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Evaluation of the mining potential of the São Domingos mine wastes, Iberian Pyrite Belt, Portugal

Avaliação do potencial mineiro das escombreiras da mina de São Domingos, Faixa Piritosa Ibérica, Portugal

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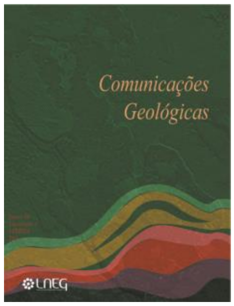

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Abstract: The outcropping São Domingos Iberian Pyrite Belt deposit was mined since Roman time and between 1857 and 1966. The mine is formed by a 120 m depth flooded open pit and galleries until 420 m depth. Associated with felsic volcanic rocks and black shales of the Volcano-Sedimentary Complex, the deposit is formed by massive sulphide and stockwork ore (py, ccp, sp, ga, tt, apy) and related supergene enrichment ore (hematite gossan and covellite/chalcocite). Different mine wastes classes were mapped: gossan, felsic volcanic and shales, shales and landfill. Considering the CONASA mining waste characterization (162 shafts and 160 reverse circulation boreholes/LNEG database), new inferred resources are presented, using block modelling software: 2.38 Mt @ 0.77 g/t Au and 8.26 g/t Ag in non-conditioned volumes. Considering all evaluated wastes, including urban areas, an inferred resource of 4.0 Mt @ 0.64 g/t Au and 7.30 g/t Ag is presented, corresponding to a metal content of 82,878 oz t Au and 955,753 oz t Ag.

Keywords: São Domingos mine, mining wastes resources, Iberian Pyrite Belt.

Resumo: Localizado na Faixa Piritosa Ibérica, o jazigo de São Domingos foi explorado na época Romana e no período entre 1857 e 1966, tendo sido escavada uma corta com 120 m de profundidade e abertas galerias mineiras até 420 m. O minério é formado por sulfuretos maciços e *stockwork* (py, ccp, sp, ga, tt, apy) e respetivo enriquecimento supergénico (chapéu de ferro hematítico e zona de covelite/calcocite), encontrando-se associado a rochas vulcânicas félsicas e xistos negros do Complexo Vulcano-Sedimentar. Cartografaram-se diferentes classes de escombreiras: chapéu de ferro, rochas vulcânicas e xistos, xistos e aterros. Considerando a sua caracterização efetuada pela empresa CONASA (162 poços e 160 sondagens de circulação inversa/base de dados LNEG), foram inferidos novos recursos usando *software* de modelação por blocos: 2,38 Mt @ 0,77 g/t Au e 8,26 g/t Ag (volumes não condicionados). Considerando todos os recursos avaliados (incluindo áreas urbanas) inferem-se valores de 4,0 Mt @ 0.64 g/t Au e 7,30 g/t Ag, correspondendo a um conteúdo em metal de 82 878 oz t Au e 955 753 oz t Ag.

Palavras-chave: Mina São Domingos, recursos em escombreiras mineiras, Faixa Piritosa Ibérica.

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1. Introduction

Rediscovered in 1854 and exploited between 1857 and 1966 by the Mason and Barry Company, the São Domingos mine is an example of old exploitation of an Iberian Pyrite Belt (IPB) pyrite rich massive sulphide deposit (Webb, 1958; Matos *et al.*, 2006, 2008; Matos and Martins, 2006). The orebody is associated to black shales and felsic, intermediate and basic volcanics of the IPB Volcano-Sedimentary Complex (VSC), of Strunian-Upper Visean age. These rocks are surrounded by shales and quartzites of the Phyllite-Quartzite Formation of Famennian age (Oliveira and Matos, 2004; Matos *et al.*, 2006; Pereira *et al.*, 2008), all affected by SW vergent thrust faults. The VSC and the deposit are preserved in a tectonic sheet with sigmoidal geometry (Matos *et al.*, 2006). The mineralization is represented by massive sulphide and stockwork ore (pyrite, chalcopyrite, sphalerite, galena, tetrahedrite, arsenopyrite and sulfossalts). Intense oxidation and supergene enrichment occur related with the deposit erosion and represented by hematite gossan and covellite/chalcocite zone.

The mine is located in the northern IPB sector, 5 km westwards from the Spanish border. The São Domingos subvertical E-W ore-body (537 m length, with variable thickness from 45 m to 70 m) was exploited in open pit until 120 m depth and in underground mining (chambers and pillars, cut and fill) until 420 m depth (Webb, 1958; Matos *et al.*, 2006, 2008). Between 1867 and 1880, 3 M m^3 of rock were extracted from the open pit (Cabral *et al.*, 1889). The pyrite ore was transported by railway to the Moitinha ore mills, and then to the Achada do Gamo sulphur factories. The final products were transported to the Pomarão mine harbour, located 18 km south, at the Guadiana River. The mine products were pyrite, roasted pyrite, sulphur and copper. Native copper was obtained through extensive ore leaching cementation at Moitinha plateaus (Matos *et al.*, 2006, 2008). Associated intense acid mine drainage occurs and large areas are occupied by different mine wastes (Quental *et al.*, 2003; Matos, 2004; Abreu *et al.*, 2010; Mateus *et al.*, 2011; Batista *et al.*, 2012).

The extractive activities affected a total area of 3,076,900 m^2, from the São Domingos village to the Chumbeiro dam, located 11 km downstream. A total of 14,7 M m^3 of mining wastes are estimated, presenting heterogeneous dimensions (from $\leq$1 to $\geq$14 m thickness) (Matos, 2004; Pérez-Lopéz *et al.* 2008; Alvarez-Valero *et al.* 2008; Pérez-Lopéz *et al.*, 2008; Mateus *et al.*, 2011).

The present work is focused in the São Domingos mine northern sector wastes, considering their high economic potential, characterized by gossan, volcanic and sedimentary ore host rocks. These wastes were mapped in detail by Matos (2004) and previously evaluated by the Spanish mining company Compañia Nacional de Piritas, S.A. (CONASA) (Fernandez and Mora, 1992). The metal distribution was based in the CONASA lithogeochemical results archived at the LNEG's database. Considering the presence of urban areas settled above the mining wastes (São Domingos 19th and 20th village constructions) two different scenarios were considered: total resources and conditioned resources.

2. Data used for resource estimation

The evaluation of the São Domingos mine wastes was based on a data set from an historical drilling and sampling program carried between 1990 and 1991 by CONASA (Fernandez and Mora, 1992). The sampling was carried out in 17 piles of four waste classes: gossan (W1), felsic volcanics and shales (W2), shales (W3) and 6 landfill locations (W4) (Fig. 1), by mean of reverse circulation drilling (RC) for sampling, and pitting for size fraction sampling and waste thickness measuring. Waste mapping (Matos, 2004) was updated using field work and Bing Maps aerial orthophotographs.

The CONASA mine waste evaluation program was focused in the northern mining area, around the open pit and the Mina de São Domingos village (Fig. 2). The modern slags and brittle pyrite ore mine wastes located respectively in the southern and western sectors of the mine open pit were not evaluated by the Spanish company. Other key areas of the mine were not evaluated like the São Domingos stream valley, Moitinha and Achada do Gamo landfills and mine wastes (see waste location in Matos, 2004; Mateus *et al.*, 2011).

The CONASA borehole and pit distribution pattern is irregular, seeming to be randomly distributed through the waste piles areas, with an average sampling spacing of 30 m (Fig. 2).

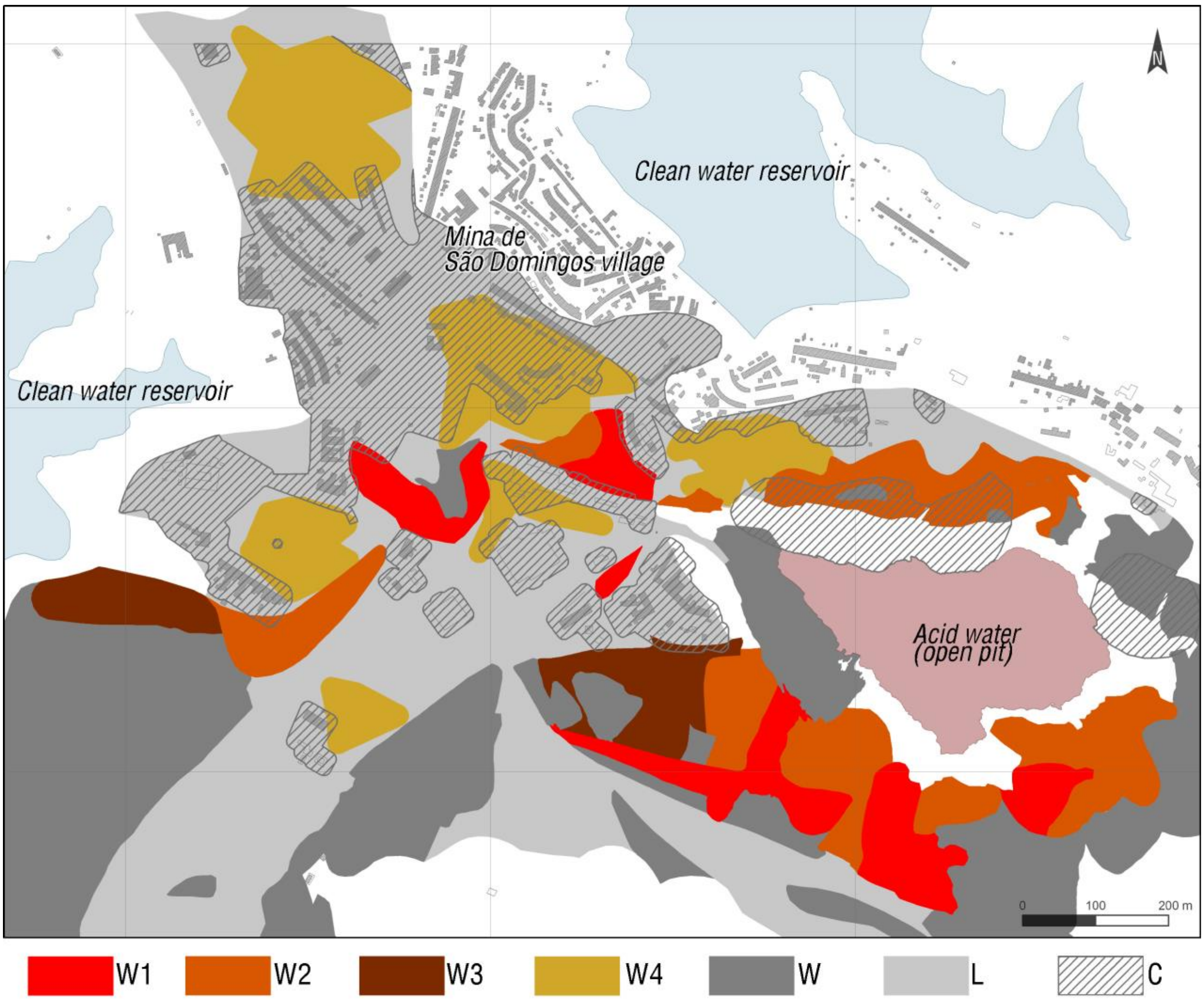

Figure 1. Study area located near the old mine open pit: location of the mining wastes and landfill areas assayed for gold and silver. W1 – gossan; W2 – felsic volcanic rocks and shales; W3 – shales; W4 – landfill areas for resource estimation; W – other mining wastepiles; L – landfill mining wastes; C – conditioned exploration waste areas. Mine tailings mapping (Matos, 2004).

Figura 1. Área de estudo localizada na proximidade da antiga corta mineira: localização das escombreiras e áreas de aterro analisadas para ouro e prata. W1 – Chapéu de ferro; W2 – rochas vulcânicas e xistos; W3 – xistos; W4 – áreas de aterro para estimação de recursos; W – outros resíduos em escombreira; L – resíduos em aterro; P – áreas com exploração condicionada. Cartografia de escombreiras (Matos, 2004).

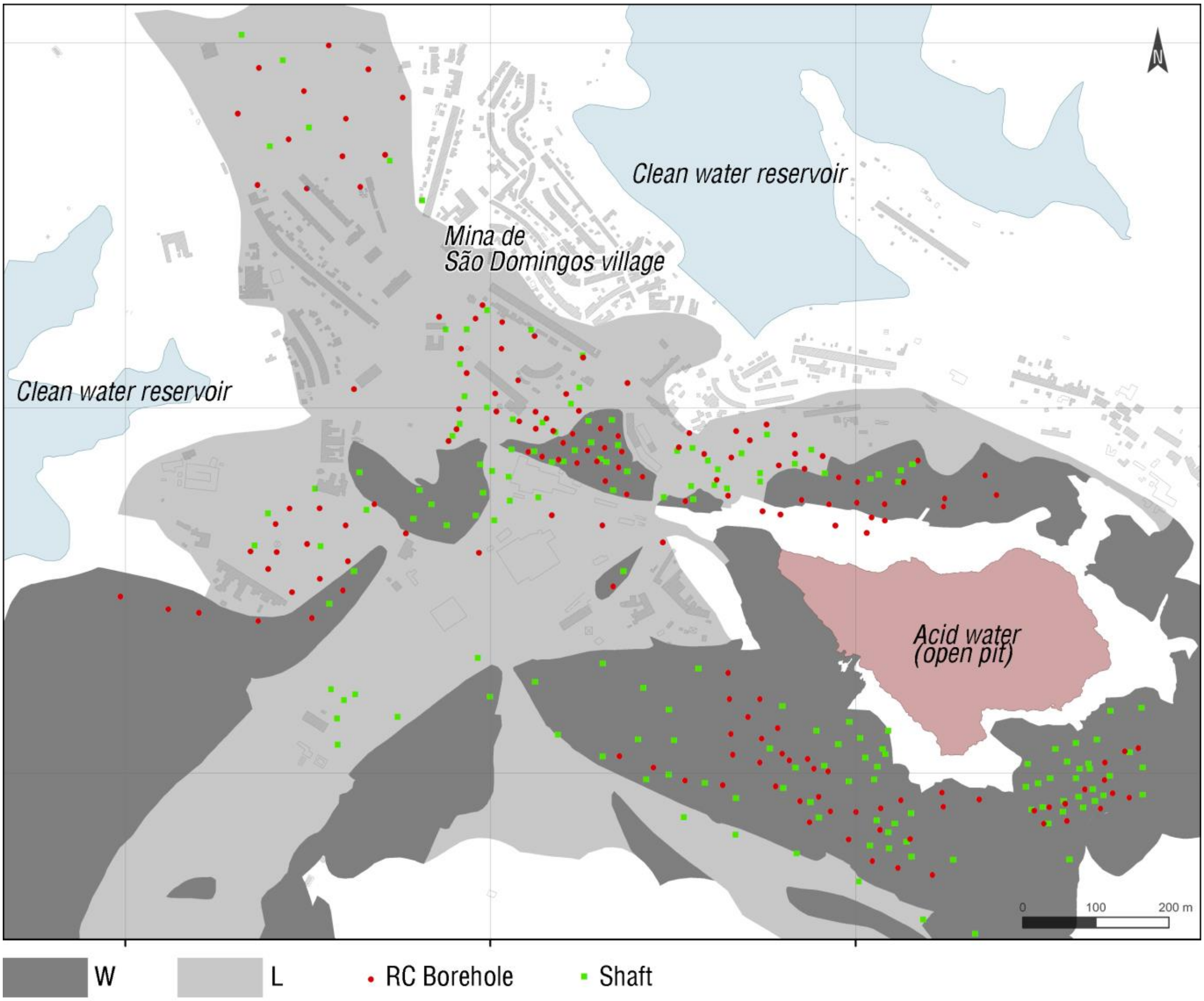

Figure 2. Evaluation of the São Domingos mine wastes by CONASA and location of the shafts and reverse circulation boreholes (Fernandèz and Mora, 1992). W – waste piles; L – landfills.

Figura 2. Avaliação das escombreiras efetuada pela CONASA e localização dos poços e sondagens de circulação inversa (Fernandèz e Mora, 1992). W – escombreira; L – aterros.

The data set contains 160 vertical boreholes (total of 1,884 m) and 162 pits (total of 1,307 m), acomplishing 1148 samples analysed by fire assay for Au and Ag (detection limits: 0.10 g/t Au; 1.0 g/t Ag). The RC boreholes were sampled in fixed length intervals (2 m), and the pits in varying lengths, providing 1 to 3 samples at successively deeper levels (maximum 12.5 m deep). The individual pit samples were sorted into 4 size fractions (> 40 mm; 40-9 mm; 9-5 mm; < 5 mm) and assayed for Au and Ag.

A statistical analysis of the data set was conducted using the raw assay data grouped by waste pile, material class and size fraction (Tab. 1). Assay statistics were calculated with GEOVIA Surpac 6.6 using the "basic statistics window" tool, and size fraction assay statistics with R language (R project).

The highest average gold grades are in the wastes composed by gossan fragments (class W1; Fig. 1, Tab. 1), with waste piles average gold concentrations ranging from 0.52 to 1.62 g/t (class mean = 0.93 g/t Au), and silver from 6.10 to 20.00 g/t (class mean = 10.07 g/t Ag). The assays from waste piles composed by felsic volcanics rocks and shales (class W2; Fig. 1) have gold concentrations varying from 0.16 to 0.85 g/t (class mean = 0.60 g/t Au), and silver from 1.81 to 34.93 g/t (class mean 8.34 g/t Ag). The landfill wastes (class W4; Fig. 1) have average gold concentrations varying from 0.58 to 0.94 g/t (class mean = 0.63 g/t Au), and silver average concentrations ranging from 7.19 to 9.10 g/t (class mean = 7.24 g/t Ag). The shale piles (class W3; Fig. 1) seems to be the waste class with least economic value, with average gold grades ranging from 0.21 to 0.26 g/t Au (class mean = 0.22 g/t Au), and also the lowest silver concentrations, varying from 2.73 to 3.45 g/t (class mean = 3.04 g/t Ag). The average concentration for all the sample assays is 0.69 g/t gold and 8.27 g/t Ag (Vieira, 2015).

As shown by the standard deviations and coefficients of variation (Tab. 1), the variability in gold and silver content of the samples is high, probably due to the process of dumping material from various parts of the mine into the stockpiles, which is expected to decrease the continuity and increase the nugget effect. The standard deviation for all waste classes sample assays is 0.79 g/t Au and 10.40 g/t Ag. In a further variability of the gold and silver assays test, the statistics for the sample assays were recalculated with extreme high-grade values (outliers) capped. In this process, the assay data was capped accordingly the anomalous outlier population identified in each body data set, by the definition of an upper limit based on the data statistical parameters (mean plus two standard deviations (Parrish, 1997)). The capping affected a total of 41 samples, corresponding approximately to 5% of the total used in estimation (877). This procedure led to the reduction of the global standard deviation by 17.4%, which is a large change for the elimination of so few values. The global assay mean was reduced by 5.2%.

Table 1. Basic statistics for São Domingos mine sample assay data, and average Au and Ag grades in the waste size fractions.

Tabela 1. Parâmetros estatísticos básicos da informação amostral recolhida em São Domingos, e teores médios de Au e Ag nas frações granulométricas.

Class	W1		W2		W3		W4	
	Au (g/t)	Ag (g/t)	Au (g/t)	Ag (g/t)	Au (g/t)	Ag (g/t)	Au (g/t)	Ag (g/t)
Maximum	5.25	202.00	6.45	97.00	0.55	6.00	8.00	44.65
Mean	0.93	10.07	0.60	8.34	0.22	3.04	0.63	7.24
Std. dev.	0.89	14.90	0.73	10.00	0.14	1.65	0.76	7.40
CV	0.95	1.48	1.22	1.20	0.60	0.54	1.20	1.02
Average grades in the fraction sizes								
> 40 mm	1.59	8.77	1.20	12.88	0.22	3.06	1.22	9.92
9-40 mm	1.18	9.38	0.93	8.14	0.17	3.13	0.77	9.20
5-9mm	1.05	9.74	0.60	8.72	0.18	2.00	0.73	8.40
< 5 mm	0.87	10.15	0.58	10.86	0.25	3.38	0.70	10.61

Note: Std. dev. – standard deviation; CV – coefficient of variation

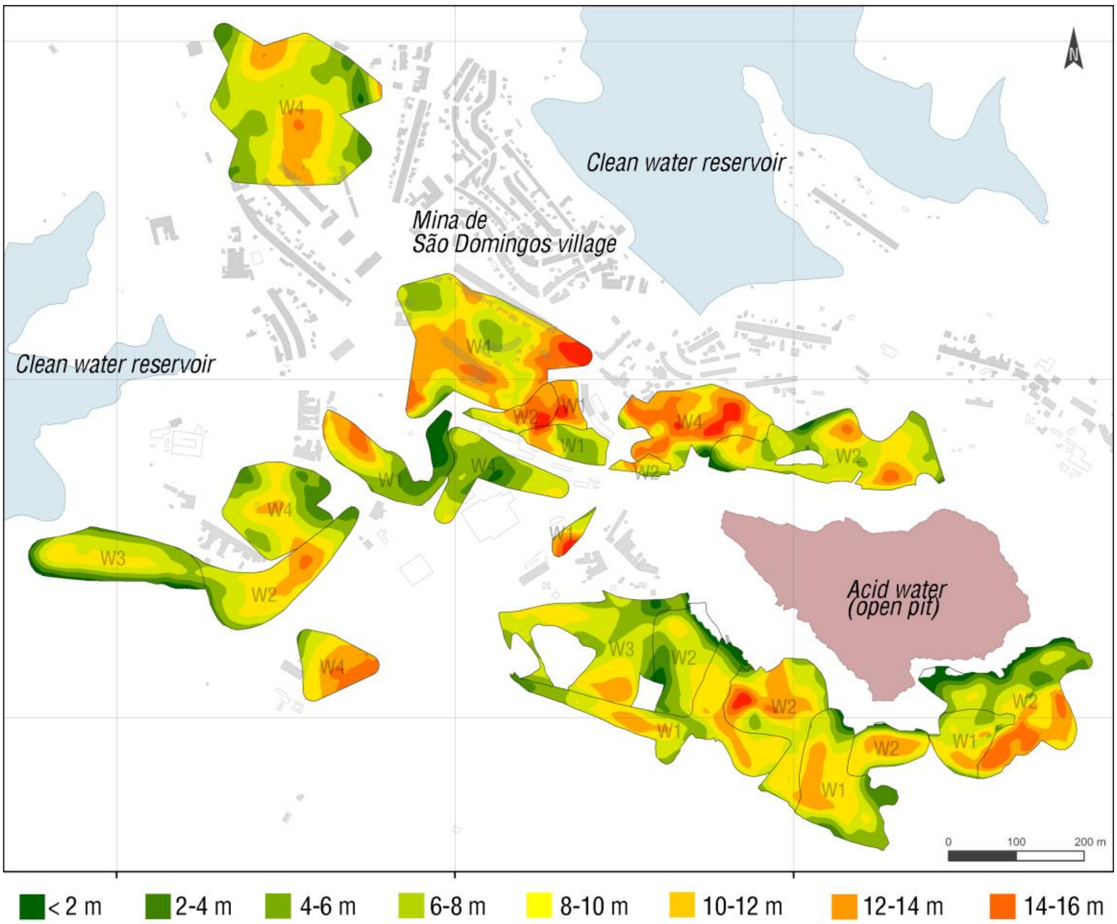

Figure 3. Thickness of the São Domingos mine waste piles and landfills evaluated by CONASA in 1991. Mine tailings mapping ad. Matos (2004). W1 – gossan; W2 – felsic volcanic and shales; W3 – shales; W4 – landfill areas for resource estimation.

Figura 3. Espessura das escombreiras e aterros da mina de São Domingos avaliados pela CONASA em 1991. Cartografia de escombreiras ad. Matos (2004). W1 – Chapéu de ferro; W2 – rochas vulcânicas e xistos; W3 – xistos; W4 – áreas de aterro para estimativa de recursos.

From table 1, an overall increase in Au correlates with an increase in size fraction. The average grade in the coarser fraction (> 40 mm) had grades greater than 1.20 g/t Au in all classes, with exception of W3 class (shales), where the Au grades were consistently low (< 0.25 g/t Au) in all size fractions. No apparent correlation is visible for Ag grades and size fraction, being the average grades of the size fractions very proximate.

3. Mine waste volume modelling methodology

The volume modelling was performed by defining a group of boundaries for each waste pile: the present terrain surface (upper boundary); the original terrain surface, before the waste heaping (lower boundary); and a polygon representing the extent of the pile (lateral boundary).

The upper boundary was extracted from a digital elevation model (DEM) from the INETI MINEO project (10 m res.) (Quental *et al.*, 2003). The lower boundary surface was interpolated in ArcMap 10.2 from the coordinate points of the bottom of the pits (true thickness), using a spline function for interpolation (2 m res.). The thickness of the evaluated mine tailings and landfills are presented in figure 3, showing major volume of mine wastes in the north-western and southern open pit sectors. In some areas, the waste thickness is greater than the excavator reach (12.5 m). Every pit with a depth equal to the equipment maximum reach was compared with the nearby borehole data, and, if suspected more than 12.5 m of waste thickness, the pit was discarded for surface modelling purposes, and drillhole data was used instead. The quality of the lower surface boundary model was assessed by modelling a drainage system from the surface model with ArcMap hydrology tools, and by comparing it with the drainage system and old mine waste heaps (probably all with Roman age) mapped in the 1850´s, in the initial administrative phase of the São Domingos mine (demand of exploitation polygon) prior to the development of the modern mining works. These were initially defined by sub-vertical mine shafts and a near surface network of galleries and later (after 1867) by a large open pit, shafts and deep galleries (Ribeiro, 1857; Cabral, *et al.*, 1889; Custódio, 1996; Matos *et al.*, 2011).

The results revealed a good correlation between the modelled drainage system and the existing one in the 19th century (Fig. 4), and thus the modelled surface was accepted as representative of the original terrain surface. In both cases the mainstream drainage is to SW, being the basin conditioned by differential erosion of VSC rhyolite volcanic rocks, by the siliceous gossan of the São Domingos deposit and also by the Phyllite-Quartzite Formation.

The lateral waste pile boundaries were created in ArcMap based on the mine waste cartography (Matos, 2004). During this process, it was considered the fact that a part of the wastes is under the São Domingos Mine village (*vd.* Fig. 1) and in the vicinity of protected sites (*e.g.*, mine heritage sites like roman galleries and slags and 19th and 20th centuries mining infrastructures).

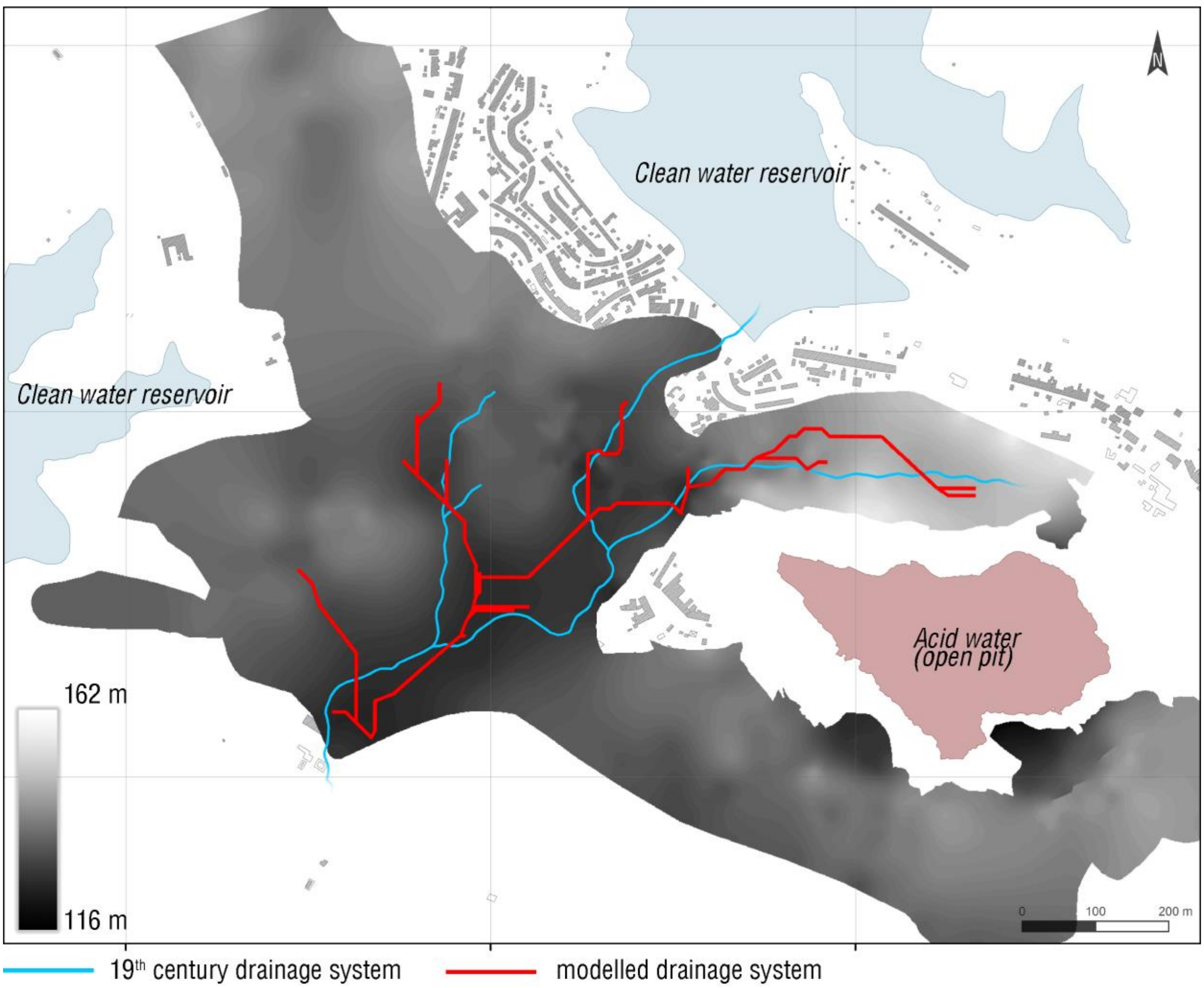

Figure 4. Waste lower boundary surface model and drainage systems (19th century, prior to waste dumping (Ribeiro, 1857), and modelled from the surface model).

Figura 4. Modelo da superfície da base dos resíduos e redes de drenagem (séc. XIX, antes da deposição de resíduos (Ribeiro, 1857) e inferida a partir do modelo).

This means that part of the area occupied by the mine wastes is conditioned for exploration, wherein the waste removal will be either impossible, or will have negative socio-economic impacts that need to be thoroughly assessed beforehand. Having this possible restriction in mind, a second set of polygon boundaries was defined, corresponding only to the non-conditioned part of the waste areas, where waste remobilization is possible.

Separate block models, constrained by the defined boundaries, were created for each of the 23 waste piles and landfill bodies in GEOVIA Surpac software. Block sizes were chosen to take into account the sample spacing – a quarter of the average sample spacing (Sinclair and Blackwell, 2004). The average thickness of the block models varies between 7 and 12 m, and the maximum thickness observed is 16 m. The volume for all the block models is 2,615,850 m^3, or 2,152,559 m^3 if considered only the non-conditioned portion.

The assay data analysis revealed that a few of the boreholes have bottom interval samples with high Au and Ag grades when compared to the remaining borehole samples. If the location of these boreholes is superimposed with the roman slags mapped in the 19th century (Ribeiro, 1857), before the modern exploration of the mine and waste dumping, it's possible to realize that those samples are located in roman slag areas (Fig. 5), which have a high precious metal content (Mateus *et al*., 2011; Matos *et al*., 2011). This means that some of the waste models are possibly not formed by one waste material, but by a mixture of different layered waste types, and that the existent roman slags are still beneath the modern mine wastes deposited in the 19th century, above Roman scorial fields, *e.g.*, the southern mine open pit area.

4. Resource estimation

Grades for gold and silver were interpolated into the block models by the inverse distance squared method, using between 2 to 12 samples to estimate block grades [Figs. 6a (Au) and 6b (Ag)]. The size of the search neighbourhoods was set accordingly to the average spacing between samples, assuring that all the blocks reached the minimum samples required. Bulk density values between 1.83 and 1.30 were applied to all blocks within the models, considering the average specific gravity of the main lithological constituents and a void ratio of 0.30.

Considering the fact that the resource estimates are for mining wastes, no cut-off grade was applied to the reported resource, as any practical recovery of the precious metals will probably require the processing of all the materials in the piles.

However, in order to determine an amount of material with reasonable prospects for eventual economic extraction, *i.e.*, "high grade" materials with no removal restrictions, only the piles with an average gold grade above 0.50 g/t were considered for reporting (Tab. 2).

These criteria excluded all the piles of the shales class (W3), in which the average modelled Au and Ag grades are very low, averaging between 0.19 to 0.21 g/t Au and 2.70 to 2.83 g/t Ag.

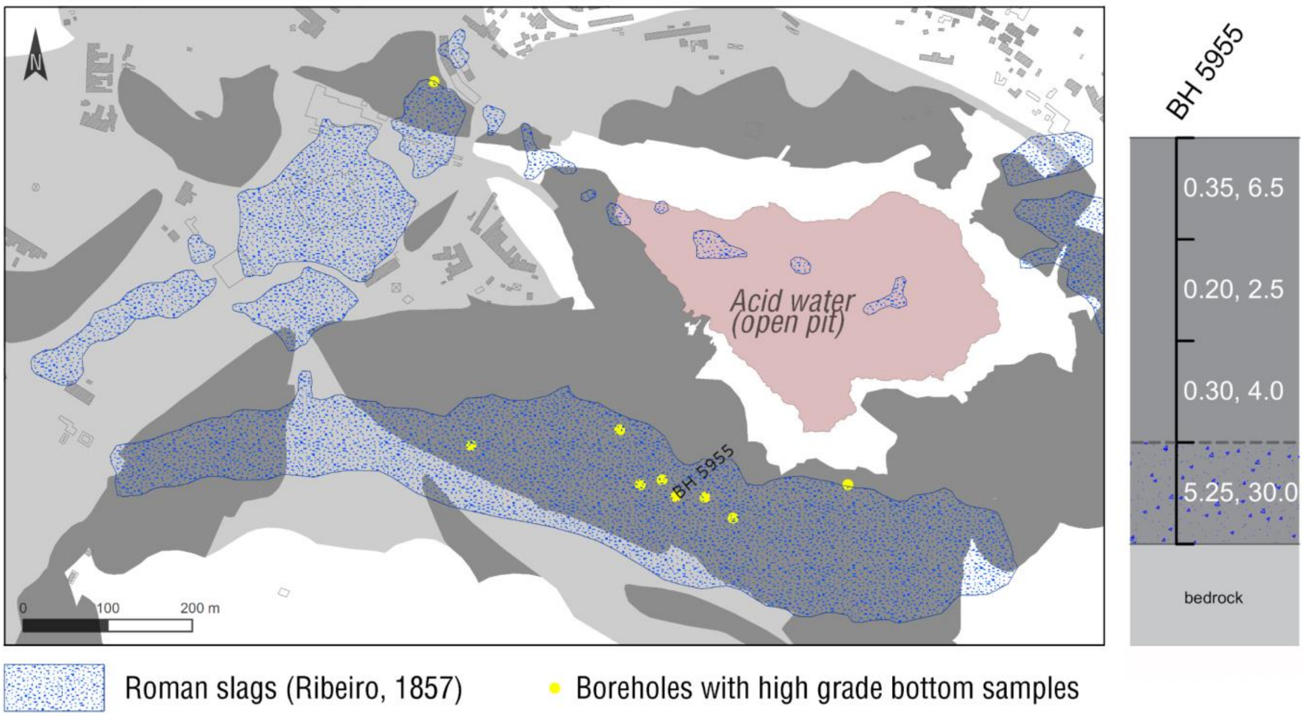

Figure 5. Left: high grade borehole bottom samples and 19th century roman slag locations (Ribeiro, 1857). Right: interpretation of the profile of the borehole n.er 5955 (Au (left), Ag (right) in g/t). The bottom interval has much higher values, thus corresponding to roman slags identified by CONASA.

Figura 5. Esquerda: localização das amostras da base dos furos com teores elevados e localização das escórias romanas no séc. XIX (Ribeiro, 1857). Direita: interpretação do perfil do furo n.º 5955 (Au (esquerda) e Ag (direita) em g/t). O intervalo da base tem valores muito mais elevados, correspondendo a escórias romanas identificadas pela CONASA.

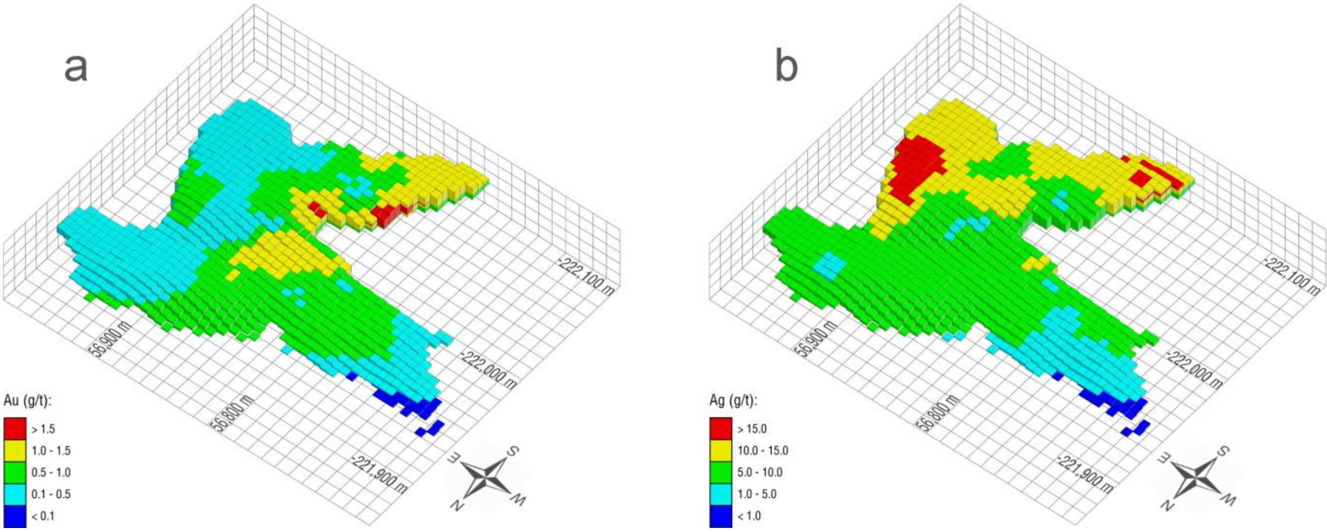

Figure 6. Distribution of gold (a) and silver (b) grades in one of the block models from a felsic volcanics and shales (class W2) waste pile. Grid line intervals: 10 m.

Figura 6. Distribuição de teores de ouro (a) e prata (b) num dos modelos de blocos das escombreiras de rochas vulcânicas e xistos (classe W2). Grelha de 10 m.

Three of the eight piles composed of felsic volcanic rocks and shales (class W2) were also excluded, with average grades ranging from 0.08 to 0.40 g/t Au and 0.60 to 5.76 g/t Ag. Only one model of the gossan wastes class (W1) was excluded, averaging 0.43 g/t Au and 5.08 g/t Ag. None of the landfill models (class W4) were excluded.

Table 2. Estimated resources in the non-conditioned volumes of the waste pile and landfill models with an average gold grade above 0.50 g/t.

Tabela 2. Recursos estimados no volume não condicionado dos modelos de escombreira e aterro com teor médio de ouro acima de 0,50 g/t.

Class		W1	W2	W4	Total
Quantity (t)		613,208	667,150	1,105,121	2,385,479
Grade (g/t)					
	Gold	1.07	0.71	0.65	0.77
	Silver	10.01	8.61	7.08	8.26
Contained metal (oz t)					
	Gold	21,145	15,266	23,078	59,489
	Silver	197,443	184,581	251,464	633,488

Due to the inexistence of bulk density data in the historical drilling campaign reports, poor spatial distribution of the boreholes, and high variability gold and silver grades within the wastes, it is deemed appropriate to consider all modelled blocks as *Inferred resources*. Considering the economic profit associated to a future re-mining phase of the São Domingos mine, further and finer work must be developed in the mine, in order to improve the data resolution related to the special distribution of precious metals in the mine wastes. This mining scenario must consider and integrate the other land uses planed to the São Domingos region like mine rehabilitation (Matos and Martins, 2006), mine and geological tourism (Matos *et al*., 2008; Matos and Pereira, 2013) and nature tourism (Sardinha *et al*., 2013).

5. Conclusions

The research work is focused on the study of the gold and silver rich mining wastes present in the mine northern sector. These wastes were produced by the old mine owner Mason and Barry Company and are characterized by gossan, volcanic and sedimentary rocks of the IPB Volcano-Sedimentary Complex. These wastes were mapped in detail by Matos (2004) and previously evaluated by the CONASA Company (Fernandez and Mora, 1992). The metal distribution study was based in the CONASA waste lithogeochemistry data, present at LNEG databases, related with shafts and reverse circulation boreholes performed at São Domingos mine site. The results revealed an inferred mineral resource of 2.38 Mt in the non-conditioned volumes of the “high grade” waste piles and landfill models (Au > 0.5 g/t), with an average grade of 0.77 g/t Au and 8.26 g/t Ag, totalling a metal content of 59,489 oz t gold and 633,488 oz t silver. If the conditioned part of the volumes were to be considered, the mineral resource increases to 2.94 Mt with an average grade of 0.77 g/t Au and 8.27 g/t Ag, corresponding to 72,871 oz t Au and 781,531 oz t Ag.

If all the 17 waste piles and 6 landfill resource models estimated in this investigation were to be considered (Figs. 7 and 8), *i.e*., including both high and low grade models, and the portions with probable conditioned exploitation, *i.e*., edified and protected areas, the mineral resource could be increased to 4.0 Mt with an average grade of 0.64 g/t Au and 7.30 g/t Ag, corresponding to a metal content of 82,878 oz t gold and 955,753 oz t silver.

The size fraction analysis revealed that the highest gold grade is in the fraction above 40 mm in all the waste classes, indicating that is possible to concentrate the highest-grade materials by screening the coarser fragments. However, the weight percentages for each fraction are unknown, because there is no

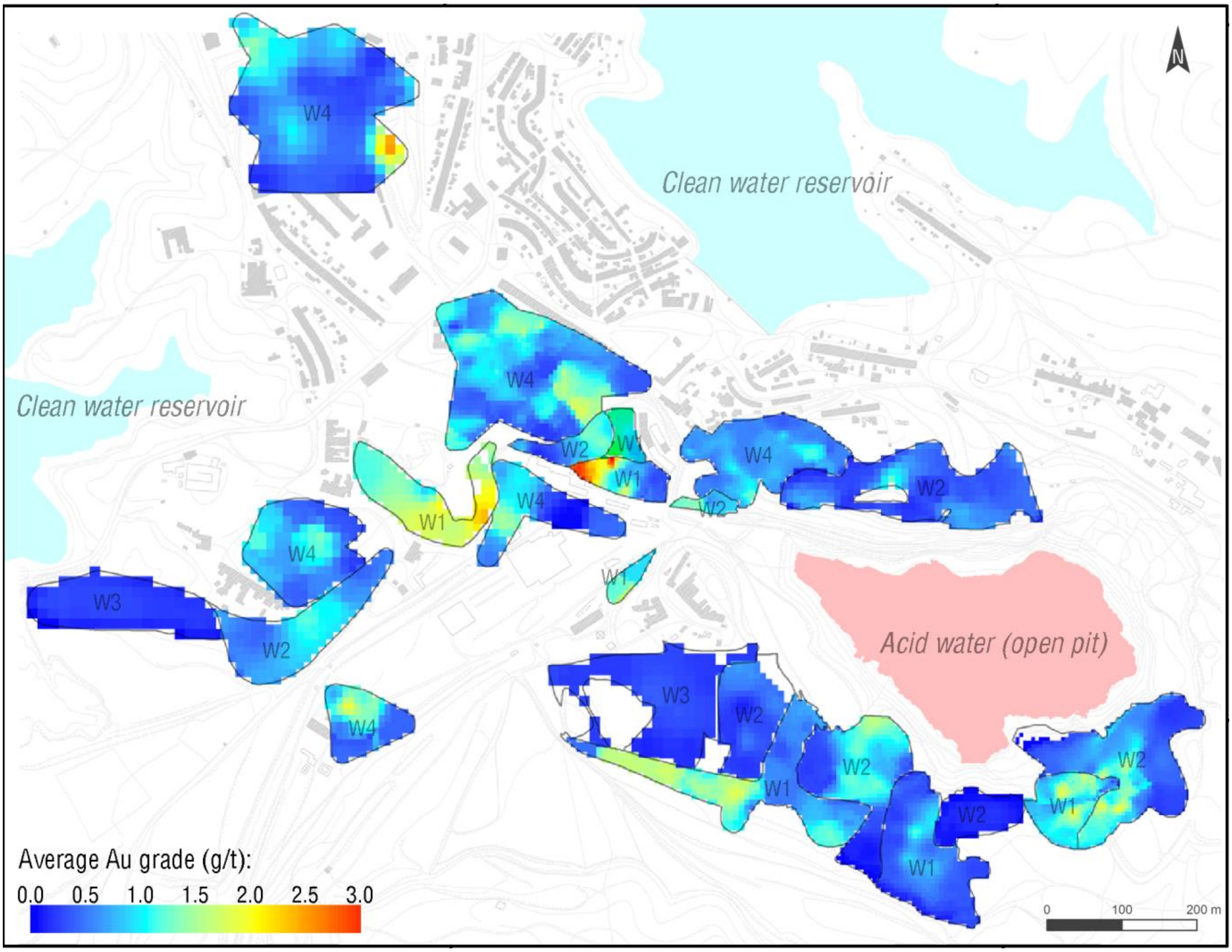

Figure 7. Estimated gold grades distribution in the sampled waste piles and landfill areas. W1 – gossan; W2 – felsic volcanic and shales; W3 – shales; W4 – landfill areas for resource estimation.

Figura 7. Distribuição dos teores de ouro estimados nas escombreiras e zonas de aterro amostradas. W1 – Chapéu de ferro; W2 – rochas vulcânicas e xistos; W3 – xistos; W4 – áreas de aterro para estimação de recursos.

information about these values in the CONASA historical borehole database, therefore, further characterization of the waste particle size is needed in order to effectively verify this possibility.

Considering the presence of urban areas (São Domingos village) on top of the mining wastes, two different resource scenarios must be considered: total resources and conditioned resources. In possible future mine extractive projects, a further detailed knowledge is needed, complementary to the CONASA exploration previous work. The characterization of the vertical zonation of the mining wastes will be essential to define high grade levels. In future land use plans of the São Domingos mining area, the balance between economic mine profit and negative impacts of the waste exploitation must be evaluated.

The São Domingos mine re-mining phase must be properly planned, considering the mine rehabilitation plan and current heritage promotion projects (geossites, mining and archaeological sites). In this balance is essential to improve the knowledge related to the existing geological resources (non-mined massive sulphide ore and mine wastes). The present evaluation work is a contribution to the understanding of the São Domingos mining potential.

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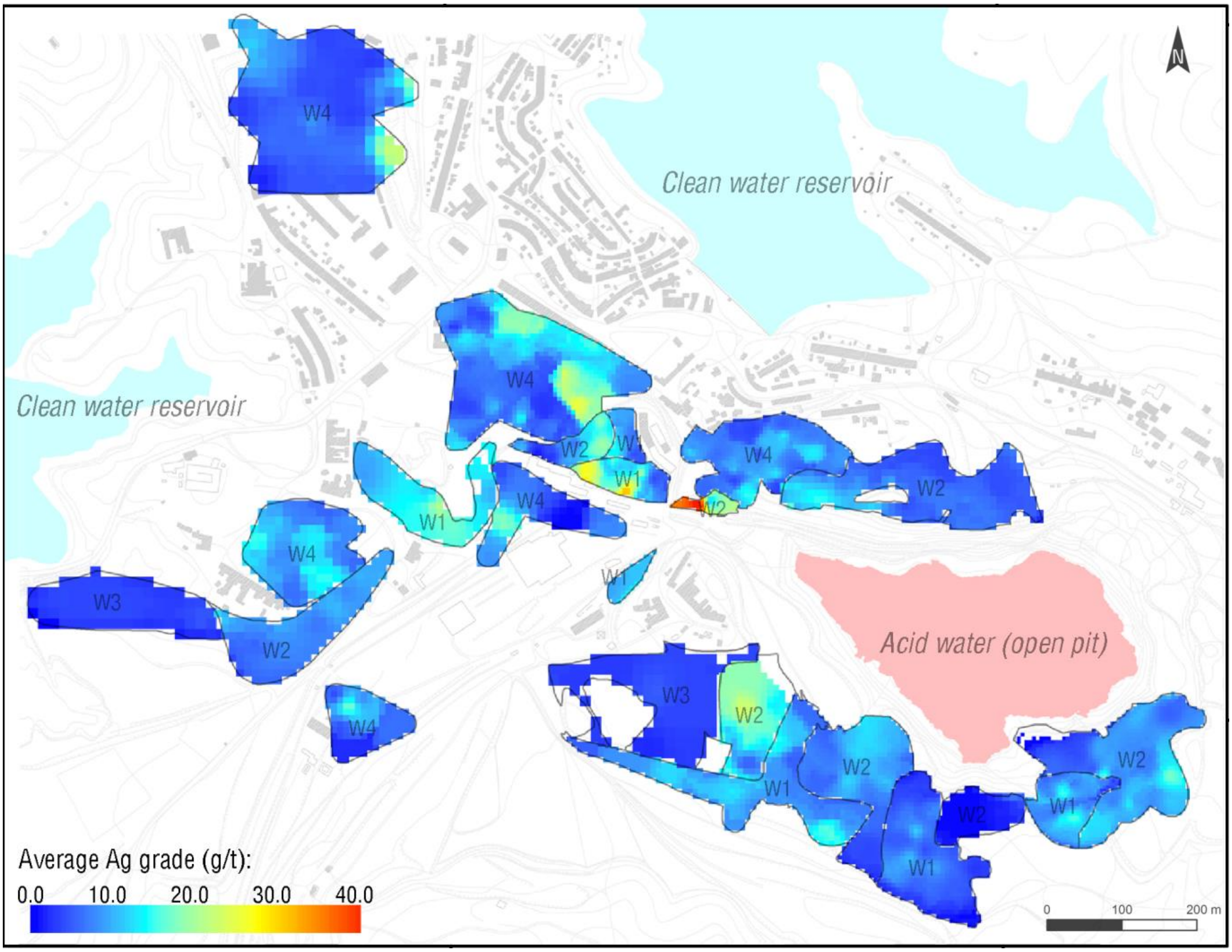

Figure 8. Estimated silver grades distribution in the sampled waste piles and landfill areas. W1 – gossan; W2 – felsic volcanic and shales; W3 – shales; W4 – landfill areas for resource estimation.

Figura 8. Distribuição dos teores de prata estimados nas escombreiras e zonas de aterro amostradas. W1 – Chapéu de ferro; W2 – rochas vulcânicas e xistos; W3 – xistos; W4 – áreas de aterro para estimação de recursos.

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