Basin are the differential erosion of the Rio de Moínhos jaspers crest intersected by the IGM SD.RM1 drill hole at 102 m (depth of the Paleozoic/Cenozoic interface, see details in Oliveira *et al.*, 1998a, b; Oliveira *et al.*, 2001; Pereira *et al.*, 2008) and Lagoa Salgada felsic volcanic rocks, cherts and gossan (Represas and Matos, 2012).

The 1/400 000 gravimetric map reflects, at a regional scale, the main SPZ structures and, in particular, the IPB different sectors. The VSC/PQ geological lineaments are reflected as higher amplitude anomalies in contrast with the Baixo Alentejo

Flysch Group sequences, which appear as lower amplitude anomalies, see selected anomalies in figure 6: Serrinha (1, VSC/PQ); Porto de Mel (2, VSC); Pedrogão (3, VSC); Cidrão (4, VSC); Caveira (C, 7, VSC/PQ); Lousal (L, VSC/PQ); Brejo (8, VSC/PQ), Montinho (M, VSC); Casével (9, VSC); Castro Verde (10, VSC); Rosário and Neves-Corvo (11, NC, VSC/PQ); Alvares-S. Barão (16, VSC/PQ); São Domingos (SD, VSC/PQ); Alcoutim (17, VSC) and Foupana (12, VSC). The Cercal Antiform region (19 in Fig. 6) and Chança (CH in Fig. 6) are exceptions. At the Cercal sector (19 in Fig. 6), the VSC appears as a large low amplitude anomaly (see also Faria, 2007). This gravimetric setting is probably due to the presence of low density silica rich felsic volcanic rocks and São Luís Formation siliceous shales (Famennian age, Pereira *et al.*, 2008), in contrast with higher density of the black shales with disseminated pyrite of the Abertas Shales Member (Serpukhovian age, Mira Formation) (Carvalho, 1976; Oliveira *et al.*, 1988). These sediments outcrop in the NE border area of the Cercal antiform. The gravity survey performed in this sector by the Empresa Mineira da Serra do Cercal in the 1990's allow to define a positive NW-SE trend Bouguer anomaly axis probably reflecting the VSC structure along strike and down dip (Costa, 1997). Nevertheless, the favourable geological and geophysical setting, the 96/17 EMSC 602.2 m vertical drill hole intercepted a monotonous and continuous graphitic shale sequence with fine grained disseminated pyrite. On the other hand, at the NE sector of the Cercal Antiform, the Bouguer anomaly data (S in Fig. 6) were useful to the discovery of the Salgadinho massive sulphide deposit by SFM (Carvalho, 1979). In the Chança antiform, a similar scenario occurs related with an important rhyolite structure of Tournaisian age (Rosa *et al.*, 2009; Solá *et al.*, 2019), locally with dome facies and strong hydrothermal silica and chlorite alteration, surrounded by flysch sediments of the Gafo Formation (Carlos Inverno geological mapping in Carvalho, 1979; Oliveira *et al.*, 2006). The Chança target is defined, by a large > 1 mGal Bouguer anomaly (Palomero and Mora, 1996; Palomero, 1999) with 2 km of extension along E-W direction (parallel to the geological main direction and subparallel to the main cleavage S1) and 1 km length in the N-S transverse direction. Whereas the rhyolite structure is reflected by a negative gravimetric anomaly, an important positive target was detected in the northern sector of the structure, representing sulphide *stockwork* mineralization. Exploration drill holes carried out by Atlantic Copper and AGC companies confirm this model and the intersection of > 100 m thick *stockwork* zone located in the northern area of the antiform (see location in Matos and Filipe Eds., 2013). E-W positive Bouguer anomalies are defined near the Portuguese/Spanish border, concordant with the VSC/PQ structures trend in this sector, such as São Domingos (SD in Fig. 6, Matos *et al.*, 2006), Pomarão and Foupana (12 in Fig. 6, Carvalho *et al.*, 2017). In this sector, basic volcanic rocks were intersected by Billinton drill holes in the late 1980s (Poiton, 1986). At the central and NW IPB sectors, the Bouguer anomalies present a NW-SE direction, concordant with the main direction of VSC and VSC/PQ structures, forming lineaments with kilometres of extension, important in the definition of favourable exploration scenarios (Carvalho, 1982; Oliveira *et al.*, 1998b, 2001; Oliveira *et al.*, 2006; Matos and Sousa, 2008). Examples of these lineaments are in the northern IPB branch (Oliveira *et al.*, 2019) the Roxo dam-Albernôa-Serra Branca-São Domingos (14, 15 and SD in Fig. 6) and in central IPB area the Caveira (C)–Lousal (L)–Sesmarias (SE)–Brejo (8)–Montinho (M)–Rosário (11)–Neves-Corvo (NC)–Foupana (12) lineament (references in Fig. 6). This last lineament presents a significant mineral potential, considering the presence of several massive

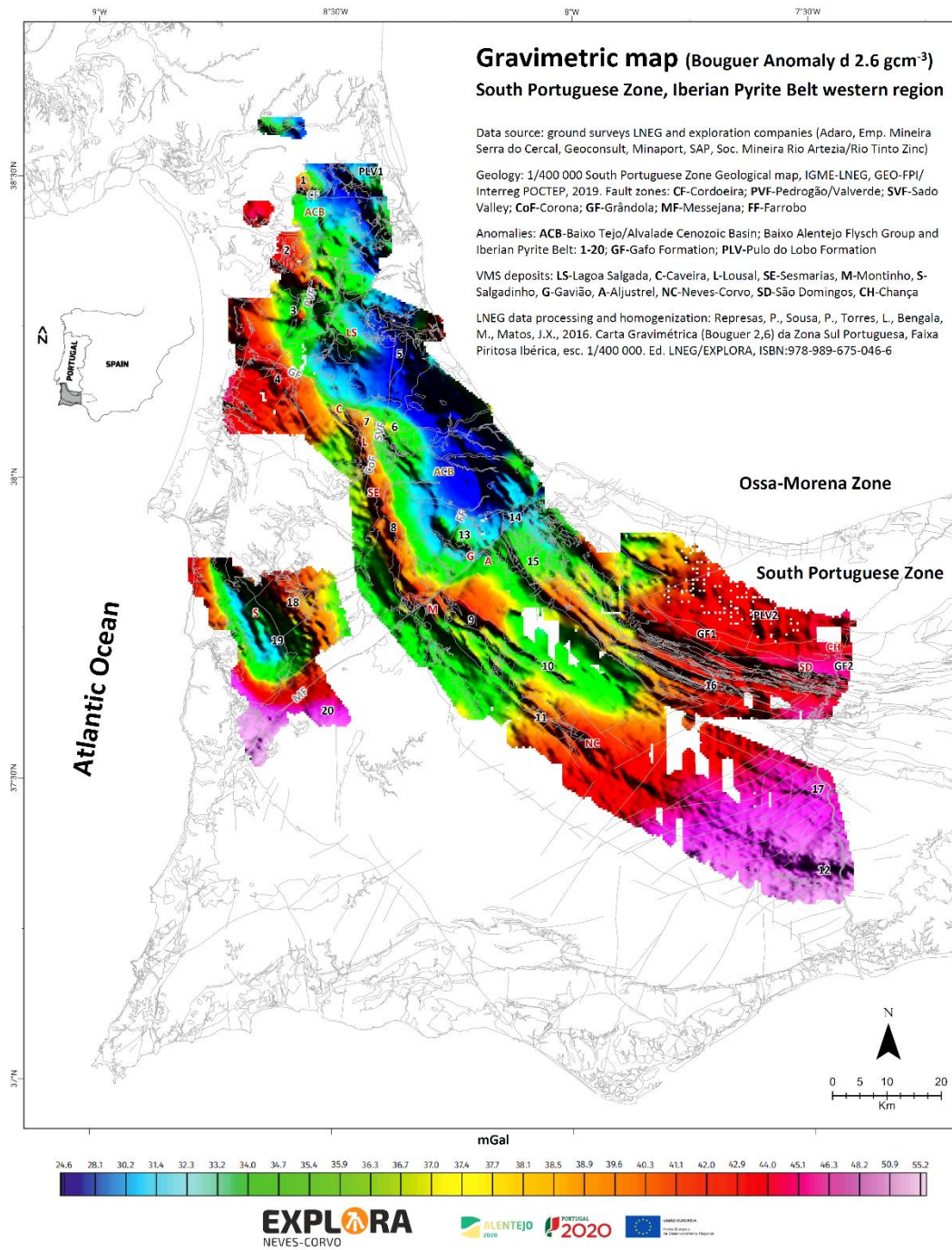


Figure 6. Gravimetric map (Bouguer Anomaly $d\ 2.6\ \text{gcm}^{-3}$) of the South Portuguese Zone and Iberian Pyrite Belt Portuguese sector (Represas *et al.*, 2016b). Interpreted main fault zones: CF-Cordoeira; PVF-Pedrogão/Valverde; SVF- Sado Valley; CoF-Corona; GF-Grândola; MF- Messejana; FF- Farrobo. Negative anomalies: ACB- Baixo Tejo/Alvalade Basin; 5- Batão graben; G- Morgado graben (See Fig. 5); 14- Dolerito Messejana; 19- Cercal do CVS com rochas vulcânicas félsicas muito siliciosas. Anomalias positivas: Jazigos VMS: LS- Lagoa Salgada and horst structure; C- Caveira; L- Lousal; SE- Sesmarias; S- Salgadinho; G- Gavião; A- Aljustrel; M- Montinho; NC- Neves-Corvo; SD- São Domingos; CH- Chança. Rochas vulcânicas félsicas do CVS (e sedimentos do PQ quando ocorrem): 1- horst Serrinha; 2- horst Porto de Mel; 3- horst Pedrogão; 4- Antiforma CVS Cidrão; 6- Garcia Menino/Vale Parreira; 8- Brejo structure; 11- Rosário Antiform; 17- Alcoutim horst. VSC basic volcanic rocks: 9- Casével; 10- Castro Verde-São Pedro das Cabeças; 12- Foupana-Corte São Tomé; 13- Milhuros (including horst structure). Baixo Alentejo Flysch Group: 18- Abertas Shales Member (Mira Formation). Gafo Formation: GF1- Corte Gafo, GF2- Chança sul. Pulo do Lobo Formation: PLV1- Barrancão, Santa Susana west, PLV2- Pulo do Lobo region. Geology: 1/400 000 South Portuguese Zone Geological map, IGME-LNEG 2019, GEO-FPI/Interreg POCTEP. See Annex 1.

Figura 6. Carta gravimétrica (Anomalia de Bouguer $d\ 2.6\ \text{gcm}^{-3}$) da Zona Sul Portuguesa e setor português da Faixa Piritosa Ibérica (Represas *et al.*, 2016b). Falhas interpretadas: CF-Cordoeira; PVF-Pedrogão/Valverde; SVF-Vale do Sado; CoF-Corona; GF-Grândola; MF-Messejana; FF-Farrobo. Anomalias negativas: ACB- Bacia do Baixo Tejo/Alvalade; 5- Graben Batão; G- Morgado graben (Fig. 5); 14- Dolerito Messejana; 19- setor Cercal do CVS com rochas vulcânicas félsicas muito siliciosas. Anomalias positivas: Jazigos VMS: LS- Lagoa Salgada e estrutura horst; C- Caveira; L- Lousal; SE- Sesmarias; S- Salgadinho; G- Gavião; A- Aljustrel; M- Montinho; NC- Neves-Corvo; SD- São Domingos; CH- Chança. Rochas vulcânicas félsicas do CVS (e sedimentos do PQ quando ocorrem): 1- horst Serrinha; 2- horst Porto de Mel; 3- horst Pedrogão; 4- Antiforma CVS Cidrão; 6- Garcia Menino/Vale Parreira; 8- estrutura Brejo; 11- Antiforma Rosário; 17- horst Alcoutim. Rochas vulcânicas básicas do CVS: 9- Casével; 10- Castro Verde-São Pedro das Cabeças; 12- Foupana-Corte São Tomé; 13- Milhuros (incluindo estrutura em horst); Grupo do Flysch do Baixo Alentejo: 18- Membro Xistos das Abertas (Formação de Mira); Formação do Gafo: GF1- Corte Gafo, GF2- Chança sul; Formação Pulo do Lobo: PLV1- Barrancão, Santa Susana oeste, PLV2- região Pulo do Lobo. Geologia: Mapa Geológico 1/400 000 Zona Sul Portuguesa, IGME-LNEG 2019, GEO-FPI/Interreg POCTEP. Ver Anexo 1.

sulphide deposits both with Strunian age: Neves-Corvo (giant deposit), Montinho, Lousal and Caveira (Matos *et al.*, 2011). Another important VSC lineament is the Aljustrel structure (A in Figs. 5 and 6) and its extension to Gavião (G).

The regional IPB gravimetric map (Fig. 6) indicates important anomalies at local scale, most of them with a strong correlation with the local geology. In some cases, gravity data can be correlated with sulphide ores (massive and semi-massive) and sulphide disseminations in depth and associated with VSC felsic volcanic rocks and black shales. Detailed Bouguer anomaly geometry can be observed in the LNEG archive data, related with the SFM 1/25 000 and 1/5 000 scale map collection, produced considering a bulk density of 2.6 g.cm^{-3} , see example of the Aljustrel Bouguer 1/25 000 scale map n° 529 (Fig. 5) and Neves-Corvo mine gravity residual map in figure 7. Moreover, detailed gravimetric maps are present in dozens of exploration reports. A good example of exploration mapping is the Bouguer and Residual Non Filtered gravimetric maps, produced by Minaport-EDM at 1/25 000 scale, considering densities of 2.1 g.cm^{-3} (Cenozoic outcropping areas) and 2.7 g.cm^{-3} (Paleozoic outcropping areas) (T. Burvenich *in* La Fuente, 1995). Other regional gravimetric maps were produced by companies such as AGC, Billinton, Elf

Aquitaine, Emp. Mineira da Serra do Cercal, Northern Lion Oy, Somincor and SMRA for their exploration permit areas (Albouby *et al.*, 1981; Castelo Branco, 1995; Carvalho, 1996; Castelo Branco and Sá, 1997; Faria, 2007; Araújo and Castelo Branco, 2010; Nobre, 2013). Similar methodology was used by SFM and IGM team in the Lagoa Salgada-Valverde project area, the first to be developed in the northern Grândola Fault sector, an area represented by large outcrops of Cenozoic age sediments, included in the Sado/Alvalade Basin (Oliveira *et al.*, 1993, 1998a; Matos *et al.*, 2018). These gravimetric surveys were essential to the discussion and understanding of the gravity field, even if they were limited to the exploration polygon boundaries. In each project, the regional gravimetric maps, produced at 1/100 000, 1/50 000 and 1/25 000 scales (*e.g.* Oliveira *et al.*, 1993; La Fuente, 1995) were important tools to define priority target areas, later investigated by specific drill hole programs. The same approach is being developed in the near mining EXPLORA/Alentejo2020 research project in the Neves-Corvo - São Pedro das Cabeças IPB sector (Figs. 4 and 7) (Matos *et al.*, 2017, 2019; Marques *et al.*, 2019). In this critical IPB area, the gravity survey allowed the definition of ore related anomalies, also linked to geological formations and structural plans.

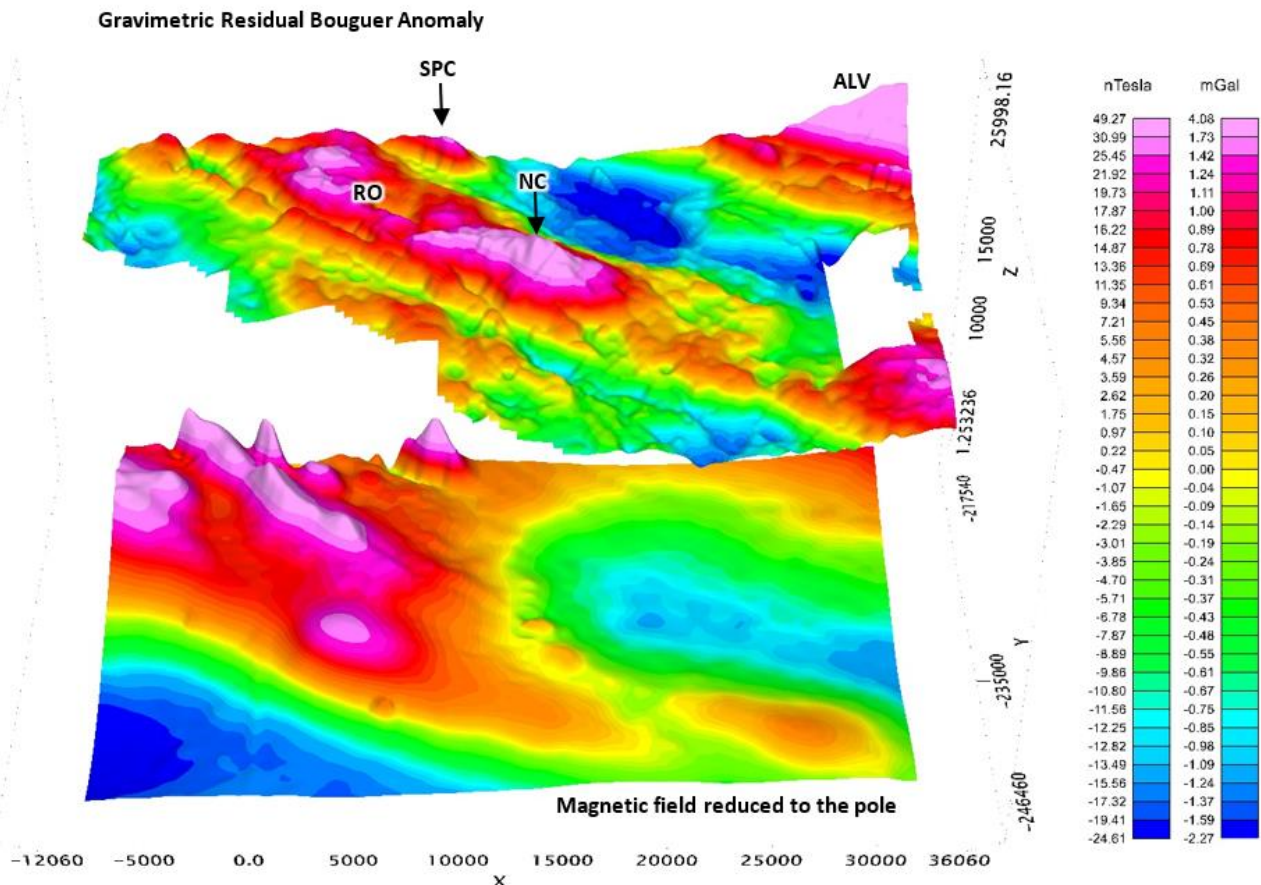


Figure 7. Residual Bouguer anomaly map (top) and Magnetic field reduced to pole map (base). Neves-Corvo (NC) and São Pedro das Cabeças (SPC) regions including Rosário (Ro) and Alvares (ALV) sectors (location in Fig. 1), EXPLORA Project processing data, LNEG databases: top – 3D Residual Bouguer anomaly map, reference density 2.6 g.cm^{-3} , ground survey (Fig. 4). The residual anomaly was produced by removal of a second-degree polynomial surface (Marques *et al.*, 2019); base – 3D Magnetic field reduced to the pole map, data from Geotrex 1991 airborne survey, LNEG database. Artificial magnetic punctual anomaly related with Neves-Corvo mine ore plant has been extracted. Coord. Hayford-Gauss Lisbon IPCC in meters.

Figura 7. Mapa da anomalia residual de (topo) e o mapa do campo magnético reduzido ao polo (base): Região de Neves-Corvo (NC) e São Pedro das Cabeças (SPC) incluindo os setores de Rosário (Ro) e Alvares (ALV) (ver localização na Fig. 1), processamento Proj. EXPLORA, base de dados LNEG: topo – vista 3D da carta de Anomalia Bouguer Residual, densidade 2.6 g.cm^{-3} , levantamentos terrestres (Fig. 4). A anomalia residual foi produzida removendo um campo regional calculado pela aproximação da anomalia de Bouguer a uma superfície polinomial de segundo grau (Marques *et al.*, 2019); base – vista 3D do Campo Magnético reduzido ao polo, dados Geotrex (1991), levantamento aerotransportado. Base de dados LNEG. A anomalia relacionada com a unidade de processamento mineral da mina de Neves-Corvo foi removida. Coordenadas Hayford-Gauss Lisboa IPCC em metros.

At a local scale, the massive sulphide deposits appear as oval shaped anomalies, *e.g.* Feitais (FE in Fig. 5 and A in Fig. 6), Neves-Corvo (Fig. 4 and NC in Figs. 6 and 7, Alvouy *et al.*, 1981; Leca *et al.*, 1983; Carvalho *et al.*, 1996; Marques *et al.*, 2019) and Lagoa Salgada (LS in Fig. 6, Oliveira *et al.*, 1993; Castelo Branco, 1995; Oliveira *et al.*, 1998a, b; Represas and Matos, 2012). All examples present a local amplitude of > 0.5 mGal. These anomalies are aligned in accordance with the global direction of the ore deposits and parallel to the VSC host rocks and correspond to key exploration targets (Carvalho, 1982; Castelo Branco, 1995; Carvalho, 1996; Oliveira *et al.*, 1993, 1998b, 2001; Matos and Sousa, 2008; Matos *et al.*, 2017, 2019). Usually these local gravimetric anomalies are investigated with other geophysical methods, through an interactive interpretation process (*e.g.* vertical electrical soundings (VES), magnetotelluric and magnetic surveys and *mise-à-la-masse* performed at Lagoa Salgada, (Oliveira *et al.*, 1993; 1998b) and TEM surveys largely used by Somincor/Lundin Mining in areas like Rosário, Neves-Corvo and São Pedro das Cabeças). An underground gravimetric profile was carried out by SFM in the late 1960s at level -160 m of the Lousal mine, with positive identification of the massive sulphide and *stockwork* mineralizations (Matzke, 1971). At Neves-Corvo, the interpretation of the 2nd vertical derivative of the Bouguer anomaly field was essential to the discovery of the Lombador deep orebody, in 1988 (Carvalho, 1996). However, the deep location of possible mineralized structures raises difficulties in gravimetric data interpretation, as it is the case of Semblana deposit, recently discovered by Lundin and located at 800 m deep, in the northeast sector of the Neves-Corvo mine (Newall, 2017; Marques *et al.*, 2019; Pereira *et al.*, 2020, accepted in this volume). In this case, the gravimetric response is weak and conditioned by other lithological factors. Other geological scenarios become ambiguous for gravity field interpretation, like the effect produced by rocks with local higher density (*e.g.* basic rocks or black shales with disseminated pyrite, both common in the VSC sequences), or lower density (*e.g.* by intense rock weathering) (see Tab. 5). The Neves-Corvo case study (3D gravity and magnetic model in Fig. 7) shows different responses regarding rock petrophysics and the VSC NW-SE trend lineaments are well defined. Bouguer anomaly data were acquired in SFM, ASARCO/IGM, S.A.P.A./SOMINCOR gravity surveys carried out between the 1960s and 1990s in the Neves-Corvo region (see also Fig. 4). The 3D map was produced using Oasis Montaj *software* and the interpolation *kriging* method that allowed to define a regular 400 m spacing grid (96 lines x 61 rows). At Neves-Corvo, seven known ore lenses and associated stockworks are reflected by a large gravimetric with NW-SE global trend. At São Pedro das Cabeças sector (SPC in Fig. 7), VSC basic volcanic rocks and jaspers with magnetite are reflected by well correlated gravimetric and magnetic anomalies. Intrusive basic volcanic rocks present in the Upper VSC sequence of Rosário (RO in Fig. 7) can be correlated with NW-SE trend magnetic anomalies. Both methods are essential to follow VSC hidden structures in areas covered by young sediments of the Mértola Fm. (Baixo Alentejo Flysch Group, late Viséan) like SW Almodôvar lineament and SE Neves-Corvo mine sectors (*e.g.* Cotovio and Barrigão). The structural complex area of Alvares (Oliveira *et al.*, 2016) is represented by an important gravity gradient to NE, probably related with the proximity of the Pulo do Lobo domain (see also Fig. 6).

In 2013, the discovery of the La Magdalena ore deposit, located in the IPB Spanish sector near Aguas Teñidas, only at 190 m depth, between two layers of basic rocks and discovered after several exploration phases, shows the necessity of detailed and accurate studies of the geophysical and geological models. A similar scenario happened in the discovery of the Sesmarias

deposit by MAEPA/AVRUPA at ~130 m depth, located near Azinheira dos Barros (SE in Fig. 6, Khun, 2017; Coder and Kuhn, 2020) associated with black shales and close to VSC basic volcanic rocks. In fact, in areas with significant tectonic deformation, ore deposits can be limited by thrust planes and different density layers can be found in the same sector. This poses a problem in gravity field interpretation and modelling, as this type of data has a very strong equivalence problem regarding the identification of sub horizontal discontinuities. Gravimetric data interpretation, complemented with other geophysical methods (*e.g.* seismics, magnetometry and electromagnetics) and an accurate geological interpretation is therefore a key success factor in the exploration of the IPB. Accurate gravimetric modelling programs must be developed in the near future considering the geological and structural settings of selected targets, high resolution stratigraphy and ore horizons definition and rock petrophysics - massive and *stockwork* mineralization, host rocks and hydrothermal alteration and distal to mineralization rocks units. Near surface rock weathering and consequent lower density must be considered. The study of recent deep drill holes, below 1 500 m (*e.g.* Neves-Corvo, Newall *et al.*, 2017) will allow to know constrains related with petrophysical changes at depth.

5. Magnetometry

Magnetic prospecting was one of the first geophysical techniques used by the former SFM, in the early 1940s (Queiroz *et al.*, 1990). Magnetic susceptibility is the physical property that magnetometry studies. The reader can consult Milsom (2003) or Telford *et al.* (2012), for a more comprehensive approach of the magnetic method. In 1954, this method became a regular tool in SFM and OMZ iron ore explorations. These surveys were initiated in a context of active mining operations like Orada mine (see location in Matos and Filipe Eds., 2013). The SFM magnetic ground surveys were planned with a similar layout to those used for the gravimetric surveys, based on N-S, E-W oriented grids, with 200 m to 100 m spacing between stations. In 1991, by request of the Rio Tinto Company, Geoterrex carried out a regional airborne survey using NE-SW direction flight lines and 250 m and 500 m spacing with the airborne sensor located ~90 m above ground surface (Castelo Branco, 1995; Castelo Branco and Sá, 1997; Torres and Carvalho, 1998). Other airborne surveys, carried out by Minaport (Anglo American), allowed a large coverage of the IPB Portuguese sector with high resolution aeromagnetic. The IPB Magnetic map (IGRF removed) (1/400 000 scale, Represas *et al.*, 2016a) is presented in figure 8 and Annex 2, and provides useful information about Southern Portugal geology, including the Paleozoic structures of the South Portuguese Zone, the main geological region where IPB is included. In the western and southern areas, the Rio Tinto survey includes the Mesozoic sequences of Santiago do Cacém and Algarve (see anomalies M1 and M3 in Fig. 8). In its northern border, the airborne survey comprises the Pulo do Lobo Antiform and the Beja Acebues Ophiolite Complex, near Ferreira do Alentejo, included in the OMZ domain (BAOC+BIC in Fig. 8). Data homogenization and validation were conducted by LNEG team, using Geosoft *software*. Original data were from airborne exploration surveys performed by Rio Tinto (Geoterrex, 1991), Anglo American (Minaport)/EDM, Urganhart, 1991) and IGM (Sanders Geophysics, 1997). Anomalies of anthropogenic source such as power lines and industries (*e.g.* Neves-Corvo ore treatment plant) were filtered and are not indicated.

The magnetic anomalies depicted in figure 8 and Annex 2 are originated from shallow sources, locally related with geological formations outcrops and with deep hidden sources. The magnetic

anomalies of exploration interest are related with shallow source anomalies (Fig. 8): i) VSC basic intrusive and/or extrusive volcanic rocks with disseminated magnetite (Oliveira *et al.*, 1982; Munhá, 1983; Oliveira *et al.*, 2016) present at Serrinha (1) and Cordoeira (Matos *et al.*, 2009a, b), Vale de Guiso and Vale de Água (2) (Oliveira *et al.*, 1998b; Oliveira *et al.*, 2001; Castelo Branco, 1995; Matos *et al.*, 2018), Rio de Moinhos (3) (Oliveira *et al.*, 1998b; Pereira *et al.*, 2008), Caveira (C) (Matos *et al.*, 2015); Caveira E and Azinheira de Barros (4) (Oliveira *et al.*, 1982), Lousal (L) (Matos and Relvas, 2006), Milhousos (5) (Oliveira *et al.*, 1982; La Fuente, 1995), Torgal, south Cercal Antiform (6) (Oliveira *et al.*, 1982; Faria, 2007), Grandãos (7) and Rosário (Oliveira *et al.*, 2016), Casével (8) and Castro Verde-São Pedro das Cabeças (9, see also Fig. 7), Roxo (10), São Domingos mine open pit (SD) and Bicadas sector (11) (Oliveira and Silva, 1990; Matos *et al.*, 2006; Oliveira, *et al.*, 2007) and Corte S. Tomé-Foupana (12) (Carvalho *et al.*, 2017); ii) VSC jaspers with disseminated magnetite located at Penique (J1) (Oliveira *et al.*, 1991), Rio de Moinhos (J2) (Pereira *et al.*, 2008; Oliveira *et al.*, 2001; Matos *et al.*, 2018), Feitais, Malpique, Senhora do Castelo and Mangancha, Aljustrel (J3, A) (Schermerhorn *et al.*, 1987; Leitão, 1998; Matos *et al.*, 2010) and São Pedro das Cabeças (J4, see also Fig. 7) (Oliveira *et al.*, 2016); iii) Mesozoic basic volcanic rocks and dolerites of Jurassic age (Sinemurian-Hettangian) (G. Manupella in Inverno *et al.*, 1993) of the Santiago do Cacém (M1) and Algarve (M3); iv) late Variscan dolerites, *e.g.* Alentejo Messejana dike (D1) of Middle Jurassic (Bathonian) age, 168 ± 5 Ma (Schermerhorn *et al.*, 1987) and dolerite dikes associated with ENE-WSW late Variscan faults located at the Zambujal area (D2) (Oliveira, 1983; Matos *et al.*, 2003); v) Mesozoic Monchique massif (M2) (predominant nepheline sienite of Late Cretaceous age, Gomes and Pereira, 2004; Grange *et al.*, 2010). In the northern SPZ areas, very intense magnetic anomalies occur related with the Pulo do Lobo Antiform, where basic rocks with basaltic tholeiitic affinity (Munhá, 1983) are known at NE Coordoeira, Santa Susana (PLV1 in Fig. 8) (Matos *et al.*, 2009a, 2018) and Trindade and Alfarrobeira (PLV2) (Zbyszewski *et al.*, 1964; Oliveira *et al.*, 1992; Ferreira and Oliveira, 2019). Near Ferreira do Alentejo, the airborne data shows an intense positive gradient towards NE, corresponding to the mafic and ultramafic rocks of the Beja Acebuches Ophiolite Complex (BAOC+BIC in Fig. 8) included in the OMZ domain (Oliveira *et al.*, 1992, 2019). The Baixo Alentejo Flysch Mértola, Mira and Brejeira formations (Late Carboniferous age, Oliveira *et al.*, 2006; Pereira *et al.*, 2008) are characterized by a low magnetic background and large negative anomalies.

For the purpose of massive sulphide exploration, the definition of VSC lineaments along the belt is an important research goal. The magnetic total field map (Represas *et al.*, 2016a) shows consistent VSC NW-SE trend lineaments especially in the central IPB area characterized by VSC antiforms, showing minor complexity when compared to the northern IPB sector (Oliveira *et al.*, 2006; Pereira *et al.*, 2008). The magnetic airborne surveys reflect near surface anomalies associated with VSC structures of basic volcanic rocks (spillites lavas and dolerites) and jaspers with magnetite, commonly associated with the VSC upper sequence (Late Visean age, Oliveira, 1983; Oliveira *et al.*, 1992, 2006, 2013, 2016, 2019). Basic volcanic lavas (spillites) are also present in the base of the VSC sequence (Famennian age) in the Lousal mine (L) (Matos and Relvas, 2006; Relvas *et al.*, 2012; Matos *et al.*, 2014) and Forno da Cal area (SE sector of the Rosário-Neves-Corvo Antiform, Oliveira *et al.*, 2013, 2016). Preliminary results show

different magnetic intensity. Future paleomagnetism studies should help to define constrains in the VSC basic volcanism of Famennian and Late Visean age (~30 Ma of time span). Regarding the Casével-Castro Verde-São Pedro das Cabeças VSC Late Visean age lineament (8 and 9 in Fig. 8 and SP in Fig. 7, Oliveira, 1983), the Total Field Magnetic map shows differences in magnetic intensity (lower in the northwest Casével sector and higher in the south eastern Castro Verde sector). These differences could be related with the presence of volcanic breccia facies with minor content in magnetic minerals described at Casével (Oliveira *et al.*, 1998).

Despite the constraints associated with the magnetic method, the presence of massive sulphide deposit orebodies near basic volcanic rocks, *e.g.* Lousal (L), Sesmarias (SE), Montinho (M) and São Domingos (SD) ore lenses in Portugal (Oliveira *et al.*, 1992; Oliveira and Silva, 2007; Matos and Relvas, 2006; Matos *et al.*, 2006, 2011, 2014), La Magdalena ore lens in Spain (Sáenz de Sicilia, 2013), support this methodology as a key exploration tool. The magnetic data are very useful, and even essential, to follow VSC lineaments in areas where the Paleozoic basement is covered by Cenozoic age sediments. Case studies can be followed in the NW IPB region of the Baixo Tejo/Alvalade Basin (Oliveira *et al.*, 1993, 1998a, b; Castelo Branco, 1995; Oliveira *et al.*, 2001; Matos *et al.*, 2009a, b; 2018). Here, the NW-SE trend of the VSC related magnetic anomalies confirms that the Pyrite Belt province extends north-westward to the Setúbal region under Cenozoic and Mesozoic sequences (see IPB northern area at Serrinha Paleozoic window, 1 in figure 8, and details in Matos *et al.*, 2009a, b, 2018). Several magnetic targets were investigated by exploration drill holes and VSC basic volcanic rocks with disseminated magnetite were confirmed at Vale de Água, near Vale de Guiso (2 in Fig. 8, GA14 SMRA drill hole, Castelo Branco, 1994) and Rio de Moinhos sectors (3) (IGM, SD.RM1 drill hole, Oliveira *et al.*, 1998b; Oliveira *et al.*, 2001; Oliveira *et al.*, 2006, 2013, 2019; Pereira *et al.*, 2008).

The basic rocks intersections occurred at a depth of 50 m in Vale de Água (GA14 hole) and at 186 m in Rio de Moinhos (SD.RM1 hole). Here the magnetic anomaly presents a mix source represented by VSC jaspers + basic volcanic rocks with veins and disseminated magnetite. In other sectors, several magnetic anomalies identified in the Cenozoic basin are not yet fully studied in depth by exploratory drill-holes, like the Charneca sector (DS1 in Fig. 3), located between the Valverde and Pedrogão Paleozoic windows (Oliveira *et al.*, 1998a; Matos *et al.*, 2018). VSC basic volcanic rocks located at relatively great depths are expected to be associated with this NW-SE trend magnetic lineament. In fact, the magnetic map shows not only signs of shallow sources, but also of deep sources, most of which are concealed and unknown. The deep source magnetic anomalies are more diffuse and present larger wavelengths if compared with the narrow anomalies associated with outcropping and/or near surface VSC basic rocks/jaspers. Examples of deep magnetic source anomalies are Louzelos-Boticos N (west Lousal, DS2), Cercal (DS3), Corte Gafo (DS4), Aldeia dos Fernandes-Almodôvar (DS5) and Vaqueiros (DS6), the last two hidden by thick flysch sediments of the Mértola Formation. Near the Portuguese/Spanish border, Billinton exploration holes drilled in 1986 over the magnetic and gravimetric Foupana large anomaly (12 in Figs. 6 and 8) intersected VSC basic volcanic rocks at ~710 m depth (Corte São Tomé CST1 drill hole) and ~750 m depth (Foupana FP1 drill hole) (Oliveira *et al.*, 1992; Matos and Filipe Eds., 2013; Inverno *et al.*, 2015; Carvalho *et al.*, 2017). Considering this particular case study, similar occurrences can be expected in the concealed

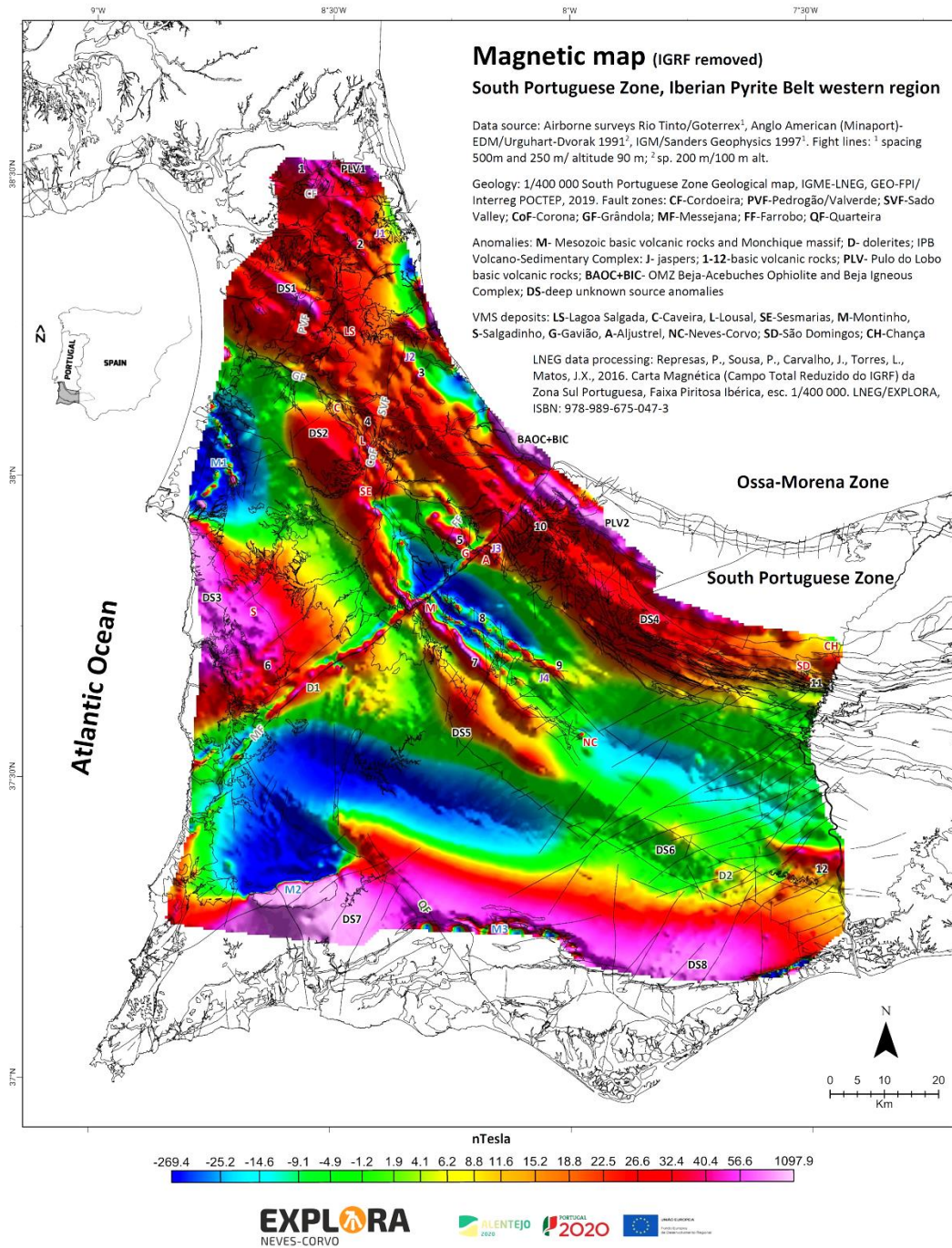


Figure 8. Magnetic map (IGRF removed) of the South Portuguese Zone and Iberian Pyrite Belt Portuguese sector (ad. Represas *et al.*, 2016a). Interpreted main fault zones: CF – Cordoeira; PVF – Pedrogão/Valverde; SVF – Sado Valley; CoF – Corona; GF – Grândola; MF – Messejana; FF – Farrobo; QF – S. Marcos-Quarteira. **Superficial source anomalies:** i) VSC basic volcanic rocks: Serrinha and Cordoeira (1), Vale de Guiso and Vale de Água (2), Rio Moinhos (3), Caveira E and Azinheira de Barros (4), Milhouros (5), Torgal (6), Grandaços and Rosário (7), Casével (8) and Castro Verde/São Pedro das Cabeças (9), Roxo (10), São Domingos open pit (SD) and Bicadas (11), Corte S. Tomé-Foupana (12); ii) jaspers with magnetite: Penique (J1), Rio Moinhos (J2), Aljustrel (J3) and São Pedro das Cabeças (J4); iii) Mesozoic basic volcanic rocks: Santiago do Cacém (M1) and Alte (M3); iv) Late Variscan dolerites: Messejana Fault (D1), Zambujal area (D2); v) Mesozoic igneous massif: Monchique (M2). **Anomalies related with deep hidden structures:** Charneca (DS1), Louzelos-Boticos N (DS2), Cercal (DS3), Corte Pequena-Corte Gafo (DS4), Aldeia dos Fernandes-Almodôvar (DS5), Vaqueiros (DS6), Portimão N/Algarve W (DS7), Tavira NW/Algarve E (DS8). Other sectors: Pulo do Lobo Formation basic volcanics: Santa Susana (PLV1), Trindade-Alfarrobeira (PLV2); Beja Acebuches Ophiolite Complex (BAOC) and Beja Igneous Complex (BIC) (Ossa Morena-Zone). Geology: 1/400 000 South Portuguese Zone Geological map, IGME-LNEG 2019, GEO-FPI/Interreg POCTEP. See Annex 2.

Figura 8. Carta Magnética (reduzida do IGRF) da Zona Sul Portuguesa e setor português da Faixa Piritosa Ibérica (Represas *et al.*, 2016a). Falhas interpretadas: CF – Cordoeira; PVF – Pedrogão/Valverde; SVF – Vale do Sado; CoF – Corona; GF – Grândola; MF – Messejana; FF – Farrobo; QF – S. Marcos-Quarteira. **Anomalias sobre fontes superficiais:** i) rochas vulcânicas básicas do CVS: Serrinha e Cordoeira (1), Vale de Guiso e Vale de Água (2), Rio Moinhos (3), Caveira E e Azinheira de Barros (4), Milhouros (5), Torgal (6), Grandaços e Rosário (7), Casével (8) e Castro Verde/São Pedro das Cabeças (9), Roxo (10), corte São Domingos (SD) e Bicadas (11), Corte S. Tomé-Foupana (12); ii) jaspers com magnetite: Penique (J1), Rio Moinhos (J2), Aljustrel (J3) e São Pedro das Cabeças (J4); iii) Mesozoico, rochas vulcânicas básicas: Santiago do Cacém (M1) e Alte (M3); iv) doleritos tardivariscos: Falha Messejana (D1), área de Zambujal (D2). **Anomalias associadas a fontes ocultas e profundas:** Charneca (DS1), Louzelos-Boticos N (DS2), Cercal (DS3), Corte Pequena-Corte Gafo (DS4), Aldeia dos Fernandes-Almodôvar (DS5), Vaqueiros (DS6), Portimão N/Algarve W (DS7), Tavira NW/Algarve E (DS8). Maciços ígneos mesozoicos: Sines (M1), Monchique (M2). Outros setores: Formação Pulo do Lobo, rochas vulcânicas básicas: Santa Susana (PLV1), Trindade-Alfarrobeira (PLV2); Complexo Ofolítico Beja Acebuches (BAOC) e Complexo Ígneo de Beja (BIC) (Zona Ossa-Morena). Geologia: Mapa Geológico 1/400 000 Zona Sul Portuguesa, IGME-LNEG 2019, GEO-FPI/Interreg POCTEP. Ver Anexo 2.

sources of the DS2, DS5 and DS6 anomalies, both with NW-SE main direction, similar to the VSC geological structures.

Regional magnetic anomalies related with high magnetic background areas occur in the Pulo do Lobo Antiform (PLV1, west of Santa Susana and PLV2, Alfarrobeira), Chança Group and northern IPB area (DS4, Corte Gafo). At the Baixo Tejo/Alvalade Basin sector located northward of the Grândola Fault, a high magnetic background occurs. This setting can be related with the presence of coarse Cenozoic age conglomerates with floats of OMZ basic igneous rocks (Oliveira *et al.*, 1998a, b), associated with the erosion of mafic and ultramafic OMZ massifs. At Cercal region, the high magnetic background (DS3 in Fig. 8) is clearly limited, at southeast, by the Messejana Fault (MF). The proximity of the Sines Cretaceous Massif must be considered, as mentioned by some authors (Torres and Carvalho, 1998), but other sources can also be responsible for the observed field, such as the Earth crust zonation near the Portuguese coastal area. Similar interpretations can be forwarded for the southern Algarve sector (DS7 – Portimão north and DS8 – Tavira NW anomalies), also indicated by González-Castillo *et al.* (2014), as a regional anomaly extending to Spain. These authors correlate the high magnetic background with the Monchique massif, but this relation is not completely clear. In fact, the Monchique Massif (anomaly M2) is located at the boundary between two well defined magnetic domains (low values in the northern side, high values in the southern side – DS7 anomaly). The Monchique massif location was probably controlled by an ENE-WSW fracture, perpendicular to the regional main fracture that correlate the Sintra, Sines and Monchique Cretaceous massifs (Ribeiro *et al.*, 2007, see Fig. 3). In the eastern region of Monchique, a strong NW-SE direction gradient can be observed, corresponding to the northern sector of the S. Marcos-Quarteira Fault Zone (QF) (Oliveira *et al.*, 1984; Terrinha, 1998; Dias, 2001; Cabral, 2018). At the Iberian Peninsula scale dimension, a Moho structure anomaly located at the Algarve region, with a similar E-W direction is referred by Moraleda *et al.* (2013). The southwards increase of the magnetic field corresponds to a similar increase of the Bouguer gravity field values (see Fig. 2 gravimetric map). Probably both geophysical methods reflect the same origin that is the probable presence of ocean crust in the southern and western Portugal. These data are consistent with the global magnetic field map of the western Iberia Atlantic territory.

6. Radiometry

Radiometry is a geophysical method used to measure the natural radioactivity. The most common method for radiometric exploration is the measurement of the total radiation, which measures the full range of existing radioactive isotopes in Nature. Measured in total count, in the present maps it was expressed in exposure rate. Total radiation corresponds mainly in the detection of U, Th and K by the equipment and traces of the rest of radioactive isotopes. K is measured from the direct radioactive decay of ^{40}K to ^{40}Ar . The U itself does not emit gamma radiation. The measurement made correspond to its most energetic decay to ^{214}Bi . Like the U, Th itself does not emit gamma radiation, this radiation, therefore is measured at its descendent isotope ^{208}Tl (IAEA, 2003). Currently, in the IPB, this method is applied jointly with other geophysical methods as well as with geochemistry in the exploration of massive sulphides (Batista *et al.*, 2016a, 2020) and also in geothermal studies (Torres *et al.*, 2000; Ramalho *et al.*, 2017). However, the SPZ was included in a regional exploration radiometric survey comprising acquisition in U, Th, K and Total Count channels and magnetometry (referred in the last chapter) performed by Geoterrex in 1991 for the Rio

Tinto Company. The airborne survey was carried out using a NE-SW flight lines direction and 250 m and 500 m spacing and the airborne sensor located ~90 m above the land surface (Castelo Branco, 1995; Castelo Branco and Sá, 1997; Torres and Carvalho, 1998). The areas not covered by Geoterrex survey were covered by LNEG team on ground surveys since the late 1990's until 2012, using a NaI (TI) scintillation crystal - SPP2-NF scintillometer. These surveys were essential to the edition of the Portuguese Radiometric Map (Batista *et al.*, 2013). Figure 9 and Annex 3 in A3 depict Radiometric map (Natural Radioactivity) (Batista *et al.*, 2016b), that was produced as an extract of the national map, considering the area of the south of Portugal included in the SPZ main geological unit.

Considering the specifications of the radiometric method, limited to near surface information, a global overview is presented and related with the SPZ geological setting. The figure 9 map (Batista *et al.*, 2016b) reflects the main geological units of the Paleozoic basement, showing, in several sectors, an accurate concordance with the boundaries of the geological formations. The response of the Mesozoic and Cenozoic age lithologies is not so clear and is more diffuse. Irregular low anomalies are related with water plans (*e.g.* Santa Clara and Monte da Rocha dams). Because it is a method with small penetrating rate (about 30-50 cm bellow the surface) proves to be very effective in geological mapping support, especially when differentiating units with a radiometric contrast (*e.g.* felsic and mafic volcanic rocks). In IPB mineral exploration scenario radiometry can provide useful data related with K rich hydrothermal alteration present in felsic volcanic rocks (Dickson and Scott, 1997).

High natural gamma radiation zones are represented by the following lithologies from older to young age (see Fig. 9): i) Pulo do Lobo Domain: chloritic and sericitic shales of the Pulo do Lobo Formation (PLV2, Vale de Rocins, Frasnian age, Pereira *et al.*, 2018); Ribeira de Limas Formation (Frasnian age, Pereira *et al.*, 2008) (see PLV1, west Santa Susana and PLV2); flysch sediments of the Santa Iria Formation (Famennian age, Pereira *et al.*, 2008), *e.g.* sandstones (PLV1, Barrancão, west Santa Susana) and shales and greywackes (PLV3, Santa Iria); ii) Iberian Pyrite Belt: quartzites and shales of the Phyllite-Quartzite Formation (Givetian-Famennian, Pereira *et al.*, 2008; Matos *et al.*, 2014), *e.g.* Pego do Altar (2), Caveira (C, 4), Azinheira de Barros (5), Lousal (L, 6), Albernôa (8), Serra Branca (9), Senhora de Aracelis (11), Mértola (12) and Pomarão (13); Vale Parreira Formation (mid-late Famennian age, Mendes *et al.*, 2020a), white mica rich shales and quartzwackes Garcia Menino/Vale de Parreiras (5); IPB Volcano-Sedimentary Complex – felsic volcanic rocks with regional sericite alteration (Famennian-Upper Viséan, Oliveira *et al.*, 2006; Pereira *et al.*, 2008; Oliveira *et al.*, 2013), *e.g.* from north to south: Serrinha (1), Caveira (C), Cercal (17), Maria Delgada (14), Rosário (15), Albernôa (8), Serra Branca (9), Bicasdas (10), Mértola SE (12), São Domingos (SD) and Achada do Gamo and Pomarão (13). Similar results are referred in the Spanish IPB sector (Garcia *et al.*, 1998) to the VSC and PQ lithologies; iii) Baixo Alentejo Flysch Group: Mértola Formation (Late Viséan, Oliveira 1983; Pereira *et al.*, 2008) - several areas represented by shale rich units, are reflected by high radiometric background (see 16, São Sebastião dos Carros in Fig. 9 well correlated with regional geological mapping, 46-D Mértola, Oliveira and Silva, 1990 and 46-C Almodôvar, Oliveira *et al.*, 2016); Mira Formation (Late Viséan-Lower Bashkirian, Oliveira *et al.*, 2006; Pereira *et al.*, 2008) – intercalations of shales and impure quartzites and quartzwackes, *e.g.* Cachopo and Dougueno (18B), Abertas Shales Member (18A, Silveiras) and SW limit with Brejeira Formation (18C)

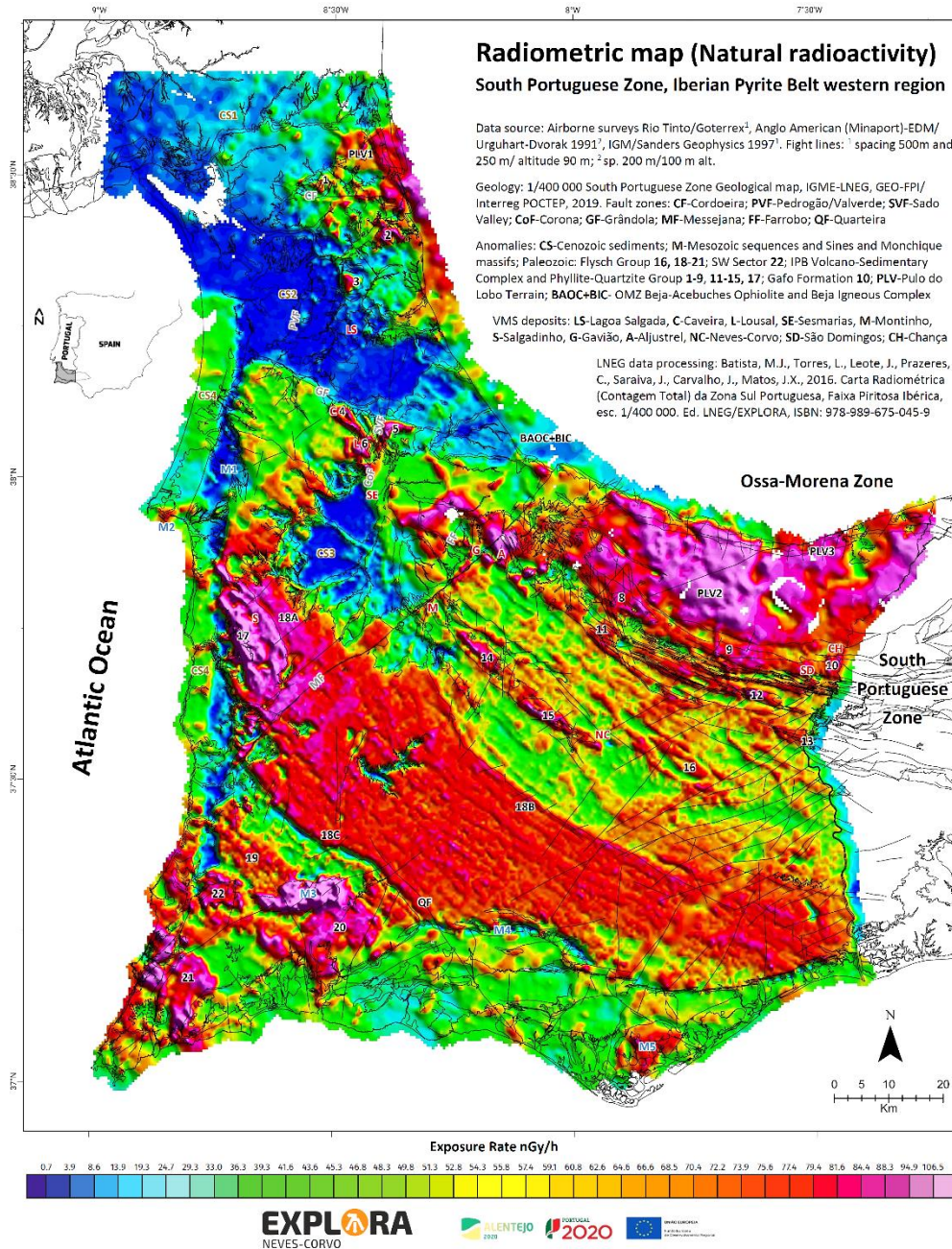


Figure 9. Radiometric map (Natural Radioactivity) of the South Portuguese Zone and Iberian Pyrite Belt Portuguese sector (Batista *et al.*, 2016b). Interpreted main fault zones: CF – Cordoeira; PVF – Pedrogão/Valverde; SVF – Sado Valley; CoF – Corona; GF – Grândola; MF – Messejana; FF – Farrobo; QF – São Marcos-Quarteira. Baixo Tejo/Alvalade Basin sectors: Setúbal NE region (CS1); Alcácer do Sal-Grândola (CS2); Alvalade (CS3). Litoral plain sediments: Vila Nova de Mil Fontes (CS4). Mesozoic sequences: Santiago do Cacém (M1) and Algarve Alte (M4) and Quelfes regions. Cretaceous age igneous massifs: Sines (M2) and Monchique (M3). Paleozoic: SW Sector Terceiras Formation (22); Baixo Alentejo Flysch Group: Brejeira Formation: Foz do Besteiro (19), Odelouca (20) and Espinhaço de Cão (21); Mira Formation: Abertas Shales Member (18A), Dougueno-Cachopo sector (18B) and Nave Redonda (18C); Mértola Formation: Barrosinha (3) and São Sebastião dos Carros (16); IPB Volcano-Sedimentary Complex and Phyllite-Quartzite Group when occurs: Serrinha (1), Pego do Altar (2), Caveira (C, 4), Garcia Menino/Vale Parreira (5), Lousal (L, 6), Aljustrel (A), Albernôa (8), Serra Branca (9), Corte Pinto (10), Senhora de Aracelis (11), Mértola (12), Pomarão (13), Maria Delgada (14), Rosário (15) and Cercal (17); Pulo do Lobo Terrain: Barranção, Santa Susana W (PLV1), Vale de Rocins (PLV2), Santa Iria (PLV3). Other sectors: Beja Acebuches Ophiolite Complex (BAOC) and Beja Igneous Complex (BIC), Ossa-Morena Zone. Geology: 1/400 000 South Portuguese Zone Geological map, IGME-LNEG 2019, GEO-FPI/Interreg POCTEP. See Annex 3.

Figure 9. Carta radiométrica (Radioatividade Natural) da Zona Sul Portuguesa e setor português da Faixa Piritosa Ibérica (Batista *et al.*, 2016b). Falhas interpretadas: CF – Cordoeira; PVF – Pedrogão/Valverde; SVF – Vale do Sado; CoF – Corona; GF – Grândola; MF – Messejana; FF – Farrobo; QF – São Marcos-Quarteira. Bacia Baixo Tejo/Alvalade: região NE Setúbal (CS1); Alcácer do Sal-Grândola (CS2); Alvalade (CS3). Sedimentos de planícies litorais: Vila Nova de Mil Fontes (CS4). Sequências mesozoicas: Santiago do Cacém (M1) e região de Alte (M4) e de Quelfes (M5) da Bacia do Algarve. Maciços de idade cretácica: Sines (M2) e Monchique (M3). Paleozoico: Setor SW Formação de Terceiras (22); Grupo Flysch do Baixo Alentejo: Formação da Brejeira: Foz do Besteiro (19), Odelouca (20) e Espinhaço de Cão (21); Formação de Mira: Membro Xistos das Abertas (18A), setor Dougueno-Cachopo (18B) e Nave Redonda (18C); Formação de Mértola: Barrosinha (3) e São Sebastião dos Carros (16); Faixa Piritosa Ibérica - Complexo Vulcano-Sedimentar e Grupo Filito-Quartzítico quando presente: Serrinha (1), Pego do Altar (2), Caveira (C, 4), Garcia Menino/Vale Parreira (5), Lousal (L, 6), Aljustrel (A), Albernôa (8), Serra Branca (9), Corte Pinto (10), Senhora de Aracelis (11), Mértola (12), Pomarão (13), Maria Delgada (14), Rosário (15) e Cercal (17); Terreno Pulo do Lobo: Barranção, Santa Susana W (PLV1), Vale de Rocins (PLV2), Santa Iria (PLV3). Outros setores: Complexo Ofiolítico Beja Acebuches (BAOC) e Complexo Ígneo de Beja (BIC), Zona Ossa-Morena. Geologia: Mapa Geológico 1/400 000 Zona Sul Portuguesa, IGME-LNEG 2019, GEO-FPI/Interreg POCTEP. Ver Anexo 3.

south of Santa Clara dam region; Brejeira Formation (Bashkiriano-Upper Moscovian, Pereira *et al.*, 2008) – similar anomalies occur, but with a more heterogeneous distribution. Local lithological changes in sedimentary units of the Brejeira Formation are reflected by different radiometric signatures at the Foz do Besteiro (19), Oudelouca (20) and Espinhaço de Cão (21) areas; iv) South West Sector – shales and quartzites of the Tercenas Formation (Strunian-Early Tournaisian, Pereira *et al.*, 2008) (22, Aljezur structure).

The geology of south of Portugal is well reflected in the radiometric map (Exposure Rate) (Fig. 9) in all geological domains of South Portuguese Zone: Pulo do Lobo, Pyrite Belt, Baixo Alentejo Flysch Group (BAFG) and SW Sector. In the Mesozoic sequences and Baixo Tejo/Alvalade Basin the results are also quite consistent. In particular scenarios, such as the BAFG the radiometric, it shows a remarkable resolution, when comparing with the LNEG 1/200 000 scale mapping (Oliveira *et al.*, 1992) and new LNEG/IGME 2019 1/400 000 mapping. The Mira Formation high background related with common white detrital K rich mica (sericite) observed in the shale, greywacke and quartzwacke matrix allows a good contrast with the BAFG Mértola Formation (located NE, *e.g.* Dougueno and Cachopo

sections 18B in Fig. 9) and with the Brejeira Formation (*e.g.* Nave Redonda sector, 18C in Fig. 9). Considering the homogeneous characteristics of these flysch sequences radiometry is a good mapping support, based on lithological different mineral composition.

High natural gamma radiation zones are represented by the following lithologies from older to young age (see Fig. 9): i) Pulo do Lobo Domain: chloritic and sericitic shales of the Pulo do Lobo Formation (PLV2, Vale de Rocins, Frasnian age, Pereira *et al.*, 2018); Ribeira de Limas Formation (Frasnian age, Pereira *et al.*, 2008) (see PLV1, west Santa Susana and PLV2); flysch sediments of the Santa Iria Formation (Famennian age, Pereira *et al.*, 2008), *e.g.* sandstones (PLV1, Barrancão, west Santa Susana) and shales and greywackes (PLV3, Santa Iria); ii) Iberian Pyrite Belt: quartzites and shales of the Phyllite-Quartzite Formation (Givetian-Famennian, Pereira *et al.*, 2008; Matos *et al.*, 2014), *e.g.* Pego do Altar (2), Caveira (C, 4), Azinheira de Barros (5), Lousal (L, 6), Albernôa (8), Serra Branca (9), Senhora de Aracelis (11), Mértola (12) and Pomarão (13); Vale Parreira Formation (mid-late Famennian age, Mendes *et al.*, 2020a), white mica rich shales and quartzwackes Garcia Menino/Vale de Parreiras (5); IPB Volcano-Sedimentary Complex – felsic

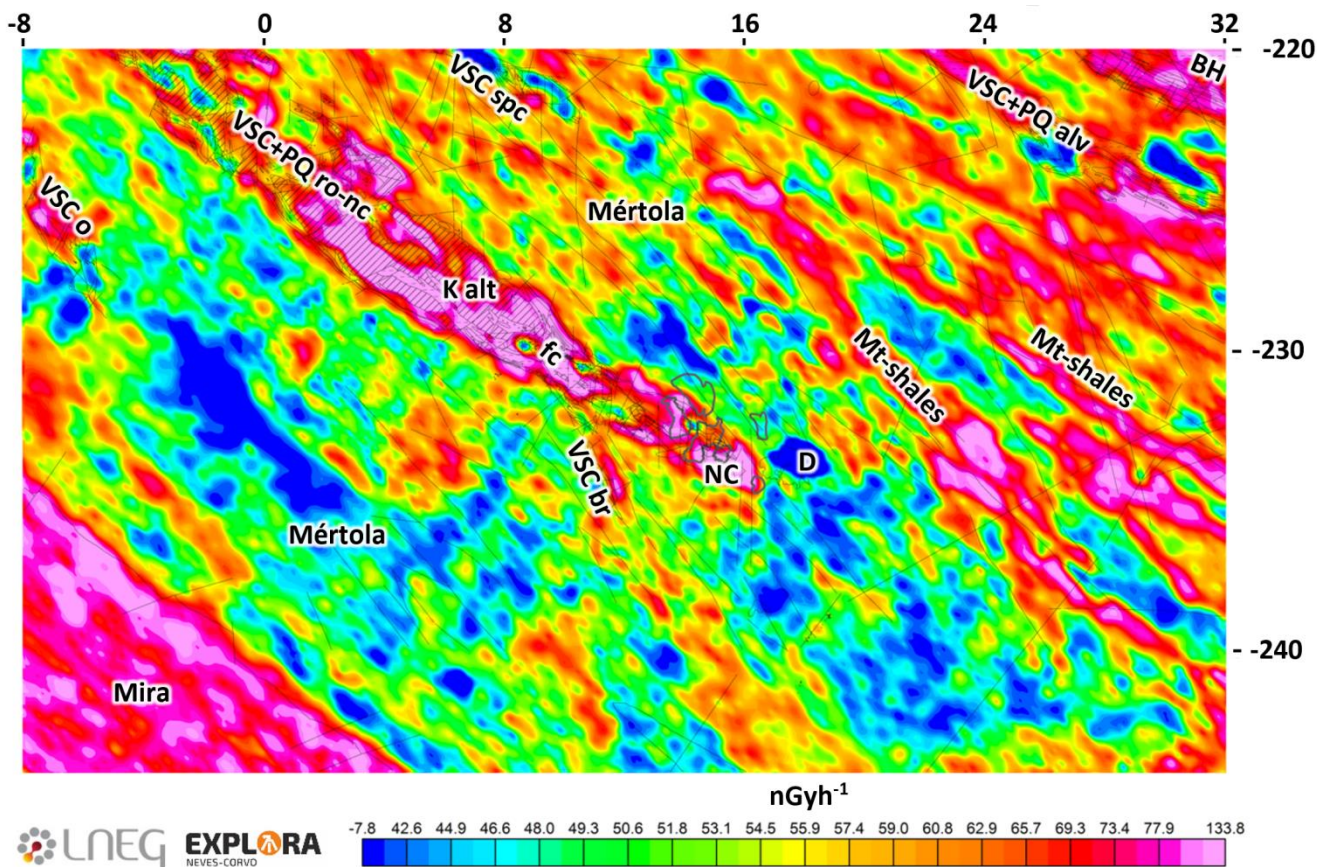


Figure 10. Neves-Corvo region Radiometric (Natural Radioactivity) map, 1/50 000 scale (LNEG EXPLORA Project, Marques *et al.*, 2019). Data source: Rio Tinto/Soc. Mineira Rio Artezia, Geoterrex airborne survey 1991, LNEG data processing (Batista *et al.*, 2016b). Geological limits from Oliveira *et al.* (2016) and EXPLORA unpublished mapping. Legend: BH – Barranco do Homem Formation (PQ Group), Alvalade sector; VSC and PQ structures: Alvalade (alv), Rosário-Neves-Corvo (ro-nc); VSC structures: Ourique (o), São Pedro das Cabeças (spc), Forno da Cal basic volcanic rocks (fc), Brancaneles (br); Baixo Alentejo Flysch Group: Mértola and Mira formations. NC – Neves-Corvo mine. D – Cerro do Lobo Somincor mine waste dam. Coordinates Hayford-Gauss, Lisboa IPCC in km.

Figura 10. Carta Radiométrica (Radioatividade Natural) da região de Neves-Corvo, escala 1/50 000 (Projecto LNEG EXPLORA, Marques *et al.*, 2019). Dados Rio Tinto/Soc. Mineira Rio Artezia, levantamento aéreo Geoterrex 1991, processamento de dados LNEG (Batista *et al.*, 2016b). Limites geológicos a partir de Oliveira *et al.* (2016) e cartografia não publicada Proj. EXPLORA. Legenda: BH - Formação Barranco do Homem (Grupo PQ), setor Alvalade; estruturas CVS e PQ: Alvalade (alv), Rosário-Neves-Corvo (ro-nc); estruturas CVS: Ourique (o), São Pedro das Cabeças (spc), rochas vulcânicas básicas de Forno da Cal (fc), Brancaneles (br); Grupo Flysch do Baixo Alentejo: formações de Mértola e Mira. NC – mina de Neves-Corvo. D – Barragem de rejeitados mineiros de Cerro do Lobo, Somincor. Coordenadas Hayford-Gauss, Lisboa IPCC em km.

volcanic rocks with regional sericite alteration (Famennian–Upper Visean, Oliveira *et al.*, 2006; Pereira *et al.*, 2008; Oliveira *et al.*, 2013), *e.g.* from north to south: Serrinha (1), Caveira (C), Cercal (17), Maria Delgada (14), Rosário (15), Albernôa (8), Serra Branca (9), Bicadas (10), Mértola SE (12), São Domingos (SD) and Achada do Gamo and Pomarão (13). Similar results are referred in the Spanish IPB sector (García *et al.*, 1998) to the VSC and PQ lithologies; iii) Baixo Alentejo Flysch Group: Mértola Formation (Late Visean, Oliveira 1983; Pereira *et al.*, 2008) – several areas represented by shale rich units, are reflected by high radiometric background (see 16, São Sebastião dos Carros in Fig. 9 well correlated with regional geological mapping, Mértola 46D, Oliveira and Silva, 1990 and Almodôvar 46C, Oliveira *et al.*, 2016); Mira Formation (Late Visean–Lower Bashkirian, Oliveira *et al.*, 2006; Pereira *et al.*, 2008) – intercalations of shales and impure quartzites and quartzwackes, *e.g.* Cachopo and Dougueno (18B), Abertas Shales Member (18A, Silveiras) and SW limit with Brejeira Formation (18C) south of Santa Clara dam region; Brejeira Formation (Bashkiriano–Upper Moscovian, Pereira *et al.*, 2008) – similar anomalies occur, but with a more heterogeneous distribution. Local lithological changes in sedimentary units of the Brejeira Formation are reflected by different radiometric signatures at the Foz do Besteiro (19), Oudelouca (20) and Espinhaço de Cão (21) areas; iv) South West Sector – shales and quartzites of the Tercenas Formation (Strunian–Early Tournaisian, Pereira *et al.*, 2008) (22, Aljezur structure).

The geology of south of Portugal is well reflected in the radiometric map (Exposure Rate) (Fig. 9) in all geological domains of South Portuguese Zone: Pulo do Lobo, Pyrite Belt, Baixo Alentejo Flysch Group (BAFG) and SW Sector. In the Mesozoic sequences and Baixo Tejo/Alvalade Basin the results are also quite consistent. In particular scenarios, such as the BAFG the radiometric, it shows a remarkable resolution, when comparing with the LNEG 1/200 000 scale mapping (Oliveira *et al.*, 1992) and new LNEG/IGME 2019 1/400 000 mapping. The Mira Formation high background related with common white detrital K rich mica (sericite) observed in the shale, greywacke and quartzwacke matrix allows a good contrast with the BAFG Mértola Formation (located NE, *e.g.* Dougueno and Cachopo sections 18B in Fig. 9) and with the Brejeira Formation (*e.g.* Nave Redonda sector, 18C in Fig. 9). Considering the homogeneous characteristics of these flysch sequences radiometry is a good mapping support, based on lithological different mineral composition.

High natural gamma radiation areas are also related with the Late Cretaceous age Sines (M2) and Monchique (M3) massifs, especially in the K channel. Middle to low anomalies can be observed at Algarve Mesozoic Basin sectors of Alte (M4) and are related with basic volcanism of Cretaceous age. Low radiation areas are present at Santiago do Cacém Mesozoic Sequence of the Lusitanian Basin (M1) and regions covered by Cenozoic age sediments, at Baixo Tejo/Alvalade Basin, in the region NE of Setúbal (CS1) and between Alcácer do Sal and Alvalade (CS2). Littoral plains along the Atlantic coast (CS3) are reflected by the radiometric map as middle-low values. The radiometric contrast between the Paleozoic basement lithologies and the Cenozoic sediments can be shown in the northern IPB Paleozoic windows of Serrinha (1) and Barrosinha (3).

Radiometric data reflect lithological variations in the same geological unit, *e.g.* phyllite rich areas in the Pulo do Lobo Formation, mapped SE of Salvada in the western margin of the Guadiana, Matos, 2016). At local scale the radiometric anomalies show the existence of folds in sedimentary formations (*e.g.* 16, shales rich horizons and greywacke rich horizons in the Mértola

Formation, mapped near São Sebastião dos Carros, Oliveira *et al.*, 2016). Strike-slip fault structures can also be identified in the radiometric map (*e.g.* see Messejana fault zone between Colos and Ervidel, Fig. 9).

The radiometric airborne data were applied in the EXPLORA Project study of Neves–Corvo mine region (Marques *et al.*, 2019, Fig. 10, see location in IPB, Fig. 1). The radiometric map reflects the near surface lithologies of IPB PQ and VSC and flysch BAFG Mértola and Mira formations. The latter flysch sediments present an extreme high background showing a monotonous and more distal sedimentation facies characterized by the typical intercalations of white detrital K rich mica (sericite) in shales and fine greywackes (Oliveira *et al.*, 2006, 2016, 2019). The correlation between radiometry and geology is notable (see also Mértola/Mira formations limit at regional scale in Fig. 9). The shale rich members of the Mértola Formation (Oliveira and Silva, 1990 and Oliveira *et al.*, 2016) are reflected at São Sebastião dos Carros by NW–SE trend anomalies. At Estação de Ourique (14 in Fig. 9) and Rosário–Neves–Corvo (15 and NC in Fig. 9) anticlines intense anomalies can be observed related with volcanogenic sediments and clay rich shales (Godinho Formation), purple shales (Borra de Vinho Formation) and shales with nodules (Grandaços Formation), both representing the Upper VSC sequence. In the late structure felsic volcanic rocks with sericite hydrothermal alteration occur. This halo is reflected by an extreme high K radiometric anomaly. The definition of the hydrothermal halo is a key vector in mineral exploration (Carvalho, 1976, 1982; Barriga, 1997; Carvalho *et al.*, 1999; Relvas *et al.*, 2006; Matos and Sousa, 2008). In the Alvares region (Fig. 10 NE map sector) the complex tectonic setting defined by alloctonous structures limited by thrust faults (Oliveira *et al.*, 2016) can be correlated with high radiometric anomalies. These halos are also related with the deformed Freixial Formation flysch sediments, VSC sediments, PQ phyllites and quartzites and Barranco do Homem (PQ Group) quartzwackes and phyllites. Rich clay fault plans could also be reflected in the radiometric survey.

In figure 10 the VSC basic volcanic rocks of São Pedro das Cabeças (VSC spc) and Forno da Cal (fc) are defined by low radiometric backgrounds. These values can be related with the soil development over these rocks, poor in the main radioactive isotopes, comparing with the whitish skeletal soils poorly developed above the flysch sediments and felsic volcanic rocks richer in the radioactive isotopes. The Neves–Corvo mine Cerro do Lobo mine waste dam is well delimited by a very low spoty anomaly in the higher natural gamma radiation areas (D in Fig. 10).

7. Electromagnetic methods

Electromagnetic methods (EM), either airborne, ground or from drill hole logs, especially in time domain (TDEM), are particularly useful in massive sulphide exploration, due to high electrical conductivity of these structures. However, there are several logistical constraints in their use in the field, that is the existence of power lines and telecommunication facilities, metallic fences and collapsed drill holes. High conductivity geological units, *e.g.* graphitic black shales, acid volcanic rocks with sulphide dissemination or veins, basic volcanic rocks and jaspers with disseminated magnetite can also cause strong EM anomalies. Cenozoic sediments are often also very conductive. In the proximity of fault zones EM anomalies can occur related with the presence of graphite (in the case of shales affected by thrust faults) or fissural aquifers (*e.g.* in brittle deformation areas). For a more comprehensive approach of the electromagnetic methods applied to mineral prospecting, the reader can consult Milsom (2003) or Telford *et al.* (2012) for instance.

7.1. The Turam SFM surveys and new data interpretation at Caveira mine

As previously referred, the first geophysical method used in the IPB by the SFM was the electromagnetic method Turam applied in sulphides exploration on several areas, such as São Domingos, Aljustrel, Caveira-Lousal or Algaré and Brancanes in the SE sector of the Rosário VSC Antiform (Fig. 2). This method was used until the 1950s (Gomes, 1955; Gomes and Silva, 1955; Queiroz *et al.*, 1990; Telford *et al.*, 2012), when it was replaced by other methods capable of providing larger investigation depths, as well as more detail and resolution. Nowadays, there still is a large archive of these Turam data at LNEG and a method to process them was developed by Guerra (2008) at the Caveira IPB mine site, where near surface sulphide mineralizations are known (Matos *et al.*, 2015). One of the problems with the Turam geophysical heritage dataset is the use of old local coordinate systems defined according to geological structures and surveys goals. Before modelling, coordinates have to be transformed into a standard regular system compatible with other layers of information (*e.g.* geology and topography) so that data may be accurately modelled and reinterpreted (Guerra *et al.*, 2008). Although the area contains about 100 000 Turam stations, a selected area with 600 stations located 500 m southeast from Caveira mine, was selected to test the model. Turam data shows a strong anomaly towards the limit of VSC with PQ Formation in a sector where SMRA CA01 and CA02 drill holes intersected sulphide mineralization (Mora, 2002; Pereira *et al.*, 2008, 2010; Matos *et al.*, 2015). The main features of CA01 drill hole (Fig. 11) are presented in a 3D model (Almeida *et al.*, 2018) including the digital terrain model and creation of a cloud of points from the observed induced currents. These currents were intercepted by lines drawn with support of an ArcGIS

interpolation algorithm based on the continuity of the horizontal plan. These lines were drawn according with the alignments of the current and based on estimated depth and induced current intensity. After connecting the points with higher current, Turam modelling estimates their depth between 121 m and 169 m (Guerra, 2009; Almeida *et al.* 2018), which is a good approximation to the mineralized zone identified in the drill hole CA01 (107 m and 213 m, semi-massive and *stockwork* sulphides). The network and coordinate conversion errors in this area range between 15 m and 28 m (Guerra, 2009), which means that results of Turam data representation can be considered very reliable. Positive correlation between Turam data modelling and the Caveira mineralized zone located in an anticline structure shows the potential of this methodology. Even in modern days, heritage Turam data modelling can therefore be an important asset for the general understanding of the way the mineralized ores are distributed.

7.2. Magnetotellurics

Magnetotellurics (MT) has not been used as a regular prospecting method in the IPB, due to the high costs and complex logistics. Therefore, it was only applied in a few areas in the search for deep conductors, namely in Ervidel and Martim Longo in the 1980s and in Lagoa Salgada (1991 and 1992) (Oliveira *et al.*, 1993; Oliveira *et al.*, 1998a). Other MT surveys (Monteiro Santos *et al.*, 1999; Almeida *et al.* 2001, 2005; Ribeiro, 2018) conducted in the OMZ and SPZ aimed to understand the structure of the lithosphere. These studies are also important to understand the main geological structures and therefore having a detailed comprehension on the smaller located prospecting surveys. Monteiro Santos *et al.* (1999) conducted MT surveys with the aiming to understand contrasts between electrical conductivity of the Earth crust across the OMZ and SPZ, in a profile 40 km long with 9 deep MT soundings. These

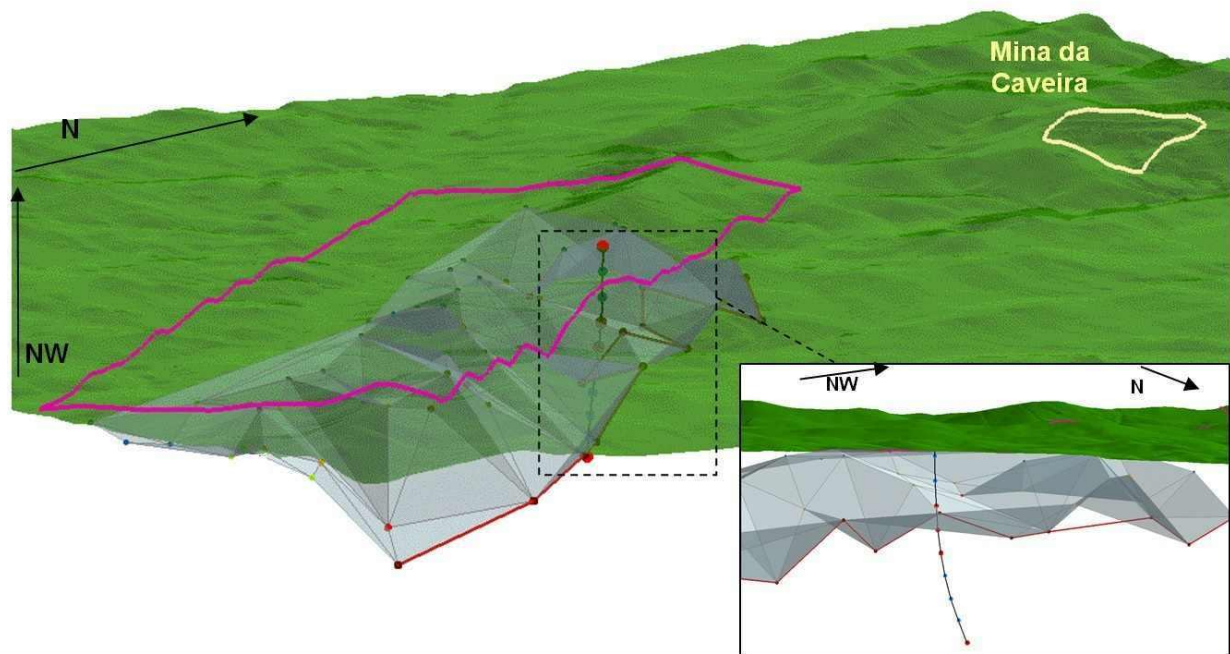


Figure 11. 3D model representation of the Caveira mine southeastern sector (Almeida *et al.*, 2018). Selected area inside the pink lines with zoom of the CA1 drill hole area highlighting the lines with major currents coincident with mineralization intersected by this exploration drill hole (mineralized zones indicated by red colour dots and non-mineralized zones indicated with green dots).

Figura 11. Representação em modelo 3D do setor SE da Mina da Caveira (Almeida *et al.*, 2018). A área seleccionada no interior das linhas rosa, com zoom na área da sondagem CA1, realçando as linhas com correntes mais elevadas coincidentes com a mineralização intersectada por esta sondagem (as zonas mineralizadas estão indicadas pelos pontos de cor vermelha e as zonas não mineralizadas estão indicadas por pontos verdes).

authors calculated a rheological profile for the SPZ that shows a soft layer at an interpreted depth of 11-13 km, strengthening the association of the detachment level with the low-conductivity layer at that depth in the SPZ. Later, Almeida *et al.* (2005) conducted a 200 km MT profile, with 30 new MT soundings, with its SE edge reaching the SPZ, and that same deep conductor beneath the IPB.

Ribeiro (2018) acquired MT data with MMS03E and GMS-06, both from METRONIX, with a site spacing of approximately 5 km. In this project 5 MT profiles crossed the IBP, reaching interpretation depths of 30 km. Some stations referred in Ribeiro (2018) were previously studied in Monteiro Santos *et al.* (1999) and Almeida (2001, 2005). At the surface, (Fig. 12) it is possible to recognise regions of very high conductivity in the SPZ related with IPB (VSC+PQ structures). They are more pronounced in the vicinity of the sites from W to E: S05-S06, D09-11, Co4-C05 and B04 with the resistivity range of 1-5 ohm.m. At interpreted depths of 0.5 km there is a deep electrical conductivity difference between the regions separated by OMZ Beja-Acebuches Ophiolitic Complex and the Santa Susana Shear Zone. The electrical resistivity distribution is related with distant lithological features of the OMZ and SPZ basements (Ribeiro, 2018).

The MT model on profile P shows a strong resistivity contrast between the OMZ and the SPZ, along a steeply dipping structure, representing the Ferreira-Ficalho Overthrust, extending parallel to the Beja-Acebuches Ophiolitic Complex. There is a wavy structure in the SPZ separating a more conductive upper layer, the IPB, underlain by a more resistive layer. This unknown geological formation is related with a resistive anomaly and could be related with probable igneous plutonic rock structures (basic?). These wavy resistive anomalies are also recognized in OMZ, much more extensive (*e.g.* R1). Conductive layers C2 and C4 in the OMZ may be related with magnetite deposits and/or sulphides mineralizations (Ribeiro, 2018), similar to those that occur in the Moura-Ficalho OMZ Sector (Mateus *et al.*, 2013; Matos and Filipe Eds., LNEG, 2013).

Regarding prospecting issues, as large investigation depths were required in Ervidel (> 300 m), two sites were chosen to conduct MT studies, each of them comprising one profile, more than 1 km long and 51 soundings, presumably transverse to the layers to investigate (van Ngoc, 1982). This survey interpreted the sedimentary overburden with thicknesses ranging from 20 m to 100 m depth. The contact between the Cenozoic sediments and the Palaeozoic basement was interpreted and corresponds to a very conductive low thickness layer (< 10 m), with resistivity typical of massive sulphides, that is about 1 ohm.m. Another deeper conductive layer was found at 1 km deep with resistivities of about 100 ohm.m and thickness of a few hundred meters. A survey conducted in Martim Longo by Billiton Portuguesa, S.A. (1985) consisting of 43 MT stations, showed similar patterns, with a shallower more conductive layer at 100-150 m interpreted depth and a deeper one, more conductive, at possible depths ranging from about 500 m to 1100 m. In the Spanish IPB sector magnetotelluric surveys were conducted at Valverde region, showing MT conductors associated with sulphide mineralization located ~550 m depth (Rodríguez, 2015). This research was developed using 9 MT stations with a regular 800 m of detachment. MT data shows accuracy below 700 m modelled depth.

In 1991, at Lagoa Salgada (see location in Fig. 1), 37 soundings were conducted along four N45°E direction profiles

with 100 m station spacing (van Ngoc and Daniele, 1992; Oliveira *et al.*, 1998). These profiles were transverse to the local gravimetric anomaly (see LS in Figs. 6 and 14). This method showed three pronounced conductive lineaments with an approximate NW-SE lineament direction. The coincidence between the location of these conductors and some of the maximum gravimetric anomaly was an argument in favour of the presence of massive sulphides, especially in the NW nucleus of the Lagoa Salgada Bouguer anomaly (Oliveira *et al.*, 1993, 1998). Planned with this geophysical setting the LS4 discovery drill hole intersected in August 1992 a gossan and massive mineralization between 128 and 190 m depth and stockwork mineralization between 190 and 205.8 m depth. A second horizon of semi-massive disseminated sulphide mineralization was intersected by the same drill hole between 522 m and 557 m (end of hole). The detected MT conductors are relatively deep (around 600 - 700 m) and located near and to NE of the known massive and stockworks mineralizations intersected by several drill holes carried out between 1992 and 2019 (Ascendant, 2020). Considering the Lagoa Salgada geological setting (Oliveira *et al.*, 1998; Matos *et al.*, 2000, 2017, 2019; De Oliveira *et al.*, 2011) the respective MT anomalies could correspond to a still unknown massive sulphide ore lenses and/or stockwork mineralizations. These deep MT targets can also be overlapped by the presently known Lagoa Salgada sulphide mineralization. A more detailed MT survey could be an important goal to follow.

7.3. EM techniques

The definition of electromagnetic conductors is a common methodology used to test gravimetric anomalies or geological formations considered as key ore horizons. The information obtained by EM methods can be important to define consistent targets, later selected for drill-hole research. Despite the excellent response of the sulphide ores (massive and semi-massive) to EM surveys, in several cases the electromagnetic conductors are related with lithological characteristics (*e.g.* black shales, locally graphitic and fault structures). Shear zones, commonly present disseminated and/or sulphides veins, also important conductors. Several examples are presented in different geological scenarios.

At the Cercal area (Fig. 1) Northern Lion used the VTEM-Versatile Time-domain ElectroMagnetic system, helicopter airborne survey performed by Geotech Airborne Limited (Faria, 2009), with NE-SW 200 m spacing flight lines (perpendicular to the Cercal Antiform geological formations) in a total of 1342 km of linear surveys. Two targets areas were identified by the consulting company Condor Consulting, well correlated with the Torgal/Pendões Cu, Zn old mines, and São Luís Cu soil geochemistry anomalies. However, the VTEM presented an ambiguous response in the Salgado sector (Fig. 1), located in the Cercal Anticline NE sector, where massive/semi-massive sulphide mineralization occurs (Carvalho, 1982, Fig. 1). The use of the VTEM system was conditioned by the presence of the REN National electric power lines and high conductivity of the black shales with disseminated pyrite of the Abertas Shales Member (Mira Formation) (Faria, 2009). In the NE IPB region of Serra Branca-Mértola (Fig. 1), AGC/Lundin Mining carried out a Z-Tipper Axis Electromagnetic (ZTEM) airborne survey, with 500 m spacing lines, with four magneto-telluric measurements (37.5, 75, 150 and 300 Hz) using magnetic sensors 90 m and 60 m above terrain surface (Araújo and Castelo Branco, 2010).

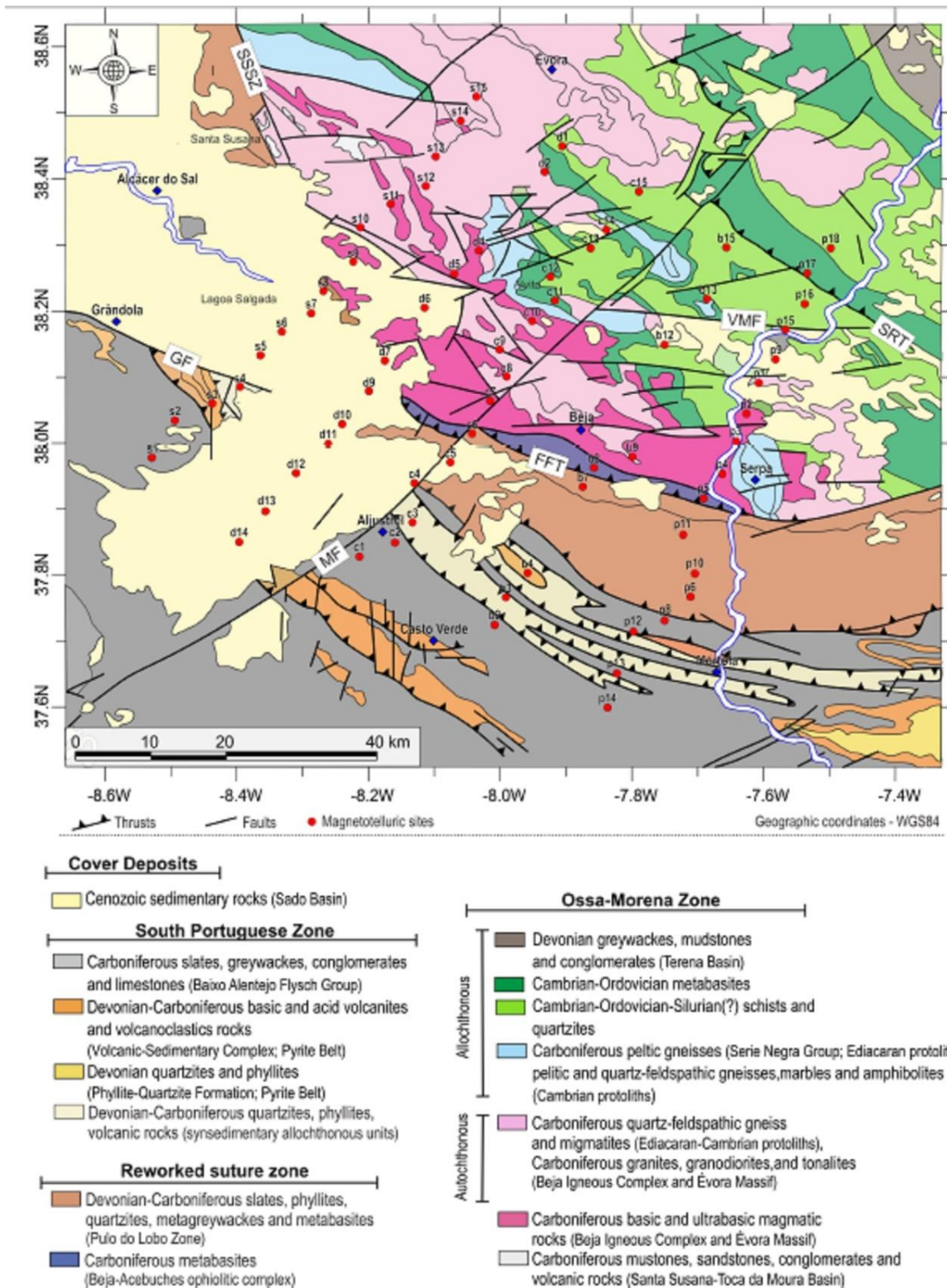


Figure 12. Geological map of the Grândola-Serpa area adapted from Geological Map of Portugal, 1/500-000 (SGP, 1992), showing the relation between the lithostratigraphy and the tectonic units. The aligned red dots represent the sites of the 5 MT profiles used in Ribeiro (2018). MF – Messejana Fault; GF – Grândola Fault; FFT – Ferreira-Ficalho Overthrust; SSSZ – Santa Susana Shear Zone; VMF – Vidigueira-Moura Fault; SRT – Santo Aleixo da Restauração Thrust (Ribeiro, 2018). See indicated MT profiles in figure 13.

Figure 12. Mapa geológico da área de Grândola-Serpa adaptado da Carta Geológica de Portugal à escala 1/500 000, mostrando a relação entre a litoestratigrafia e as unidades tectónicas. Os pontos vermelhos alinhados representam as estações dos 5 perfis de MT estudados por Ribeiro (2018). MF – Falha de Messejana; GF – Falha de Grândola; FFT – Cavaleamento de Ferreira-Ficalho; SSSZ – Zona de Cisalhamento de Santa Susana; VMF – Falha de Vidigueira-Moura; SRT – Cavaleamento de Santo Aleixo da Restauração (Ribeiro, 2018). Ver perfis MT indicados na figura 13.

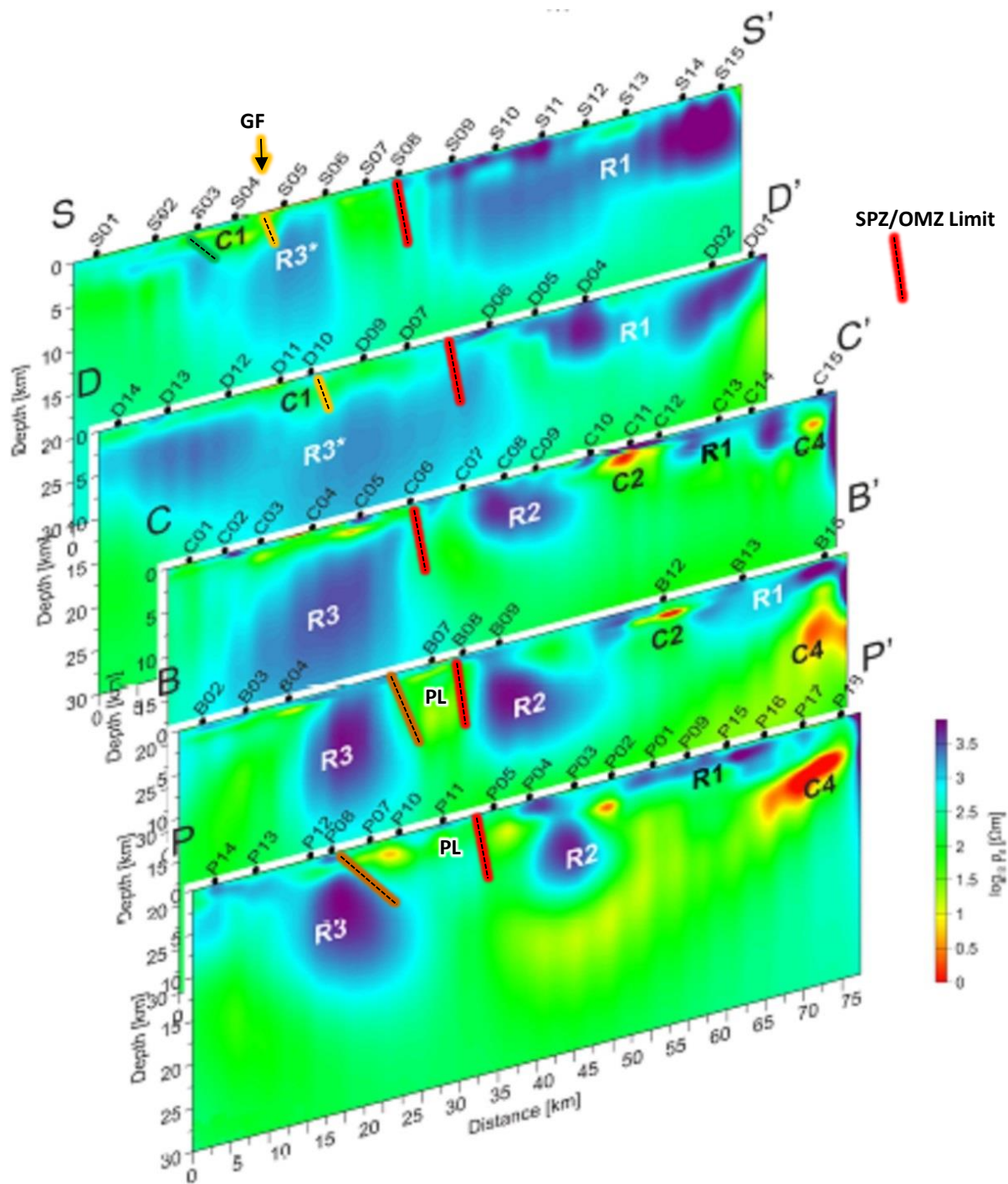


Figure 13. Cross sections of the MT 3D inversion profiles from figure 12 with the main resistive and conductive anomalies (Ribeiro, 2018). R1 and R2 – strong resistive anomalies located in the OMZ, belonging to the Beja-Acebuches Ophiolite Complex and Beja Igneous Complex; R3 and R3* – probably represents a hidden IPB resistive basement anomalies related with plutonic rock structures (?); C1 – VSC/PQ Lousal-Caveira structure located south of Grândola Fault (GF) and limited at SW by a thrust fault (green dashed line); C2 – anomaly located at 1 km depth, it may be justified by Fe-rich deposits consisting of irregular masses and stratiform lenses of magnetite and also sulphides that are associated with OMZ Moura-Ficalho sector mineralizations (Mateus *et al.*, 2013; Matos and Filipe Eds., LNEG 2013); C4 – anomaly related with a possible magnetite mineralization associated with the Xistos de Moura Phyllite intercalated Complex basic volcanic rocks. Dash lines: red/SPZ/OMZ limit – Ferreira-Ficalho Thrust Zone; brown – Pulo do Lobo (PL) Domain SW Thrust limit; green – Lousal-Caveira (VSC+PQ) structure SW thrust; orange/GF – Grândola Fault.

Figura 13. Perfis de inversão MT 3D da figura 12, com as principais anomalias condutivas e resistivas (Ribeiro, 2018). R1 e R2 – anomalias fortemente resistivas correspondendo ao Complexo Ophiolítico Beja-Acebuches e Complexo Ígneo de Beja (Zona Ossa-Morena); R3 and R3* – anomalias correspondentes a estruturas basais da Faixa Piritosa Ibérica relacionadas com prováveis rochas ígneas plutónicas (?); C1 – Estrutura CVS/PQ de Lousal-Caveira situada a sul da Falha de Grândola (GF) e limitada a SW por uma zona de cavalgamento (linha tracejada de cor verde); C2 – anomalia localizada a 1 km de profundidade, que pode ser justificada por mineralizações de magnetite e/ou sulfuretos associadas ao Setor de Moura-Ficalho da Zona Ossa-Morena (Mateus *et al.*, 2013); C4 – anomalia positiva que pode estar associada a mineralizações de magnetite associadas ao Complexo Filítico dos Xistos de Moura. as rochas vulcânicas básicas intercaladas no Complexo Filítico dos Xistos de Moura. Linhas a tracejado: vermelho – limite Zona Sul Portuguesa e Zona Ossa-Morena – Cavalgamento Ferreira-Ficalho; castanho – limite SW do Domínio Pulo do Lobo marcado por cavalgamentos; verde – limite SW da estrutura Lousal-Caveira (Comp. Vulcano-Sedimentar + Grupo Filito-Quartzítico) marcado por plano de cavalgamento; laranja – falha de Grândola (GF).

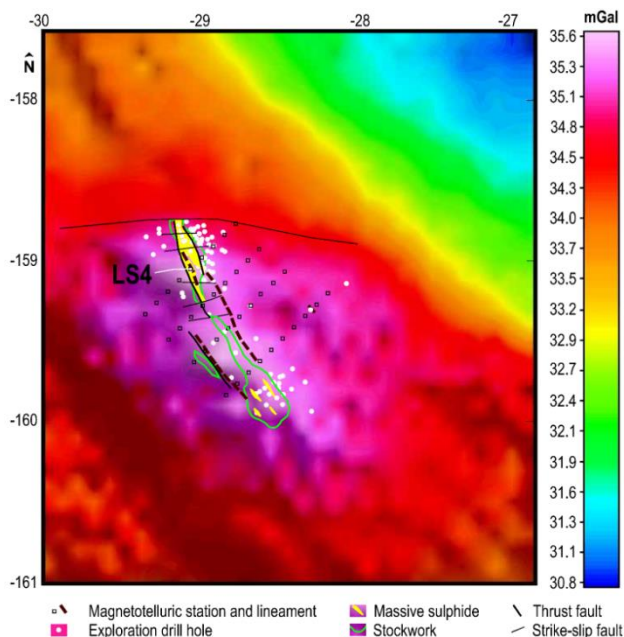


Figure 14. IPB Lagoa Salgada deposit Gravimetric map (Bouguer Anomaly d 2.6 g.cm^{-3}) and correlation between magnetotelluric lineaments and massive sulphide and stockwork mineralization. LNEG data source and Matos *et al.* (2019) mineralization mapping (-70m level). LS4 – discovery drill hole.

Figura 14. Mapa gravimétrico (Anomalia de Bouguer d $2,6 \text{ g.cm}^{-3}$) da jazida de Lagoa Salgada e correlação entre alinhamentos magnetotélúricos e mineralização maciça e de tipo stockwork. Dados LNEG e cartografia das mineralizações (nível - 70 m) por Matos *et al.* (2019). LS4 – sondagem de descoberta.

Survey data inversion and processing allowed the construction of apparent conductivity maps corresponding to the 37.5 Hz and 150 Hz frequencies, that identified electric conductors related with deep lithological sources. These were later studied with SQUID-TEM (Superconducting Quantum Interference Device – Transient Electromagnetics) loop ground surveys. The conductors identified in the Mértola region were correlated with black shales of the Phyllite-Quartzite Formation and shale units of the Gafo and Pulo do Lobo formations (Araújo and Castelo Branco, 2010). Several EM conductors were well correlated with shear zones with WNW-ESE direction. Under this scenario, the prior geological model characterized by intense deformation and tectonic contacts between allochthonous units/blocks (Oliveira *et al.*, 2013) was confirmed by the geophysical EM models (Owen *et al.*, 2013).

The Somincor/AGC Company used the TEM method in the Rosário-Neves-Corvo Antiform with positive results in the NE region of the Neves-Corvo mine, where TEM data were essential to the discovery of the Semblana massive sulphide ore lens in 2010 (Araújo, 2009; Araújo and Castelo Branco, 2010; Owen *et al.*, 2013). The TEM survey allowed identifying the sulphide mineralization associated with the black shales of the Neves Formation (Strunian age) considered a favourable conductor horizon (Oliveira *et al.*, 2004; Matos *et al.*, 2011). The same methodology applied at the Forno da Cal sector, allowed to identify EM conductors below the VSC basic volcanic rocks and associated with black shales of the Phyllite-Quartzite Formation, both confirmed by the Somincor FC09001 drill hole (Araújo, 2009). At Algaré sector similar EM conductors were found, in this case associated with black shales and felsic volcanic rocks with sulphide veins as confirmed by the Somincor CA09001 drill hole.

Figure 15 shows an EM profile carried out at São Pedro das Cabeças VSC structure (SPC in Fig. 7 and CVS spc in Fig. 10).

This profile results from the 1D inversion of ground TEM loop data and stitched together to produce the 2D profile. Each squared loop had a length of 1 km and along each line the stations were placed every 100 m, while the current had an intensity between 12 and 15 A. The vertical component of the secondary field data was inverted using the EM1DTM (UBC software). The TEM profile of figure 15 shows the VSC outcropping basic volcanic rocks that contact to SW with the VSC Grandaços Formation (Late Viséan age, Oliveira *et al.*, 2016) represented by dark grey shales with disseminated sulphides.

Thrust faults are recognized in the SW sector. The positive correlation between geology and EM led to the acquisition with very similar parameters, contracted by Somincor/Lundin (AGC/Lundin Mining, 2009), of hundreds of linear kms of ground loop TEM data in the Portuguese sector of the IPB. These data continue to provide important results for exploration in the region, either by supplying structural/stratigraphic information to 3D geological model building (Carvalho *et al.*, 2020) or through 1D inversion and 3D forward modelling to directly infer the presence of massive sulphides or stockwork mineralization (Dias *et al.*, 2020, see Fig. 13).

Figure 16 shows a total of 118 TEM profiles carried out for AGC and Somincor (Lundin Mining) in the IPB Neves-Corvo mine region (see location in Fig. 1). The 2D TEM profiles were acquired between 2007 and 2011 (*e.g.* Pinto, 2008; Araújo and Castelo Branco, 2011) and resulted from the 1D inversion of ground loop data, acquired with similar parameters as in the example of figure 13, using also the EM1DTM software. All the TEM data were imported into the GOCAD™ software, as well as 2D and 3D seismic data, geological mapping and drill-hole data and used to generate 3D geological models (Carvalho, *et al.* 2020).

The TEM profiles were located in the Rosário-Neves-Corvo VSC+PQ Antiform, in the structure northeast limb and possible extension to SW and SE. The TEM crosslines covers a total of 220-line km in this IPB area, and provide useful interpretation related with geological formations and main tectonic structures like thrust and shear zones and late Variscan faults. The TEM conductors shows a good accuracy at local scale and are related with VMS mineralization (Neves-Corvo deposit). Other TEM anomalies can be also related with black shales with disseminated sulphides (mainly pyrite) that occur in the VSC sequence (*e.g.* Brancanes, Grandaços, Graça and Neves formations).

Parallel TEM profiles allow a lateral correlation between electromagnetic conductive areas and thus enable following regional scale conductors like geological domains or regional thrust faults. Based on the TEM profiles data and the above mentioned geophysical-geological information, a 3D surface corresponding to the footwall contact of Mértola Formation (Baixo Alentejo Flysch Group) with the VSC sequence was prepared (Carvalho *et al.*, 2020; Dias *et al.*, 2020) (see Fig. 16 indicated layer). This surface and others like the VSC/PQ boundary and Neves-Corvo ore lenses are key issues in the 3D modelling research programs carried out in the Neves-Corvo region by the SmartExploration™/H2020 and EXPLORA/Alentejo2020 projects. Preliminary data shows an increase of the VSC upper limit location (in depth below the flysch sediments) to NE and SW of the Rosário-Neves-Corvo Antiform. To SE of Neves-Corvo mine a basement downlift occur with large exposure of the Mértola Formation (*e.g.* Barrigão area) confirmed by seismic profiles (P1, P2 and P3 Promine profiles in Carvalho *et al.*, 2017), gravity survey (see Fig. 4 SE sector and Marques *et al.*, 2019) and AGC, Somincor and Billinton drill holes.

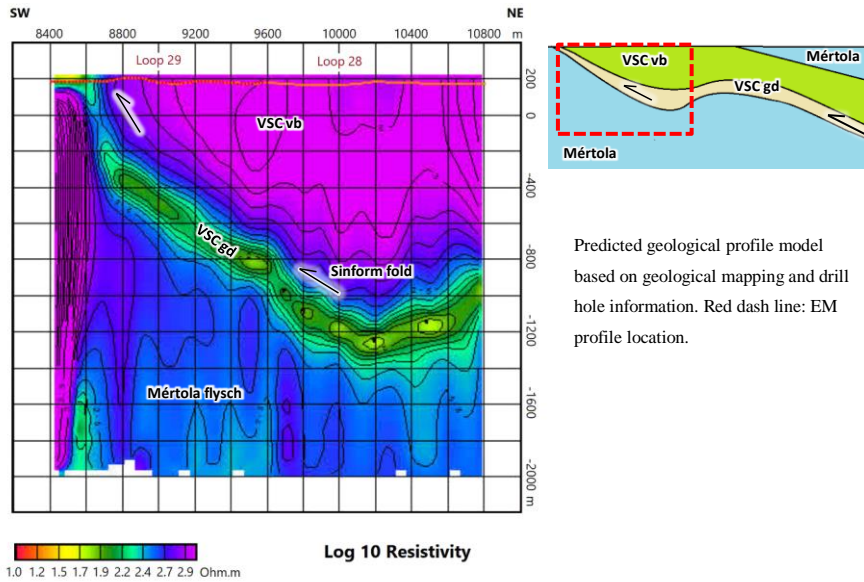


Figure 15. São Pedro das Cabeças EM profile-Line 10400N-Loops 28 and 29. Inversion by Scott Napier, grid and stitch by Carla Bastos 2009 (AGC/Lundin Mining, 2009). Interpretation based on mapping data (Oliveira *et al.*, 2016) and drill hole information: VSC – vb basic volcanic rocks; gd – Grandações Formation dark grey shales; Mértola Flysch – Mértola Formation shales and greywackes (turbidite). Arrow: movement of the basal thrust plan.

Figura 15. Perfil EM de São Pedro das Cabeças-Linha 10400N-Loops 28 e 29. Inversão por Scott Napier, grid e stitch por Carla Bastos 2009 (AGC/Lundin Mining, 2009). Interpretação com base em cartografia geológica (Oliveira *et al.*, 2016) e sondagens de prospeção: VSC – vb rochas vulcânicas básicas do CVS; gd – Formação de Grandações xistos cinza-escuros com disseminações de sulfuretos; Mértola flysch – Formação de Mértola xistos e grauwaques (turbiditos). Setas: movimento do plano basal de cavalgamento.

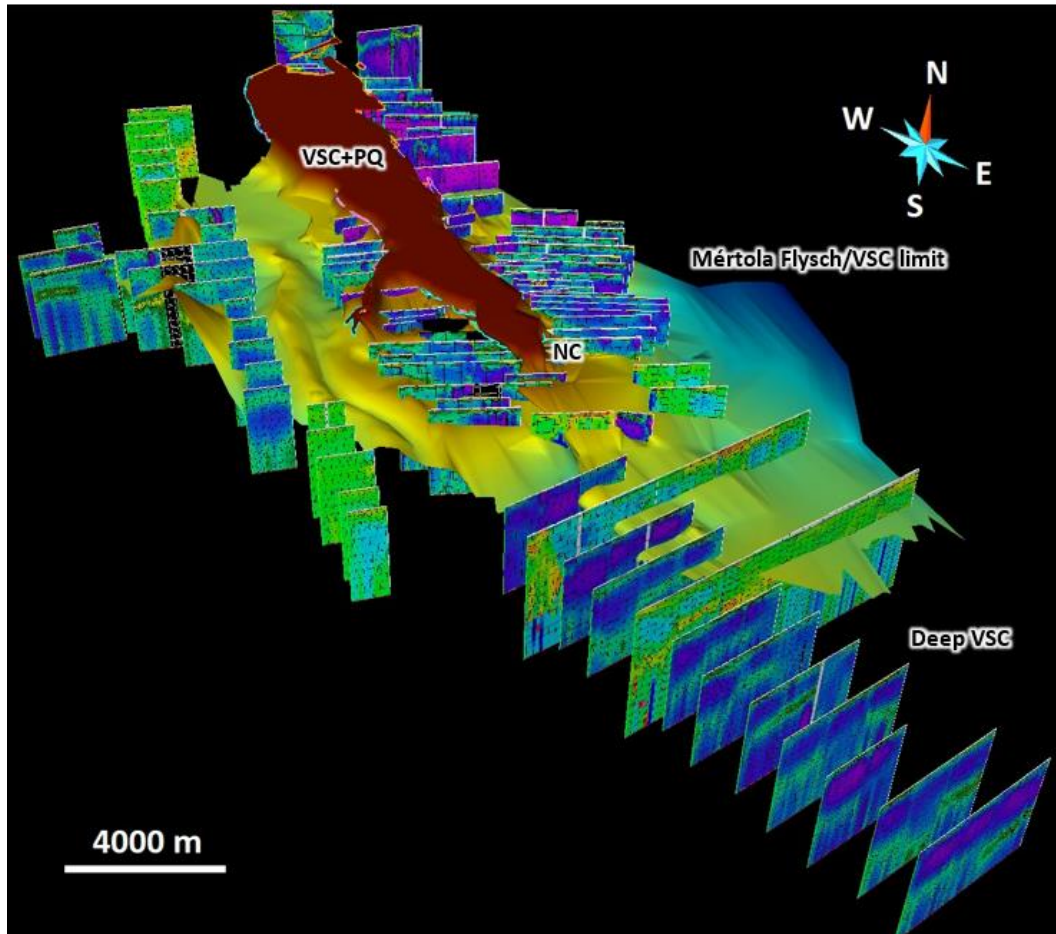


Figure 16. Location of 118 TEM Profiles contracted by AGC and Somincor/Lundin Mining in the Neves-Corvo mine region, overlaid to the 3D surface representing the footwall contact of Mértola Formation (Baixo Alentejo Flysch Group) with VSC sequence. VSC+PQ – Rosário – Neves-Corvo Antiform characterized by VSC formations and sediments of the Phyllite-Quartzite Group. In the SE Neves-Corvo mine (NC) region (*e.g.* Barrigão area) the VSC is hidden below the Mértola Formation flysch sediments being present at >1000 m depth.

Figura 16. Localização dos 118 perfis TEM contratados pela AGC e Somincor/Lundin Mining na região mineira de Neves-Corvo, sobrepostos ao modelo 3D da superfície que representa o contacto basal da Formação de Mértola (Grupo Flysch do Baixo Alentejo) com a sequência do Complexo Vulcano-Sedimentar (CVS). VSC+PQ – Antiforma Rosário – Neves-Corvo com formações do CVS e sedimentos do Grupo Filito-Quartzítico. Na região SE da mina de Neves-Corvo (NC) (ex. área do Barrigão) o CVS encontra-se oculto sob os sedimentos flysch da Formação de Mértola, a profundidade superior a 1000 m.

8. Electrical resistivity and induced polarization

Electrical methods and induced polarization (IP) (c.f. Telford *et al.*, 2012) use contrasts in electrical resistivity and/or chargeability of rock formations to detect resistivity variations or chargeability that can be interpreted as disseminated and massive sulphides. These methods started to be extensively used in the IPB in the late 1960's - electric resistivity and spontaneous potential (SP) applied to the study of complex sulphides and manganese ores and IP applied to the study of copper veins and also manganese (Queiroz *et al.*, 1990). Vertical Electric Soundings (VES) used mostly dipole-dipole arrays, but Wenner and Schlumberger arrays were also used. Thanks to this, there is a large electrical prospecting database in LNEG that can be enhanced by reprocessing with new algorithms and reinterpretation. Regularly, nowadays 2D and 3D reprocessing and remodelling is conducted, and new data are acquired, for mining prospecting, hydrogeology and environment purposes (*e.g.* Represas *et al.*, 2005; Ramalho and Matos, 2009). Time Domain IP surveys were added in the 1970's SFM surveys, with a Scintrex TSQ3 device (LNEG archives). Geological and geophysical data interpretation has been enhanced using joint methodologies. Nowadays, electrical resistivity and IP data are simultaneously acquired on a regular base in the IPB, especially by mining companies. 2D and 3D modelling have been done for these data and these models obtained with Res2DInv and Res3DInv (deGroot-Hedlin and Constable, 1990; Sasaki, 1992) are particularly useful in finding massive sulphide masses and defining borehole locations. That is the case of the Serrinha area (IPB northern sector, see Figs. 1 and 15, Ramalho and Matos, 2009), where both resistivity IP layers and profiles clearly show two different geological units, namely the VSC felsic volcanic rocks with sulphide disseminations and shale units of the PQ and VSC. IP profiles carried out in the Serrinha sector revealed chargeability anomalies down to the investigated depth (~220 m), compatible with the presence of sulphide ores vein type and/or *stockwork* type or disseminated type. Structurally, the autochthonous VSC block of Serrinha is marked with resistivity and chargeability anomalies suggesting a horst affecting the basement. The coexistence of high resistivity zones with high chargeability zones was justified by the presence of hydrothermal silica in the felsic volcanic rocks observed during the geological mapping survey (Matos *et al.*, 2009a). These ores are also responsible for the existence of anomalies in the gravimetric gradient previously detected in Serrinha, see Serrinha horst (1) in figure 6, Annex 1. In the SW area of the Serrinha sector Cenozoic sediments were marked by very low electrical resistivities. According with the geological and geophysical models proposed by the LNEG team (see Figs. 17 and 18) an exploration drill hole SE11-01/01A was conducted by Avrupa/Maepa in 2011, until a depth of 338,8 m. This hole confirmed the presence of sulphide mineralization, intersected between 141.4 m and 174.4 m deep. This success confirms the high exploration potential of the area and the useful EM methodology in a favourable geological environment. The geological and geophysical data could be correlated with important Cu, Zn, As and Pb values in soil geochemistry analysis.

In the 1990s, Empresa Mineira da Serra do Cercal (EMSC) carried out a multi-method approach in the favourable ore-horizon crossing the contacts upper VSC volcanic unit/jaspers/S. Luis Formation volcanogenic sediments/Abertas Shales Member (Mira Formation, Baixo Alentejo Flysch Group). They selected different essentially electric-base tools to run in 17 lines across the above-mentioned contact in different sectors of the NE/E/SE sectors of the Cercal-Odemira anticline. Geophysical methods

included magnetic surveys and SP, VLF, VES and IP, the last two using the Schlumberger array.

The SP method, based on the natural current measured between a fixed base station pot electrode and a mobile station pot electrode, increases to higher millivolt potentials when conductive ore bodies are studied. IP requires current injection and voltage decay is reported as function of time or with different frequencies. An electrode distance of $a = 100$ was used with 6 dipole-dipole pairs later reduced to $a = 25$ using a VIP-3000 Transmitter and ELREC-6 Receiver from IRIS instruments. The VLF technique uses low frequencies, 15-30 kHz, used in remote radio transmitters for military communications (used stations were Moscow, Annapolis and Cutler) and can identify shallow subsurface conductive structures. Field set up was 10 meters spacing readings recording horizontal and vertical VLF. In this case, VES was a 1D resistivity method providing information like depth and thickness of subsurface bodies or layers. In these lines, EMSC followed 4 potential areas where the whole geophysical data, including gravimetry, have pointed to favourable conditions for mineralizations. Nevertheless, no mineralization was intercepted, and IP anomalies remain unsolved (Albardeiro, 1996).

9. Seismics

Seismic reflection and refraction prospecting is based on seismic wave propagation in the earth rocks, and the way that information can be retrieved from their path across the multiple geological formations. More references concerning this method can be found in (Dobrin and Savit, 1988; Telford *et al.*, 2012). Reflection and refraction seismics started in former IGM in the early 1990s, when a EG&G Geometrics ES-2401 24 channel system with A/D converters of 16 bits was purchased and used with explosives as seismic source in Santa Susana/Jongeis Ossa-Morena Zone sector in 1993, for coal prospecting. Seismic data were used to constrain structural models derived from gravimetric modelling and help to distinguish between anomalies with a structural origin from those generated by the presence of volcanic rocks and coal layers (Lopes *et al.*, 2014). Private mining companies also started to recognize the benefits of the use of seismic data in massive sulphides exploration. Somincor financed the acquisition of 2D seismic reflection data in the Neves-Corvo area in 1991 and 1996 in the Corte Gafo exploration area (Carvalho *et al.*, 1996), where eleven profiles were shot by Compagnie Générale de Géophysique (CCG) using explosives as a seismic source and a system of 48 or 96 live channels. The fold of the data acquired by CGG was low (24% coverage) when compared to similar data acquired for the oil industry. The 3D nature of the geological underground, with high-angle structures, strong deformation and metamorphism prevented the image of continuous reflectors to obtain clear images of the subsurface (Carvalho *et al.*, 1996). Nevertheless, the presence of major faults and thrusts as well as the occurrence of strong reflectivity events could be inferred. Recent developments in migration algorithms, new methods which increase coverage and signal to noise ratio in poor reflectivity areas, such as the common reflection surface (CRS) method or 3D seismic, helped to increase the quality of seismic reflection imaging. Furthermore, advances in the acquisition systems such as 24 bit A/D converters, cable-less systems and new generation sensors (*e.g.* MEMS), have lead in the 21st century to a new burst in the number of applications of the seismic reflection method to hard-rock exploration (Eaton, 2003; Juhlin and Stephens, 2006; Schmelzbach *et al.*, 2007; Malehmir *et al.*, 2012; Heinonen *et al.*, 2013; Manzi *et al.*, 2012, 2013; Ehsan *et al.*, 2014). The first deep seismic reflection profiling started in

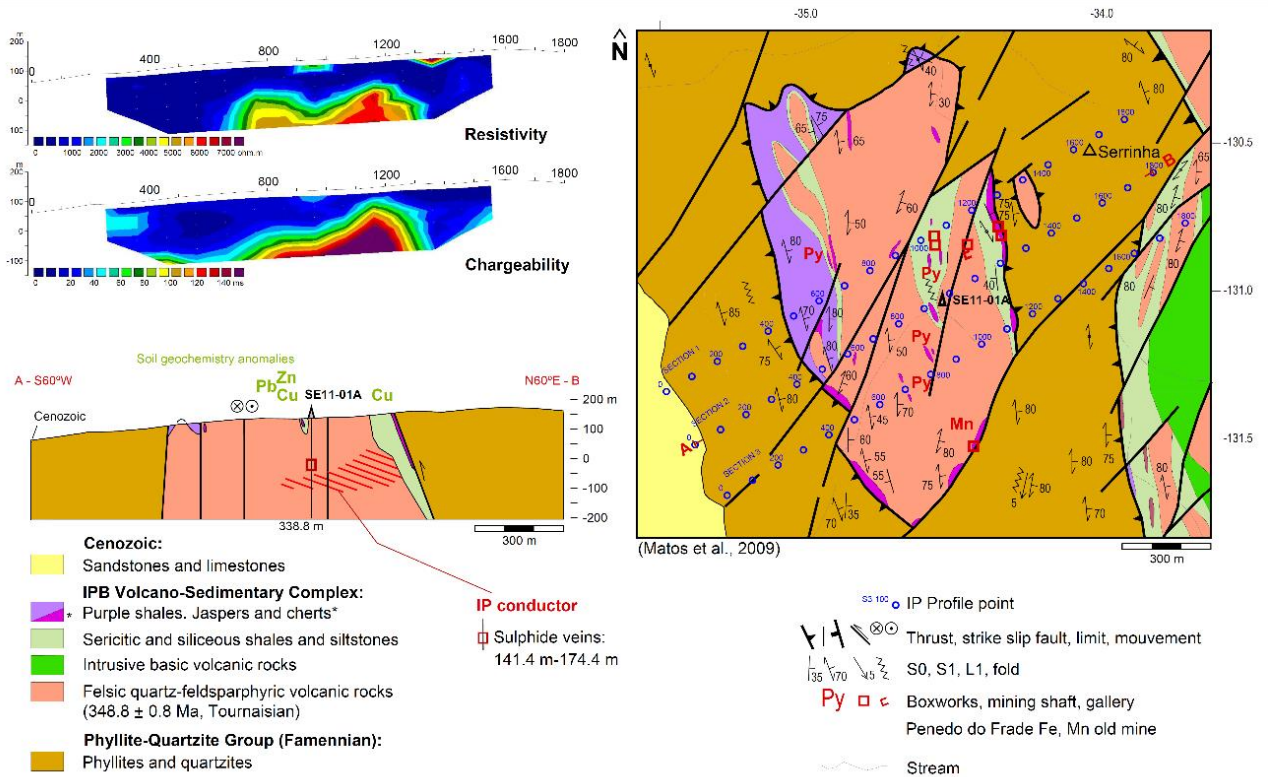


Figure 17. IPB Serrinha Paleozoic window sector LNEG exploration surveys carried out to Maepa Company (Matos *et al.*, 2009a, b; Ramalho and Matos, 2009): Resistivity and IP 2D profile S2 and geological A-B section of the SE11-01A drill hole (left) and 1/5000 scale geological map (Matos *et al.*, 2009). Coordinates Hayford-Gauss Lisbon IPCC in km.

Figura 17. Campanhas de prospeção realizadas pelo LNEG para a empresa MAEPA no setor da janela Paleozóica da Serrinha (Matos *et al.*, 2009a, b; Ramalho and Matos, 2009): Modelo 2D de resistividade eléctrica e polarização induzida S2 e secção geológica A-B da sondagem SE11-01 A (esquerda) e carta geológica à escala 1/5 000 (Matos *et al.*, 2009). Coordenadas Hayford-Gauss Lisboa IPCC em km.

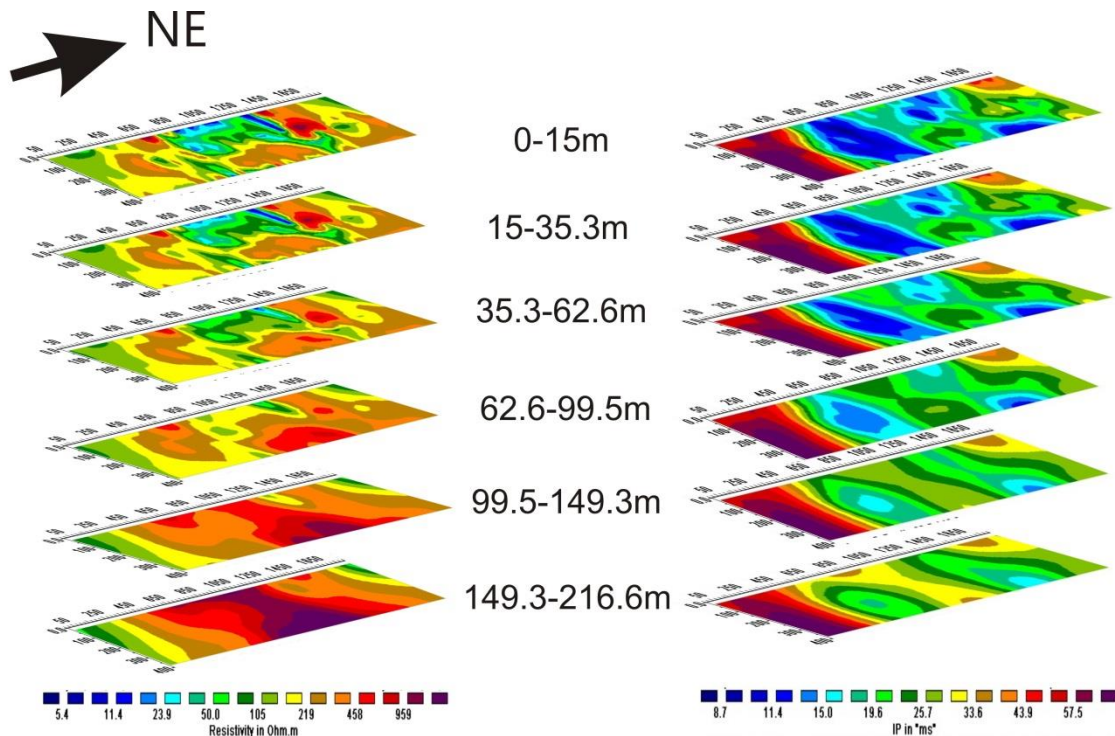


Figure 18. 3D models of electrical resistivity and IP profiles S1, S2 and S3, with interelectrode spacing of 100 m. See location in figure 17 (Matos *et al.*, 2009a, Ramalho and Matos, 2009).

Figura 18. Modelos 3D de resistividade eléctrica e polarização induzida dos perfis S1, S2 e S3, com espaçamento intereletrodo de 100 m. Ver localização na figura 17 (Matos *et al.*, 2009a, Ramalho and Matos, 2009).

the Spanish sector of the IPB, close to the Portuguese border (Simancas *et al.*, 2003). For the first time, the crust down to the Moho was imaged, giving unprecedented information about the rooting of several outcropping structures and geological formations (e.g. Simancas *et al.*, 2003; Carbonnell *et al.*, 2004). In Portugal, from 2010 onwards, AGC/Lundin Mining started to acquire 2D and 3D seismic reflection data in the Neves-Corvo area (Castelo Branco, 2011; Nobre *et al.*, 2013; Yavuz *et al.*, 2015). The results were positive and integrated with other geophysical and borehole data provided important results about the complex structure of the region and the possible location of orebodies (e.g. Lombador Neves-Corvo deposit).

At approximately the same time, useful results were obtained using high-resolution seismic reflection and gravimetric modelling for shallow massive sulphides exploration in the IPB western region (Carvalho *et al.*, 2011). Several profiles were acquired in the Marateca and Figueira de Cavaleiros/Lameira IPB sectors (Fig. 1), to estimate the thickness of Cenozoic sediments in the region, and

to identify the depth of the Palaeozoic basement and to locate the major fault zones. The structural information provided by these profiles and borehole data were available and were used to constrain gravimetric modelling. This methodology, supported by other geophysical data and density measurements in drill-holes, led to the identification of the sources of several gravimetric anomalies. Most of them had a structural origin.

Thus, in the Lameira case study (Carvalho *et al.*, 2011), seismic profiles developed across the Grândola Fault (see location in Fig. 1) were useful to detect the listric fault's geometry. The seismic information was correlated with three exploration holes, gravimetry and magnetometry. The geological and geophysical models are presented in figure 19.

Encouraged by these results, under the scope of the European Promine project it was decided to acquire a set of 2D seismic reflection profiles to provide structural information up to 4-5 km in the Portuguese sector of the IPB, from Neves-Corvo to the Spanish border in near Alcoutim (Inverno *et al.*, 2013; Inverno *et*

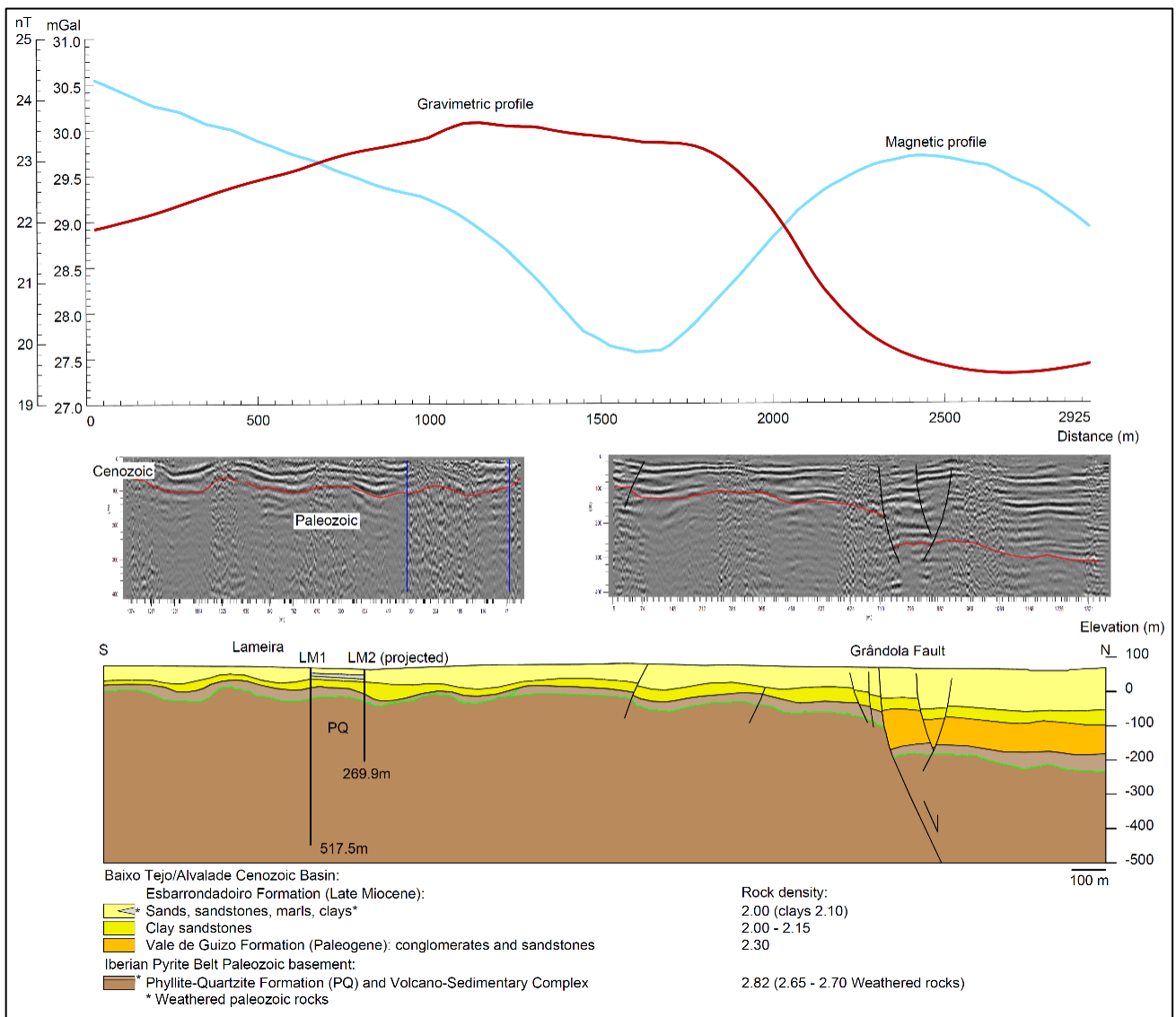


Figure 19. Lameira Grândola Fault sector geological section based on geophysical and geological data (geological mapping and IGM LM1 and LM2 drill holes). Top: Bouguer anomaly and magnetic anomaly profiles. Middle: depth converted seismic section (modified from Carvalho *et al.*, 2011); Bottom: geological cross-section resulting from the integrated interpretation.

Figura 19. Secção geológica da Falha de Grândola no setor de Lameira produzida a partir da interpretação de dados geológicos e geofísicos (cartografia geológica e sondagens LM1 e LM2 do IGM). Topo: perfis da anomalia de Bouguer e anomalia magnética. Meio: secção sísmica convertida para profundidade (atualizado de Carvalho *et al.*, 2011); Base: secção geológica.

et al., 2015; Carvalho, *et al.*, 2016). These profiles were acquired by LNEG with equipment rented to Prospectiuni and used in the Promine 3D geological modelling of the area, including data interpretation reaching a depth of 10 km.

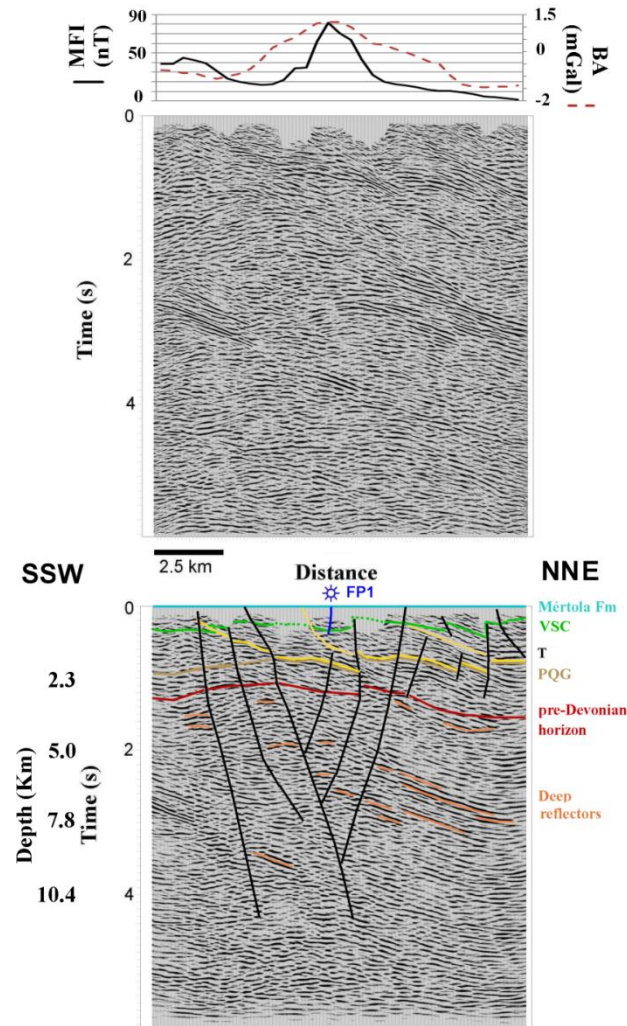


Figure 20. Unmigrated, Promine stacked seismic profile 6 with gravimetric and magnetic profiles plotted over the seismic section (top) and same profile with post-stack time migration applied and overlaid with stratigraphic and structural interpretation (bottom) (*in* Carvalho *et al.*, 2017). Mfi – magnetic field intensity (reduced to the pole); Ba – Bouguer anomaly. Black lines – faults; yellow lines/T – thrust planes; green line/VSC – Volcano-Sedimentary Complex; brown line/PQG – Phyllite-Quartzite Group; red line – pre-Devonian horizon. Fp1 – Foupana 1 drill hole with 890.1 m length, done by Billiton in 1986 at Odeleite region, NE Algarve (LNEG database).

Figura 20. Stack do perfil sísmico 6 do projeto Promine, não migrado e com os perfis da anomalia de Bouguer e anomalia magnética indicados em cabeçalho (topo) e o mesmo perfil com aplicação de migração no tempo pós-stack, com sobreposição da interpretação estratigráfica e estrutural (*in* Carvalho *et al.*, 2017) (fundo). Mfi – Intensidade do Campo Magnético (reduzida ao pólo); Ba – Anomalia de Bouguer. Linhas pretas – falhas; linhas amarelas/T – planos de cavalgamento; linha verde/VSC – Complexo Vulcano-Sedimentar; linha castanha/PQG – Grupo Filito-Quartzítico; linha vermelha – horizonte pré-Devónico. Fp1 – Sondagem Foupana 1 com 890,1 m de comprimento, executada em 1986 pela Billiton na região de Odeleite (NE do Algarve) (base de dados LNEG).

Data were acquired using a wireless Unite Sercel system with three synchronized 28 tonnes-each vibrators used as a seismic source, which provided energy to be recorded up to depths of 10 km (see Fig. 20). The interpretation of the seismic reflection data was undertaken in a 3D environment using geological outcrop,

radiometric, gravimetric, magnetic and drill-hole data (Carvalho *et al.*, 2017). Several SW-verging, deeply rooted thrust faults and nappes were identified in the seismic profiles that are cut by multiple late-Variscan strike slip faults, sometimes with minor normal component, also identified by the seismic data (Inverno *et al.*, 2015; Carvalho *et al.*, 2017). The interpretation confirmed the extension of the volcanic axis to the SE of Neves-Corvo until the Spanish border and allowed to estimate the depth of the ore bearing VSC rocks along those axes

10. Final remarks

Considering the large exploration experience acquired by different entities in the Portuguese and Spanish sectors of the Iberian Pyrite Belt, Geophysics is well established as an essential tool in research surveys. Considering the key IPB target, that is, massive, semi-massive, *stockwork*, vein and disseminated sulphide mineralizations, different geophysical methods must be used, and an integrated and multi-task exploration methodology must be considered. Therefore, different physical and rheological characteristics of the sulphide mineralizations, and associated host rock and hydrothermal systems must be considered in data interpretation. Other important factors in geophysical interpretation are rock deformation and lateral changes and internal facies variations of the volcanic and sedimentary geological formations, which form the geological setting of each IPB deposit. Regional IPB geophysical surveys are essential for the initial planning of the exploration projects. Considering this goal, LNEG's 1/400 000 mapping program allows an excellent approach to the western (Portuguese) sector of the belt, allowing a good correlation of the gravimetric, magnetic and radiometric maps (Batista *et al.*, 2016b; Represas *et al.*, 2016a, b). These maps can also be correlated with the IPB soil copper geochemistry data (Batista *et al.*, 2016a, 2020; Batista and Matos, 2016), remote sensing data (Quental *et al.*, 2020) and province mineral occurrence and drill hole distribution 1/400 000 scale map (Matos and Filipe Eds., 2013).

The IPB regional studies and research must be continued, considering the SPZ geological setting and earth crust zonation in the SW Iberia region. Future projects will involve magnetic and gravimetric data integration considering onshore and offshore surveys. This research is very important to achieve a better understanding of the deep source anomalies. Considering the SPZ regional study, new surveys must be considered involving gravimetric and magnetic surveys between the Cercal area and the Rosário/Ourique central IPB areas. Seismic profiles developed in the Neves-Corvo - Alcoutim region shows significant detail in the definition of the deep geological structures. Similar methodology must be applied in key sectors like Aljustrel-Roxo-Albernôa; Lousal/Caveira-Cidrão-São Francisco da Serra; Cercal, Alvalade Basin (Grândola-Alcácer) and São Domingos-Pomarão regions. These regional surveys are essential to the improvement of the IPB geological and geophysical knowledge. Considering the Iberian dimension of the belt, Portuguese-Spanish common IPB mapping must be considered by LNEG and IGME, following the past joint experiences in gravimetry, magnetometry and radiometry surveys.

At regional scale, the definition of accurate geological and geophysical 3D models is an important step to define sulphide ores targets, mainly with small dimension (< 1 000 m length). Considering the *near mining exploration* surveys performed by different companies close to the Neves-Corvo and Aljustrel mine centres, the use of different techniques and data integration is an essential approach, even if deep targets are considered (> 800 m

depth). Drill hole data interpretation is of crucial importance to define high resolution local scale models of the geological structures, which must consider sulphide ore type and zonation, hydrothermal events, geological units and variscan and late-variscan tectonics. Several sulphide ore structures show incipient geophysical studies, considering their high exploration potential (e.g. Lagoa Salgada, Rio de Moinhos, São Domingos, Chança and Montinho). In these and others geological favourable scenarios the gravimetric data, complemented with electromagnetic surveys, seismic reflection profiles and down hole EM logging can provide new targets to explore. In the near future, the *stockwork*, fissural/vein type ores, probably rich in > 1% Cu grades, are other key targets to follow. Geophysical methods must be adapted to these mineralizations hosted by volcanic and/or sedimentary rocks. Both Lower VSC sequence and PQ sediments must be considered favourable to *stockwork* mineralizations in this geological setting. In the case of Neves-Corvo, the combination of geophysical methods and drill-hole geochemistry is used presently to carry out 3D modelling, using Automated Neural Network that allows the management of a great amount of data. This approach allows an accurate exploration in complex areas.

The present paper is a contribution to the IPB exploration development and planning, considering the successful methodologies applied by the mining companies and the LNEG Geological Survey in the province, focused on the sulphide ore exploration. Since the 1950s an intense and fruitful dialogue between geologists and geophysicists started, forming the IPB exploration history and legacy. Prior to the mapping production and discussion, intense field work was developed on ground and airborne surveys, forming the basis of the present mining knowledge of the IPB European mine region, a Paleozoic territory with enormous potential in mineral exploration!

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