(1) SÃO DOMINGOS MINING SITE - IBERIAN PYRITE BELT

João Xavier Matos[a], Zélia Pereira[b], Maria João Batista[c], Daniel De Oliveira[c]

[a]LNEG, Unidade de Recursos Minerais e Geofísica, Ap. 104, 7801-902 Beja, Portugal.
[b]LNEG, Unidade de Geologia e Cartografia Geológica, Ap. 1089, 4466-901 S. Mamede de Infesta
[c]LNEG, Unidade de Recursos Minerais e Geofísica, Ap. 7586, 2721-866 Alfragide, Portugal.

The São Domingos VHMS deposit geology

Located in the northern sector of the Iberian Pyrite Belt (IPB) the São Domingos deposit was mined between 1857 and 1966 for pyrite, copper and sulfur production. During the Roman era the superficial and oxidized part of the unique vertical massive sulphide lens was intensely exploited (Matos et al. 2006; 2011). The São Domingos mine is one of the >90 volcanic-hosted massive sulfide IPB deposits, forming the main European mining region and a world-class base metal belt. The IPB is included in the South Portuguese Zone geological terrain, a major Variscan basement unit. The belt extends 250 km with WNW-ESE direction, from the Marateca area in the Portuguese Atlantic coast, southeast of Lisbon (Alentejo region), to the Seville area in Spain (Andalusia region) (Matos & Martins, 2006; Relvas et al. 2006; Tornos, 2006, Oliveira et al. 2006; Pereira et al. 2008; Matos et al. 2008). The IPB region has a Mediterranean climate characterized by a dry period from May to September and wet period from November to March.

The São Domingos mine is located in the northern branch of the IPB (Oliveira et al. 2006) and is characterized by a complex tectonic dominated by alocthnous structures, where two major units are considered (Oliveira, 1990; Barriga et al. 1997; Silva et al. 1997; Saez et al, 1999; Oliveira et al. 1992; 1997; 2005; 2006; Pereira et al. 2007; 2008): the Phyllite Quartzite Group (PQG) dated as Middle to Upper Devonian age and formed by a succession of phyllites, quartzites, quartzwackes and shales with intercalations of limestone lenses and nodules in the upper part, and the Volcano-Sedimentary Complex (VSC) dated as Upper Devonian to Upper Visean age. The PQG represents the detritic IPB basement forming a marine siliciclastic platform. The base of the unit is unknown [the older sediments where recognized at S. Francisco da Serra and Lousal (Pereira et al. 2010, Matos et al. 2011)]. The VSC incorporates several submarine volcanic episodes with dominant rhyolites, dacites, basalts, minor andesites, and intercalations of black shales, siltstones, minor quartzwackes, siliceous shales, jaspers and cherts, and purple shales. The massive sulphides and the manganese IPB deposits are related with the VSC units. Locally stockwork-type structures occur in the PQG (Barriga et al. 1997, Leistel et al. 1998; Matos et al. 2008; Oliveira et al. 2006; Pereira et al. 2008; Relvas et al. 2006). Above the IPB, VSC and PQG units a thick flysch turbiditic succession occurs (Oliveira, 1990; Pereira, 1999, Oliveira et al. 2006; Pereira et al. 2008) represented by the Baixo Alentejo Flysch Group (BAFG), with > 5 km thickness. The BAFG is represented by the Mértola (Upper Visean), Mira (Upper Visean to Lower Bashkirian) and Brejeira (Bashkirian to Upper Moscovian) formations. In the São Domingos region the first flysch sedimentation is represented by the Feixial Formation (Upper Visean). The IPB contacts in the north area of São Domingos with the Gafo Formation (Lower Frasnian, Pereira et al. 2008), formed by flysch units.

The São Domingos mine was one of the main industrial projects located in southern Portugal in the 19th century and until 1950's. Associated with the mining project one of the first railway system was built between the mine open pit and the Pomarão Guadiana River harbor, located 18 km south (Matos et al. 2006). The mine is located ~5kms near the Spanish border. Detailed geological mapping of the old open pit, of the mining area wastes and infrastructures between the São Domingos clear water dams (Tapada Grande and Tapada Pequena) and the downstream Chumbeiro dam permitted a correct interpretation of the mine site characteristics, see Fig. 3 (Matos 2004, Oliveira & Matos 2004, Matos et al. 2006a,b, Alvarez-Valero et al. 2008; Mateus et al. in press; Pérez-Lopéz et al. 2008).

The São Domingos deposit is a sub-vertical massive sulfide orebody located at the top of a VSC geological sequence, represented by black shales, felsic, basic and intermediate-basic volcanic rocks

(Matos et al. 2006a). These rocks are bounded, through thrust faults vergent to SW, by shales and quartzites of the Phyllite-Quartzite Formation and black shales and banded shales ascribed to the PQG Formation, both of late Devonian age (Pereira et al. 2008). The CVS and the deposit are preserved in a tectonic sheet with sigmoidal geometry and sinistral tectonic tension displacement.

The São Domingos VHMS deposit present the following main characteristics (Alvarez-Valero et al. 2008 in Mateus et al. 2011, Matos et al. 2006a,b, Matos & Oliveira 2004, Carvalho 1971, Webb 1958, Cabral 1889, inc. ref.):
Mineral assemblage: pyrite, sphalerite, chalcopyrite, galena, arsenopyrite and sulfosalts. Orebody footwall rich in copper (actual orebody northern sector), western and southern sectors rich in zinc.
Ore grades: 1,25% Cu, 2-3% Zn and 45-48% S.
Dimension: ~25Mt of massive sulfides, one pyrite lens being 537m long and 45m to 70m thick.
Mining methods: open pit and underground, pillars and chambers, cut and fill. Ore transported from open pit by railway to **Moitinha ore mills**, to the **Achada do Gamo sulphur factories** and to the **Pomarão harbour** (Guadiana River). Cu obtained by cementation evolving intensive ore leaching at Moitinha plateaus. Sulphur obtained by Orkla process.
Mine products: py, roasted py, sulphur, copper.
Reserves: gossan and roman slag wastes in excess of 1Mt have 1g/t Au.
Mining waste types: gossan (oxidized pyrite ore), host rocks (volcanics+shales), brittle massive pyrite and stockworks, roasted pyrite, sulphur plants ashes, modern slag and roman slag.

The São Domingos mine life cycle, from Romans to closure

The São Domingos gossan (iron cap) and associated roman slags were discovered in 1854 (Matos et al. 2006a,b inc. ref.]. The Mason & Barry Company mine owner exploited the São Domingos deposit by open pit until 120m depth and by underground works until 420m depth. Between 1867 and 1880 3 Mm^3 of rock were extracted from the open pit (Cabral et al. 1889). The drift network extends 1080m at the 150m level, from the main water pump shaft (headgear nº 6) to the ventilation shaft (nº 7) located in the eastern sector of the mine.

The mine closure in 1966 led to a social and economic decline of the region. Presently, a large negative environmental impact is detected in the mining area along the São Domingos stream valley, 11km affected by direct Acid Mine Drainage (AMD) from mine infrastructures (Matos & Martins 2006, Alvarez-Valero et al. 2008; Mateus et al. in press; Pérez-Lopéz et al. 2008). The Achada do Gamo sulfur factories area is marked by significant Pb, As, Sb, Cu, Zn and Fe anomalies in stream sediments, soils and waters. From 2004 onwards LNEG, the municipality of Mértola and the CCDR Alentejo have promoted a new approach to the São Domingos mining site with geo-eco-mining tourism as a possible solution. The excellent geological and mining heritage site conditions have been largely promoted, considering a network of geossites and mining areas along the Portuguese and Spanish Iberian Pyrite Belt (Matos et al. 2011).

The São Domingos massive sulphides ore mined in the mine's open pit and galleries were transported by railway to the Moitinha ore mills located downstream (see Fig. 1). Underground acid water pumped from 150 m depth at Shaft nr. 6 was transported by a network of channels to the Moitinha plateaus (Matos et al. 2006a,b). Here the pyrite ore was leached by acid water (Cabral 1889). The resulting copper enriched liquid was transported to the Achada do Gamo tanks to obtain native copper by cementation process (ionic change between iron from added scrap and copper dissolved in the mine acid water). At Achada do Gamo, Orkla process sulfur factories were constructed in the 1930's. This ore process method permitted the production of sulphur after pyrite roasting and gas control with a catalytic system. All mine products were transported by railway to the Pomarão harbor on the Guadiana River and exported mainly to Great Britain.

The São Domingos mining wastes were mapped at 1/2500 scale by ex-INETI (current LNEG). Several waste classes were identified at São Domingos during the LNEG mapping surveys performed in the terrain (Matos 2004, Matos et al. 2006a,b) and validated by hyperspectral image classification (Quental et al. 2002, 2003). Several mining wastes are considered (see Fig. 1): gossan material, brittle pyrite ore, host

rocks (volcanics and sediments), slag (Roman and modern), pyrite roasting products (Pb-rich ash and hematite-rich material), clay-silt leached materials.

Slag piles at São Domingos represent 8% of the mine residues accumulated in that place, recording discarded outputs of the ore smelting carried out in different periods of the massive sulfide and related gossan exploitation. The major slag constituents are crystalline silicates (mostly olivine and pyroxene), magnetite and glass; accessory amounts of sulfides and metal alloys are also present, sometimes coupled by sulfosalts (Pinto et al. 2007, Mateus et al. 2011). The slag is typically Fe-rich (30-40%) and contains up to 1.7% Zn, 0.9% Pb and 0.5% Cu, besides minor to trace contents in many other metals (e.g. Mn, Sb, Co, As, In, Ag, Bi, Ge). The maximum tailing thicknesses are found near the open pit with up to 14m of gossan+volcanic wastes (Matos et al. 2006a,b). Mining activities at São Domingos affected a total area of 2,963,900 m^2, from the village to the Chumbeiro downstream dam, located 11km southeast. Along the valley of the São Domingos stream, 767,659 m^2 is the area occupied by industrial landfill+leaching/cementation tanks and 722,737 m^2 of ore + host rocks tailings. In the mine area a total of 14,7Mm^3 of mining wastes are estimated, present in mining landfills and tailings with a heterogeneous size, changing from 14m near the open pit to less than 1m in the downstream areas (Matos 2004, Matos & Martins 2006, Alvarez-Valero et al. 2008; Mateus et al. in press; Pérez-Lopéz et al. 2008). Between Moitinha and the downstream Chumbeiro dam, and especially in the vicinity of the Achada do Gamo sulphur factories, large and significant AMD effects can be seen (Abreu et al. 2010). Large no-vegetation areas reflect the negative impact of decades of old mining techniques including acid water volume control using down slope water percolation to increase evaporation. Geochemical research shows anomalies in the following materials (Oliveira 1997, Batista et al. 2003, Quental et al. 2003, Matos & Martins 2006, Pinto et al. 2007):
Soils – Pb, As, S, Cu, Cd, Hg; Stream sediments - Pb, As, Sb, Cu, Zn, Fe, Ag, (V, Cr); Tailings – Zn, Pb, Sb, Cu, Ag, Hg, Cd; Superficial waters – Fe, Al, Mn, Co, Cu, As, Sb, Ni.

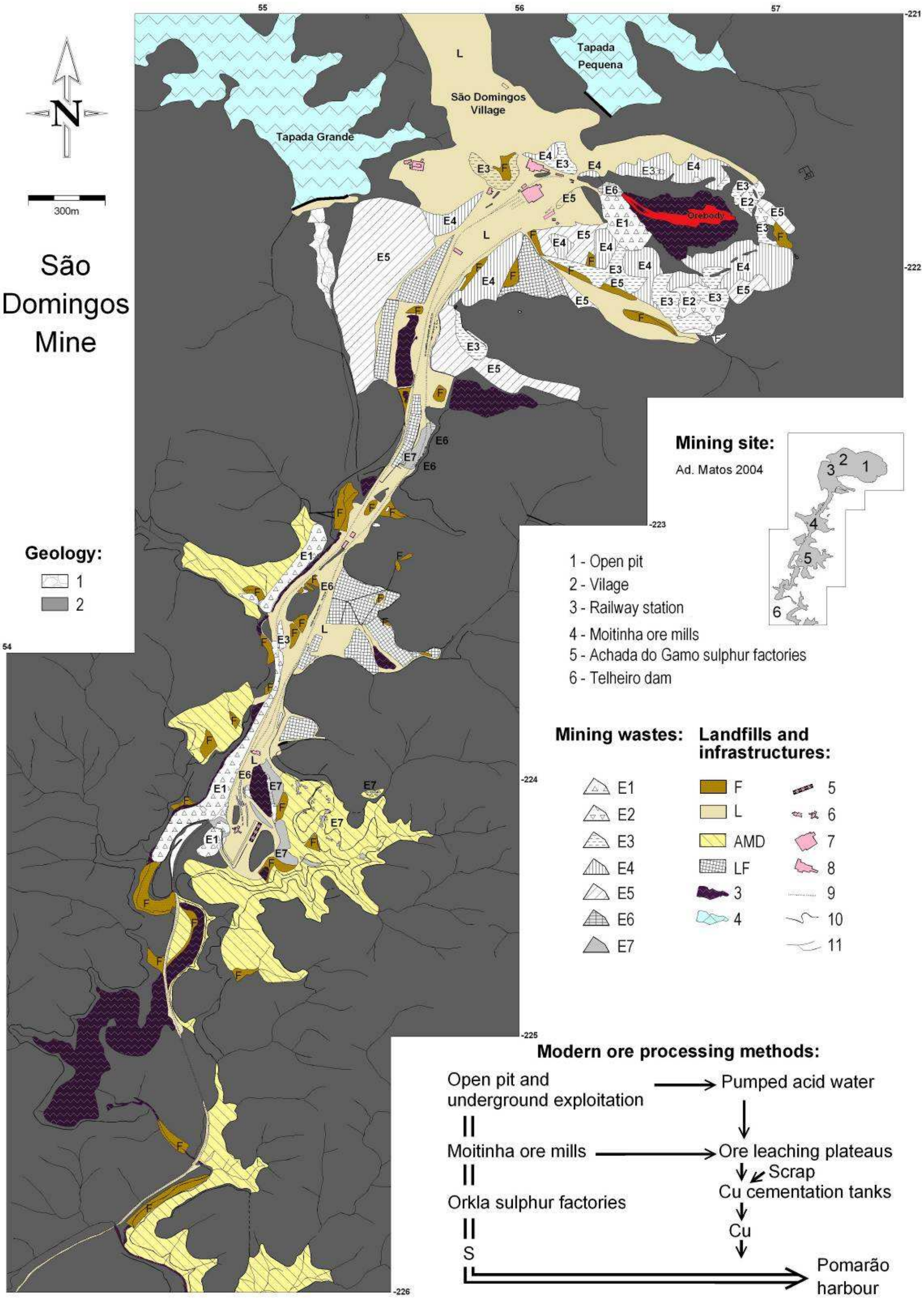

Fig. 1 - Simplified mining map of the São Domingos mine (ad. Matos 2004, in Mateus et al. 2011), Hayford-Gauss coordinates in km. Geology: 1. Alluvium; 2. Paleozoic basement. Mining waste: E1. Modern slag; E2. Roman slag; E3. Iron-hat material; E4. Meta-volcanic rocks and shales; E5. Shales; E6. Finely crushed sulphide ore; E7. Roasted sulphide ore. Landfills and infrastructures: F. Water-laid contaminated materials in seasonally flooded areas; L. Mine/urban contaminated landfills; AMD. Soilless areas due to ancient protracted acid mine water flow; LF. Sulphide ore leaching plateau; 3. Acid water dam/lagoon; 4. Clean

water dam; 5. Cu cementation tank; 6. Orkla sulphur factories; 7. Railway station; 8. Power plant; 9. Abandoned mine railway; 10. Mine canal; 11. Stream

References:

- Abreu, M.; Batista, M.J.; Magalhães, M.C.F.; Matos, J.X. (2010) Acid Mine Drainage in the Portuguese Iberian Pyrite Belt. Cap. II In Mine Drainage and Related Problems Book, Editor Brock C. Robinson, Nova Science Publishers, ISBN: 978-1-60741-285-4, New York, USA, 51pp.
- Abreu, MM; Tavares, MT; Batista, MJ. (2008). Potential use of Erica andevalensis and Erica australis in phytoremediation of sulphide mine environments: São Domingos, Portugal. Journal of Geochemical Exploration, 96, 210-222.
- Álvarez-Valero, A.M.; Pérez-López, R.; Matos, J.X.; Capitán, M.A.; Nieto, J.M.; Saez, R.; Delgado, J.; Caraballo, M. (2008) Potential environmental impact at São Domingos mining district (Iberian Pyrite Belt, SW Iberian Peninsula): evidence from a chemical and mineralogical characterization. Environ Geololgy 55, DOI 10.1007/s00254-007-1797-1809.
- Barriga, F., Carvalho, D., Ribeiro, A., 1997. Introduction to the Iberian Pyrite Belt. SEG Neves Field Conference. Guidebook Series, Vol.27. 1-20.
- Batista, M. J. (2000) Environmental State in the Portuguese Test Site S. Domingos Mine: Past and Present Report European Comission (http://www.brgm.fr/mineo/IGM_test_site.pdf): 41 p.
- Batista, M. J. Brito, M. G. Abreu, M. M. Sousa, A. J. Quental L. & Vairinho M. (2003) - Avaliação por modelação em SIG da contaminação mineira por drenagem ácida em S. Domingos (Faixa Piritosa, Alentejo). Ciências da Terra (UNL), Lisboa, nºesp. V. CD-ROM, pp. M6-M10.
- Cabral, J.; Monteiro, S.; Barata, J. (1889) – Catalogo Descriptivo da Secção de Minas Gr. I e II. Associação Industrial Portugueza, Exposição Nacional das Industrias Fabris, Lisboa, Imprensa Nacional, 502pp..
- Carvalho, D. (1971) Mina de S. Domingos. Jazigos Minerais do Sul de Portugal, Livro-Guia nº4, pp. 59-64.
- Cunha T., Oliveira J., 1989. Upper Devonian Palynomorphs from the Represa and Phyllite- Quartzite Formationa, Mina de São Domingos region, Southwest Portugal. Tectonostratigraphic implications. Bulletin Société Belge Géologie 98/3-4, 295-309.
- Feliciano, R.; Mateus, A.; Matos, J.X. (2008) - Distribuições espaciais das concentrações em Cu, Zn, Pb e Co apresentadas por sedimentos de corrente no domínio setentrional da Zona Sul Portuguesa; implicações para a prospecção mineral. V Sem. Rec. Geológicos, Ambiente e Ordenamento do Território, UTAD Vila Real, pp. 13-22.
- Gama, H. (2005) – Questões ambientais na indústria mineira moderna. Abst. III Encontro de Comunidades Mineiras de Aljustrel, CM Aljustrel.
- Jorge, RCGS, Relvas, JMRS, Matos, JX, 2006. Geochemistry of metasediments from the Phyllite-Quartzite Group, Iberian Pyrite Belt: provenance, source-area weathering and geotectonic implications. Geochimica et Cosmochimica Acta, 70(18), supplement 1: A298.
- Leistel, J., Marcoux, E., Thieblemont, D., Quesada, C., Sanchez, A., Almodovar, G., Pascual, E., Saez, R, 1998. The volcanic-hosted massive sulphide deposits of the Iberian Pyrite Belt. Review and preface to the special issue. Mineralium Deposita 33, 2-30.
- Marcoux, E., 1998. Lead isotope systematics in the giant massive sulphide deposits in the Iberian Pyrite belt. Mineralium Deposita 33, 45-58.
- Mateus, A.; Pinto, A.; Alves, L.C.; Matos, J.X.; Figueiras, J.; Neng, N. (2011) Roman and modern slag at S. Domingos mine (IPB, Portugal): compositional features and implications for their long-term stability and potential re-use. International Journal of Environment and Waste Management Inderscience Publishers Ltd, Vol. 8, nº1/2, 39pp.
- Matos, J.X. (2004) Carta geológico-mineira de S. Domingos, esc. 1/5000, IGM.
- Matos, J.X. (2005). Carta geológica e mineira da Mina de Aljustrel esc. 1/5000, INETI.
- Matos, J.X., Martins, L.P., 2006. Reabilitação ambiental de áreas mineiras do sector português da Faixa Piritosa Ibérica: estado da arte e perspectivas futuras; Boletín Geológico y Minero, Espanha, 117 (2), 289-304.
- Matos, J.X.; Barriga, F.J.A.S.; Oliveira, V. (2003) - Alunite veins versus supergene kaolinite/halloysite alteration in the Lagoa Salgada, Algares and S. João (Aljustrel) and S. Domingos massive sulfide deposits, Iberian Pyrite Belt, Portugal Ciências da Terra (UNL), Lisboa, V, pp. B56-B59.
- Matos, J.X.; Martins, L.P.; Oliveira, J.T.; Pereira, Z.; Batista, M.J.; Quental, L. (2008) - Rota da pirite no sector português da Faixa Piritosa Ibérica, desafios para um desenvolvimento sustentado do turismo geológico e mineiro. Livro Rutas Minerales en Iberoamérica, Ed. Paul Carrion, Esc. Sup. Politécnica, Guayaquil, Equador, pp 136-155.
- Matos, J.X.; Pereira, Z.; Oliveira, V.; Oliveira, J.T. (2006a) The geological setting of the São Domingos pyrite orebody, Iberian Pyrite Belt. VII Cong. Nac. Geologia, Estremoz, Un. Évora, Portugal, pp. 283-286.
- Matos, J.X.; Soares, S.; Claudino, C. (2006b) Caracterização Geológica-geotécnica da corta da mina de São Domingos, FPI. X Cong. Nac. Geotecnia, SPG/UNL, v. 3, pp. 741-752.
- Matos, J.X.; Pereira, Z.; Rosa, C.J.P.; Rosa, D.R.N.; Oliveira, J.T.; Relvas, J.M.R.S. 2011. Late Strunian age: a key time frame for VMS deposit exploration in the Iberian Pyrite Belt. 11TH SGA Biennial Meeting, Antofagasta, Chile, Abs. Book 4 pp.
- Nero, G. 2005. A problemática da recuperação ambiental das áreas mineiras degradadas a nível nacional. Abst. III Encontro Comunidades Mineiras de Aljustrel, CM Aljustrel.
- Oliveira J.T., Carvalho P., Pereira Z., Pacheco N., Fernandes J., Korn D., 1997. The stratigraphy of the Neves Corvo Mine Region. Society
- Oliveira, J.T., Relvas, J. M. R. S., Pereira, Z., Matos, J. X.,Rosa, C. J., Rosa, D. 2006. O Complexo Vulcano-Sedimentar da Faixa Piritosa: estratigrafia, vulcanismo, mineralizações associadas e evolução tectonoestratigráfica no contexto da Zona Sul Portegusa. In R. Dias, A. Araújo, P. Terrinha, & J.C. Kulberg (Eds.), Geologia de Portugal no Contexto da Ibéria (pp. 207–244). Univ. Évora, Portugal: VII Cong. Nac. Geologia.
- Oliveira, J., Silva, J., 1990. Carta Geológica de Portugal à escala 1:50000, Folha 46-D, Mértola. Serviços Geológicos de Portugal.
- Oliveira, J., Silva, J., Oliveira, V., Munhá, J., Matos, J., 1998. Geologia da região compreendida entre Mértola, Pomarão e Mina de São Domingos. In: Oliveira, J.T., Dias R.P. (Eds.,), Livro Guia de Excursões. V Congresso Nacional de Geologia, Instituto Geológico e Mineiro, 101-110.
- Oliveira, J.T., 1990. Stratigraphy and syn-sedimentary tectonism in the South Portuguese Zone. In: Dallmeyer R.D., Martinez Garcia E., (Eds.,), Pre-Mesozoic Geology of Iberia, 334-347.
- Oliveira, J. T., coord. (1984) - Not. Explicativa Carta Geológica de Portugal na escala 1/200.000 Notícia Explicativa da Folha 7 Serv. Geológicos de Portugal.
- Oliveira, J.T.; Matos, J.X. (2004) – O caminho de ferro da Mina de S. Domingos ao Pomarão: um percurso geo-educacional na Faixa Piritosa Ibérica. XXIV Encontro Prof. Geociências APGeólogos, Beja, 19pp..
- Oliveira, J.T.; Silva, J.B. (1990) Carta Geológica de Mértola Fl. 46D na escala 1/50000, SGP.
- Pereira, R., Ribeiro, R. and Gonçalves, F., 2004. Plan for an Integrated Human and Environmental Risk Assessment in the S. Domingos Mine Area (Portugal). Human and Ecological Risk Assessment: An International Journal 10, 3. 543-578.
- Pereira, Z. (1999) Palinoestratigrafia do Sector Sudoeste da Zona Sul Portuguesa. Comunicações IGM, Portugal 86, pp. 25-57.
- Pereira, Z., Matos, J., Fernandes, P., Oliveira, J.T., 2007. Devonian and Carboniferous palynostratigraphy of the South Portuguese Zone, Portugal - An overview. Comunicações Geológicas, 94, 53-79.

- Pereira, Z., Matos, J.X., Fernandes, P., Oliveira J.T., 2008. Palynostratigraphy and Systematic Palynology of the Devonian and Carboniferous Successions of the South Portuguese Zone, Portugal. Memórias do INETI, N.º 34, 1-176.
- Pérez-López, R; Álvarez-Valero, AM; Nieto, JM; Sáez, R; Matos, JX. (2008). Use of sequential extraction procedure for assessing the environmental impact at regional scale of the São Domingos Mine (Iberian Pyrite Belt). Applied Geochemistry, 23, 3452-3463.
- Pinto, A.; Mateus, A.; Alves, L.C.; Matos, J.X.; Neng, N.; Figueiras, J. (2007) - Detailed slag characterization relevance in environmental and economic assessments; the example of São Domingos (Iberian Pyrite Belt, Portugal), VI Cong. Geoquímica, UTAD Vila Real, pp. 345-348.
- Quental, L.; Bourguignon, A.; Sousa, A. J.; Batista, M. J.; Brito, M. G.; Tavares, T.; Abreu, M.M.; Vairinho, M. & Cottard F. (2002) - MINEO Southern Europe environment test site Contamination /impact mapping and modelling – Final report. Assessing and monitoring the environmental impact of mining activities in Europe using advanced Earth Observation techniques (MINEO) 5thFP - IST–1999-10337.
- Quental, L.; Brito, M. G.; Sousa, A. J.; Abreu, M. M.; Batista, M. J.; Oliveira, V.; Vairinho, M. & Tavares, T. (2003) - Utilização de imagens hiperespectrais na avaliação da contaminação mineira em S. Domingos, Faixa Piritosa, Alentejo. Ciências da Terra (UNL), Lisboa, nºesp. V. CD-ROM, pp. M33-M36.
- Relvas JMRS, Barriga FJAS, and Longstaffe F, 2006b. Hydrothermal alteration and mineralization in the Neves-Corvo volcanic-hosted massive sulfide deposit, Portugal: II. Oxygen, Hydrogen and Carbon Isotopes. Economic Geology 101-4: 791-804.
- Relvas JMRS, Barriga, FJAS, Ferreira, A, Noiva, PC, Pacheco, N, Barriga, G, 2006a. Hydrothermal alteration and mineralization in the Neves-Corvo volcanic-hosted massive sulfide deposit, Portugal: I. Geology, Mineralogy, and Geochemistry. Economic Geology 101-4: 753-790.
- Silva, J., 1998. Enquadramento geodinâmico da Faixa Piritosa na Zona Sul Portuguesa. In: Oliveira, J.T., Dias, R.P., (Eds.,). Livro Guia, V Congresso Nacional de Geologia. Excursão 2, 79-89.
- Tornos, F., 2006. Environment of formation and styles of volcanogenic massive sulfides: the Iberian Pyrite Belt. Ore Geology Reviews, 28, 259-307. doi:10.1016/j.oregeorev. 2004.12.005.
- Webb, J. (1958) Observations on the geology and origin of the San Domingos pyrite deposit. Portugal. Com. SGP, t. 42, pp. 119-143.